# ANSYS LS-DYNA®
## KEYWORD USER'S MANUAL

## VOLUME III

## Multiphysics Solvers

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LS-DYNA MULTIPHYSICS USER'S MANUAL

# INTRODUCTION

In this manual, there are five main solvers: two compressible flow solvers, an incompressible flow solver, an electromagnetism solver, and a battery electrochemistry solver. Each of them implements coupling with the structural solver in LS-DYNA.

The keywords covered in this manual fit into one of three categories. In the first category are the keyword cards that provide input to each of the multiphysics solvers that in turn couple with the structural solver. In the second category are keyword cards involving extensions to the basic solvers. Presently, the chemistry and stochastic particle solvers are the two solvers in this category, and they are used in conjunction with the *CESE compressible flow solver discussed below. In the third category are keyword cards for support facilities. A volume mesher that creates volume tetrahedral element meshes from bounding surface meshes is one of these tools. Another is a data output mechanism for a limited set of variables from some of the solvers in this manual. This mechanism is accessed through *LSO keyword cards.

The CESE solver is a compressible flow solver based upon the Conservation Element/Solution Element (CE/SE) method, originally proposed by Chang of the NASA Glenn Research Center. This method is a novel numerical framework for conservation laws. It has many non-traditional features, including a unified treatment of space and time, the introduction of separate conservation elements (CE) and solution elements (SE), and a novel shock capturing strategy without using a Riemann solver. This method has been used to solve many types of flow problems, such as detonation waves, shock/acoustic wave interaction, cavitating flows, supersonic liquid jets, and chemically reacting flows. In LS-DYNA, it has been extended to also solve fluid-structure interaction (FSI) problems. It does this with two approaches. The first approach solves the compressible flow equations on an Eulerian mesh while the structural mechanics is solved on a moving mesh that moves through the fixed CE/SE mesh. In the second approach (new with this version), the CE/SE mesh moves in a fashion such that its FSI boundary surface matches the corresponding FSI boundary surface of the moving structural mechanics mesh. This second approach is more accurate for FSI problems, especially with boundary layers flows. Another feature with the CESE moving mesh solver is conjugate heat transfer coupling with the solid thermal solver. The chemistry and stochastic particle solvers are two add-don solvers that extend the CESE solver.

The dual CESE solver is another compressible flow solver that is also based upon the Conservation Element/Solution Element (CE/SE) method, but with improvements related to accuracy and robustness. This method follows a similar novel numerical

framework for conservation laws. In LS-DYNA, the dual CESE solver also include fluid-structure interaction (FSI) capabilities. It also does this with two approaches. The first approach solves the compressible flow equations on an Eulerian mesh while the structural mechanics is solved on a moving mesh that moves through the fixed dual CE/SE mesh. In the second approach. the dual CE/SE mesh moves in a fashion such that its FSI boundary surface matches the corresponding FSI boundary surface of the moving structural mechanics mesh. This second approach is more accurate for FSI problems, especially with boundary layers flows. One of the advances in these FSI computations with the dual CESE solver as compared with the older CESE solver is that each FSI approach (or fixed mesh Eulerian solver) may be employed in different subregions of the fluid mesh in the same problem. Unlike the \*CESE solvers, the dual CESE solvers do not have conjugate heat transfer coupling with the solid thermal solver, nor coupling with the chemistry or stochastic particle solvers. It is not clear if these \*CESE capabilities will be added to dual CESE solver. On the other hand, another advance capability available only with the dual CESE solvers is the availability of equations of state for pure and pseudo-pure fluids of industrial interest in the REFPROP and COOLPROP EOS libraries. These complex EOSes are generally expensive to evaluate, so a bi-cubic table look-up mechanism has been developed that greatly accelerates their use.

The third solver is the incompressible flow solver (ICFD) that is fully coupled with the solid mechanics solver. This coupling permits robust FSI analysis via either an explicit technique when the FSI is weak, or using an implicit coupling when the FSI coupling is strong. In addition to being able to handle free surface flows, there is also a bi-phasic flow capability that involves modeling using a conservative Lagrangian interface tracking technique. Basic turbulence models are also supported. This solver is the first in LS-DYNA to make use of a new volume mesher that takes surface meshes bounding the fluid domain as input (\*MESH keywords). In addition, during the time advancement of the incompressible flow, the solution is adaptively re-meshed as an automatic feature of the solver. Another important feature of the mesher is the ability to create boundary layer meshes. These anisotropic meshes become a crucial part of the model when shear stresses are to be calculated near fluid walls. The ICFD solver is also coupled to the solid thermal solver using a monolithic approach for conjugate heat transfer problems.

The fourth solver is an electromagnetics (EM) solver. This module solves the Maxwell equations in the Eddy current (induction-diffusion) approximation. This is suitable for cases where the propagation of electromagnetic waves in air (or vacuum) can be considered as instantaneous. Therefore, the wave propagation is not solved. The main applications are Magnetic Metal Forming, bending or welding, induced heating, ring expansions and so forth. The EM module allows the introduction of a source of electrical current into solid conductors and the computation of the associated magnetic field, electric field, as well as induced currents. The EM solver is coupled with the structural mechanics solver (the Lorentz forces are added to the mechanics equations of motion), and with the structural thermal solver (the ohmic heating is added to the thermal solver as an extra source of heat). The EM fields are solved using a Finite Element Method (FEM) for

the conductors and a Boundary Element Method (BEM) for the surrounding air/insulators. Thus no air mesh is necessary.

The fifth solver is a battery electrochemistry solver. At this time, the available capability involves a one-dimensional electrochemistry solver that is coupled to the structural mechanics and structural thermal solver in each structural element identified as being part of a battery cell. It solves these one-dimensional models implicitly so as to be able to run simulations for very long physical times that are typical of battery-structure interaction problems.

As stated above, the *CHEMISTRY and *STOCHASTIC cards are only used in the CESE solver at this time.

# \*BATTERY

The keyword \*BATTERY provides input data for the electrochemistry solver:

>\*BATTERY_DATABASE_HISTORY_ALLNDS_ON_ELESET
>
>\*BATTERY_DATABASE_HISTORY_GLOBALS
>
>\*BATTERY_DATABASE_HISTORY_NODELIST_ON_ELESET
>
>\*BATTERY_ECHEM_CELL_GEOMETRY
>
>\*BATTERY_ECHEM_CONTROL_SOLVER
>
>\*BATTERY_ECHEM_INITIAL
>
>\*BATTERY_ECHEM_MAT_ANODE
>
>\*BATTERY_ECHEM_MAT_CATHODE
>
>\*BATTERY_ECHEM_MAT_ELECTROLYTE
>
>\*BATTERY_ECHEM_THERMAL

For now, the available capability involves a one-dimensional electrochemistry solver that is coupled to the structural mechanics and structural thermal solver in each structural element identified as being part of a battery cell.

## \*BATTERY_DATABASE_HISTORY_ALLNDS_ON_ELESET

Purpose: Enable output of battery electrochemistry solver data for all one-dimensional battery mesh nodes on each element in an element set. The output goes to binary database binout.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | LCUR | IOOPT | ESID | | | | |
| Type | F | I | I | I | | | | |
| Default | 0.0 | 0 | 0 | none | | | | |

|  VARIABLE  |  DESCRIPTION  |
|---|---|

<div>

**VARIABLE** | **DESCRIPTION**

DT — Time interval between outputs. If DT is zero, no output is generated.

LCUR — Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs.

IOOPT — Flag to govern behavior of the output frequency load curve defined by LCUR:

> EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as
>
> $$t_{n+1} = t_n + \text{LCUR}(t_n) \, .$$
>
> This is the default behavior.

> EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as
>
> $$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \, .$$

> EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

ESID — ID of a \*SET_SOLID element set to use for the binout operation. The selected elements in the element set of volume structural elements must also be battery electrochemistry elements.

</div>

**\*BATTERY_DATABASE_HISTORY_NODELIST_ON_ELESET**

Purpose:  Enable output of battery electrochemistry solver data for a specified set of one-dimensional battery mesh nodes on each element in an element set.  The output goes to binary database binout.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | LCUR | IOOPT | ESID | | | | |
| Type | F | I | I | I | | | | |
| Default | 0.0 | 0 | 0 | none | | | | |

**Node ID Cards.** Battery mesh nodes to select for battery data output in the elements selected by ESID in Card 1.  Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NID1 | NID2 | NID3 | NID4 | NID5 | NID6 | NID7 | NID8 |
| Type | I | I | I | I | I | I | I | I |

|  VARIABLE  |  DESCRIPTION  |
|---|---|
| DT | Time interval between outputs.  If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

EQ.1:  When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) \ .$$

This is the default behavior.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as $$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \,.$$ |
| | EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored. |
| ESID | ID of a \*SET_SOLID element set to use for the binout operation. The selected elements in the element set of volume structural elements must also be battery electrochemistry elements. |
| NID*i* | Node ID *i* |

## \*BATTERY_DATABASE_HISTORY_GLOBALS

Purpose: Enable output of battery electrochemistry solver data. The output goes to binary database binout.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-------|---|---|---|---|---|
| Variable | DT | LCUR | IOOPT | | | | | |
| Type | F | I | I | | | | | |
| Default | 0.0 | 0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DT | Time interval between outputs. If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \mathrm{LCUR}(t_n) \ .$$

This is the default behavior.

EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \mathrm{LCUR}(t_{n+1}) \ .$$

EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

## *BATTERY_ECHEM_CELL_GEOMETRY

Purpose: Set general-purpose geometry variables for a single cell BATTERY model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IMODEL | ALEN | SLEN | CLEN | ACCLEN | CCCLEN | | |
| Type | I | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NELEA | NELES | NELEC | NELECCA | NELECCC | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IMODEL | Battery model identifier (see Remark 1) |
| ALEN | Length of the anode side electrode |
| SLEN | Length of the separator |
| CLEN | Length of the cathode side electrode |
| ACCLEN | Length of the negative current collector |
| CCCLEN | Length of the positive current collector |
| NELEA | Number of elements in the anode electrode |
| NELES | Number of elements in the separator |
| NELEC | Number of elements in the cathode electrode |
| NELECCA | Number of elements in the anode current collector |

| VARIABLE | DESCRIPTION |
|---|---|
| NELECCC | Number of elements in the cathode current collector |

**Remarks:**

1.  **Identifier.** The battery model identifier (IMODEL) should match the IMODEL value specified in the corresponding \*BATTERY_ECHEM_CONTROL_-SOLVER card. If a different value is given, the value on the \*BATTERY_-ECHEM_CONTROL_SOLVER card will be the default.

## *BATTERY_ECHEM_CONTROL_SOLVER

Purpose: Set general purpose control variables for a battery electrochemistry simulation.

**Card Summary:**

**Card 1.** This card is required.

| IMODEL | IDIMEN | NCYCLE | IAGING | ITRA | IGAS | | |
|--------|--------|--------|--------|------|------|---|---|

**Card 2.** Include NCYCLE instances of this card, one for each cycle.

| CMODE | CTYPE | CEND | TCUT | VCUT | RCURR | | |
|-------|-------|------|------|------|-------|---|---|

**Card 3.1.** Include this card if IAGING = 1.

| SEIMW | SEIRHO | SEIBRUG | SEIEPS | SEICO | SEITO | | |
|-------|--------|---------|--------|-------|-------|---|---|

**Card 3.2.** Include this card if IAGING = 1.

| SEIIO | SEIRKA | SEICON | ECCO | ECDFS | | | |
|-------|--------|--------|------|-------|---|---|---|

**Card 4.1.** Include this card if ITRA = 1.

| AFI | EAT | HOFEC | HOFLI | HOFLED | | | |
|-----|-----|-------|-------|--------|---|---|---|

**Card 4.2.** Include this card if ITRA = 1.

| HOFC2H4 | HOFLC | HOFCO2 | HOFO2 | | | | |
|---------|-------|--------|-------|---|---|---|---|

**Card 5.** Include this card if IGAS = 1.

| IC2H4 | IO2 | ICO2 | IH2O | AG1 | AG2 | EG1 | EG2 |
|-------|-----|------|------|-----|-----|-----|-----|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | IMODEL | IDIMEN | NCYCLE | IAGING | ITRA | IGAS | | |
| Type | I | I | I | I | I | I | | |
| Default | none | none | 1 | 1 | 0 | 0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IMODEL | Sets the battery model: |

IMODEL — Sets the battery model:

> EQ.1: Dual insertion model (Newman). IAGING, ITRA, and IGAS must be set to 0.
>
> EQ.2: Multiphysics LIB model. With IGAS = 0, the model includes thermal effects while with IGAS = 1, the model includes both thermal and chemistry effects. Note that IAGING and ITRA must be set to 1 for either case. See Remark 1.
>
> EQ.3: Lithium metal battery

IDIMEN — Sets the geometric dimension:

> EQ.1:    1D LIB models
>
> EQ.101: 1D models with thermo-mechanical coupling (available for IMODEL = 1 and 2). See Remark 2.

NCYCLE — Number of cycles to run. Default is 1 cycle.

IAGING — Aging model flag (see Remark 3):

> EQ.0: Off
>
> EQ.1: On

ITRA — Thermal runaway model flag (see Remark 3):

> EQ.0: Off
>
> EQ.1: On

IGAS — Gas generation model flag (see Remark 4):

> EQ.0: Off
>
> EQ.1: On

**Cycle Card.** Include NCYCLE instances of this card, that is, one for each cycle.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | CMODE | CTYPE | CEND | TCUT | VCUT | RCURR | | |
| Type | I | I | I | F | F | F | | |
| Default | 1 | 0 | none | none | none | none | | |

|   VARIABLE   |   DESCRIPTION   |
|---|---|

CMODE        Battery running mode flag:

        EQ.0: Galvanostatic run

        EQ.1: Potentiostatic run (This is under development and not recommended.)

CTYPE        Running current type:

        EQ.0: Constant current

        EQ.1: Variable current

CEND         Cause of battery cycle termination:

        EQ.1: Cycle run for a given time period.

        EQ.2: Cycle run until a given cut-off voltage.

TCUT         Total running time for the cycle

VCUT         Cut-off voltage for the cycle

RCURR        Cycle operating current in the case of constant current

**Aging Card 1.** Include this card if IAGING = 1.

| Card 3.1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SEIMW | SEIRHO | SEIBRUG | SEIEPS | SEIC0 | SEIT0 | | |
| Type | F | F | F | F | F | F | | |
| Default | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | |

**Aging Card 2.** Include this card if IAGING = 1.

| Card 3.2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SEII0 | SEIRKA | SEICON | ECC0 | ECDFS | | | |
| Type | F | F | F | F | F | | | |
| Default | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SEIMW | Molecular weight of the SEI |
| SEIRHO | Density of the SEI |
| SEIBRUG | The Bruggeman constant of the SEI |
| SEIEPS | Initial SEI porosity |
| SEIC0 | Initial SEI concentration (units: $mol/m^3$) |
| SEIT0 | Initial thickness of the SEI layer (units: m) |
| SEII0 | Exchange current density for the SEI reaction |
| SEIRKA | Reaction rate constant for the SEI reaction (ignored if SEII0 $\neq$ 0.0) |
| SEICON | Ionic conductivity (units: S/m) |
| ECC0 | Initial concentration of EC (ethylene carbonate). This field is ignored if SEII0 $\neq$ 0.0. |

| VARIABLE | DESCRIPTION |
|---|---|
| ECDFS | Diffusion coefficient of EC |

**Thermal Runaway Card 1.** Include this card if ITRA = 1.

| Card 4.1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AFI | EAT | HOFEC | HOFLI | HOFLED | | | |
| Type | F | F | F | F | F | | | |
| Default | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | |

**Thermal Runaway Card 2.** Include this card if ITRA = 1.

| Card 4.2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HOFC2H4 | HOFLC | HOFCO2 | HOFO2 | | | | |
| Type | F | F | F | F | | | | |
| Default | 0.0 | 0.0 | 0.0 | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| AFI | Frequency factor for the reaction |
| EAT | Activation energy for the reaction |
| HOFEC | Formation enthalpy of the EC (units: kJ/mol) |
| HOFLI | Formation enthalpy of the LI |
| HOFLED | Formation enthalpy of the SEI layer (units: kJ/mol) |
| HOFC2H4 | Formation enthalpy of ethylene (units: kJ/mol) |
| HOFLC | Formation enthalpy of LC ($Li_2CO_3$; units: kJ/mol) |
| HOFCO2 | Formation enthalpy of $CO_2$ (units: kJ/mol) |
| HOFO2 | Formation enthalpy of $O_2$ (units: kJ/mol) |

**Gas Initial Conditions Card.** Include this card if IGAS = 1.

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IC2H4 | IO2 | ICO2 | IH2O | AG1 | AG2 | EG1 | EG2 |
| Type | F | F | F | F | F | F | F | F |
| Default | 0.0 | 0.0 | 0.0 | 0.0 | 3.426E26 | 5.028E-6 | 2.50e5 | 2.51e5 |
| Remarks |  |  |  |  | 5 | 5 | 5 | 5 |

| VARIABLE | DESCRIPTION |
|---|---|
| IC2H4 | Initial concentration of $C_2H_2$ gas (units: mol/m³) |
| IO2 | Initial concentration of $O_2$ gas (units: mol/m³) |
| ICO2 | Initial concentration of $CO_2$ gas (units: mol/m³) |
| IH2O | Initial concentration of $H_2O$ gas (units: mol/m³) |
| AG1 | Frequency factor for Ethylene oxidation (units: m/s) |
| AG2 | Frequency factor for Lithium hydration (units: m/s) |
| EG1 | Activation energy of Ethylene oxidation (units: J/mol) |
| EG2 | Activation energy of Lithium hydration (units: J/mol) |

**Remarks:**

1.  **Multiphysics Battery Models.** With IMODEL = 2, you can model a battery with thermal effects or a battery with both thermal and chemistry effects depending on the value of IGAS. These two battery models include battery aging, thermal runaway, and battery swelling. The battery and chemistry effects model additionally includes a gas generation model for modeling the chemistry effects.

2.  **Shutdown Key.** For coupled battery models (IDIMEN = 101) with IMODEL = 1 or 2, the shutdown key will work if the minimum ignition energy in the battery system reaches the critical condition like pre-thermal-runaway.

3.  **Input Requirements for Aging and Thermal Runaway Models.** When IAG-ING = 1, all the variables on Cards 3.1 and 3.2 must be filled. A similar

requirement applies when ITRA = 1 in that all the variables of Cards 41 and 4.2 must be filled.  For more details about these models, please see the Theory manual.

4.   **Battery Chemistry Files.**  When IGAS = 1, \*CHEMISTRY_BATTERY must be included in the input deck to provide the file names for the battery chemistry input file, the corresponding thermodynamics data file, and the transport properties file.  Please refer to the \*CHEMISTRY chapter for further details about the \*CHEMISTRY_BATTERY keyword.

5.   **AG1, AG2, EG1, and EG2.**  AG1, AG2, EG1, and EG2 are used to compute the rate of reaction based on Arrhenius equation as

$$r = A_k c_k e^{-\frac{EG_k}{RT}} \quad .$$

$A_k$ is the frequency factor for the reaction, $c_k$ is the concentration, $EG_k$ is the activation energy for the reaction, $R$ is the universal gas constant, and $T$ is the temperature.

## \*BATTERY_ECHEM_INITIAL

Purpose:  Initializes the composite electrodes and electrolyte in every element of the BAT-TERY simulation mesh.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT0 | LICE | PHI1 | LICS | CURRIC | FLUXIC | PHI2 | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| DT0 | Initial time step size |
| LICE | Initial concentration of lithium ions in the electrolyte |
| PHI1 | Initial condition of the electrolyte potential |
| LICS | Initial concentration of lithium in the solid particles |
| CURRIC | Initial current of the cycle operation |
| FLUXIC | Initial pore wall flux |
| PHI2 | Initial condition of the electrode potential |

## *BATTERY_ECHEM_MAT_ANODE

Purpose:  Set the battery material variables for the anode side electrode.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PIDA | IOCPA | CAPTA | SOCA | RADA | RATEA | RANODE | |
| Type | I | I | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RHOEA | RHOFA | RHOCCA | DFSA | CONDA | MWA | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VFEA | VFPA | VFFA | VFGA | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PIDA | Part ID |
| IOCPA | Material type for the OCP in the anode electrode: |

        EQ.1: Sony carbon (petroleum coke)

        EQ.2: MCMB 2510

        EQ.3: MCMB 2528

| VARIABLE | DESCRIPTION |
|----------|-------------|
| | EQ.4: KS6 graphite |
| CAPTA | Coulombic capacity of anode material (units: mAh/g) |
| SOCA | Initial lithium stoichiometric coefficient of the anode side active material. For example, $Li_xC_6$ ($0 < x < 0.7$). |
| RADA | Radius of spherical particles in the anode side active material (units: m) |
| RATEA | Reaction rate constant for the anode electrode |
| RANODE | Film resistance for the anode electrode |
| RHOEA | Density of anode insertion material (electrode particles) ($kg/m^3$) |
| RHOFA | Density of the inert filler in the anode (units: $kg/m^3$) |
| RHOCCA | Density of the current collector in the anode (units: $kg/m^3$) |
| DFSA | Diffusion coefficient of lithium ions in the anode electrode material (units: $m^2/s$) |
| CONDA | Effective electronic conductivity of the anode porous electrode (units: S/m) |
| MWA | Molecular weight of the anode electrode (units: kg/mol) |
| VFEA | Volume fraction of electrolyte in the anode electrode |
| VFPA | Volume fraction of the polymer phase in the anode electrode |
| VFFA | Volume fraction of the inert filler in the anode electrode |
| VFGA | Volume fraction of the gas in the anode electrode |

## *BATTERY_ECHEM_MAT_CATHODE

Purpose: Set the battery material variables for the positive electrode.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PIDC | IOCPC | CAPTC | SOCC | RADC | RATEC | RCATHDE | |
| Type | I | I | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RHOEC | RHOFC | RHOCCC | DFSC | CONDC | MWC | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VFEC | VFPC | VFFC | VFGC | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PIDC | Part ID |
| IOCPC | Material type for the open-circuit potential: |

        EQ.1: $Mn_2O_4$(lower plateau) $(1.1 < y < 1.99)$

        EQ.2: $Mn_2O_4$ (upper plateau) $(0.17 < y < 0.99)$

        EQ.3: Cobalt dioxide 1, $Li_yCoO_2$ $(0.0 < y < 0.99)$

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.4: Cobalt dioxide 2, $Li_yCoO_2$ ($0.0 < y < 0.99$) |
| | EQ.5: $Mn_2O_4$ (literature version) ($0.17 < y < 0.99$) |
| | EQ.6: NMC-111 |
| | EQ.7: NMC-811 |
| CAPTC | Coulombic capacity of the cathode material (units: mAh/g) |
| SOCC | Initial lithium stoichiometric coefficient for the cathode side active material. For example, $Li_yWO_3$ ($0 < y < 0.67$). |
| RADC | Radius of spherical particle in the cathode side active material. (units: m) |
| RATEC | Reaction rate constant for the cathode electrode |
| RCATH | Film resistance for the cathode electrode |
| RHOEC | Density of the cathode insertion material (electrode particles). (units: $kg/m^3$) |
| RHOFC | Density of the cathode side inert filler (units: $kg/m^3$) |
| RHOCCC | Density of the cathode side current collector (units: $kg/m^3$) |
| DFSC | Diffusion coefficient of lithium ions in the cathode insertion material (units: $m^2/s$) |
| CONDC | Effective electronic conductivity of the cathode porous electrode (units: S/m). |
| MWC | Molecular weight of the cathode electrode (units: kg/mol) |
| VFEC | Volume fraction of electrolyte in the cathode electrode |
| VFPC | Volume fraction of the polymer phase in the cathode electrode |
| VFFC | Volume fraction of the inert filler in the cathode electrode |
| VFGC | Volume fraction of the gas in the cathode electrode |

## *BATTERY_ECHEM_MAT_ELECTROLYTE

Purpose: Set the battery material variables for the electrolyte and separator.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PIDEL | IOCPE | IELTYPE | RHOEL | RHOP | RHOS | | |
| Type | I | I | I | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VFES | VFPS | VFGS | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PIDEL | Part ID |
| IOPCE | Material type for the open-circuit potential: |

      EQ.1: LiPF6 in EC : DMC (1:1).

      EQ.2: LiPF6 in EC : DMC (2:1).

      EQ.3: LiPF6 in EC : DMC (1:2).

      EQ.4: LiPF6 in PC

      EQ.5: LiClO4 in PC

Here, EC is ethylene carbonate, DMC is dimethyl carbonate, and PC is propylene carbonate.

| IELTYPE | Type of electrolyte (units: $kg/m^3$): |
|---|---|

      EQ.0: Liquid electrolyte

      EQ.1: Polymer electrolyte

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RHOEL | Density of the electrolyte (units: kg/m$^3$) |
| RHOP | Density of the polymer phase (units: kg/m$^3$) |
| RHOS | Density of the separator material (units: kg/m$^3$) |
| VFES | Volume fraction of electrolyte in the separator |
| VFPS | Volume fraction of the polymer phase in the separator |
| VFGS | Volume fraction of the gas in the separator |

## \*BATTERY_ECHEM_THERMAL

Purpose:  Set parameters for the thermal treatment in a cell stack.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|--------|------|------|-------|------|---|---|
| Variable | TNAME | ITTYPE | IPRT | CP | HCONV | TEMP | | |
| Type | A | I | I | F | F | F | | |
| Default | none | none | none | none | none | none | | |
| Remarks | | | 3 | 2 | 2 | 2 | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|------|---|---|---|---|
| Variable | | | | FILE | | | | |
| Type | | | | A | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TNAME | Thermal material identifier |
| ITTYPE | Flag for how temperature is determined:<br>EQ.0:  Constant temperature mode<br>EQ.1:  Isothermal temperature with time<br>EQ.2:  Thermal coupling with LS-DYNA thermal solver |
| IPRT | Data print in ASCII format:<br>EQ.0:  No data print out.<br>EQ.1:  Time versus heat flux print out for thermal solver |
| CP | Specific heat coefficient of the cell (units: J/(kg K)) |
| HCONV | Convective heat transfer coefficient with external medium.  (units: W/(m²K)) |
| TEMP | Ambient temperature around the cell stack (K) |

| VARIABLE | DESCRIPTION |
|---|---|
| FILE | Name of the battery cell output file (ASCII) |

**Remarks:**

1. **Battery Parts for Thermal-Mechanical Coupling.** In case of thermal-mechanical coupling, the part number for the battery simulation must be specified, so only this part number is considered in the battery parts.

2. **Material Properties for Thermal-Mechanical Coupling.** If ITTYPE is 2, the material properties are set through the thermal material card, including anisotropic conductivities (see \*MAT_THERMAL_ORTHOTROPIC). CP, HCONV, and TEMP specified here are ignored.

3. **Heat Flux Output.** If IPRT = 1, then the heat flux generated by the battery solver is printed out.

**Example:**

The following is a partial example for 1D Electrochemisty.

```
*Keyword
$
*TITLE
1D battery models
$
*BATTERY_ECHEM_CONTROL_SOLVER
$--------1---------2---------3---------4---------5---------6---------7
$   imodel    idimen    ncycle    iaging      itra      igas
         2         1         1         1         1         1
$    cmode     ctype      cend      tcut      vcut     rcurr
         0         0         2       0.0       3.0      8.75
$ aging cards
$    seimw    seirho   seibrug    seieps     seic0     seit0
       0.0       0.0       0.0       0.0       0.0       0.0
$    seii0    seirka    seicon      ecc0      ecdfs
       0.0       0.0       0.0       0.0       0.0
$ thermal runaway cards
$      afi       eat     hofec     hofli    hofled
       0.0       0.0       0.0       0.0       0.0
$  hofc2h4     hoflc    hofco2     hofo2
       0.0       0.0       0.0       0.0
$ gas initial conditions card
     ic2h4       io2      ico2      ih2o       ag1       ag2       eg1       eg2
    1.0e-10   1.0e-10   1.0e-10   1.0e-10       0.0       0.0       0.0       0.0
*CHEMISTRY_BATTERY
  battery.inp
  btherm.dat
  btran.dat
$
*BATTERY_ECHEM_INITIAL
$--------1---------2---------3---------4---------5---------6---------7
$     dt0      lice      phi1      lics    curric    fluxic      phi2
      0.02    1000.0       0.0      0.05       0.0       5.0    -1.0e-7
$
```

```
*BATTERY_ECHEM_CELL_GEOMETRY
$--------1---------2---------3---------4---------5---------6---------7
$  imodel     alen      slen      clen    acclen    ccclen
        2    9.6e-5    2.5e-5    6.0e-5    1.0e-5    1.0e-5
$   nelea     neles     nelec
       40        40        80
$
*BATTERY_ECHEM_MAT_ANODE
$--------1---------2---------3---------4---------5---------6---------7
$    pida     i0cpa     capta      soca      rada     ratea   ranode
        2         3     372.0       0.6     8.0e-6    3.0e-9  0.35e-2
$   rhoea     rhofa    rhocca      dfsa     conda       mwa
   1800.0    1800.0    8954.0    7.0e-14    100.0     0.079
$    vfec      vfpc      vffc      vfgc
      0.4       0.0     0.064       0.0
$
*BATTERY_ECHEM_MAT_CATHODE
$--------1---------2---------3---------4---------5---------6---------7
$    pidc      iocpc     captc      socc      radc     ratec   rcathde
        2         3     274.0       0.8     5.0e-6    3.0e-9      0.0
$   rhoec     rhofc    rhoccc      dfsc     condc       mwc
   5010.0    1800.0    2707.0    3.0e-14     0.5      0.9787
$   vfelc     vfplc     vffic     vfgsx
     0.36       0.0     0.106       0.0
$
*BATTERY_ECHEM_MAT_ELECTROLYTE
$--------1---------2---------3---------4---------5---------6---------7
$   pidel     iocpe   ieltype     rhoel      rhop      rhos
        2         1         0    1324.0    1780.0     552.0
$   vfels     vfpls     vfgss
      0.4       0.0       0.0
$
*BATTERY_ECHEM_THERMAL
$--------1---------2---------3---------4---------5---------6---------7
$   tname    ittype      iprt        cp     hconv      temp
  hot_batt        1         0     500.0       0.0    298.15
heat_discharg_lco.k
$
*END
```

# \*CESE

The keyword \*CESE provides input data for the Conservation Element/Solution Element (CESE) compressible fluid solver:

\*CESE_BOUNDARY_AXISYMMETRIC_*{OPTION}*

\*CESE_BOUNDARY_BLAST_LOAD*}*

\*CESE_BOUNDARY_CONJ_HEAT_*{OPTION}*

\*CESE_BOUNDARY_CYCLIC_*{OPTION}*

\*CESE_BOUNDARY_FSI_*{OPTION}*

\*CESE_BOUNDARY_NON_REFLECTIVE_*{OPTION}*

\*CESE_BOUNDARY_PRESCRIBED_*{OPTION}*

\*CESE_BOUNDARY_REFLECTIVE_*{OPTION}*

\*CESE_BOUNDARY_SLIDING_*{OPTION}*

\*CESE_BOUNDARY_SOLID_WALL_*{OPTION1}_{OPTION2}*

\*CESE_CHEMISTRY_D3PLOT

\*CESE_CONTROL_LIMITER

\*CESE_CONTROL_MESH_MOV

\*CESE_CONTROL_SOLVER

\*CESE_CONTROL_TIMESTEP

\*CESE_DATABASE_ELOUT

\*CESE_DATABASE_FLUXAVG

\*CESE_DATABASE_FSIDRAG

\*CESE_DATABASE_POINTOUT

\*CESE_DATABASE_SSETDRAG

\*CESE_DEFINE_NONINERTIAL

\*CESE_DEFINE_POINT

# *CESE

*CESE_DRAG

*CESE_EOS_CAV_HOMOG_EQUILIB_

*CESE_EOS_IDEAL_GAS

*CESE_EOS_INFLATOR1

*CESE_EOS_INFLATOR2

*CESE_FSI_EXCLUDE

*CESE_INITIAL

*CESE_INITIAL_*{OPTION}*

*CESE_INITIAL_CHEMISTRY

*CESE_INITIAL_CHEMISTRY_ELEMENT

*CESE_INITIAL_CHEMISTRY_PART

*CESE_INITIAL_CHEMISTRY_SET

*CESE_MAT_000

*CESE_MAT_001 (*CESE_MAT_GAS)

*CESE_MAT_002

*CESE_PART

*CESE_SURFACE_MECHSSID_D3PLOT

*CESE_SURFACE_MECHVARS_D3PLOT

Note that when performing a chemistry calculation with the CESE solver, initialization should only be done with the *CESE_INITIAL_CHEMISTRY_… cards, not the *CESE_-INITIAL… cards.

**\*CESE_BOUNDARY_AXISYMMETRIC_**_OPTION_

Available options are:

> MSURF
>
> MSURF_SET
>
> SET
>
> SEGMENT

Purpose: Define an axisymmetric boundary condition on the axisymmetric axis for the 2D axisymmetric CESE compressible flow solver.

The MSURF and MSURF_SET options are used when the CESE mesh has been created using \*MESH cards.  The SET and SEGMENT cards are used when \*ELEMENT_SOLID cards are used to define the CESE mesh.


**Card Summary:**


**Card 1a.**  This card is included if the keyword option is MSURF. Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| MSURFID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  This card is included if the keyword option is MSURF_SET. Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| MSURF_S | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1c.**  This card is included if the keyword option is SET. Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1d.**  This card is included if the keyword option is SEGMENT. Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| N1 | N2 | N3 | N4 | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced in *MESH_SURFACE_ELEMENT cards. |

**Surface Part Set Card.** Card 1 format used when the MSURF_SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURF_S | Identifier of a set of mesh surface part IDs created with a *LSO_-ID_SET card, where each mesh surface part ID in the set is referenced in *MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 format used when the SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID |

**Segment Cards.** Card 1 format used when SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("\*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N1, N2, … | Node IDs defining a segment |

**Remarks:**

1.   **Restrictions.** This boundary condition can only be used on the axisymmetric axis for the 2D axisymmetric CESE fluid solver.

**\*CESE_BOUNDARY_BLAST_LOAD**_OPTION_

Available options include:

>   MSURF

>   MSURF_SET

>   SET

>   SEGMENT

Purpose: For the CESE compressible flow solver, set boundary values for velocity, density, and pressure from a blast wave defined by a *LOAD_BLAST_ENHANCED card. Boundary values are applied at the centroid of elements connected with this boundary. _OPTION_ = SET and _OPTION_ = SEGMENT are for user defined meshes whereas _OPTION_ = MSURF and _OPTION_ = MSURF_SET are associated with the automatic volume mesher (See *MESH keywords). In other words, the MSURF and MSURF_SET options are used when the CESE mesh has been created using *MESH cards. The SET and SEGMENT cards are used when *ELEMENT_SOLID cards are used to define the CESE mesh.

**Card Summary:**

**Card 1a.** This card is included if the keyword option is MSURF.

| BID | MSURFID | | | | | | |
|-----|---------|--|--|--|--|--|--|

**Card 1b.** This card is included if the keyword option is MSURF_SET.

| BID | MSURF_S | | | | | | |
|-----|---------|--|--|--|--|--|--|

**Card 1c.** This card is included if the keyword option is SET.

| BID | SSID | | | | | | |
|-----|------|--|--|--|--|--|--|

**Card 1d.** This card is included if the keyword option is SEGMENT.

| BID | N1 | N2 | N3 | N4 | | | |
|-----|----|----|----|----|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|---------|---|---|---|---|---|---|
| Variable | BID | MSURFID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| BID | Blast source ID (see \*LOAD_BLAST_ENHANCED) |
| MSURFID | A mesh surface part ID referenced in \*MESH_SURFACE_ELE-MENT cards |

**Surface Part Set Card.** Card 1 format used when the MSURF_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|---------|---|---|---|---|---|---|
| Variable | BID | MSURF_S | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| BID | Blast source ID (see \*LOAD_BLAST_ENHANCED) |
| MSURF_S | Identifier of a set of mesh surface part IDs created with a \*LSO_-ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 format used when the SET keyword option is active.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|------|---|---|---|---|---|---|
| Variable | BID | SSID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| BID | Blast source ID (see \*LOAD_BLAST_ENHANCED) |
| SSID | Segment set ID |

**Segment Card.** Card 1 for SEGMENT keyword option is active.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|------|------|------|------|---|---|---|
| Variable | BID | N1 | N2 | N3 | N4 | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| BID | Blast source ID (see \*LOAD_BLAST_ENHANCED) |
| N1, N2, … | Node ID's defining a segment |

**\*CESE_BOUNDARY_CONJ_HEAT_*OPTION***

Available options are:

        MSURF

        MSURF_SET

        SET

        SEGMENT

Purpose: Define a conjugate heat transfer interface condition for CESE compressible flows. This condition identifies those boundary faces of the CESE mesh that are in contact with non-moving structural parts and through which heat flows. This is only possible when the structural thermal solver is also being used in the structural parts.

The MSURF and MSURF_SET options are used when the CESE mesh has been created using \*MESH cards. The SET and SEGMENT cards are used when \*ELEMENT_SOLID cards are used to define the CESE mesh.

**Card Summary:**

**Card 1a.** This card is included when the keyword option is MSURF. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURFID | | | | | | | |
|---------|---|---|---|---|---|---|---|

**Card 1b.** This card is included when the keyword option is MSURF_SET. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURF_S | | | | | | | |
|---------|---|---|---|---|---|---|---|

**Card 1c.** This card is included when the keyword option is SET. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|------|---|---|---|---|---|---|---|

**Card 1d.** This card is included when the keyword option is SEGMENT. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| N1 | N2 | N3 | N4 | | | | |
|----|----|----|----|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 used when the MSURF keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURFID | Mesh surface part ID referenced in *MESH_SURFACE_ELEMENT cards. |

**Surface Part Set Card.** Card 1 used when the MSURF_SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURF_S | Identifier of a set of mesh surface part IDs created with an *LSO_ID_SET card, where each mesh surface part ID in the set is referenced in *MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 used when the SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID |

**Segment Cards.** Card 1 used when SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N1, N2, … | Node IDs defining a segment |

**Remarks:**

1.  **Restrictions.** This boundary condition should only be imposed on a CESE mesh boundary that is in contact with non-moving structural parts. An Eulerian CESE solver is required as is use of the structural thermal solver.

**\*CESE_BOUNDARY_CYCLIC_**_OPTION_

Available options are:

>    MSURF

>    MSURF_SET

>    SET

>    SEGMENT

Purpose: Define a cyclic (periodic) boundary condition for CESE compressible flows. This cyclic boundary condition can be used on periodic boundary surfaces.

The MSURF and MSURF_SET options are used when the CESE mesh has been created using \*MESH cards. The SET and SEGMENT cards are used when \*ELEMENT_SOLID cards are used to define the CESE mesh.

**Card Summary:**

Include as many sets of the following cards as needed. This input ends at the next keyword ("\*") card.

**Card 1a.** This card is included when the keyword option is set to MSURF.

| MSURFID1 | MSURFID2 | CYCTYP | | | | | |
|----------|----------|--------|--|--|--|--|--|

**Card 1b.** This card is included when the keyword option is set to MSURF_SET.

| MSRF_S1 | MSRF_S2 | CYCTYP | | | | | |
|---------|---------|--------|--|--|--|--|--|

**Card 1c.** This card is included when the keyword option is set to SET.

| SSID1 | SSID2 | CYCTYP | | | | | |
|-------|-------|--------|--|--|--|--|--|

**Card 1d.** This card is included when the keyword option is set to SEGMENT.

| ND1 | ND2 | ND3 | ND4 | NP1 | NP2 | NP3 | NP4 |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 2a.** This card is included for the MSURF, MSURF_SET, and SET options when CYCTYP = 1.

| AXISX1 | AXISY1 | AXISZ1 | DIRX | DIRY | DIRZ | ROTANG | |
|--------|--------|--------|------|------|------|--------|--|

**Card 2b.** This card is included for the MSURF, MSURF_SET, and SET options when CYCTYP = 2.

| TRANSX | TRANSY | TRANSZ | | | | | |
|--------|--------|--------|--|--|--|--|--|
| | | | | | | | |

**Data Card Definitions:**

**Surface Part Card.** Card 1 format when the MSURF keyword option is active

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID1 | MSURFID2 | CYCTYP | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |
| Remarks | 2 | 2 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID1, MSURFID2 | Mesh surface part IDs referenced in \*MESH_SURFACE_ELE-MENT cards. |
| CYCTYP | Relationship between the two cyclic boundary condition surfaces: |

        EQ.0: None assumed (default)

        EQ.1: The first surface is rotated about an axis to match the second surface.

        EQ.2: The faces of the first surface are translated in a given direction to obtain the corresponding faces on the second surface.

**Surface Part Set Card.** Card 1 format when the MSURF_SET keyword option is active

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSRF_S1 | MSRF_S2 | CYCTYP | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |
| Remarks | 3 | 3 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSRF_S1, MSRF_S2 | Identifiers of two sets of mesh surface part IDs, each created with a \*LSO_ID_SET card, where each mesh surface part ID in each set is referenced in \*MESH_SURFACE_ELEMENT cards. |
| CYCTYP | Relationship between the two cyclic boundary condition surfaces: |

> EQ.0: None assumed (default)
>
> EQ.1: The first surface is rotated about an axis to match the second surface.
>
> EQ.2: The faces of the first surface are translated in a given direction to obtain the corresponding faces on the second surface.

**Set Card.** Card 1 format when the SET keyword option is active

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID1 | SSID2 | CYCTYP | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |
| Remarks | 4 | 4 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID1, SSID2 | A pair of segment set IDs. |
| CYCTYP | Relationship between the two cyclic boundary condition surfaces: |

         EQ.0: None assumed (default)

         EQ.1: The first surface is rotated about an axis to match the second surface.

         EQ.2: The faces of the first surface are translated in a given direction to obtain the corresponding faces on the second surface.

**Segment Card.** Card 1 format when SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("\*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ND1 | ND2 | ND3 | ND4 | NP1 | NP2 | NP3 | NP4 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| ND$i$, NP$i$ | Node IDs defining a pair of segments: ND1, ND2, ND3, ND4 define the first segment, while NP1, NP2, NP3, NP4 define the second segment. This pair of segments must match either through a geometric translation or rotation. |

**Rotation Case Card.** Additional card for the MSURF, MSURF_SET, and SET options when CYCTYP = 1.

| Card 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AXISX1 | AXISY1 | AXISZ1 | DIRX | DIRY | DIRZ | ROTANG | |
| Type | F | F | F | F | F | F | F | |
| Default | 0.0 | 0.0 | 0.0 | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| AXIS[Z,Y,Z]1 | A point on the axis of rotation |
| DIR[X,Y,Z] | The direction which together with AXIS[X,Y,Z]1 defines the axis of rotation |
| ROTANG | The angle of rotation (in degrees) that transforms the centroid of each face on the first surface to the centroid of the corresponding face on the second surface |

**Translation Case Card.** Additional card for the MSURF, MSURF_SET, and SET options when CYCTYP = 2.

| Card 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TRANSX | TRANSY | TRANSZ | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| TRANS[X,Y,Z] | The translation direction that enables the identification of the segment in the second surface that matches a segment in the first surface |

**Remarks:**

1. **CYCTYP.** For the MSURF, MSURF_SET, or SET options with CYCTYP = 0, the code examines the geometry of two faces of the two surfaces in order to determine if the surfaces are approximately parallel (CYCTYP = 2) or related through a rotation (CYCTYP = 1). The geometric parameters required are then computed.

2. **MSURF.** For the MSURF option, the number of mesh surface elements must be the same in each mesh surface part. The mesh surface elements in each mesh surface part are then internally ordered to match pairwise between the two mesh surface parts.

3. **MSURF_SET.** For the MSURF_SET option, the number of mesh surface elements must be the same in each mesh surface part set. The mesh surface elements in each mesh surface part set are then internally ordered to match pairwise between the two mesh surface part sets.

4. **SET.** For the SET option, the same number of segments must be in each set. The segments in each set are then internally ordered to match pairwise between the two sets.

**\*CESE_BOUNDARY_FSI**_OPTION_

Available options are:

MSURF

MSURF_SET

SET

SEGMENT

Purpose: Define an FSI boundary condition for the moving mesh CESE compressible flow solver. This card must not be combined with the immersed-boundary method CESE solver; doing so will result in an error termination condition.

This boundary condition must be applied on a surface of the CESE computational domain that is co-located with surfaces of the outside boundary of the structural mechanics' mesh. The nodes of the two meshes will generally not be shared.

The MSURF and MSURF_SET options are used when the CESE mesh has been created using \*MESH cards. The SET and SEGMENT cards are used when \*ELEMENT_SOLID cards are used to define the CESE mesh.

**Card Summary:**

**Card 1a.** This card is included if the keyword option is MSURF. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| MSURFID | | | | | | | |
|---------|--|--|--|--|--|--|--|

**Card 1b.** This card is included if the keyword option is MSURF_SET. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| MSURF_S | | | | | | | |
|---------|--|--|--|--|--|--|--|

**Card 1c.** This card is included if the keyword option is SET. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| SSID | | | | | | | |
|------|--|--|--|--|--|--|--|

**Card 1d.** This card is included if the keyword option is SEGMENT. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| N1 | N2 | N3 | N4 | | | | |
|----|----|----|----|--|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards |

**Surface Part Set Card.** Card 1 format used when the MSURF_SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURF_S | Identifier of a set of mesh surface part IDs created with a \*LSO_-ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 format used when the SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID |

**Segment Cards.** Card 1 format used when SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| N1, … | Node IDs defining a segment |

**Remarks:**

1. **Conjugate Heat Transfer Problems.** This boundary condition card is also needed for conjugate heat transfer problems with the moving mesh CESE solver.

**\*CESE_BOUNDARY_NON_REFLECTIVE_**_OPTION_

Available options are:

   MSURF

   MSURF_SET

   SET

   SEGMENT

Purpose: Define a passive boundary condition for CESE compressible flows. This non-reflective boundary condition (NBC) provides an artificial computational boundary for an open boundary that is passive.

Use the MSURF and MSURF_SET options when you use the \*MESH cards to generate the CESE mesh. Use the SET and SEGMENT cards when \*ELEMENT_SOLID cards define the CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURFID | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1b.** Include this card for the MSURF_SET keyword option. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURF_S | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1c.** Include this card for the SET keyword option. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1d.** Include this card for the SEGMENT keyword option. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("\*") card.

| N1 | N2 | N3 | N4 | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Data Card Definitions:**

**Surface Part Card.**  Card 1 used when the MSURF keyword option is active.  Include as many cards as necessary.  This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced by *MESH_SURFACE_ELEMENT cards |

**Surface Part Set Card.**  Card 1 used when the MSURF_SET keyword option is active. Include as many cards as necessary.  This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---------|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURF_S | ID of a set of mesh surface parts created with an *LSO_ID_SET card, where each mesh surface part ID in the set is referenced by *MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 used when the SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID |

**Segment Cards.** Card 1 used when the SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("\*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N1, N2, … | Node IDs defining a segment |

**Remarks:**

1. **Normal application of this boundary condition.** We recommend imposing this boundary condition on an open surface far from the main disturbed flow (the further away, the better), meaning an almost uniform flow on the boundary surface.

2. **Default boundary condition for CESE.** LS-DYNA automatically assigns the non-reflective boundary condition to any boundary segment not already assigned a boundary condition by any of the \*CESE_BOUNDARY_… cards.

**\*CESE_BOUNDARY_PRESCRIBED_**_OPTION_

Available options include:

      MSURF

      MSURF_SET

      SET

      SEGMENT

Purpose:  For the CESE compressible flow solver, set boundary values for velocity, density, pressure, and temperature.  Boundary values are applied at the centroid of elements connected with this boundary.  Use keyword options SET or SEGMENT for user-defined meshes, meaning mesh specified with \*ELEMENT_SOLID card.  Use MSURF or MSURF_SET for meshes created with the automatic volume mesher, meaning meshes generated with the \*MESH cards.

**Card Summary:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each boundary condition to be specified include one set of cards.  This input ends at the next keyword ("\*") card.

**Card 1a.**  Include this card for the MSURF keyword option.

| MSURFID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1b.**  Include this card for the MSURF_SET keyword option.

| MSURF_S | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1c.**  Include this card for the SET keyword option.

| SSID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1d.**  Include this card for the SEGMENT keyword option.

| N1 | N1 | N3 | N4 | IDCOMP | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.** This card is required.

| LC_U | LC_V | LC_W | LC_RHO | LC_P | LC_T | | |
|------|------|------|--------|------|------|--|--|

**Card 3.** This card is required.

| SF_U | SF_V | SF_W | SF_RHO | SF_P | SF_T | | |
|------|------|------|--------|------|------|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format for the MSURF keyword option

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain |

**Surface Part Set Card.** Card 1 format for the MSURF_SET keyword option

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURF_S | ID of a set of mesh surface parts created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain |

**Set Card.** Card 1 format for the SET keyword option

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain |

**Segment Card.** Card 1 for the SEGMENT keyword option

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N1 | N3 | N4 | IDCOMP | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| N1, N2, … | Node IDs defining a segment |

| VARIABLE | DESCRIPTION |
|---|---|
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_U | LC_V | LC_W | LC_RHO | LC_P | LC_T | | |
| Type | I | I | I | I | I | I | | |
| Remarks | 1 | 1 | 1 | 1 | 1 | 1 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_U | Load curve ID to describe the $x$-component of the velocity as a function of time; see \*DEFINE_CURVE. |

GT.0:  Load curve ID

EQ.0:  Constant value of SF_U

EQ.-1: Solver computes the boundary value for $x$-component of velocity

| | |
|---|---|
| LC_V | Load curve ID to describe the $y$-component of the velocity as a function of time |

GT.0:  Load curve ID

EQ.0:  Constant value of SF_V

EQ.-1: Solver computes the boundary value for $y$-component of velocity

| | |
|---|---|
| LC_W | Load curve ID to describe the $z$-component of the velocity as a function of time |

GT.0:  Load curve ID

EQ.0:  Constant value of SF_W

EQ.-1: Solver computes the boundary value for $x$-component of velocity

| VARIABLE | DESCRIPTION |
|---|---|
| LC_RHO | Load curve ID to describe the density as a function of time |
| | GT.0:   Load curve ID |
| | EQ.0:   Constant value of SF_RHO |
| | EQ.-1: Solver computes the boundary value for density |
| LC_P | Load curve ID to describe the pressure as a function of time |
| | GT.0:   Load curve ID |
| | EQ.0:   Constant value of SF_P |
| | EQ.-1: Solver computes the boundary value for pressure |
| LC_T | Load curve ID to describe the temperature as a function of time |
| | GT.0:   Load curve ID |
| | EQ.0:   Constant value of SF_T |
| | EQ.-1: Solver computes the boundary value for temperature |

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_U | SF_V | SF_W | SF_RH0 | SF_P | SF_T | | |
| Type | F | F | F | F | F | F | | |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_U | Scale factor for LC_U |
| SF_V | Scale factor for LC_V |
| SF_W | Scale factor for LC_W |
| SF_RHO | Scale factor for LC_RHO |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1.  **Well-posed boundaries.** On each centroid or set of centroids, the variables ($v_x$, $v_y$, $v_z$, $\rho$, $P$, $T$) with provided values must be consistent and make the model well-posed (that is, be such that the solution of the model exists, is unique, and is physical).

**\*CESE_BOUNDARY_PRESCRIBED_VN_**_OPTION_

Available options include:

       MSURF

       MSURF_SET

       SET

       SEGMENT

Purpose: For the CESE compressible flow solver, set boundary values for velocity, density, pressure, and temperature. Boundary values are applied at the centroid of elements connected with this boundary. Use keyword options SET or SEGMENT for user-defined meshes, that is, meshes specified with \*ELEMENT_SOLID cards. Use MSURF or MSURF_SET for meshes generated with the automatic volume mesher, meaning created with \*MESH cards.

**Card Summary:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the object to which the boundary condition is applied. Its format depends on the keyword option.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each boundary condition, include one set of cards. This input ends at the next keyword ("\*") card.

**Card 1a.** Include this card for the MSURF keyword option.

| MSURFID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the MSURF_SET keyword option.

| MSURF_S | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1c.** Include this card for the SET keyword option.

| SSID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1d.** Include this card for the SEGMENT keyword option.

| N1 | N1 | N3 | N4 | IDCOMP | | | |
|---|---|---|---|---|---|---|---|

**Card 2.** This card is required.

| LC_VN | | | LC_RHO | LC_P | LC_T | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_VN | | | SF_RHO | SF_P | SF_T | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format for the MSURF keyword option

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURFID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURFID | A mesh surface part ID referenced in \*MESH_SURFACE_ELE-MENT cards |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain. |

.

**Surface Part Set Card.** Card 1 format for the MSURF_SET keyword option

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURF_S | ID of a set of mesh surface parts created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain. |

**Set Card.** Card 1 format for the SET keyword option

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain. |

**Segment Card.** Card 1 for the SEGMENT keyword option

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N1 | N3 | N4 | IDCOMP | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| N1, N2, … | Node IDs defining a segment |

| VARIABLE | DESCRIPTION |
|---|---|
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, this ID references a \*CHEMISTRY_COMPOSITION card that gives the chemical mixture of the fluid entering the domain. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_VN | | | LC_RHO | LC_P | LC_T | | |
| Type | I | | | I | I | I | | |
| Remarks | 1 | | | 1 | 1 | 1 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_VN | Load curve ID to describe the normal velocity as a function of time; see \*DEFINE_CURVE.<br><br>GT.0:  Load curve ID<br><br>EQ.0:  Constant value of SF_VN<br><br>EQ.-1: Solver determines the boundary value for the normal velocity |
| LC_RHO | Load curve ID to describe the density as a function of time<br><br>GT.0:  Load curve ID<br><br>EQ.0:  Constant value of SF_RHO<br><br>EQ.-1: Solver determines the boundary value for the density |
| LC_P | Load curve ID to describe the pressure as a function of time<br><br>GT.0:  Load curve ID<br><br>EQ.0:  Constant value of SF_P<br><br>EQ.-1: Solver determines the boundary value for the pressure |
| LC_T | Load curve ID to describe the temperature as a function of time<br><br>GT.0:  Load curve ID<br><br>EQ.0:  Constant value of SF_T |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.-1: Solver determines the boundary value for the temperature |

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_VN | | | SF_RH0 | SF_P | SF_T | | |
| Type | F | | | F | F | F | | |
| Default | 1.0 | | | 1.0 | 1.0 | 1.0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_VN | Scale factor for LC_VN |
| SF_RHO | Scale factor for LC_RHO |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1. **Well-posed boundary conditions.** On each centroid or set of centroids, the variables ($V_N, \rho, P, T$) with provided values must be consistent and make the model well-posed (that is, be such that the solution of the model exists, is unique and physical).

**\*CESE_BOUNDARY_REFLECTIVE_***OPTION*

Available options are:

>   MSURF
>
>   MSURF_SET
>
>   SET
>
>   SEGMENT

Purpose: Define a reflective boundary condition for the CESE compressible flow solver. You can apply this boundary condition on a symmetrical surface or a solid wall of the computational domain. Use the MSURF or MSURF_SET keyword options when generating the CESE mesh with the \*MESH cards. Use the SET or SEGMENT keyword options cards when \*ELEMENT_SOLID cards specify CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURFID |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the MSURF_SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURF_S |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|

**Card 1c.** Include this card for the SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|

**Card 1d.** Include this card for the SEGMENT keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| N1 | N2 | N3 | N4 |  |  |  |  |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format for the MSURF keyword option. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards. |

**Surface Part Set Card.** Card 1 format for the MSURF_SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURF_S | ID of a set of mesh surface parts created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 format for the SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID |

**Segment Cards.** Card 1 format for the SEGMENT keyword option. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N1, N2, … | Node IDs defining a segment |

**Remarks:**

1. **Effect of the boundary condition.** This boundary condition has the same effect as a solid-wall boundary condition for inviscid flows.

**\*CESE_BOUNDARY_SLIDING_**_OPTION_

Available options are:

      MSURF

      MSURF_SET

      SET

      SEGMENT

Purpose: Allows the nodes of a fluid surface to translate in the main direction of the mesh movement. This feature is useful in piston-type applications.

Use the MSURF or MSURF_SET keyword options when generating the CESE mesh with \*MESH cards. Use the SET and SEGMENT keywords when \*ELEMENT_SOLID cards specify the CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURFID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the MSURF_SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSURF_S | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1c.** Include this card for the SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1d.** Include this card for the SEGMENT keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| N1 | N2 | N3 | N4 | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format for the MSURF keyword option.  Provide as many cards as necessary.  This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards. |

**Surface Part Set Card.** Card 1 format used when the MSURF_SET keyword option is active.  Provide as many cards as necessary.  This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSURF_S | ID of a set of mesh surface parts created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |

**Set Card.** Card 1 format used when the SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID |

**Segment Cards.** Card 1 format used when SEGMENT keyword option is active. Include an additional card for each corresponding pair of segments. This input ends at the next keyword ("\*") card.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N1, N2, … | Node IDs defining a segment |

**\*CESE_BOUNDARY_SOLID_WALL**_OPTION1_{OPTION2}_

For _OPTION1_, the choices are:

MSURF

MSURF_SET

SET

SEGMENT

For _OPTION2_, the choices are:

<BLANK>

ROTAT

Purpose: Define a solid wall boundary condition for this CESE compressible flow solver. This boundary condition models a solid boundary, that is, the physical boundary for the flow field. This boundary condition is a slip boundary condition for inviscid flows and a no-slip boundary condition for viscous flows.

Use the MSURF or MSURF_SET options when generating the CESE mesh through the *MESH cards. Use the SET or SEGMENT keyword options cards when *ELEMENT_-SOLID cards define the CESE mesh. Use the ROTAT keyword option for a rotating solid boundary condition.

**Card Summary:**

**Card Sets.** The following sequence of cards comprises a _single set_. LS-DYNA continues reading *CESE_BOUNDARY_SOLID_WALL card sets until the next keyword ("*") card.

**Card 1a.** Include this card when _OPTION1_ is MSURF and _OPTION2_ is not set (<BLANK>).

| MSURFID | LCID | VX | VY | VZ | | | |
|---------|------|----|----|----|--|--|--|

**Card 1b.** Include this card when _OPTION1_ is MSURF and _OPTION2_ is ROTAT.

| MSURFID | LCID | VX | VY | VZ | NX | NY | NZ |
|---------|------|----|----|----|----|----|----|

**Card 1c.** Include this card when _OPTION1_ is MSURF_SET and _OPTION2_ is not set (<BLANK>).

| MSURF_S | LCID | VX | VY | VZ | | | |
|---------|------|----|----|----|--|--|--|

**Card 1d.** Include this card when *OPTION1* is MSURF_SET and *OPTION2* is ROTAT.

| MSURF_S | LCID | VX | VY | VZ | NX | NY | NZ |
|---|---|---|---|---|---|---|---|

**Card 1e.** Include this card when *OPTION1* is SET and *OPTION2* is not set (<BLANK>).

| SSID | LCID | VX | VY | VZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1f.** Include this card when *OPTION1* is SET and *OPTION2* is ROTAT.

| SSID | LCID | VX | VY | VZ | NX | NY | NZ |
|---|---|---|---|---|---|---|---|

**Card 1g.** Include this card when *OPTION1* is SEGMENT and *OPTION2* is not set (<BLANK>).

| N1 | N2 | N3 | N4 | LCID | VX | VY | VZ |
|---|---|---|---|---|---|---|---|

**Card 1h.1.** Include this card when *OPTION1* is SEGMENT and *OPTION2* is ROTAT.

| N1 | N2 | N3 | N4 | LCID | VX | VY | VZ |
|---|---|---|---|---|---|---|---|

**Card 1h.2.** Include this card when *OPTION1* is SEGMENT and *OPTION2* is ROTAT.

| N1 | N2 | N3 | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card (Non-Rotating Boundary).** Card 1 format used when the MSURF keyword option is active and the ROTAT keyword option is inactive.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURFID | LCID | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |
| Remarks | | 2 | 2 | 2 | 2 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards. |
| LCID | Load curve ID to define this solid wall boundary movement |
| VX, VY, VZ | Velocity vector of the solid wall:<br><br>LCID.EQ.0: Vector defined by (VX, VY, VZ).<br><br>LCID.NE.0: Vector defined by both the load curve and (VX, VY, VZ). |

**Surface Part Card (Rotating Boundary).**   Card 1 format used when the MSURF keyword option is active and the ROTAT keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURFID | LCID | VX | VY | VZ | NX | NY | NZ |
| Type | I | I | F | F | F | F | F | F |
| Default | none | none | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURFID | Mesh surface part ID referenced in \*MESH_SURFACE_ELEMENT cards. |
| LCID | Load curve ID giving the rotating speed frequency (HZ).  LCID must be specified. |
| VX, VY, VZ | $x$, $y$, and $z$-coordinates of a point on the rotating axis |
| NX, NY, NZ | Unit vector of the rotating axis (not used for the 2D case) |

**Surface Part Set Card (Non-Rotating Boundary).** Card 1 format used when the MSURF_SET keyword option is active and the ROTAT keyword option is not active.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | LCID | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |
| Remarks | | 2 | 2 | 2 | 2 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURF_S | ID of a set of mesh surface part IDs created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |
| LCID | Load curve ID to define this solid wall boundary movement |
| VX, VY, VZ | Velocity vector of the solid wall:<br>LCID.EQ.0: Vector defined by (VX, VY, VZ).<br>LCID.NE.0: Vector defined by both the load curve and (VX, VY, VZ). |

**Surface Part Set Card (Rotating Boundary).** Card 1 format used when the MSURF_-SET keyword option is active and the ROTAT keyword option is active.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSURF_S | LCID | VX | VY | VZ | NX | NY | NZ |
| Type | I | I | F | F | F | F | F | F |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| VARIABLE | DESCRIPTION |
|---|---|
| MSURF_S | ID of a set of mesh surface part IDs created with a \*LSO_ID_SET card, where each mesh surface part ID in the set is referenced in \*MESH_SURFACE_ELEMENT cards. |
| LCID | Load curve ID giving the rotating speed frequency (HZ). LCID must be specified. |
| VX, VY, VZ | *x*, *y*, and *z*-coordinates of a point on the rotating axis |
| NX, NY, NZ | Unit vector of the rotating axis (not used for the 2D case) |

**Segment Set Card (Non-Rotating Boundary).** Card 1 format used when the SET keyword option is active and the ROTAT keyword option is not active.

| Card 1e | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | LCID | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | none | 0.0 | 0.0 | 0.0 | | | |
| Remarks | | 2 | 2 | 2 | 2 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID |
| LCID | Load curve ID to define this solid wall boundary movement |
| VX, VY, VZ | Velocity vector of the solid wall:<br><br>LCID.EQ.0: Vector defined by (VX, VY, VZ).<br><br>LCID.NE.0: Vector defined by both the load curve and (VX, VY, VZ). |

**Segment Set Card (Rotating Boundary).** Card 1 format used when the SET keyword option is active and the ROTAT keyword option is active.

| Card 1f | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | LCID | VX | VY | VZ | NX | NY | NZ |
| Type | I | I | F | F | F | F | F | F |
| Default | none | none | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID |
| LCID | Load curve ID giving the rotating speed frequency (HZ). LCID must be specified. |
| VX, VY, VZ | $x$, $y$, and $z$-coordinates of a point on the rotating axis |
| NX, NY, NZ | Unit vector of the rotating axis (not used for the 2D case) |

**Segment Card (Non-Rotating Boundary).** Card 1 format used when the SEGMENT keyword option is active and the ROTAT keyword option is not active.

| Card 1g | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | LCID | VX | VY | VZ |
| Type | I | I | I | I | I | F | F | F |
| Default | none | none | none | none | 0 | 0.0 | 0.0 | 0.0 |
| Remarks | | | | | 2 | 2 | 2 | 2 |

| VARIABLE | DESCRIPTION |
|---|---|
| N1, N2, N3, N4 | Node IDs defining a segment |
| LCID | Load curve ID to define this solid wall boundary movement |

| VARIABLE | DESCRIPTION |
|---|---|
| VX, VY, VZ | Velocity vector of the solid wall: |

        LCID.EQ.0: Vector defined by (VX, VY, VZ).

        LCID.NE.0: Vector defined by both the load curve and (VX, VY, VZ).

**Segment Card (Rotating Boundary).** Card 1 format used when the SEGMENT keyword option is active and the ROTAT keyword option is active.

| Card 1h.1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | LCID | VX | VY | VZ |
| Type | I | I | I | I | I | F | F | F |
| Default | none | none | none | none | 0 | 0.0 | 0.0 | 0.0 |

**Rotating Axis Card for Segment.** Additional card for the "Segment Card (Rotating Boundary)" case that is read when the ROTAT keyword option is used.

| Card 1h.2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NX | NY | NZ | | | | | |
| Type | F | F | F | | | | | |
| Default | 0.0 | 0.0 | 0.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| N1, N2, N3, N4 | Node IDs defining a segment |
| LCID | Load curve ID giving the rotating speed frequency (HZ). LCID must be specified. |
| VX, VY, VZ | $x$, $y$, and $z$-coordinates of a point on the rotating axis |
| NX, NY, NZ | Unit vector of the rotating axis (not used for the 2D case) |

**Remarks:**

1.  **Boundary movement.**  In this solid-wall condition, the boundary movement can only be in the tangential direction of the wall and should not affect the fluid domain size and mesh during the calculation. Otherwise, you should use an FSI or moving mesh solver.  Also, this moving solid boundary condition only affects viscous flows (no-slip BC).

2.  **Regular solid wall boundary condition.**  If LCID = 0 and VX = VY = VZ = 0.0 (default), this boundary condition is a regular solid wall boundary condition.

## \*CESE\_CHEMISTRY\_D3PLOT

Purpose: Cause mass fractions of the listed chemical species to be added to the CESE d3plot output. This is only used when chemistry is being solved with the CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MODELID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Species Cards.** Include one card for each species to be included in the d3plot database. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SPECIES | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MODELID | Identifier of a Chemkin-compatible chemistry model. |
| SPECIES | Name of a chemical species that is defined in the chemistry model identified by MODELID (see \*CHEMISTRY\_MODEL). |

## \*CESE_CONTROL_LIMITER

Purpose: Sets some stability parameters used in the CESE scheme for this CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IDLMT | ALFA | BETA | EPSR | | | | |
| Type | I | F | F | F | | | | |
| Default | 0 | 0.0 | 0.0 | 0.0 | | | | |
| Remarks | | 1 | 2 | 3 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IDLMT | Set the stability limiter option (See CESE theory manual): |
| | EQ.0: limiter format 1 (Re-weighting). |
| | EQ.1: limiter format 2 (Relaxing). |
| ALFA | Re-weighting coefficient (See CESE theory manual) |
| BETA | Numerical viscosity control coefficient (See CESE theory manual) |
| EPSR | Stability control coefficient (See CESE theory manual) |

**Remarks:**

1. $\alpha \geq 0$; larger values give more stability, but less accuracy. Usually $\alpha = 2.0$ or $4.0$ will be enough for normal shock problems.

2. $0 \leq \beta \leq 1$; larger values give more stability. For problems with shock waves, $\beta = 1.0$ is recommended.

3. $\varepsilon \geq 0$; larger values give more stability, but less accuracy.

## \*CESE_CONTROL_MESH_MOV

Purpose:  For moving mesh CESE, this keyword is used to choose the type of algorithm to be used for calculating mesh movement.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MMSH | LIM_ITER | RELTOL | | | | | |
| Type | I | I | F | | | | | |
| Default | 1 | 100 | 1.0e-3 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MMSH | Mesh motion selector: |
| |     EQ.1: mesh moves using an implicit ball-vertex spring method. |
| |     EQ.9: the IDW scheme is used to move the mesh. |
| LIM_ITER | Maximum number of linear solver iterations for the ball-vertex linear system. |
| RELTOL | Relative tolerance to use as a stopping criterion for the iterative linear solver (conjugate gradient solver with diagonal scaling preconditioner). |

.

### \*CESE_CONTROL_SOLVER

Purpose: Set general purpose control variables for the CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | ICESE | IFLOW | IGEOM | IFRAME | MIXID | IDC | ISNAN | |
| Type | I | I | I | I | I | F | I | |
| Default | 0 | 0 | none | 0 | none | 0.25 | 0 | |
| Remarks | | | 1 | | | 2 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

ICESE           Sets the framework of the CESE solver.

                    EQ.0:    Fixed Eulerian

                    EQ.100:  Moving Mesh FSI

                    EQ.200:  Immersed boundary FSI

IFLOW           Sets the compressible flow types:

                    EQ.0: Viscous flows (laminar)

                    EQ.1: Inviscid flows

IGEOM          Sets the geometric dimension:

                    EQ.2:    Two-dimensional (2D) problem

                    EQ.3:    Three-dimensional (3D) problem

                    EQ.101: 2D axisymmetric

IFRAME         Choose the frame of reference:

                    EQ.0:     Usual non-moving reference frame (default)

                    EQ.1000: Non-inertial rotating reference frame

MIXID          Chemistry model ID that defines the chemical species to include in the mixing model (see \*CHEMISTRY_MODEL). The species information is given through the model's card specifying the Chemkin-compatible input.

| VARIABLE | DESCRIPTION |
|---|---|
| IDC | Contact interaction detection coefficient (for FSI and conjugate heat transfer problems). |
| ISNAN | Flag to check for a NaN in the CESE solver solution arrays at the completion of each time step. This option can be useful for debugging purposes. There is a cost overhead when this option is active.<br><br>EQ.0: No checking<br><br>EQ.1: Checking is active. |

**Remarks:**

1.  **2D Solvers and Mesh Geometry.** For the 2D (IGEOM = 2) or 2D axisymmetric (IGEOM = 101) solver, the mesh should only be distributed in the *x-y* plane with the boundary conditions given only at the *x-y* domain boundaries. Otherwise, a warning message will be given, and the 3D solver will be triggered instead.

    The 2D axisymmetric case will work only if the 2D mesh and corresponding boundary conditions are properly defined, with the *x* and *y* coordinates corresponding to the radial and axial directions, respectively.

2.  **Contact Interaction Detection Coefficient.** IDC is the same type of variable that is input on the \*ICFD_CONTROL_FSI card. For an explanation, see Remark 1 for the \*ICFD_CONTROL_FSI card.

3.  **CESE Solver and Restarts.** Restarts are supported for the CESE solver. However, restarts do not currently work for simulations with conjugate heat transfer.

## *CESE_CONTROL_TIMESTEP

Purpose: Sets the time-step control parameters for the CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IDDT | CFL | DTINT | | | | | |
| Type | I | F | F | | | | | |
| Default | 0 | 0.9 | $10^{-3}$ | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

IDDT        Sets the time step option:

    EQ.0: fixed time step size (DTINT, meaning the given initial time step size)

    NE.0: the time step size will be calculated based on the given CFL-number and the flow solution at the previous time step.

CFL         CFL number (Courant–Friedrichs–Lewy condition)
    (0.0 < CFL ≤ 1.0)

DTINT       Initial time step size

### \*CESE_DATABASE_ELOUT

Purpose: Enable the output of CESE data on elements. If more than one element set is defined, then several output files will be generated.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

**Element Sets Card.** Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|---|---|---|---|---|---|---|
| Variable | ELSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be created: |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the CESE timestep will be used. |
| ELSID | Solid elements set ID |

**Remarks:**

1. **Database File Name.** The file name for this database is cese_elout.dat.

2. **Restrictions.** The \*CESE_DATABASE… cards (pointout/elout) are restricted to CFD-only problems. They do not give correct results for chemically reacting flow where \*CESE couples with \*CHEMISTRY.

## \*CESE_DATABASE_FLUXAVG

Purpose: Enable the output of CESE data on segment sets. If more than one segment set is defined, then several output files will be generated.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

**Segment Sets Card.** Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be created: |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file giving the average fluxes is generated. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the CESE time step will be used. |
| SSID | Segment set ID |

**Remarks:**

1. **Database File Name.** The file name for this database is cese_fluxavg.dat.

2.   **Restrictions.** The \*CESE_DATABASE… cards (pointout/elout/…) are re-
     stricted to CFD-only problems.  They do not give correct results for chemically
     reacting flow where \*CESE couples with \*CHEMISTRY.

**\*CESE_DATABASE_FSIDRAG**

Purpose:  Enable the output of the total fluid pressure force applied to solid parts in FSI problems at every time step.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | OUTLV | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be created: |

      EQ.0: No output file is generated.

      EQ.1: The output file giving the pressure forces is generated.

**Remarks:**

1. **Database File Names.** The file names for this database are cese_dragsol.dat, cese_dragshell.dat, cese_dragsol2D.dat and cese_dragbeam.dat, depending on what kind of solid is used.

## *CESE_DATABASE_POINTOUT

Purpose: Enable the output of CESE data at points.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|--------|------|------|------|---|---|
| Variable | PSID | DTOUT | PSTYPE | VX | VY | VZ | | |
| Type | I | F | I | F | F | F | | |
| Default | 0 | 0. | 0 | 0. | 0. | 0. | | |

**Point Specification Card.** Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|---|---|---|---|
| Variable | PID | X | Y | Z | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PSID | Point set ID |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the CESE timestep will be used. |
| PSTYPE | Point set type:<br>EQ.0: Fixed points<br>EQ.1: Tracer points using prescribed velocity<br>EQ.2: Tracer points using fluid velocity |
| VX, VY, VZ | Constant velocities to be used when PSTYPE = 1 |
| PID | Point ID |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| X, Y, Z | Initial coordinates of the point |

**Remarks:**

1.  **Database File Name.**  The file name for this database is cese_pointout.dat.

2.  **Restrictions.** The \*CESE_DATABASE… cards (pointout/elout) are restricted to CFD-only problems.  They do not give correct results for chemically reacting flow where \*CESE couples with \*CHEMISTRY.

## \*CESE_DATABASE_SSETDRAG

Purpose:  Enable the output of CESE drag forces on segment sets.  If more than one segment set is specified, then several output files will be generated.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

**Segment Sets Card.**  Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be created: |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file giving the average fluxes is generated. |
| DTOUT | Time interval to print the output.  If DTOUT is equal to 0.0, then the CESE timestep will be used. |
| SSID | Segment set ID |

**Remarks:**

1.  **Database File Name.** The file name for this database is cese_ssetdrag.dat.

2.  **Friction Drag Results and Mesh Size.**  For the friction drag to give consistent results, special care must be given to the mesh close to the solid wall boundary (good capturing of the boundary layer behavior).  We recommend a very fine structured mesh.

## \*CESE_DEFINE_NONINERTIAL

Purpose: Define the CESE problem domain as a non-inertial rotating frame that rotates at a constant rate. This is used in rotating problems such as spinning cylinders, wind turbines and turbo machinery.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|------|------|---|---|
| Variable | FREQ | LCID | PID | Nx | Ny | Nz | | |
| Type | F | I | I | F | F | F | | |
| Default | none | 0 | none | none | none | none | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|---|---|---|---|---|
| Variable | L | R | RELV | | | | | |
| Type | F | F | I | | | | | |
| Default | none | none | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FREQ | Frequency of rotation. |
| LCID | Load curve ID for scaling factor of FREQ. |
| PID | Starting point ID for the reference frame (See \*CESE_DEFINE_-POINT). |
| Nx, Ny, Nz | Rotating axis direction. |
| L | Length of rotating frame. |
| R | Radius of rotating frame. |

| VARIABLE | DESCRIPTION |
| --- | --- |

RELV        Velocity display mode:

           EQ.0:  Relative velocity, only the non-rotating components of the velocity are output.

           EQ.1:  Absolute velocity is output.

## \*CESE_DEFINE_POINT

Purpose: Define points to be used by the CESE solver.

**Point Cards.** Include one card for each point. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|---|---|---|---|
| Variable | NID | X | Y | Z | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Identifier for this point. |
| X, Y, Z | Coordinates of the point. |

**\*CESE_DRAG**

Purpose: Provide the far-field (or free-stream) fluid pressure.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | PRESS | | | | | | | |
| Type | F | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PRESS | Value of the free-stream fluid pressure (in units used by the current problem). |

## *CESE_EOS_CAV_HOMOG_EQUILIB

Purpose: Define the coefficients in the equation of state (EOS) for the homogeneous equilibrium cavitation model.

Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | $\rho_{vap}$ | $\rho_{liq}$ | $a_{vap}$ | $a_{liq}$ | $\mu_{vap}$ | $\mu_{liq}$ | $P_{SatVap}$ |
| Type | I | F | F | F | F | F | F | F |
| Default | none | 0.8 | 880.0 | 334.0 | 1386.0 | 1.435e-5 | 1.586e-4 | 1.2e+4 |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state identifier |
| $\rho_{vap}$ | density of the saturated vapor |
| $\rho_{liq}$ | density of the saturated liquid |
| $a_{vap}$ | sound speed of the saturated vapor |
| $a_{liq}$ | sound speed of the saturated liquid |
| $\mu_{vap}$ | dynamic viscosity of the vapor |
| $\mu_{liq}$ | dynamic viscosity of the liquid |
| $P_{SatVap}$ | pressure of the saturated vapor |

**Remarks:**

1.  Once a cavitation EOS is used, the cavitation flow solver will be triggered.

2.  In this homogeneous equilibrium cavitation model, a barotropic equation of state is used.  This model can be used in small scale & high speed cavitation flows, and it is not good for large-scale, low-speed cavitation calculations.

**\*CESE_EOS_IDEAL_GAS**

Purpose: Define the coefficients Cv and Cp in the equation of state for an ideal gas in the CESE fluid solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|------|---|---|---|---|---|
| Variable | EOSID | Cv | Cp | | | | | |
| Type | I | F | F | | | | | |
| Default | none | 717.5 | 1004.5 | | | | | |

|        VARIABLE        |                DESCRIPTION                |
|------------------------|-------------------------------------------|
| EOSID | Equation of state identifier |
| Cv | Specific heat at constant volume |
| Cp | Specific heat at constant pressure |

**Remarks:**

1.  **Units.**  As with other solvers in LS-DYNA, the user is responsible for unit consistency.  For example, if a user wants to use dimensionless variables, Cv and Cp should also be replaced by the corresponding dimensionless ones.

## *CESE_EOS_INFLATOR1

Purpose: To define an EOS using Cp and Cv thermodynamic expansions for an inflator gas mixture with a single temperature range.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Cp0 | Cp1 | Cp2 | Cp3 | Cp4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Cv0 | Cv1 | Cv2 | Cv3 | Cv4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state identifier for the CESE solver. |
| Cp0, …, Cp4 | Coefficients of temperature-dependent specific heat at constant pressure<br><br>$C_p(T) = C_{p0} + C_{p1} T + C_{p2} T^2 + C_{p3} T^3 + C_{p4} T^4$ |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| Cv0, ..., Cv4 | Coefficients of temperature-dependent specific heat at constant volume $$C_v(T) = C_{v0} + C_{v1}\,T + C_{v2}\,T^2 + C_{v3}\,T^3 + C_{v4}\,T^4$$ |

**Remark:**

1. These coefficient expansions for the specific heats over the entire temperature range are generated by the 0-D inflator model solver. See \*CHEMISTRY_CONTROL_-INFLATOR and \*CHEMISTRY_INFLATOR_PROPERTIES for details related to running that solver.

## *CESE_EOS_INFLATOR2

Purpose:  To define an EOS using Cp and Cv thermodynamic expansions for an inflator gas mixture with two temperature ranges, one below 1000 degrees Kelvin, and the other above 1000 degrees Kelvin.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Card for the expansion of Specific Heat at Constant Pressure.** Valid for T < 1000 $^0$K

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Cp1_0 | Cp1_1 | Cp1_2 | Cp1_3 | Cp1_4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

**Card for the expansion of Specific Heat at Constant Pressure.** Valid for T > 1000 $^0$K.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Cp2_0 | Cp2_1 | Cp2_2 | Cp2_3 | Cp2_4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

**Card for the expansion of Specific Heat at Constant Volume.** Valid for T < 1000 $^0$K

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|------|---|---|---|
| Variable | Cv1_0 | Cv1_1 | Cv1_2 | Cv1_3 | Cv1_4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

**Card for the expansion of Specific Heat at Constant Volume.** Valid for T > 1000 $^0$K.

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|------|---|---|---|
| Variable | Cv2_0 | Cv2_1 | Cv2_2 | Cv2_3 | Cv2_4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | Equation of state identifier for the CESE solver. |
| Cp1_0, …, Cp1_4 | Coefficients of temperature-dependent specific heat at constant pressure valid for T < 1000 $^0$K. <br><br> $C_{p1}(T) = C_{p1\_0} + C_{p1\_1}\,T + C_{p1\_2}\,T^2 + C_{p1\_3}\,T^3 + C_{p1\_4}\,T^4$ |
| Cp2_0, …, Cp2_4 | Coefficients of temperature-dependent specific heat at constant pressure valid for T > 1000 $^0$K. <br><br> $C_{p2}(T) = C_{p2\_0} + C_{p2\_1}\,T + C_{p2\_2}\,T^2 + C_{p2\_3}\,T^3 + C_{p2\_4}\,T^4$ |
| Cv1_0, …, Cv1_4 | Coefficients of temperature-dependent specific heat at constant volume valid for T < 1000 $^0$K. <br><br> $C_{v1}(T) = C_{v1\_0} + C_{v1\_1}\,T + C_{v1\_2}\,T^2 + C_{v1\_3}\,T^3 + C_{v1\_4}\,T^4$ |
| Cv2_0, …, Cv2_4 | Coefficients of temperature-dependent specific heat at constant volume valid for T > 1000 $^0$K. <br><br> $C_{v2}(T) = C_{v2\_0} + C_{v2\_1}\,T + C_{v2\_2}\,T^2 + C_{v2\_3}\,T^3 + C_{v2\_4}\,T^4$ |

**Remark:**

2. These coefficient expansions for the specific heats over two temperature ranges are generated by the 0-D inflator model solver. See \*CHEMISTRY_CONTROL_IN-FLATOR and \*CHEMISTRY_INFLATOR_PROPERTIES for details related to running that solver.

## \*CESE_FSI_EXCLUDE

Purpose: Provide a list of mechanics solver parts that are not involve in the CESE FSI calculation. This is intended to be used as an efficiency measure for parts that will not involve significant FSI interactions with the CESE compressible fluid solver..

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PIDn | IDs of mechanics parts that will be excluded from the FSI interaction calculation with the CESE solver. |

## *CESE_INITIAL

Purpose: Specify constant initial conditions (ICs) for flow variables at the centroid of each fluid element.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | U | V | W | RH | P | T | | |
| Type | F | F | F | F | F | F | | |
| Default | 0 | 0.0 | 0.0 | 1.225 | 0.0 | 0.0 | | |

|        VARIABLE        |                        DESCRIPTION                        |
|---|---|
| U, V, W | $x$-, $y$-, $z$-velocity components, respectively |
| RHO | Density, $\rho$ |
| P | Pressure, $P$ |
| T | Temperature, $T$ |

**Remarks:**

1. **Required Input.** Usually, only two of $\rho$, $P$, and $T$ need to be specified (besides the velocity). If all three are given, only $\rho$ and $P$ will be used.

2. **Applicable Elements.** These initial conditions will be applied only in those elements that have not been assigned a value by *CESE_INITIAL_*OPTION* cards for individual elements or sets of elements.

**\*CESE_INITIAL**_OPTION_

Available options include:

SET

ELEMENT

Purpose: Specify initial conditions for the flow variables at the centroid of each element in a set of elements or at the centroid of a single element.

Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EID/ESID | U | V | W | RHO | P | T | |
| Type | I | F | F | F | F | F | F | |
| Default | none | 0.0 | 0.0 | 0.0 | 1.225 | 0.0 | 0.0 | |
| Remarks | | | | | 1 | 1 | 1 | |

| VARIABLE | DESCRIPTION |
|---|---|
| EID/ESID | Solid element ID (EID) or solid element set ID (ESID) |
| U, V, W | $x$-, $y$-, $z$-velocity components, respectively |
| RHO | Density, $\rho$ |
| P | Pressure, $P$ |
| T | Temperature, $T$ |

**Remarks:**

1.  **Required Input.**  Usually, only two of $\rho$, $P$, and $T$ need to be specified (along with the velocity).  If all three are given, only $\rho$ and $P$ will be used.

2.  **Initial Condition Specification Priority.**  The priority of this card is higher than \*CESE_INITIAL, meaning that if an element is assigned an initial value by this card, \*CESE_INITIAL will no longer apply to that element.

## \*CESE_INITIAL_CHEMISTRY

Purpose: Initializes the chemistry and fluid state in every element of the CESE mesh that has not already been initialized by one of the other \*CESE_INITIAL_CHEMISTRY cards. This is only used when chemistry is being solved with the CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CHEMID | COMPID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHOIC | PIC | TIC | HIC | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| CHEMID | Identifier of chemistry control card to use |
| COMPID | Identifier of chemical composition to use |
| UIC | *X*-component of the fluid velocity |
| VIC | *Y*-component of the fluid velocity |
| WIC | *Z*-component of the fluid velocity |
| RHOIC | Initial fluid density |
| PIC | Initial fluid pressure |
| TIC | Initial fluid temperature |

| VARIABLE | DESCRIPTION |
| --- | --- |
| HIC | Initial fluid enthalpy. However, when CHEMID refers to a ZND 1-step reaction card, this is the progressive variable (degree of combustion). |

## \*CESE_INITIAL_CHEMISTRY_ELEMENT

Purpose: Initialize the chemistry and fluid state in every element of the list of CESE elements. This keyword is only used when chemistry is being solved with the CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CHEMID | COMPID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHOIC | PIC | TIC | HIC | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

**Element List Card.** Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ELE1 | ELE2 | ELE3 | ELE4 | ELE5 | ELE6 | ELE7 | ELE8 |
| Type | I | I | I | I | I | I | I | I |

| VARIABLE | DESCRIPTION |
|---|---|
| CHEMID | Identifier of chemistry control card to use (see \*CHEMISTRY_-CONTROL._...) |
| COMPID | Identifier of chemical composition to use (see *CHEMISTRY_-COMPOSITION) |
| UIC | X-component of the fluid velocity |

| VARIABLE | DESCRIPTION |
| --- | --- |
| VIC | $Y$-component of the fluid velocity |
| WIC | $Z$-component of the fluid velocity |
| RHOIC | Initial fluid density |
| PIC | Initial fluid pressure |
| TIC | Initial fluid temperature |
| HIC | Initial fluid enthalpy. However, when CHEMID refers to a ZND 1-step reaction card (see \*CHEMISTRY_CONTROL_ZND), this is the progressive variable (degree of combustion). |
| ELE*i* | User element numbers to initialize |

## \*CESE_INITIAL_CHEMISTRY_PART

Purpose: Initialize the chemistry and fluid state in every element of the specified CESE part that has not already been initialized by \*CESE_INITIAL_CHEMISTRY_ELEMENT or \*CESE_INITIAL_CHEMISTRY_SET cards. This keyword is only used when chemistry is being solved with the CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PARTID | CHEMID | COMPID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHOIC | PIC | TIC | HIC | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| PARTID | Identifier of the CESE part on which to initialize (see \*CESE_PART) |
| CHEMID | Identifier of the chemistry control card to use (see \*CHEMISTRY_-CONTROL._...) |
| COMPID | Identifier of the chemical composition to use (see \*CHEMISTRY_-COMPOSITION) |
| UIC | X-component of the fluid velocity |
| VIC | Y-component of the fluid velocity |
| WIC | Z-component of the fluid velocity |
| RHOIC | Initial fluid density |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PIC | Initial fluid pressure |
| TIC | Initial fluid temperature |
| HIC | Initial fluid enthalpy.  However, when CHEMID refers to a ZND 1-step reaction card (see \*CHEMISTRY_CONTROL_ZND), this is the progressive variable (degree of combustion). |

## *CESE_INITIAL_CHEMISTRY_SET

Purpose: Initializes the chemistry and fluid state in every element of the specified element set in the CESE mesh that has not already been initialized by *CESE_INITIAL_CHEMISTRY_ELEMENT cards. This is only used when chemistry is being solved with the CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SETID | CHEMID | COMPID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHOIC | PIC | TIC | HIC | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| SETID | Identifier of the CESE element set to initialize |
| CHEMID | Identifier of chemistry control card to use (see *CHEMISTRY_-CONTROL._...) |
| COMPID | Identifier of chemical composition to use (see *CHEMISTRY_-COMPOSITION) |
| UIC | $X$-component of the fluid velocity |
| VIC | $Y$-component of the fluid velocity |
| WIC | $Z$-component of the fluid velocity |
| RHOIC | Initial fluid density |

| VARIABLE | DESCRIPTION |
| --- | --- |
| PIC | Initial fluid pressure |
| TIC | Initial fluid temperature |
| HIC | Initial fluid enthalpy.  However, when CHEMID refers to a ZND 1-step reaction card (see \*CHEMISTRY_CONTROL_ZND), this is the progressive variable (degree of combustion). |

## \*CESE_MAT_000

Purpose: Define the fluid (gas) properties in a viscous flow for the CESE solver.

**Material Definition Cards.** Include one card for each instance of this material type. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|---|---|---|---|---|
| Variable | MID | MU | K | | | | | |
| Type | I | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material identifier |
| MU | Fluid dynamic viscosity. For Air at 15 °C, MU $= 1.81 \times 10^{-5}$ $\text{kg}/\text{ms}$ |
| K | Thermal conductivity of the fluid |

**Remarks:**

1.  The viscosity is only used viscous flows, so for inviscid flows, it is not necessary to define it. The thermal conductivity is only used to calculate the heat transfer between the structure and the thermal solver when coupling is activated.

2.  As with other solvers in LS-DYNA, the user is responsible for unit consistency. For example, if dimensionless variables are used, MU should be replaced by the corresponding dimensionless one.

**\*CESE_MAT_001( _GAS)**

Purpose: Define the fluid (gas) properties in a viscous flow for the CESE solver.

Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | MID | C1 | C2 | PRND | | | | |
| Type | I | F | F | F | | | | |
| Default | none | 1.458E-6 | 110.4 | 0.72 | | | | |

|              VARIABLE              |                              DESCRIPTION                              |
|------------------------------------|----------------------------------------------------------------------|

MID        Material identifier

C1, C2        Two coefficients in the Sutherland's formula for viscosity, i.e.,

$$\mu = \frac{C_1 T^{\frac{3}{2}}}{T + C_2}$$

where $C_1$ and $C_2$ are constants for a given gas.  For example, for air at moderate temperatures,

$$C_1 = 1.458 \times 10^{-6}\, \mathrm{kg/msK}^{\frac{1}{2}}, \quad C_2 = 110.4\ \mathrm{K}$$

PRND        The Prandtl Number (used to determine the coefficient of thermal conductivity).  It is approximately constant for most gases.  For air at standard conditions PRND = 0.72.

**Remarks:**

1.    C1 and C2 are only used to calculate the viscosity in viscous flows, so for inviscid flows, this material card is not needed.  The Prandtl number is used to extract the thermal conductivity, which is used when thermal coupling with the structure is activated.

2.    As with other solvers in LS-DYNA, the user is responsible for unit consistency.  For example, if dimensionless variables are used, $C_1$ and $C_2$ should be replaced by the corresponding dimensionless ones.

## *CESE_MAT_002

Purpose: Define the fluid (gas) properties in a viscous flow for the CESE solver.

**Material Definition Cards.** Include one card for each instance of this material type. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|---|---|
| Variable | MID | MU0 | SMU | K0 | SK | T0 | | |
| Type | I | F | F | F | F | F | | |
| Default | none | 1.716E-5 | 111. | 0.0241 | 194.0 | 273.0 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material identifier |

MU0 / SMU      Two coefficients appearing in the equation derived by combining Sutherland's formula with the power law for dilute gases:

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S_\mu}{T + S_\mu} \ .$$

$\mu_0$ is a reference value, and $S_\mu$ is an effective temperature called the Sutherland constant, which is characteristic of the gas. For air at moderate temperatures,

$$\mu_0 = 1.716 \times 10^{-5}\,\mathrm{Ns/m^2}, \qquad S_\mu = 111\ \mathrm{K}$$

K0/SK      Two coefficients appearing in the equation derived by combining Sutherland's formula with the power law for dilute gases:

$$\frac{k}{k_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S_k}{T + S_k} \ .$$

Here $k$ is the thermal conductivity, $k_0$ is a reference value, and $S_k$ is the Sutherland constant, which is characteristic of the gas. For air at moderate temperatures,

$$k_0 = 0.0241\ \mathrm{W/m}, \qquad S_k = 194\ \mathrm{K}$$

T0      Reference temperature, $T_0$. The default value (273.0) is for air, in degrees K.

**Remarks:**

1. **Fields that Depend on Problem Physics.** The viscosity is only used for viscous flow. Therefore, for inviscid flows, it is not necessary to define it. The thermal conductivity is only used to calculate the heat transfer between the structure and the thermal solver when coupling is activated.

2. **Unit Consistency.** As with other solvers in LS-DYNA, the user is responsible for unit consistency. For example, if dimensionless variables are used, MU should be replaced by the corresponding dimensionless one.

## *CESE_PART

Purpose: Define CESE solver parts, meaning connect CESE material and EOS information.

**Part Cards.** Include one card for each CESE part. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | MID | EOSID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part identifier (must be different from any PID on a *PART card) |
| MID | Material identifier defined by a *CESE_MAT_… card |
| EOSID | Equation of state identifier defined by a *CESE_EOS_… card |

**Remarks:**

1. **Material for inviscid flows.** Since material coefficients are only used in viscous flows, the MID can be left blank for inviscid flows.

**\*CESE_SURFACE_MECHSSID_D3PLOT**

Purpose: Identify the surfaces to be used in generating surface D3PLOT output for the CESE solver. These surfaces must be on the outside of volume element parts that are in contact with the CESE fluid mesh. The variables in question are part of the CESE FSI solution process or of the CESE conjugate heat transfer solver.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | SSID | SurfaceLabel | | | | | | |
| Type | I | A | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Mechanics solver segment set ID that is in contact with the fluid CESE mesh. |
| SurfaceLabel | Name to use in d3plot output to identify the SSID for the LSPP user. |

## **\*CESE_SURFACE_MECHVARS_D3PLOT**

Purpose:  List of variables to output on the surfaces designated by the segment set IDs given in the \*CESE_SURFACE_MECHSSID_D3PLOT cards.  Most of the allowed variables are defined only on the fluid-structure interface, and so the segment set IDs defining a portion of the fluid-structure interface must involve only segments (element faces) that are on the outside of volume element parts that are in contact with the CESE fluid mesh.

Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | Output Quantity | | | | | | | |
| Type | A | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| Output Quantity | Descriptive phrase for  the mechanics surface variable to output for the LSPP user.  Output will be done on all SSIDs selected by the \*CESE_SURFACE_MECHSSID_D3PLOT cards in the problem. |

Supported variables include:

FLUID FSI FORCE
FLUID FSI PRESSURE
INTERFACE TEMPERATURE
SOLID INTERFACE HEAT FLUX
FLUID INTERFACE HEAT FLUX
INTERFACE HEAT FLUX RATE
SOLID INTERFACE DISPLACEMENT
SOLID INTERFACE VELOCITY
SOLID INTERFACE ACCELERATION

Force, displacement, velocity, and acceleration are output as vector quantities.  The rest of the variables are scalar quantities.  The fluxes are in the normal direction to the fluid/structure interface, with the heat fluxes relative to the normal pointing into the structure.

# \*CHEMISTRY

The keyword \*CHEMISTRY is used to access chemistry databases that include Chemkin-based descriptions of a chemical model, as well as to select a method of solving the model. The keyword cards in this section are defined in alphabetical order:

\*CHEMISTRY_BATTERY[†]

\*CHEMISTRY_COMPOSITION

\*CHEMISTRY_CONTROL_0D

\*CHEMISTRY_CONTROL_1D[†]

\*CHEMISTRY_CONTROL_CSP

\*CHEMISTRY_CONTROL_FULL

\*CHEMISTRY_CONTROL_INFLATOR[†]

\*CHEMISTRY_CONTROL_TBX

\*CHEMISTRY_CONTROL_ZND[†]

\*CHEMISTRY_DET_INITIATION[†]

\*CHEMISTRY_INFLATOR_PROPERTIES[†]

\*CHEMISTRY_MODEL

\*CHEMISTRY_PATH

†: Card may be used only once in a given model

An additional option **"_TITLE"** may be appended to all \*CHEMISTRY keywords. If this option is used, then an 80 character string is read as a title from the first card of that keyword's input. At present, LS-DYNA does not make use of the title. Inclusion of titles gives greater clarity to input decks.

The \*CHEMISTRY_BATTERY card is only intended to be used in battery electrochemistry models that involve \*BATTERY_... cards. Note that none of the comments below apply for this particular case.

# *CHEMISTRY

In order to use one of the chemistry solvers, the input must include at least one *CHEM-ISTRY_MODEL card. For each spatial region containing a different chemical composition, at least one *CHEMISTRY_COMPOSITION card is required.

The *CHEMISTRY_CONTROL_0D card is intended to be used in a standalone fashion to verify the validity of a given chemistry model. This model includes the total number of species and all elementary reactions with their Arrhenius rate parameters. For instance, this solver could be used to check the induction time of the model.

The *CHEMISTRY_BLAST_INITIATION, *CHEMISTRY_CONTROL_1D, *CHEMIS-TRY_DET_INITIATION, and *CHEMISTRY_CONTROL_ZND cards are intended to provide a one-dimensional initialization to a 2D or 3D chemically-reacting flow.

In order to perform a full, general purpose chemistry calculation in 2D or 3D, the *CHEM-ISTRY_CONTROL_FULL card should be used.

The *CHEMISTRY_CONTROL_CSP card is an option for reducing the number of species and reactions that are used in a general purpose chemistry calculation. Other reduction mechanisms are planned for the future.

An airbag inflator model is available with *CHEMISTRY_CONTROL_INFLATOR along with *CHEMISTRY_INFLATOR_PROPERTIES and a chemistry model that is referenced via three chemical compositions. This involves zero-dimensional modeling, with pyrotechnic inflator, and cold and hot flow hybrid inflator options.

The *CHEMISTRY_CONTROL_TBX card is intended for use only in a stochastic particle model, where the *STOCHASTIC_TBX_PARTICLES card is used.

## \*CHEMISTRY_BATTERY

Purpose: For the battery electrochemistry solver (\*BATTERY), this card identifies the files that define a Chemkin chemistry model for use with that solver.

### Battery Reaction and Species Input File Card (Chemkin-compatible).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FILE1 | | | | | | | |
| Type | A | | | | | | | |

### Thermodynamics Database File Card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FILE2 | | | | | | | |
| Type | A | | | | | | | |

### Transport Properties Database File Card.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FILE3 | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FILE1 | Name of the file containing the Chemkin-compatible input |
| FILE2 | Name of the file containing the chemistry thermodynamics database |
| FILE3 | Name of the file containing the chemistry transport properties database |

## *CHEMISTRY_COMPOSITION

Purpose: Provide a general way to specify a chemical composition via a list of species mole numbers in the context of a Chemkin database model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ID | MODELID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

**Species List Card.** Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MOLFR | SPECIES | | | | | | |
| Type | F | A | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ID | A unique identifier among all chemistry compositions |
| MODELID | Identifier of a Chemkin-compatible chemistry model (see *CHEMISTRY_MODEL) |
| MOLFR | The number of moles corresponding to the species named in the SPECIES field. But, if used with a *STOCHASTIC_TBX_PARTICLES card, it is the molar concentration of the species (in units of moles/[length]$^3$, where [length] is the user's length unit). |
| SPECIES | The Chemkin-compatible name of a chemical species that is defined in the chemistry model identified by MODELID (see *CHEMISTRY_MODEL) |

## \*CHEMISTRY_CONTROL_0D

Purpose: Performs a zero-dimensional isotropic chemistry calculation that operates standalone (does not call the CESE solver). This is for ISOBARIC or ISOCHORIC cases.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ID | COMPID | SOLTYP | PLOTDT | CSP_SEL | | | |
| Type | I | I | I | F | I | | | |
| Default | none | none | none | 1.0e-6 | 0 | | | |
| Remarks | | | | | 1 | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | TLIMIT | TIC | PIC | RIC | EIC | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

**CSP Parameters Card.** Include cards for each chemical species in the following format when CSP_SEL.GT.0. This input ends at the next keyword ("\*") card.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AMPL | YCUT | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ID | Identifier for this 0D computation. |

| VARIABLE | DESCRIPTION |
|---|---|
| COMPID | Chemical composition identifier of composition to use. |
| SOLTYP | Type of 0D calculation:<br><br>EQ.1: Isochoric<br><br>EQ.2: Isobaric |
| PLOTDT | Simulation time interval for output both to the screen and to the isocom.csv file. This file can be loaded into LS-PREPOST for curve plotting using the x-y plot facility. |
| CSP_SEL | CSP solver option:<br><br>EQ.0: Do not use the CSP solver, and ignore the AMPL and YCUT parameters (default).<br><br>GT.0: Use the CSP solver, with the AMPL and YCUT parameters. |
| DT | Initial time step |
| TLIMIT | Time limit for the simulation |
| TIC | Initial temperature |
| PIC | Initial pressure |
| RIC | Initial density |
| EIC | Initial internal energy |
| AMPL | Relative accuracy for the mass fraction of a chemical species in the Chemkin input file. |
| YCUT | Absolute accuracy for the mass fraction of a chemical species in the Chemkin input file. |

**Remarks:**

1.  If CSP_SEL.GT.0, then instead of using the full chemistry solver, the computational singular perturbation (CSP) method solver is used.

## \*CHEMISTRY_CONTROL_1D

Purpose: Loads a previously-computed one-dimensional detonation. It is then available for use in the CESE solver for initializing a computation. In the product regions, this card overrides the initialization of the \*CESE_INITIAL_CHEMISTRY_… cards.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ID | XYZD | DETDIR | CSP_SEL | | | | |
| Type | I | F | I | I | | | | |
| Default | none | none | none | 0 | | | | |
| Remarks | | | | 1 | | | | |

**One-Dimensional Solution LSDA Input File Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE | | | | | | | |
| Type | A | | | | | | | |

**CSP Parameters Card** Include cards for each chemical species in the following format when CSP_SEL > 0. This input ends at the next keyword ("\*") card.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AMPL | YCUT | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ID | Identifier for this one-dimensional detonation solution. |
| XYZD | Position of the detonation front in the DETDIR direction. |

| VARIABLE | DESCRIPTION |
|---|---|
| DETDIR | Detonation propagation direction |
| |     EQ.1: $x$ |
| |     EQ.2: $y$ |
| |     EQ.3: $z$ |
| CSP_SEL | CSP solver option: |
| |     EQ.0: Do not use the CSP solver, and ignore the AMPL and YCUT parameters (default). |
| |     GT.0: Use the CSP solver, with the AMPL and YCUT parameters. |
| FILE | Name of the LSDA file containing the one-dimensional solution. |
| AMPL | Relative accuracy for the mass fraction of a chemical species in the chemkin input file. |
| YCUT | Absolute accuracy for the mass fraction of a chemical species in the chemkin input file. |

**Remarks:**

1.  If CSP_SEL > 0, then instead of using the full chemistry solver, the computational singular perturbation (CSP) method solver is used.

**\*CHEMISTRY_CONTROL_CSP**

Purpose:  Computes reduced chemistry for a specified Chemkin chemistry model using the Computational Singular Perturbation (CSP) method.  This card can be used for general-purpose chemical reaction calculations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ID | IERROPT | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

**CSP Parameters Card.** Include cards for each chemical species in the following format as indicated by the value of IERROPT. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | AMPL | YCUT | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ID | Identifier for this computational singular perturbation solver. |
| IERROPT | Selector: |
| | EQ.0:  AMPL and YCUT values for all chemical species are required. |
| | EQ.1:  One CSP Parameter Card should be provided, and it will be used for all species. |
| AMPL | Relative accuracy for the mass fraction of a chemical species in the Chemkin input file. |
| YCUT | Absolute accuracy for the mass fraction of a chemical species in the Chemkin input file. |

## *CHEMISTRY_CONTROL_FULL

Purpose: Computes the full chemistry specified by a Chemkin chemistry model. This card can be used for general-purpose chemical reaction calculations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|--------|------|---|---|---|---|
| Variable | ID | ERRLIM | RHOMIN | TMIN | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | 0.0 | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ID | Identifier for this full chemistry calculation. |
| ERRLIM | Error tolerance for the full chemistry calculation. |
| RHOMIN | Minimum fluid density above which chemical reactions are computed. |
| TMIN | Minimum temperature above which chemical reactions are computed. |

**\*CHEMISTRY_CONTROL_INFLATOR**

Purpose:  Provide the required properties of an inflator model for airbag inflation.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MODEL | OUT_TYPE | TRUNTIM | DELT | PTIME | | | |
| Type | I | I | F | F | F | | | |
| Remarks | 1 | 2,4 | | | | | | |

**Inflator Output Database File (an ASCII file) Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE | | | | | | | |
| Type | A | | | | | | | |

**Densities for Condensed Species.** Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DENSITY | Species Name | | | | | | |
| Type | F | A | | | | | | |
| Default | none | none | | | | | | |
| Remark | | 3 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MODEL | Type of inflator model to compute. |
| | EQ.1: Pyrotechnic model |
| | EQ.2: Hybrid model with cold flow option in the gas chamber |
| | EQ.3: Hybrid model with heat flow in the gas chamber |
| | EQ.4: Hybrid model with heat flow in one additional gas chamber |
| | EQ.5: Hybrid model with heat flow in two additional gas chambers |
| OUT_TYPE | Selects the output file format that will be used in an airbag simulation. |
| | EQ.0: Screen output calibration output (see Remark 4) |
| | EQ.1: CESE compressible flow solver (default) |
| | EQ.2: ALE solver |
| | EQ.3: CPM solver (with $2^{nd}$-order expansion of $C_p$) |
| | EQ.4: CPM solver (with $4^{th}$-order expansion of $C_p$) |
| TRUNTIM | Total run time. |
| DELT | Delta(t) to use in the model calculation. |
| PTIME | Time interval for output of time history data to FILE. |
| FILE | Name of the ASCII file in which to write the time history data and other data output by the inflator simulation. |
| DENSITY | Density of a condensed-phase species present in the inflator. |
| Species Name | Chemkin-compatible name of a condensed-phase species. |

**Remarks:**

1. If MODEL = 3, the solution of an elementary reaction system is required for the finite-rate chemistry in the gas chamber. For MODEL = 4 and 5, the condensed phase is computed only in the combustion chamber.

2.  Output file includes all of the necessary thermodynamics variables and load curves for the species mass flow rate, temperature, and density curve. This will make it possible to generate the velocity curve which is required by each solver that carries out an airbag simulation.

3.  At least one of these cards will be input if condensed-phase species are present during the propellant combustion. In this case, the user must specify each condensed-phase density. This density is then used to compute the volume fractions in both the combustion and gas chamber, where the energy equations are needed.

4.  If OUT_TYPE = 0, the propellant information will be displayed on the screen, including total mass, remaining mass percentage, and mass burning rate versus time, and the calibration data will be saved in the output file, including the time versus pressure, temperature, total mass flow rate, and individual species mass fractions for all chambers. With this option, the user can quickly see the effect of changing the parameters on the first three \*CHEMISTRY_INFLATOR_PROPERTIES cards.

**\*CHEMISTRY_CONTROL_TBX**

Purpose: Specify a chemistry solver for use in conjunction with stochastic TBX particles. This is intended only for modeling the second phase of an explosion where the explosive has embedded metal (aluminum) particles that are too large to have burned in the first phase of the explosion.

This chemistry card points to a \*CHEMISTRY_MODEL card (via IDCHEM) with its associated \*CHEMISTRY_COMPOSITION cards to set up the initial conditions. That is, it establishes the spatial distribution of the species in the model.

It is assumed that there is no chemical reaction rate information in the chemistry model files. This is done since a special chemical reaction mechanism is implemented for TBX modeling. If particles other than solid aluminum particles are embedded in the explosive, then another burn model has to be implemented.

**Surface Part Card.** Card 1 format used when the PART keyword option is active.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | IDCHEM | USEPAR | | | | | | |
| Type | I | I | | | | | | |
| Default | none | 1 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| IDCHEM | Identifier for this chemistry solver. |
| USEPAR | Coupling flag indicating if a \*STOCHASTIC_TBX_PARTICLES card is provided for this model: |

        EQ.1: uses a \*STOCHASTIC_TBX_PARTICLES card (default).

        EQ.0: does not use such a card.

## \*CHEMISTRY_CONTROL_ZND

Purpose: Compute the one-dimensional reduced chemistry of a ZND model. It is then used in the initialization of the chemistry part of the CESE solver. When this card is used, the \*CESE_INITIAL_CHEMISTRY… cards must specify the progressive variable (degree of combustion) in the HIC field.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | ID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|------|------|------|--------|---|---|
| Variable | F | EPLUS | Q0 | GAM | XYZD | DETDIR | | |
| Type | F | F | F | F | F | I | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ID | Identifier for this full chemistry calculation |
| F | Overdriven factor |
| EPLUS | EPLUS parameter of the ZND model |
| Q0 | Q0 parameter of the ZND model |
| GAM | GAM parameter of the ZND model |
| XYZD | Position of the detonation front in the DETDIR direction |
| DETDIR | Detonation propagation direction: |

    EQ.1: *X*-direction

    EQ.2: *Y*-direction

| **VARIABLE** | **DESCRIPTION** |
| --- | --- |
| | EQ.3: $Z$-direction |

## \*CHEMISTRY_DET_INITIATION

Purpose: Performs a one-dimensional detonation calculation based upon a chemical composition and initial conditions. It is then available for use immediately in the CESE solver for initializing a computation, or it can be subsequently used by the \*CHEMISTRY_CONTROL_1D card in a later run. In the product regions, this card overrides the initialization of the \*CESE_INITIAL_CHEMISTRY… cards.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ID | COMPID | NMESH | DLEN | CFL | TLIMIT | XYZD | DETDIR |
| Type | I | I | I | F | F | F | F | I |
| Default | none | none | none | none | none | none | none | none |

**LSDA Output File Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE | | | | | | | |
| Type | A | | | | | | | |

|         VARIABLE         |                          DESCRIPTION                          |
|---|---|
| ID | Identifier for this one-dimensional detonation computation. |
| COMPID | Chemical composition identifier of composition to use. |
| NMESH | Number of equal-width elements in the one-dimensional domain. |
| DLEN | Length of the one-dimensional domain. |
| CFL | Time-step limiting factor. |
| TLIMIT | Time limit for the simulation |
| XYZD | Position of the detonation front in the DETDIR direction. |
| DETDIR | Detonation propagation direction (1 => X; 2 => Y; 3 => Z) |

| VARIABLE | DESCRIPTION |
| --- | --- |
| FILE | Name of the LSDA file in which to write the one-dimensional solution. |

## \*CHEMISTRY_INFLATOR_PROPERTIES

Purpose:  Provide the required properties of an inflator model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | COMP_ID | PDIA | PHEIGHT | PMASS | TOTMASS | | | |
| Type | I | F | F | F | F | | | |
| Remarks | 1 | 2 | 2 | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TFLAME | PINDEX | A0 | TDELAY | RISETIME | | | |
| Type | F | F | F | F | F | | | |
| Default | none | none | none | none | None | | | |

**Combustion Chamber Parameter Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | COMP1ID | VOL1 | AREA1 | CD1 | P1 | T1 | DELP1 | DELTI |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

**Gas Plenum Parameter Card.**

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | COMP2ID | VOL2 | AREA2 | CD2 | P2 | T2 | DELP2 | DELT2 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

**Tank Parameter Card.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | COMP3ID | VOL3 | P3 | T3 | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | none | none | | | | |

**Gas Chamber 1 (Optional, see Remark 3) Card.**

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | COMP4ID | VOL4 | AREA4 | CD4 | P4 | T4 | DELP4 | DELT4 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

**Gas Chamber 2 (Optional, see Remark 3) Card.**

| Card 7 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | COMP5ID | VOL5 | AREA5 | CD5 | P5 | T5 | DELP5 | DELT5 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| COMP_ID | Chemical composition identifier of the composition for the steady-state propellant combustion (see Remark 1). |
| PDIA | Propellant diameter (see Remark 2). |
| PHEIGHT | Propellant height (see Remark 2). |
| PMASS | Individual cylinder (or sphere) propellant mass. |
| TOTMASS | Total propellant mass. |
| TFLAME | Adiabatic flame (combustion) temperature. |
| PINDEX | Power of the pressure in rate of burn model. |
| A0 | Steady-state constant. |
| TDELAY | Ignition time delay. |
| RISETIME | Rise time. |
| COMP1ID | Chemical composition identifier of composition to use in the combustion chamber. |
| VOL1 | Volume of the combustion chamber. |
| AREA1 | Area of the combustion chamber. |
| CD1 | Discharge coefficient of the combustion chamber. |
| P1 | Pressure in the combustion chamber. |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| T1 | Temperature in the combustion chamber. |
| DELP1 | Rupture pressure in the combustion chamber. |
| DELT1 | Elapsed time for breaking the burst disk between the chambers |
| COMP2ID | Chemical composition identifier of composition to use in the gas plenum. |
| VOL2 | Volume of the gas plenum. |
| AREA2 | Area of the gas plenum. |
| CD2 | Discharge coefficient of the gas plenum. |
| P2 | Pressure in the gas plenum. |
| T2 | Temperature in the gas plenum. |
| DELP2 | Rupture pressure in the gas plenum. |
| DELT2 | Elapsed time for breaking the burst disk between the chambers |
| COMP3ID | Chemical composition identifier of composition to use in the tank. |
| VOL3 | Volume of the tank. |
| P3 | Pressure in the tank. |
| T3 | Temperature in the tank. |
| COMP4ID | Chemical composition identifier of composition to use in the additional (second) gas chamber. |
| VOL4 | Volume of the second gas chamber. |
| P4 | Pressure in the second gas chamber. |
| T4 | Temperature in the second gas chamber. |
| DELP4 | Rupture pressure in the second gas chamber. |
| DELT4 | Elapsed time for breaking the burst disk between the first and second gas chambers |
| COMP5ID | Chemical composition identifier of composition to use in the additional (third) gas chamber. |

VOL5   Volume of the third gas chamber.

P5    Pressure in the third gas chamber.

T5    Temperature in the third gas chamber.

DELP5   Rupture pressure in the third gas chamber.

DELT5   Elapsed time for breaking the burst disk between the second and third gas chambers

**Remarks:**

1. The propellant composition can be obtained by running a chemical equilibrium program such as NASA CEA, the CHEETAH code, or the PEP code. LSTC provides a modified version of the PEP code along with documentation for users; it is available upon request.

2. A spherical shape for the propellant particles can be chosen if an identical value for the diameter and height is given.

3. To simulate a 4 or 5 chamber inflator, an additional chamber card can be used. In these cases of the inflator models, the condensed phase species are limited to the combustion chamber only if involved in the propellant combustion.

## *CHEMISTRY_MODEL

Purpose:  Identifies the files that define a Chemkin chemistry model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MODELID | JACSEL | ERRLIM | | | | | |
| Type | I | I | F | | | | | |
| Default | none | 1 | 1.0e-3 | | | | | |

**Chemkin Input File Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE1 | | | | | | | |
| Type | A | | | | | | | |

**Thermodynamics Database File Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE2 | | | | | | | |
| Type | A | | | | | | | |

**Transport Properties Database File Card.**

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FILE3 | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MODELID | Identifier for this Chemkin-based chemistry model |

| VARIABLE | DESCRIPTION |
|---|---|
| JACSEL | Selects the form of the Jacobian matrix for use in the source term:<br><br>EQ.1: Fully implicit (default)<br><br>EQ.2: Simplified implicit |
| ERRLIM | Allowed error in element balance in a chemical reaction |
| FILE1 | Name of the file containing the Chemkin-compatible input |
| FILE2 | Name of the file containing the chemistry thermodynamics database |
| FILE3 | Name of the file containing the chemistry transport properties database |

**\*CHEMISTRY_PATH**

Purpose:  To specify one or more search paths to look for chemistry database files.

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | DIR | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DIR | Directory path to add to the search set. |

# *DUALCESE

The keyword *DUALCESE provides input data for the dual Conservation Element/Solution Element (dual CESE) compressible fluid solver:

*DUALCESE_BLOCKMESH

*DUALCESE_BOUNDARY_AXISYMMETRIC_*{OPTION}*

*DUALCESE_BOUNDARY_CYCLIC_*{OPTION}*

*DUALCESE_BOUNDARY_FSI_*{OPTION}*

*DUALCESE_BOUNDARY_NON_REFLECTIVE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_HYBRID_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MACHNUM_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MFRATE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_INLET_PRESSURE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_EXMFRATE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_FARFIELD_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_PRESSURE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_PHASE_CHANGE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_TWO-PHASE_*{OPTION}*

*DUALCESE_BOUNDARY_REFLECTIVE_*{OPTION}*

*DUALCESE_BOUNDARY_SLIDING_*{OPTION}*

*DUALCESE_BOUNDARY_SOLID_WALL_*{OPTION1}_{OPTION2}*

*DUALCESE_CONTROL_LIMITER

*DUALCESE_CONTROL_MESH_MOV

*DUALCESE_CONTROL_SOLVER (deprecated as of R14)

*DUALCESE_CONTROL_TIMESTEP

# *DUALCESE

*DUALCESE_DARCY-FORCHHEIMER_EQ

*DUALCESE_DATABASE_HISTORY_DRAG_LIFT

*DUALCESE_DATABASE_HISTORY_ELEMENT_SET

*DUALCESE_DATABASE_HISTORY_GLOBALS

*DUALCESE_DATABASE_HISTORY_NODE_SET

*DUALCESE_DATABASE_HISTORY_POINT_SET

*DUALCESE_DATABASE_HISTORY_SEGMENT_SET

*DUALCESE_D3PLOT

*DUALCESE_D3PLOT_FLUID_SSID

*DUALCESE_ELE2D

*DUALCESE_ELE3D

*DUALCESE_ELEMENTSET

*DUALCESE_EOS_CAV_HOMOG_EQUILIB

*DUALCESE_EOS_COCHRAN_CHAN

*DUALCESE_EOS_COOLPROP (currently not working)

*DUALCESE_EOS_IDEAL_GAS

*DUALCESE_EOS_INFLATOR1

*DUALCESE_EOS_INFLATOR2

*DUALCESE_EOS_JWL

*DUALCESE_EOS_NASG

*DUALCESE_EOS_REFPROP (available on request)

*DUALCESE_EOS_REFPROP_PATH

*DUALCESE_EOS_SET (deprecated as of R14)

*DUALCESE_EOS_STIFFENED_GAS

*DUALCESE_EOS_VAN_DER_WAALS_GENERALIZED

\*DUALCESE_FSI_EXCLUDE

\*DUALCESE_FSI_EXCLUDE_PARTSET

\*DUALCESE_GRAVITY

\*DUALCESE_INCLUDE_MODEL

\*DUALCESE_INITIAL

\*DUALCESE_INITIAL_REGION

\*DUALCESE_INITIAL_*{OPTION}*

\*DUALCESE_INITIAL_HYBRID

\*DUALCESE_INITIAL_HYBRID_SET

\*DUALCESE_INITIAL_PHASE_CHANGE

\*DUALCESE_INITIAL_PHASE_CHANGE_SET

\*DUALCESE_INITIAL_TWO-PHASE

\*DUALCESE_INITIAL_TWO-PHASE_SET

\*DUALCESE_MAT_GAS

\*DUALCESE_MAT_GAS_0

\*DUALCESE_MAT_GAS_2

\*DUALCESE_MAT_LIQUID

\*DUALCESE_MESH_GEOMETRY

\*DUALCESE_MESH_PART

\*DUALCESE_MODEL

\*DUALCESE_NODE2D

\*DUALCESE_NODE3D

\*DUALCESE_NODESET

\*DUALCESE_PART (deprecated as of R14)

\*DUALCESE_PART_MULTIPHASE (deprecated as of R14)

\*DUALCESE_POINT_SOURCE

# *DUALCESE

*DUALCESE_POINT_SOURCE_STRUCTNODE

*DUALCESE_POINT_SOURCE_TWO-PHASE

*DUALCESE_POINTSET

*DUALCESE_POROUS_MODEL

*DUALCESE_POROUS_SPECIFY_JUMP

*DUALCESE_REACTION_RATE_IG

*DUALCESE_REACTION_RATE_IG_REDUCED

*DUALCESE_REACTION_RATE_P_DEPEND

*DUALCESE_SEGMENTSET

*DUALCESE_SOLVER_SELECTION

*DUALCESE_SOLVER_CAV_EQNS

*DUALCESE_SOLVER_EULER_EQNS

*DUALCESE_SOLVER_HYBRID_MULTIPHASE

*DUALCESE_SOLVER_NAVIER_STOKES

*DUALCESE_SOLVER_PHASE_CHANGE

*DUALCESE_SOLVER_TWO-PHASE_MULTIPHASE

An additional keyword option TITLE may be appended to the *DUALCESE keywords. If this option is used, then an addition line is read for the DUALCESE card in 80a format which can be used to describe that particular DUALCESE card. At present, the title serves no purpose other than to perhaps lend clarity to input decks.

**Dual CESE Keyword Deck Structure:**

The structure of the keyword setup for the *DUALCESE solvers is different from the way most keyword input is handled in the LS-DYNA input phase. This stems from the fact that there can be several *DUALCESE models in the same problem. In order to deal with this, each such model is restricted to be specified with one file hierarchy that starts with the keyword file designated with the *DUALCESE_MODEL card.

That keyword file can include any number of other keyword files with the *DUALCESE_-INCLUDE_MODEL card, and each of those files can in turn include other keyword files, again with the *DUALCESE_INCLUDE_MODEL card. Standard *INCLUDE cards are

not allowed. In fact, in each file in the file hierarchy of a *DUALCESE_MODEL card, only *DUALCESE cards may be used. The only exception to this is when the fluid mesh is defined using *MESH cards; a fatal error will be encountered when using other non-*DU-ALCESE keywords. Any required non-*DUALCESE keyword cards should be defined in some other place in the keyword input (outside the scope of the *DUALCESE_MODEL keyword card).

The mesh for each dual CESE model must be defined within the keyword input file hierarchy for that model. If a mesh created with *MESH cards is used, the *MESH cards for that mesh must all be defined within the scope of the *DUALCESE_MODEL card.

With R14, we introduce an updated, preferred way of specifying the dual CESE problem. The required or recommended keywords to use are:

> *DUALCESE_MESH_GEOMETRY

> *DUALCESE_MESH_PART

> *DUALCESE_SOLVER_SELECTION

along with one of the following specific solver cards:

> *DUALCESE_SOLVER_CAV_EQNS

> *DUALCESE_SOLVER_EULER_EQNS

> *DUALCESE_SOLVER_HYBRID_MULTIPHASE

> *DUALCESE_SOLVER_NAVIER_STOKES

> *DUALCESE_SOLVER_PHASE_CHANGE (added in R15)

> *DUALCESE_SOLVER_TWO-PHASE_MULTIPHASE

The following keywords are deprecated as of R14:

> *DUALCESE_CONTROL_SOLVER

> *DUALCESE_EOS_SET

> *DUALCESE_PART

> *DUALCESE_PART_MULTIPHASE

We also added time history cards with R14 that cause certain output to the binout file:

> *DUALCESE_DATABASE_HISTORY_ELEMENT_SET

> *DUALCESE_DATABASE_HISTORY_GLOBALS

# *DUALCESE

*DUALCESE_DATABASE_HISTORY_NODE_SET

*DUALCESE_DATABASE_HISTORY_POINT_SET

*DUALCESE_DATABASE_HISTORY_SEGMENT_SET

Another time history-type card is new with R15; it causes drag and lift-related quantities to be output to the binout file from the immersed boundary method (IBM) FSI-type dual CESE solvers.

*DUALCESE_DATABASE_HISTORY_DRAG_LIFT

We support two external equation-of-state (EOS) libraries, REFPROP and COOLPROP, for dual CESE. Including these libraries is complex, so we will clarify how to include them here. Each of them is accessed through a shared library that has to be loaded into LS-DYNA at runtime with *MODULE_LOAD like in the follwing:

```
*MODULE_LOAD
UserA                  DUALCESE REFPROP
<path to the installed REFPROP shared library>
```

Note that this *MODULE_LOAD card must not be given inside a keyword file in the file hierarchy of a *DUALCESE_MODEL card. As discussed above, this is the case for all non-*DUALCESE keyword cards. Note also that since *MODULE is not available in the Windows version of LS-DYNA, this capability cannot be used in that version.


## REFPROP and COOLPROP Libraries:

The REFPROP v10.0 version library and its directory of data sets are provided by ANSYS. Please contact ACE support staff for the dual CESE solver to obtain these files.

At this time, COOLPROP is not functioning correctly and should not be used.


## Multiphase Capabilities

The multiphase capabilities added for R13 with modifications in R14 all have FSI capabilities, including with structural element failure. This includes the 'hybrid' multiphase, 'two-phase' multiphase, and the cavitation solvers. New with R15 is a 'phase-change' multiphase solver. These keywords are involved with these capabilities:

*DUALCESE_BOUNDARY_PRESCRIBED_HYBRID

*DUALCESE_BOUNDARY_PRESCRIBED_PHASE_CHANGE

*DUALCESE_BOUNDARY_PRESCRIBED_TWO-PHASE

*DUALCESE_EOS_CAV_HOMOG_EQUILIB

\*DUALCESE_EOS_COCHRAN_CHAN

\*DUALCESE_EOS_JWL

\*DUALCESE_EOS_NASG

\*DUALCESE_EOS_SET (deprecated as of R14; use one of the \*DUALCESE_-
SOLVER_... cards instead)

\*DUALCESE_EOS_STIFFENED_GAS

\*DUALCESE_EOS_VAN_DER_WAALS_GENERALIZED

\*DUALCESE_INITIAL_HYBRID

\*DUALCESE_INITIAL_HYBRID_SET

\*DUALCESE_INITIAL_PHASE_CHANGE

\*DUALCESE_INITIAL_PHASE_CHANGE_SET

\*DUALCESE_INITIAL_TWO-PHASE

\*DUALCESE_INITIAL_TWO-PHASE_SET

\*DUALCESE_PART_MULTIPHASE (deprecated as of R14; use \*DUALCESE_-
MESH_PART instead)

\*DUALCESE_REACTION_RATE_IG

\*DUALCESE_REACTION_RATE_IG_REDUCED

\*DUALCESE_REACTION_RATE_P_DEPEND

\*DUALCESE_SOLVER_HYBRID_MULTIPHASE (added in R14)

\*DUALCESE_SOLVER_PHASE_CHANGE  (added in R15)

\*DUALCESE_SOLVER_TWO-PHASE_MULTIPHASE (added in R14)

**Flow Inlet and Exit Boundary Conditions:**

The following prescribed inlet and prescribed outlet boundary condition cards are new
with R14:

\*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MACHNUM_*{OPTION}*

\*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MFRATE_*{OPTION}*

# *DUALCESE

*DUALCESE_BOUNDARY_PRESCRIBED_INLET_PRESSURE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_EXMFRATE_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_FARFIELD_*{OPTION}*

*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_PRESSURE_*{OPTION}*

## Comparison to CESE:

The capabilities implemented in the dual CESE solvers are only a part of what is available in the *CESE solvers, especially those that involve couplings with the *CHEMISTRY and *STOCHASTIC_PARTICLE solvers. Another *CESE capability that is partially missing in the dual CESE solver is conjugate heat transfer. It is only available for the immersed boundary method FSI single-fluid solvers in versions R17 and later.

Some capabilities are only in the newer dual CESE solvers, in particular, the multiphase solvers, the many added EOSes, the binout-based time history capabilities, and the point-source-type fluid injection methods implemented in the single-phase CFD solvers and the two-phase multiphase solvers. Also, drag, lift, and related variables are only computed for the Dual CESE IBM FSI solvers (starting with R15).

## Restarts:

Dump/restart capabilities became available for all dual CESE solvers with the R17 release.

## \*DUALCESE_BLOCKMESH

Purpose: Create a single block rectangular mesh for use with the dual CESE solver. When this approach to creating a mesh is in use, the usual cards that define a dual CESE mesh and its boundary for boundary conditions should not be included in the input. In other words, when \*DUALCESE_BLOCKMESH is used, any of the following cards will cause an error to be reported: \*DUALCESE_NODE2D, \*DUALCESE_NODE3D, \*DUALCESE_-ELE2D, \*DUALCESE_ELE3D, and \*DUALCESE_SEGMENTSET.

**Card Summary:**

**Card 1.** This card is required.

| PID | | | | | | | |
|-----|--|--|--|--|--|--|--|

**Card 2.** Include a set of Cards 2 and 2.1 to specify the one-dimensional mesh one each axis. More than one instantiation of Card 2.1 can be in a given set. Include as many sets as needed. Note that only one set is allowed per direction. See Remark 3.

| AXTYPE | SEGID_L | SEGID_H | COORD_L | SCALE | | | |
|--------|---------|---------|---------|-------|--|--|--|

**Card 2.1.** Include as many cards as required of this card in a set with Card 2 to define one or more contiguous one-dimensional meshes to cover each axis. See Remark 3.

| NELE | ALEN | RATIO | CRATIO | WID_A | WID_B | | |
|------|------|-------|--------|-------|-------|--|--|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Dual CESE part ID for all elements in the block mesh. See \*DUALCESE_MESH_PART. |

**Define mesh parameters and boundary IDs of a mesh axis.** Include as many cards as needed to define the one-dimensional mesh on each axis.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|--------|--------|---------|-------|---|---|---|
| Variable | AXTYPE | SEGID_L | SEGID_H | COORD_L | SCALE | | | |
| Type | A | F | F | F | F | | | |
| Default | none | 1 | 2 | 0.0 | 1.0 | | | |
| Remarks | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| AXTYPE | Axis to define, meaning one of 'X_AXIS', 'Y_AXIS', or 'Z_AXIS'. One of each is required for a 3D mesh, and the 'X_AXIS' and 'Y_AXIS' are required for a 2D mesh. |
| SEGID_L | ID to use for the boundary segment set to be created at the low-index boundary |
| SEGID_H | ID to use for the boundary segment set to be created at the high-index boundary |
| COORD_L | Minimum value of the coordinate on the AXTYPE axis |
| SCALE | Factor to use to scale all positions on the AXTYPE axis |

**Parameters for creating a one-dimensional mesh block.** Include as many cards as needed to define an overall one-dimensional mesh. These cards create a sequence of one-dimensional meshes that when glued together will create the net one-dimensional mesh for the active AXTYPE. The algorithm that is implemented for this takes any three of the six parameters to define the given mesh block; at least three parameters must be specified. But there are several sets of three parameters that will not suffice to create a mesh. These illegal combinations are noted in Remark 2.

| Card 2.1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|------|------|-------|--------|-------|-------|---|---|
| Variable | NELE | ALEN | RATIO | CRATIO | WID_A | WID_B |   |   |
| Type | I | I | F | F | F | F |   |   |
| Default | none | none | none | none | none | none |   |   |
| Remarks | 2 | 2 | 2 | 2 | 2 | 2 |   |   |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NELE | Number of elements to put into the current mesh block |
| ALEN | Length of the given mesh block |
| RATIO | Total growth ratio, meaning the ratio by which the length of the last element in the block changes from the first element |
| CRATIO | Element-to-element growth ratio |
| WID_A | Width of the initial element in the block |
| WID_B | Width of the last element in the block |

**Remarks:**

1.  **AXTYPE uniqueness.** Only one instance of each AXTYPE name may appear in defining the block mesh.

2.  **Invalid combinations of sets of three parameters to create a 1D-mesh.** The following are invalid combinations of parameters for Card 2.1:

    a)  ALEN, RATIO, WID_B

    b)  RATIO, WID_A, WID_B

      c)  NELE, RATIO, CRATIO

3.    **Example input.**  The following is sample input works for this keyword:

```
*DUALCESE_BLOCKMESH
$       PID
     1000
$ First set of Cards 2 and 2.1
$ Card 2 for the X-axis
$   AXTYPE   SEGID_L   SEGID_H   COORD_L     SCALE
    X_AXIS     2000      2001      20.0       1.0
$ First Card 2.1 for the X-axis set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
       20      10.0       1.5
$ Second Card 2.1 for the X-axis set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
               10.0       0.9                 0.5
$ Third Card 2.1 for the X-axis set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
       15                                    0.3      0.75
$ Card 2 for the Y-axis
$   AXTYPE   SEGID_L   SEGID_H   COORD_L     SCALE
    Y_AXIS     2002      2003      -5.0       1.0
$ First Card 2.1 for this set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
       20      10.0       1.0
$ Second Card 2.1 for this set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
       20      10.0       0.75
$ Card 2 for Z-axis
$   AXTYPE   SEGID_L   SEGID_H   COORD_L     SCALE
    Z_AXIS     2004      2005      0.0        1.0
$ First Card 2.1 for this set
$     NELE      ALEN     RATIO    CRATIO     WID_A     WID_B
               15.0                          0.5      0.95
```

**\*DUALCESE_BOUNDARY_AXISYMMETRIC_*OPTION***

Available options are:

     MSURF

     SEGMENT_SET

Purpose: Define an axisymmetric boundary condition on the axisymmetric axis for the 2D axisymmetric dual CESE compressible flow solver.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSPID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the SEGMENT_SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 used when the MSURF keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSPID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSPID | Mesh surface part ID that is referenced by *MESH_SURFACE_ELEMENT |

**Set Card.** Card 1 used when the SEGMENT_SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with *DUALCESE_SEGMENTSET or *DUALCESE_BLOCKMESH |

**Remarks:**

This boundary condition can only be used on the axisymmetric axis for the 2D axisymmetric dual CESE fluid solver.

**\*DUALCESE_BOUNDARY_CYCLIC**_OPTION_

Available options are:

      MSURF

      SEGMENT_SET

Purpose: Define a cyclic (periodic) boundary condition for dual CESE compressible flows. This cyclic boundary condition can be used on periodic boundary surfaces.

The MSURF option should be used when the dual CESE mesh has been created using *MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card Sets.** The following sequence of cards comprises a _single set_. LS-DYNA will continue reading these cards sets until the next keyword ("*") card is encountered.

**Card 1a.** Include this card if the MSURF keyword option is used.

| MSPID1 | MSPID2 | CYCTYP | | | | | |
|--------|--------|--------|---|---|---|---|---|

**Card 1b.** Include this card if the SEGMENT_SET keyword option is used.

| SSID1 | SSID2 | CYCTYP | | | | | |
|-------|-------|--------|---|---|---|---|---|

**Card 2a.** Include this card when CYCTYP = 1.

| AXISX1 | AXISY1 | AXISZ1 | DIRX | DIRY | DIRZ | ROTANG | |
|--------|--------|--------|------|------|------|--------|---|

**Card 2b.** Include this card when CYCTYP = 2.

| TRANSX | TRANSY | TRANSZ | | | | | |
|--------|--------|--------|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|-----|--------|---|---|---|---|---|
| Variable | MSPID1 | MSPID2 | CYCTYP | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |
| Remarks | | | 1, 2 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID1, MSPID2 | Mesh surface part ID that is referenced by \*MESH_SURFACE_-ELEMENT |
| CYCTYP | Relationship between the two cyclic boundary condition surfaces: |

        EQ.0: Relationship determined by LS-DYNA (default)

        EQ.1: The first surface is rotated about an axis to match the second surface.

        EQ.2: The faces of the first surface are translated in a given direction to obtain the corresponding faces on the second surface.

**Set Card.** Card 1 format used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|--------|---|---|---|---|---|
| Variable | SSID1 | SSID2 | CYCTYP | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |
| Remarks | | | 1, 3 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID1, SSID2 | Segment set ID for the segment set created with \*DUALCESE_SEGMENTSET or \*DUALCESE_BLOCKMESH |
| CYCTYP | Relationship between the two cyclic boundary condition surfaces:<br><br>EQ.0: Relationship determined by LS-DYNA (default)<br><br>EQ.1: The first surface is rotated about an axis to match the second surface.<br><br>EQ.2: The faces of the first surface are translated in a given direction to obtain the corresponding faces on the second surface. |

**Rotation Case Card.** Additional card when CYCTYP = 1.

| Card 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AXISX1 | AXISY1 | AXISZ1 | DIRX | DIRY | DIRZ | ROTANG | |
| Type | F | F | F | F | F | F | F | |
| Default | 0.0 | 0.0 | 0.0 | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| AXIS[X,Y,Z]1 | A point on the axis of rotation for the transformation between the surfaces |
| DIR[X,Y,Z] | The direction which together with AXIS[X,Y,Z]1 defines the axis of rotation for the transformation between the surfaces |
| ROTANG | The angle of rotation (in degrees) that transforms the centroid of each face on the first surface to the centroid of the corresponding face on the second surface |

**Translation Case Card.** Additional card when CYCTYP = 2.

| Card 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TRANSX | TRANSY | TRANSZ | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| TRANS[X,Y,Z] | The translation direction that enables the identification of the segment in the second surface that matches a segment in the first surface |

**Remarks:**

1. **Unspecified relationship between surfaces.** For the case CYCTYP = 0, LS-DYNA examines the geometry of two faces of the two surfaces in order to determine if the surfaces are approximately parallel (CYCTYP = 2) or related through a rotation (CYCTYP = 1). The geometric parameters required are then computed.

2. **MSURF.** For the MSURF option, each mesh surface part must contain the same number of mesh surface elements. The mesh surface elements in each mesh surface part are internally ordered for pairwise matching between the two mesh surface parts.

3. **SEGMENT_SET.** For the SEGMENT_SET option, each segment set must contain the same number of segments. The segments in each set are internally ordered for pairwise matching between the two sets.

**\*DUALCESE_BOUNDARY_FSI**_OPTION_

Available options are:

      MSURF

      SEGMENT_SET

Purpose: Define an FSI boundary condition for the moving mesh dual CESE compressible flow solver.  This keyword must not be combined with the dual CESE immersed-boundary method FSI solver in the same dual CESE part on the same dual CESE mesh.  Doing so will result in an error termination condition.

This boundary condition must be applied on a surface of the dual CESE computational domain that is co-located with surfaces of the outside boundary of the structural mesh. The nodes of the two meshes will generally not be shared.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card 1a.**  Include this card for the MSURF keyword option.  Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| MSPID | REF_P | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card for the SEGMENT_SET keyword option.  Provide as many cards as necessary.  This input ends at the next keyword ("\*") card.

| SSID | REF_P | | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 used when the MSURF keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | REF_P | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by *MESH_SURFACE_EL-EMENT |
| REF_P | Ambient/reference pressure of the fluid domain on the side opposite this structural interface to the fluid simulation domain. This ambient pressure only needs to be specified in the case where the FSI structural part(s) connected with this FSI interface are not immersed in the dual CESE mesh. This reference pressure defaults to 0.0 since moving mesh FSI calculations most often involve structures surrounded by the dual CESE mesh, and there is no need for a reference pressure in that case. |

**Set Card.** Card 1 used when the SEGMENT_SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | REF_P | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with *DUALCESE_SEGMENTSET or *DUALCESE_BLOCKMESH |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| REF_P | Ambient/reference pressure of the fluid domain on the side opposite this structural interface to the fluid simulation domain. This ambient pressure only needs to be specified in the case where the FSI structural part(s) connected with this FSI interface are not immersed in the dual CESE mesh. This reference pressure defaults to 0.0 since moving mesh FSI calculations most often involve structures surrounded by the dual CESE mesh, and there is no need for a reference pressure in that case.. |

**Remarks:**

This boundary condition card is also needed for conjugate heat transfer problems with the moving mesh dual CESE solver. However, the conjugate heat transfer capability is *not* implemented in the dual CESE solver.

**\*DUALCESE_BOUNDARY_NON_REFLECTIVE_**_OPTION_

Available options are:

> MSURF
>
> SEGMENT_SET

Purpose: Define a passive boundary condition for dual CESE compressible flows. This non-reflective boundary condition provides an artificial computational boundary for an open boundary that is passive.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card 1a.** Include this card when the MSURF keyword option is used. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| MSPID | DIRX | DIRY | DIRZ | | | | |
|-------|------|------|------|--|--|--|--|

**Card 1b.** Include this card when the SEGMENT_SET keyword option is used. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| SSID | DIRX | DIRY | DIRZ | | | | |
|------|------|------|------|--|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 used when the MSURF keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | DIRX | DIRY | DIRZ | | | | |
| Type | I | F | F | F | | | | |
| Default | none | 0.0 | 0.0 | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Set Card.** Card 1 used when the SET keyword option is active. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | DIRX | DIRY | DIRZ | | | | |
| Type | I | F | F | F | | | | |
| Default | none | 0.0 | 0.0 | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Remarks:**

1. **Boundary Surface Flow.** This boundary condition is usually imposed on an open surface that is far from the main disturbed flow (the further away, the better), meaning the flow on the boundary surface should be almost uniform.

2. **Default Boundary Condition**. If any boundary segment has not been assigned a boundary condition by any of the \*DUALCESE_BOUNDARY_… cards, then it will automatically be assigned this non-reflective boundary condition.

**\*DUALCESE_BOUNDARY_PRESCRIBED_**OPTION

Available options include:

    MSURF

    SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set boundary values for velocity, density, pressure, and temperature.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.    Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.    Card 2 reads in load curve IDs.

3.    Card 3 reads in scale factors.

For each boundary condition to be specified include one set of cards.  This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IDCOMP | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IDCOMP | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_U | LC_V | LC_W | LC_RHO | LC_P | LC_T | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_U | SF_V | SF_W | SF_RHO | SF_P | SF_T | | |
|------|------|------|--------|------|------|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IDCOMP | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | none | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, the chemical mixture of the fluid entering the domain is defined with a \*CHEMISTRY_COMPOSITION card with this ID [Not yet available]. |
| DIRX, DIRY, DIRZ | If this vector is non-zero, then it is used as the prescribed flow direction. |

**Set Card.** Card 1 format used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IDCOMP | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | none | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, the chemical mixture of the fluid entering the domain is defined with a \*CHEMISTRY_COMPOSITION card with this ID [Not yet available]. |
| DIRX, DIRY, DIRZ | If this vector is non-zero, then it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | LC_U | LC_V | LC_W | LC_RHO | LC_P | LC_T | | |
| Type | I | I | I | I | I | I | | |
| Remarks | 1 | 1 | 1 | 1 | 1 | 1 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| LC_U | Load curve ID (see \*DEFINE_CURVE) to describe the $x$-component of the velocity as a function of time or function ID (see \*DEFINE_FUNCTION) to give the $x$-component of the velocity as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0: $x$-component of velocity is a constant with value SF_U. |
| | EQ.-1: $x$-component of velocity is computed by the solver. |
| LC_V | Load curve ID to describe the $y$-component of the velocity as a function of time or function ID to give the $y$-component of the velocity as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0: $y$-component of velocity is a constant with value SF_V. |
| | EQ.-1: $y$-component of velocity is computed by the solver. |
| LC_W | Load curve ID to describe the $z$-component of the velocity as a function of time or function ID to give the $z$-component of the |

| VARIABLE | DESCRIPTION |
|---|---|
| | velocity as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

    EQ.0:   *z*-component of velocity is a constant with value SF_W.

    EQ.-1: *z*-component of velocity is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_RHO | Load curve ID to describe the density as a function of time or function ID to give the density as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

    EQ.0:   Density is a constant with value SF_RHO.

    EQ.-1: Density is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_P | Load curve ID to describe the pressure as a function of time or function ID to give the pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

    EQ.0:   Pressure is a constant with value SF_P.

    EQ.-1: Pressure is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_T | Load curve ID to describe the temperature as a function of time or function ID to give the temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

    EQ.0:   Temperature is a constant with value SF_T.

    EQ.-1: Temperature is computed by the solver.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_U | SF_V | SF_W | SF_RH0 | SF_P | SF_T | | |
| Type | F | F | F | F | F | F | | |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_U | Scale factor for LC_U |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SF_V | Scale factor for LC_V |
| SF_W | Scale factor for LC_W |
| SF_RHO | Scale factor for LC_RHO |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1. **Consistent boundary values.** On each centroid or set of centroids, the variables $(v_x, v_y, v_z, \rho, P, T)$ that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_HYBRID**_OPTION_

Available options include:

MSURF

SEGMENT_SET

Purpose: For the dual CESE compressible flow solver, set boundary values for velocity, density, pressure, temperature, and other values in the hybrid multiphase model. Boundary values are applied at the centroid of elements connected with this boundary.

Use the MSURF option when the dual CESE mesh has been created using \*MESH cards. Use the SEGMENT_SET option when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied. Its format depends on the keyword option.

2.  Cards 2 and 3 provide load curve IDs.

3.  Cards 4 and 5 provide scale factors.

For each boundary condition to be specified, include one set of cards. This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1a.** Include this card if the keyword option is set to MSURF.

| MSPID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card if the keyword option is set to SSID.

| SSID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 2.** This card is required.

| LC_Z1 | LC_RA | LC_U | LC_V | LC_W | LC_D1 | LC_DA | LC_DB |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| LC_P | LC_T | | | | | | |
|------|------|--|--|--|--|--|--|

**Card 4.** This card is required.

| SF_Z1 | SF_RA | SF_U | SF_V | SF_W | SF_D1 | SF_DA | SF_DB |
|-------|-------|------|------|------|-------|-------|-------|

**Card 5.** This card is required.

| SF_P | SF_T | | | | | | |
|------|------|--|--|--|--|--|--|

**Data Card Definitions:**

**Surface Part Set Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_ELEMENT |
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Segment Set Card.** Card 1 format used for the SEGMENT_SET keyword option.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_- SEGMENTSET or \*DUALCESE_BLOCKMESH |
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Load Curve Card.** See Remark 1.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_Z1 | LC_RA | LC_U | LC_V | LC_W | LC_D1 | LC_DA | LC_DB |
| Type | I | I | I | I | I | I | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_Z1 | Load curve ID or function ID to describe the volume fraction of material 1 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

> EQ.0: The volume fraction is a constant with value SF_Z1.
>
> EQ.-1: The volume fraction is computed by the solver.

| | |
|---|---|
| LC_RA | Load curve or function ID to describe the mass fraction of reactant (material $\alpha$) with respect to the explosive mixture (material 2) as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

> EQ.0: The mass fraction is a constant with value SF_RA.
>
> EQ.-1: The mass fraction is computed by the solver.

| | |
|---|---|
| LC_U | Load curve or defined function ID to describe the $x$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

> EQ.0: The $x$-component of velocity is a constant with value SF_- U.
>
> EQ.-1: The $x$-component of velocity is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_V | Load curve or defined function ID to describe the $y$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:　The $y$-component of velocity is a constant with value SF_-V.

    EQ.-1:　The $y$-component of velocity is computed by the solver.

| | |
|---|---|
| LC_W | Load curve or defined function ID to describe the $z$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:　The $z$-component of velocity is a constant with value SF_-W.

    EQ.-1:　The $z$-component of velocity is computed by the solver.

| | |
|---|---|
| LC_D1 | Load curve or defined function ID to describe the density of the first multiphase material as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:　The density of the first multiphase material is a constant with value SF_D1.

    EQ.-1:　The density of the first multiphase material is computed by the solver.

| | |
|---|---|
| LC_DA | Load curve or defined function ID to describe the density of the reactant (material $\alpha$) as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:　The density of the reactant is a constant with value SF_-DA.

    EQ.-1:　The density of the reactant is computed by the solver.

| | |
|---|---|
| LC_DB | Load curve or defined function ID to describe the density of the product (material $\beta$) as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:　The density of the product is a constant with value SF_-DB.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.-1: The density of the product is computed by the solver. |

**Load Curve Card 2.** See Remark 1.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_P | LC_T | | | | | | |
| Type | I | I | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_P | Load curve or defined function ID to describe the pressure as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The pressure is a constant with value SF_P. |
| | EQ.-1: The pressure is computed by the solver. |
| LC_T | Load curve or defined function ID to describe the temperature as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The temperature is a constant with value SF_T. |
| | EQ.-1: The temperature is computed by the solver. |

**Scale Factor Card.**

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_Z1 | SF_RA | SF_U | SF_V | SF_W | SF_D1 | SF_DA | SF_DB |
| Type | F | F | F | F | F | F | F | F |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SF_Z | Scale factor for LC_Z1 |
| SF_RA | Scale factor for LC_RA |
| SF_U | Scale factor for LC_U |
| SF_V | Scale factor for LC_V |
| SF_W | Scale factor for LC_W |
| SF_D1 | Scale factor for LC_D1 |
| SF_DA | Scale factor for LC_DA |
| SF_DB | Scale factor for LC_DB |

**Scale Factor Card 2.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|---|---|---|---|---|---|
| Variable | SF_P | SF_T | | | | | | |
| Type | F | F | | | | | | |
| Default | 1.0 | 1.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remark:**

1. **Consistent boundary values.** On each centroid or set of element centroids, the variables $(v_x, v_y, v_z, \rho, P, T, ...)$ that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MACHNUM_**_OPTION_

Available options include:

MSURF

SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set inlet boundary values using total pressure, total temperature, and Mach number.  Specifying an arbitrary inlet flow direction is an option.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.  Card 2 reads in load curve IDs.

3.  Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_TOTP | LC_TOTT | LC_MACH | | | | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_TOTP | SF_TOTT | SF_MACH | | | | | |
|---------|---------|---------|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Include this card when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IWALL | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by *MESH_SURFACE_EL-EMENT |
| IWALL | Artificial wall flag: |
| | EQ.0: Do not treat as an artificial wall if there is flow recirculation at this inlet boundary. |
| | EQ.1: Do treat this inlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Set Card.** Include this card when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IWALL | DIRX | DIRX | DIRY | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with *DUALCESE_SEGMENTSET or *DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag: |
| | EQ.0: Do not treat as an artificial wall if there is flow recirculation at this inlet boundary. |
| | EQ.1: Do treat this inlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_TOTP | LC_TOTT | LC_MACH | | | | | |
| Type | I | I | I | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_TOTP | Load curve ID (see *DEFINE_CURVE) to describe the total pressure as a function of time or function ID (see *DEFINE_FUNCTION) to give the total pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0:  Total pressure is a constant with value SF_TOTP. |
| LC_TOTT | Load curve ID (see *DEFINE_CURVE) to describe the total temperature as a function of time or function ID (see *DEFINE_FUNCTION) to give the total temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0:  Total temperature is a constant with value SF_TOTT. |
| LC_MACH | Load curve ID to describe the Mach number as a function of time or function ID to give the Mach number as a function of position, |

| VARIABLE | DESCRIPTION |
|---|---|
| | velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

EQ.0:   Mach number is a constant with value SF_MACH.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_TOTP | SF_TOTT | SF_MACH | | | | | |
| Type | F | F | F | | | | | |
| Default | 1.0 | 1.0 | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_TOTP | Scale factor for LC_TOTP |
| SF_TOTT | Scale factor for LC_TOTT |
| SF_MACH | Scale factor for LC_MACH |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of centroids, the variables ($P_{\text{total}}$, $T_{\text{total}}$, Mach number) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_INLET_MFRATE**_OPTION_

Available options include:

MSURF

SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set inlet boundary values using total pressure, total temperature, and mass flow rate.  Specifying an arbitrary inlet flow direction is an option.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.   Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.   Card 2 reads in load curve IDs.

3.   Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_TOTP | LC_TOTT | LC_MFRT | | | | | |
|---|---|---|---|---|---|---|---|

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with \*DUALCESE_SEGMENTSET or \*DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag: |
| | EQ.0: Do not treat as an artificial wall if there is flow recirculation at this inlet boundary. |
| | EQ.1: Do treat this inlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | LC_TOTP | LC_TOTT | LC_MFRT | | | | | |
| Type | I | I | I | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| LC_TOTP | Load curve ID (see \*DEFINE_CURVE) to describe the total pressure as a function of time or function ID (see \*DEFINE_FUNCTION) to give the total pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0:  Total pressure is a constant with value SF_TOTP. |
| LC_TOTT | Load curve ID (see \*DEFINE_CURVE) to describe the total temperature as a function of time or function ID (see \*DEFINE_FUNCTION) to give the total temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0:  Total temperature is a constant with value SF_TOTT. |
| LC_MFRT | Load curve ID to describe the mass flow rate as a function of time or function ID to give the mass flow rate as a function of position, |

| VARIABLE | DESCRIPTION |
|---|---|

velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).

> EQ.0:   Mass flow rate is a constant with value SF_MFRT.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_TOTP | SF_TOTT | SF_MFRT | | | | | |
| Type | F | F | F | | | | | |
| Default | 1.0 | 1.0 | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_TOTP | Scale factor for LC_TOTP |
| SF_TOTT | Scale factor for LC_TOTT |
| SF_MFRT | Scale factor for LC_MFRT |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of centroids, the variables ($P_{\text{total}}$, $T_{\text{total}}$, mass flow rate) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_INLET_PRESSURE_**_OPTION_

Available options include:

MSURF

SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set inlet boundary values using total pressure, total temperature, and static pressure.  Specifying an arbitrary inlet flow direction is an option.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.  Card 2 reads in load curve IDs.

3.  Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_TOTP | LC_TOTT | LC_PSTAT | | | | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_TOTP | SF_TOTT | SF_PSTAT | | | | | |
|---------|---------|----------|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Include this card when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IWALL | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| IWALL | Artificial wall flag: |
| | EQ.0: Do not treat as an artificial wall if there is flow recirculation at this inlet boundary. |
| | EQ.1: Do treat this inlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Set Card.** Include this card when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IWALL | DIRX | DIRX | DIRY | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag:<br><br>EQ.0: Do not treat as an artificial wall if there is flow recirculation at this inlet boundary.<br><br>EQ.1: Do treat this inlet boundary as an artificial wall whenever there is flow recirculation there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_TOTP | LC_TOTT | LC_PSTAT | | | | | |
| Type | I | I | I | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_TOTP | Load curve ID (see \*DEFINE_CURVE) to describe the total pressure as a function of time or function ID (see \*DEFINE_FUNCTION) to give the total pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).<br><br>EQ.0:   Total pressure is a constant with value SF_TOTP. |
| LC_TOTT | Load curve ID (see \*DEFINE_CURVE) to describe the total temperature as a function of time or function ID (see \*DEFINE_FUNCTION) to give the total temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).<br><br>EQ.0:   Total temperature is a constant with value SF_TOTT. |
| LC_PSTAT | Load curve ID to describe the static pressure as a function of time or function ID to give the static pressure as a function of position, |

| VARIABLE | DESCRIPTION |
|---|---|
| | velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

EQ.0:   Static pressure is a constant with value SF_PSTAT.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_TOTP | SF_TOTT | SF_PSTAT | | | | | |
| Type | F | F | F | | | | | |
| Default | 1.0 | 1.0 | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_TOTP | Scale factor for LC_TOTP |
| SF_TOTT | Scale factor for LC_TOTT |
| SF_PSTAT | Scale factor for LC_PSTAT |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of centroids, the variables ($P_{\text{total}}$, $T_{\text{total}}$, $P_{\text{static}}$) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

## \*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_EXMFRATE_*OPTION*

Available options include:

MSURF

SEGMENT_SET

Purpose: For the dual CESE compressible flow solver, set outlet boundary values using reference pressure, reference temperature, and exit mass flow rate. Specifying an arbitrary outlet flow direction is an option. Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using *MESH cards. The SEGMENT_SET option should be used when *DUALCESE_ELE2D, *DUALCESE_ELE3D, or *DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the object to which the boundary condition is applied. Its format depends on the keyword option.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each boundary condition to be specified include one set of cards. This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.** Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 2.** This card is required.

| LC_PREF | LC_TREF | LC_MFRT | | | | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_PREF | SF_TREF | SF_MFRT | | | | | |
|---------|---------|---------|--|--|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Include this card when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IWALL | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by *MESH_SURFACE_EL-EMENT |
| IWALL | Artificial wall flag: |

        EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary.

        EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there.

| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |
|------------------|------------------------------------------------------------------------|

**Set Card.** Include this card when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IWALL | DIRX | DIRX | DIRY | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_SEGMENTSET or \*DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag:<br><br>EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary.<br><br>EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_PREF | LC_TREF | LC_MFRT | | | | | |
| Type | I | I | I | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_PREF | Load curve ID (see \*DEFINE_CURVE) to describe the reference pressure as a function of time or function ID (see \*DEFINE_FUNCTION) to give the reference pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).<br><br>EQ.0: Reference pressure is a constant with value SF_PREF. |
| LC_TREF | Load curve ID (see \*DEFINE_CURVE) to describe the reference temperature as a function of time or function ID (see \*DEFINE_FUNCTION) to give the reference temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).<br><br>EQ.0: Reference temperature is a constant with value SF_TREF. |
| LC_MFRT | Load curve ID to describe the exit mass flow rate as a function of time or function ID to give the exit mass flow rate as a function of |

| VARIABLE | DESCRIPTION |
|---|---|

position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).

    EQ.0:   exit mass flow rate is a constant with value SF_MFRT.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_PREF | SF_TREF | SF_MFRT | | | | | |
| Type | F | F | F | | | | | |
| Default | 1.0 | 1.0 | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_PREF | Scale factor for LC_PREF |
| SF_TREF | Scale factor for LC_TREF |
| SF_MFRT | Scale factor for LC_MFRT |

**Remarks:**

1.    **Consistent boundary values.** On each centroid or set of centroids, the variables ($P_{\text{ref}}$, $T_{\text{ref}}$, Exit Mass Flow Rate) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_FARFIELD_***OPTION*

Available options include:

> MSURF
>
> SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set outlet boundary values using static pressure, static temperature, and Mach number.  Specifying an arbitrary outlet flow direction is an option.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.**  This card is required.

| LC_PSTAT | LC_TSTAT | LC_MACH | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 3.** This card is required.

| SF_PSTAT | SF_TSTAT | SF_MACH | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Include this card when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSPID | IWALL | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| IWALL | Artificial wall flag: |

    EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary.

    EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there.

| VARIABLE | DESCRIPTION |
|---|---|
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Set Card.** Include this card when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | IWALL | DIRX | DIRX | DIRY | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with *DUALCESE_-SEGMENTSET or *DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag: |
| | EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary. |
| | EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Load Curve Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_PSTAT | LC_TSTAT | LC_MACH | | | | | |
| Type | I | I | I | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_PSTAT | Load curve ID (see *DEFINE_CURVE) to describe the static pressure as a function of time or function ID (see *DEFINE_FUNCTION) to give the static pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0: Static pressure is a constant with value SF_PSTAT. |
| LC_TSTAT | Load curve ID (see *DEFINE_CURVE) to describe the static temperature as a function of time or function ID (see *DEFINE_FUNCTION) to give the static temperature as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |
| | EQ.0: Static temperature is a constant with value SF_TSTAT. |
| LC_MACH | Load curve ID to describe the Mach number as a function of time or function ID to give the Mach number as a function of position, |

| VARIABLE | DESCRIPTION |
|---|---|
| | velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time). |

EQ.0:  Mach number is a constant with value SF_MACH.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_PSTAT | SF_TSTAT | SF_MACH | | | | | |
| Type | F | F | F | | | | | |
| Default | 1.0 | 1.0 | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_PSTAT | Scale factor for LC_PSTAT |
| SF_TSTAT | Scale factor for LC_TSTAT |
| SF_MACH | Scale factor for LC_MACH |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of centroids, the variables ($P_{\text{static}}$, $T_{\text{static}}$, Mach number) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_OUTLET_PRESSURE**_OPTION_

Available options include:

> MSURF
>
> SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set outlet boundary values using static pressure.  Specifying an arbitrary outlet flow direction is an option.  Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.  Card 2 reads in load curve IDs.

3.  Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1a.**  Include this card if the MSURF keyword option is used.

| MSPID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the SEGMENT_SET keyword option is used.

| SSID | IWALL | DIR_X | DIR_Y | DIR_Z | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_PSTAT | | | | | | | |
|---|---|---|---|---|---|---|---|

| SF_PSTAT | | | | | | | |
|----------|--|--|--|--|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Include this card when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IWALL | DIRX | DIRY | DIRZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_ELEMENT |
| IWALL | Artificial wall flag:<br><br>EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary.<br><br>EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

**Set Card.** Card 1b format used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IWALL | DIRX | DIRX | DIRY | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with *DUALCESE_-SEGMENTSET or *DUALCESE_BLOCKMESH |
| IWALL | Artificial wall flag:<br><br>EQ.0: Do not treat as an artificial wall if there is flow recirculation at this outlet boundary.<br><br>EQ.1: Do treat this outlet boundary as an artificial wall whenever flow recirculation exists there. |
| DIRX, DIRY, DIRZ | If this vector is nonzero, it is used as the prescribed flow direction. |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_PSTAT | | | | | | | |
| Type | I | | | | | | | |
| Remarks | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_PSTAT | Load curve ID (see *DEFINE_CURVE) to describe the total pressure as a function of time or function ID (see *DEFINE_FUNCTION) to give the total pressure as a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time).<br><br>EQ.0: Total pressure is a constant with value SF_PSTAT. |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_PSTAT | | | | | | | |
| Type | F | | | | | | | |
| Default | 1.0 | | | | | | | |

| VARIABLE | DESCRIPTION |
| --- | --- |
| SF_PSTAT | Scale factor for LC_PSTAT |

**Remarks:**

1. **Consistent boundary values.** On each centroid or set of centroids, the variable ($P_{\text{static}}$) that is given a value must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_PHASE_CHANGE**_OPTION_

Available options are:

MSURF

SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set boundary values for velocity, density, pressure, temperature, and other values in the phase-change multiphase model. Boundary values are applied at the centroid of outside elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards.  The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.  Cards 2 and 3 provide load curve IDs.

3.  Cards 4 and 5 provide scale factors.

For each boundary condition to be specified, include one set of cards. This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.**  Include this card for the MSURF keyword option.

| MSPID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card for the SEGMENT_SET keyword option.

| SSID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LCIDU | LCIDV | LCIDW | LCIDRHO | LCIDP | LCIDT | LCIDY1 | LCIDY2 |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| LCIDY3 | | | | | | | |
|--------|--|--|--|--|--|--|--|

**Card 4.** This card is required.

| SFU | SFV | SFW | SFRHO | SFP | SFT | SFY1 | SFY2 |
|-----|-----|-----|-------|-----|-----|------|------|

**Card 5.** This card is required.

| SFY3 | | | | | | | |
|------|--|--|--|--|--|--|--|

**Data Card Definitions:**

**Surface Part Card.** Card 1 used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by *MESH_SURFACE_EL-EMENT |
| DIRX, DIRY, DIRZ | If nonzero, vector giving the prescribed flow direction |

**Set Card.** Card 1 used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with *DUALCESE_SEGMENTSET or *DUALCESE_BLOCKMESH |
| DIRX, DIRY, DIRZ | If nonzero, vector giving the prescribed flow direction |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | LCIDU | LCIDV | LCIDW | LCIDRHO | LCIDP | LCIDT | LCIDY1 | LCIDY2 |
| Type | I | I | I | I | I | I | I | I |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Remarks | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| LCIDU | Load curve or defined function ID to describe the $xx$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

> EQ.0: The $x$-component of velocity is a constant with value SFU.
>
> EQ.-1: The $x$-component of velocity is computed by the solver.

| | |
|----------|-------------|
| LCIDV | Load curve or defined function ID to describe the $yy$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

> EQ.0: The $y$-component of velocity is a constant with value SFV.
>
> EQ.-1: The $y$-component of velocity is computed by the solver.

| | |
|----------|-------------|
| LCIDW | Load curve or defined function ID to describe the $zz$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: The *z*-component of velocity is a constant with value SFW. |
| | EQ.-1: The *z*-component of velocity is computed by the solver. |
| LCIDRHO | Load curve or defined function ID to describe the mixture density as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:  The density is a constant with value SFRHO. |
| | EQ.-1: The density is computed by the solver. |
| LCIDP | Load curve or defined function ID to describe the pressure as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:  The pressure is a constant with value SFP. |
| | EQ.-1: The pressure is computed by the solver. |
| LCIDT | Load curve or defined function ID to describe the temperature as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:  The temperature is a constant with value SFT. |
| | EQ.-1: The temperature is computed by the solver. |
| LCIDY1 | Load curve or defined function ID to describe the mass fraction of material 1 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:  The mass fraction is a constant with value SFY1. |
| | EQ.-1: The mass fraction is computed by the solver. |
| LCIDY2 | Load curve or defined function ID to describe the mass fraction of material 2 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:  The mass fraction is a constant with value SFY2. |
| | EQ.-1: The mass fraction is computed by the solver. |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | LCIDY3 | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |
| Remarks | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

LCIDY3        Load curve or defined function ID to describe the mass fraction of material 3 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively.

   EQ.0:   The mass fraction is a constant with value SFY3.

   EQ.-1:  The mass fraction is computed by the solver.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | SFU | SFV | SFW | SFRHO | SFP | SFT | SFY1 | SFY2 |
| Type | F | F | F | F | F | F | F | F |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|

SFU        Scale factor for LCIDU

SFV        Scale factor for LCIDV

SFW        Scale factor for LCIDW

SFRHO      Scale factor for LCIDRHO

SFP        Scale factor for LCIDP

| VARIABLE | DESCRIPTION |
|---|---|
| SFT | Scale factor for LCIDT |
| SFY1 | Scale factor for LCIDY1 |
| SFY2 | Scale factor for LCIDY2 |

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SFY3 | | | | | | | |
| Type | F | | | | | | | |
| Default | 1.0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SFY3 | Scale factor for LCIDY3 |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of element centroids, the variables $(v_x, v_y, v_z, \rho, P, T, \dots)$ that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_TWO-PHASE_***OPTION*

Available options include:

> MSURF
>
> SEGMENT_SET

Purpose:  For the dual CESE compressible flow solver, set boundary values for velocity, density, pressure, temperature, and other values in the two-phase multiphase model. Boundary values are applied at the centroid of elements connected with this boundary.

The MSURF option should be used when the dual CESE mesh has been created using *MESH cards.  The SEGMENT_SET option should be used when *DUALCESE_ELE2D, *DUALCESE_ELE3D, or *DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the object to which the boundary condition is applied.  Its format depends on the keyword option.

2.  Card 2 provides load curve IDs.

3.  Card 3 provides scale factors.

For each boundary condition to be specified, include one set of cards.  This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1a.**  Include this card if the keyword option is set to MSURF.

| MSPID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card if the keyword option is set to SSID.

| SSID | | DIRX | DIRY | DIRZ | | | |
|---|---|---|---|---|---|---|---|

**Card 2.**  This card is required.

| LC_Z1 | LC_U | LC_V | LC_W | LC_D1 | LC_D2 | LC_P | LC_T |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_Z1 | SF_U | SF_V | SF_W | SF_D1 | SF_D2 | SF_P | SF_T |
|-------|------|------|------|-------|-------|------|------|

**Data Card Definitions:**

**Surface Part Set Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|------|------|------|---|---|---|
| Variable | MSPID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Segment Set Card.** Card 1 format used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|------|------|------|---|---|---|
| Variable | SSID | | DIRX | DIRY | DIRZ | | | |
| Type | I | | F | F | F | | | |
| Default | none | | 0.0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |

| VARIABLE | DESCRIPTION |
|---|---|
| DIRX, DIRY, DIRZ | If this vector is nonzero, then it is used as the prescribed flow direction. |

**Load Curve Card.** See Remark 1.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_Z1 | LC_U | LC_V | LC_W | LC_D1 | LC_D2 | LC_P | LC_T |
| Type | I | I | I | I | I | I | I | I |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_Z1 | Load curve or defined function ID to describe the volume fraction of material 1 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:  The volume fraction is a constant with value SF_Z1.

    EQ.-1: The volume fraction is computed by the solver.

| | |
|---|---|
| LC_U | Load curve or defined function ID to describe the $x$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:  The $x$-component of velocity is a constant with value SF_U.

    EQ.-1: The $x$-component of velocity is computed by the solver.

| | |
|---|---|
| LC_V | Load curve or defined function ID to describe the $y$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

    EQ.0:  The $y$-component of velocity is a constant with value SF_V.

    EQ.-1: The $y$-component of velocity is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_W | Load curve or defined function ID to describe the $z$-component of the velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

     EQ.0:  The $z$-component of velocity is a constant with value SF_-W.

     EQ.-1:  The $z$-component of velocity is computed by the solver.

| | |
|---|---|
| LC_D1 | Load curve or defined function ID to describe the density of material 1 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

     EQ.0:  The density is a constant with value SF_D1.

     EQ.-1:  The density is computed by the solver.

| | |
|---|---|
| LC_D2 | Load curve or defined function ID to describe the density of material 2 as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

     EQ.0:  The density is a constant with value SF_D2.

     EQ.-1:  The density is computed by the solver.

| | |
|---|---|
| LC_P | Load curve or defined function ID to describe the pressure as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

     EQ.0:  The pressure is a constant with value SF_P.

     EQ.-1:  The pressure is computed by the solver.

| | |
|---|---|
| LC_T | Load curve or defined function ID to describe the temperature as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |

     EQ.0:  The temperature is a constant with value SF_T.

     EQ.-1:  The temperature is computed by the solver.

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | SF_Z1 | SF_U | SF_V | SF_W | SF_D1 | SF_D2 | SF_P | SF_T |
| Type | F | F | F | F | F | F | F | F |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SF_Z | Scale factor for LC_Z1 |
| SF_U | Scale factor for LC_U |
| SF_V | Scale factor for LC_V |
| SF_W | Scale factor for LC_W |
| SF_D1 | Scale factor for LC_D1 |
| SF_D2 | Scale factor for LC_D2 |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remark:**

1. **Consistent boundary values.** On each centroid or set of element centroids, the variables ($v_x, v_y, v_z, \rho, P, T, ...$) that are given values must be consistent and make the model well-posed (meaning that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_BOUNDARY_PRESCRIBED_VN_***OPTION*

Available options include:

    MSURF

    SEGMENT_SET

Purpose: For the dual CESE compressible flow solver, set boundary values for the normal velocity, density, pressure, and temperature. Boundary values are applied at the centroid of elements connected with this boundary. This boundary condition differs from \*DU-ALCESE_BOUNDARY_PRESCRIBED in that the normal velocity is prescribed instead of each velocity component.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the object to which the boundary condition is applied. Its format depends on the keyword option.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each boundary condition to be specified, include one set of cards. This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1a.** Include this card if the MSURF keyword option is used.

| MSPID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 1b.** Include this card if the SEGMENT_SET keyword option is used.

| SSID | IDCOMP | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.** This card is required.

| LC_VN | | | LC_RHO | LC_P | LC_T | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 3.** This card is required.

| SF_VN | | | SF_RHO | SF_P | SF_T | | |
|-------|---|---|--------|------|------|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, the chemical mixture of the fluid entering the domain is defined with a \*CHEMISTRY_COMPOSITION card with this ID [Not yet available]. |

**Set Card.** Card 1 format used when the SEGMENT_SET keyword option is active.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | SSID | IDCOMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |

| VARIABLE | DESCRIPTION |
|---|---|
| IDCOMP | For inflow boundaries in problems involving chemical reacting flows, the chemical mixture of the fluid entering the domain is defined with a \*CHEMISTRY_COMPOSITION card with this ID [Not yet available]. |

**Load Curve Card.** See Remark 1.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_VN | | | LC_RHO | LC_P | LC_T | | |
| Type | I | | | I | I | I | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_VN | Load curve or function ID to describe the normal velocity as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The normal velocity is a constant with value SF_VN. |
| | EQ.-1: The normal velocity is computed by the solver. |
| LC_RHO | Load curve ID to describe the density as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The density is a constant with value SF_RHO. |
| | EQ.-1: The density is computed by the solver. |
| LC_P | Load curve ID to describe the pressure as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The pressure is a constant with value SF_P. |
| | EQ.-1: The pressure is computed by the solver. |
| LC_T | Load curve ID to describe the temperature as a function of time or a function of position, velocity, temperature, pressure, and time, f(x, y, z, vx, vy, vz, temp, pres, time), respectively. |
| | EQ.0:   The temperature is a constant with value SF_T. |
| | EQ.-1: The temperature is computed by the solver. |

**Scale Factor Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | SF_VN | | | SF_RH0 | SF_P | SF_T | | |
| Type | F | | | F | F | F | | |
| Default | 1.0 | | | 1.0 | 1.0 | 1.0 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SF_VN | Scale factor for LC_VN |
| SF_RHO | Scale factor for LC_RHO |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1.  **Consistent boundary values.** On each centroid or set of centroids, the variables ( $V_N, \rho, P, T$ ) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

## \*DUALCESE_BOUNDARY_REFLECTIVE_*OPTION*

Available options are:

    MSURF

    SEGMENT_SET

Purpose: Define a reflective boundary condition for the dual CESE compressible flow solver. This boundary condition can be applied to a symmetrical surface or a solid wall of the computational domain.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| MSPID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the SEGMENT_SET keyword option. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1 format used when the MSURF keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSPID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |

**Set Card.** Card 1 format used when the SEGMENT_SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |

**Remarks:**

This boundary condition has the same effect as a solid wall boundary condition for inviscid flows.

**\*DUALCESE_BOUNDARY_SLIDING_*OPTION***

Available options are:

> MSURF

> SEGMENT_SET

Purpose: Define a fluid surface that translates in the main direction of mesh movement (in the moving mesh dual CESE solvers). This is useful in piston-type applications.

The MSURF option should be used when the dual CESE mesh has been created using *MESH cards. The SEGMENT_SET option should be used when *DUALCESE_ELE2D, *DUALCESE_ELE3D, or *DUALCESE_BLOCKMESH specifies the dual CESE mesh.

**Card Summary:**

**Card 1a.** Include this card for the MSURF keyword option. Provide as many cards as necessary. This input card ends at the next keyword ("\*") card.

| MSPID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.** Include this card for the SEGMENT_SET keyword option. Provide as many cards as necessary. This input card ends at the next keyword ("\*") card.

| SSID | | | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Surface Part Card.** Card 1a format used when the MSURF keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSPID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |

**Set Card.** Card 1b format used when the SEGMENT_SET keyword option is active. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with \*DUALCESE_-SEGMENTSET or \*DUALCESE_BLOCKMESH |

**\*DUALCESE_BOUNDARY_SOLID_WALL_**_OPTION1_{OPTION2}_

For _OPTION1_ the choices are:

      MSURF

      SEGMENT_SET

For _OPTION2_ the choices are:

      <BLANK>

      ROTATE

Purpose: Define a solid wall boundary condition for the dual CESE compressible flow solver. This boundary condition can be applied at a solid boundary that is the physical boundary for the flow field. For inviscid flow, this will be a slip boundary condition, while for viscous flows, it is a no-slip boundary condition.

The MSURF option should be used when the dual CESE mesh has been created using \*MESH cards. The SEGMENT_SET option should be used when \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCKMESH specifies the dual CESE mesh. The ROTATE keyword option allows the boundary condition to rotate around an axis with a variable speed given by a load curve.

**Card Summary:**

**Card Sets.**  The following sequence of cards comprises a _single set_. LS-DYNA will continue reading data card sets until the next keyword ("\*") card is encountered.

**Card 1a.**  Include this card for the MSURF keyword option _without_ the ROTATE keyword option.

| MSPID | LCID | VX | VY | VZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card for the MSURF keyword option _with_ the ROTATE keyword option.

| MSPID | LCID | XP | YP | ZP | NX | NY | NZ |
|---|---|---|---|---|---|---|---|

**Card 1c.**  Include this card for the SEGMENT_SET keyword option _without_ the ROTATE keyword option.

| SSID | LCID | VX | VY | VZ | | | |
|---|---|---|---|---|---|---|---|

**Card 1d.** Include this card for the SEGMENT_SET keyword option *with* the ROTATE keyword option.

| SSID | LCID | XP | YP | ZP | NX | NY | NZ |
|------|------|-----|-----|-----|-----|-----|-----|

**Data Card Definitions:**

**Surface Part Card without Rotation.** Card 1 format used when the MSURF keyword option is active *without* the ROTATE keyword option

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | MSPID | LCID | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |
| Remarks | | 2 | 2 | 2 | 2 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT cards |
| LCID | Load curve ID scales the velocity vector specified with (VX, VY, VZ) to give the solid wall boundary movement. If not defined, the solid wall boundary moves with a constant velocity vector specified by (VX, VY, VZ). |
| VX, VY, VZ | Velocity vector of the solid wall boundary condition: |

      LCID.EQ.0: Constant velocity vector specified with VX, VY, and VZ.

      LCID.NE.0: VX, VY, and VZ give the velocity vector that is scaled by LCID.

**Surface Part Card with Rotation.** Card 1 format used when the MSURF keyword option is active *with* the ROTATE keyword option.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | MSPID | LCID | XP | YP | ZP | NX | NY | NZ |
| Type | I | I | F | F | F | F | F | F |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSPID | Mesh surface part ID that is referenced by \*MESH_SURFACE_EL-EMENT |
| LCID | Load curve ID for specifying the rotating speed frequency in Hz. This input is required. |
| XP, YP, ZP | Coordinates for a point on the axis of rotation |
| NX, NY, NZ | Unit vector for specifying the direction of the axis of rotation. This is not used for the 2D case. |

**Segment Set Card without Rotation.** Card 1 format used when the SEGMENT_SET keyword option is active *without* the ROTATE keyword option

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | SSID | LCID | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | | | |
| Remarks | | 2 | 2 | 2 | 2 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | ID of the segment set created with \*DUALCESE_SEGMENTSET |

| VARIABLE | DESCRIPTION |
|---|---|
| LCID | Load curve ID scales the velocity vector specified with (VX, VY, VZ) to give the solid wall boundary movement. If not defined, the solid wall boundary moves with a constant velocity vector specified by (VX, VY, VZ). |
| VX, VY, VZ | Velocity vector of the solid wall boundary condition: |

> LCID.EQ.0: Constant velocity vector specified with VX, VY, and VZ.
>
> LCID.NE.0: VX, VY, and VZ give the velocity vector that is scaled by LCID.

**Segment Set Card with Rotation.** Card 1 format used when the SEGMENT_SET keyword option is active *with* the ROTATE keyword option.

| Card 1d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID | LCID | XP | YP | ZP | NX | NY | NZ |
| Type | I | I | F | F | F | F | F | F |
| Default | none | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| VARIABLE | DESCRIPTION |
|---|---|
| SSID | Segment set ID for the segment set created with *DUALCESE_-SEGMENTSET or *DUALCESE_BLOCKMESH |
| LCID | Load curve ID for specifying the rotating speed frequency in Hz. This input is required. |
| XP, YP, ZP | Coordinates for a point on the axis of rotation |
| NX, NY, NZ | Unit vector for specifying the direction of the axis of rotation. This is not used for the 2D case. |

**Remarks:**

1. **Boundary movement restrictions.** In this solid-wall condition, the boundary movement can only be in the tangential direction of the wall and should not affect the fluid domain size and mesh during the calculation. Otherwise, an FSI

or moving mesh solver should be used.  Also, this moving boundary condition only affects viscous flows (no-slip boundary condition).

2.   **Fixed solid wall boundary condition.** If LCID = 0 and Vx = Vy = Vz = 0.0 (default), this will be a regular solid wall boundary condition.

## \*DUALCESE_CONTROL_LIMITER

Purpose: Sets some stability parameters used in the dual CESE compressible flow solver on the current dual CESE model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-------|-------|------|------|---|---|---|---|
| Variable | IDLMT | ALPHA | BETA | EPSR | | | | |
| Type | I | F | F | F | | | | |
| Default | 0 | 0.0 | 0.0 | 0.0 | | | | |
| Remarks | | 1 | 2 | 3 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| IDLMT | Set the stability limiter option (see dual CESE theory manual): <br><br> EQ.0: Limiter format 1 (re-weighting) <br><br> EQ.1: Limiter format 2 (relaxing) |
| ALPHA | Re-weighting coefficient, $\alpha$ (see dual CESE theory manual). Must be $\geq 0$. |
| BETA | Numerical viscosity control coefficient, $\beta$ (see dual CESE theory manual). $0 \leq \beta \leq 1$. |
| EPSR | Stability control coefficient, $\varepsilon$ (see dual CESE theory manual). Must be $\geq 0$. |

**Remarks:**

1. **Re-weighting Coefficient.** Larger values of $\alpha$ give more stability, but less accuracy. Usually $\alpha = 2.0$ or $4.0$ will be enough for normal shock problems.

2. **Numerical Viscosity Control Coefficient.** Larger values of $\beta$ give more stability. For problems with shock waves, $\beta = 1.0$ is recommended.

3. **Stability Control Coefficient.** Larger values of $\varepsilon$ give more stability, but less accuracy.

## \*DUALCESE_CONTROL_MESH_MOV

Purpose: Specify the algorithm for calculating the mesh movement (morphing) of a given DUALCESE part in an FSI problem. This keyword is for the moving mesh version of dual CESE.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|--------|--------|---------|---|---|---|
| Variable | ID | IALG | NINTER | RELERR | MXDISPR | | | |
| Type | I | I | I | F | F | | | |
| Default | none | 9 | 100 | $10^{-3}$ | $10^{-2}$ | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ID | ID for this mesh motion algorithm |
| IALG | Mesh motion algorithm:<br><br>EQ.9: IDW scheme (default) |
| NITER | Number of linear solver iterations (when using a linear solver specified in IALG). No linear solvers have been implemented at this time, so this field is ignored. |
| RELERR | Relative error for determining convergence when using a linear solver specified in IALG. No linear solvers have been implemented at this time, so this field is ignored. |
| MXDISPR | Maximum displacement relative to element size to use as a criterion for avoiding the full calculation of the motion of the DUALCESE part on a given time step. If the full calculation can be avoided, the elements touching an FSI interface are still morphed, but it is assumed that this approximation will not lead to elements that are overly distorted. |

## \*DUALCESE_CONTROL_SOLVER

Purpose: Set general purpose control variables for the dual CESE compressible flow solver.

> **WARNING:** As of version R14, this keyword is deprecated. Instead, in order to select the appropriate equations to solve, you should use \*DUALCESE_SOLVER_SELECTION along with the corresponding \*DUALCESE_-SOLVER_... card. Also, instead of this card, use \*DU-ALCESE_MESH_GEOMETRY for the geometry-related details.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|---------|------|-------|---|---|
| Variable | EQNS | IGEOM | IFRAME | MIXTYPE | IDC | ISNAN | | |
| Type | A | A | A | A | F | I | | |
| Default | EULER | none | FIXED | optional | 0.25 | 0 | | |
| Remarks | | 1 | | | 2 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

EQNS     Select the equations being solved with the dual CESE solver:

       EQ.NS:      Navier-Stokes equations

       EQ.EULER: Euler equations

IGEOM     Sets the geometric dimension:

       EQ.2D: Two-dimensional (2D) problem

       EQ.3D: Three-dimensional (3D) problem

       EQ.AXI: 2D axisymmetric

IFRAME     Choose the frame of reference:

       EQ.FIXED: Usual non-moving reference frame (default).

       EQ.ROT:    Non-inertial rotating reference frame. IFRAME = ROTATING may also be used.

| VARIABLE | DESCRIPTION |
|---|---|
| MIXTYPE | Select the mix or multiphase model solver (if any): |
| | EQ.<blank>:     No mix or multiphase model (default) |
| | EQ.HYBRID:     Hybrid multiphase model solver |
| | EQ.TWO-PHASE: Two-phase multiphase solver |
| IDC | Contact interaction detection coefficient (for FSI problems) |
| ISNAN | Flag to check for NaN in the dual CESE solver solution arrays at the completion of each time step. This option can be useful for debugging purposes. There is a cost overhead when this option is active. |
| | EQ.0: No checking. |
| | EQ.1: Checking is active. |

**Remarks:**

1. **Mesh and Boundary Conditions for 2D Problems.** If you want to use the 2D (IGEOM = 2D) or 2D axisymmetric (IGEOM=AXI) solver, the mesh should only be distributed in the *xy*-plane with the boundary conditions given only at the *xy* domain boundaries. Otherwise, a warning message will be given, and the 3D solver will be triggered instead.

   The 2D axisymmetric case will work only if the 2D mesh and corresponding boundary conditions are properly defined with the *x* and *y* coordinates corresponding to the radial and axial directions, respectively.

2. **Contact Interaction Detection Coefficient.** IDC is the same type of variable that is input on the \*ICFD_CONTROL_FSI card. For an explanation, see Remark 1 for the \*ICFD_CONTROL_FSI card.

3. *Dual CESE Solver and Restarts.* The dual CESE solver will support restarts beginning with release R17.

## \*DUALCESE_CONTROL_TIMESTEP

Purpose:  Sets the time step control parameters for the CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IDDT | CFL | DTINT | | | | | |
| Type | I | F | F | | | | | |
| Default | 0 | 0.9 | $10^{-3}$ | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IDDT | Sets the time step option: |

<div></div>

       EQ.0: Fixed time step size of DTINT, the given initial time step size

       NE.0: The time step size will be calculated based on the given CFL-number and the flow solution at the previous time step.

| CFL | CFL number (Courant–Friedrichs–Lewy condition). $0.0 < \text{CFL} \leq 1.0$ |
|---|---|
| DTINT | Initial time step size |

## \*DUALCESE_DARCY-FORCHHEIMER_EQ

Purpose: Provide the parameters of the Darcy-Forchheimer equation. This equation is also called the Forchheimer correction of Darcy's Law. This equation models the porous medium for compressible porous media flows, such as supersonic spacecraft parachute flows.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EQID | KP | BETA | | | | | |
| Type | I | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EQID | Equation ID of the porous medium model (see \*DUALCESE_PO-ROUS_SPECIFY_JUMP) |
| KP | Permeability of the porous medium, $k_\text{p}$. See Remark 1. |
| BETA | Inertial resistance coefficient of the porous medium, $\beta$. See Remark 1. |

**Remarks:**

1.  **Darcy-Forchheimer equation.** The Darcy-Forchheimer equation is given by:

$$\frac{\partial P}{\partial n} = \frac{\mu_\text{f}}{k_\text{p}} v_n + \beta \rho_\text{f} v_n$$

  where

    $\frac{\partial P}{\partial n}$  Pressure gradient (in the normal direction) across the porous medium

    $\rho_\text{f}$  Fluid density

    $\mu_\text{f}$  Fluid dynamic viscosity

    $v_n$  Wall normal velocity of the flow through the porous medium

    $k_p$  Permeablity of the porous media

    $\beta$  Inertial resistance coefficient

2. **Restrictions for the structure.** The porous media model can only be used in FSI problems with thin shell structures (such as fabric). It is intended for modeling supersonic spacecraft parachutes and airbags.

3. **Porous media model.** Currently, only a jump condition method is available for modeling porous media flow.

## *DUALCESE_DATABASE_HISTORY_DRAG_LIFT

Purpose: Enable output of drag and lift-related data for all pieces of structural parts participating in FSI with the dual CESE immersed boundary method (IBM). This data output goes to binary database binout. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | LCUR | IOOPT | REFDENS | REFVEL | REFPRESS | REFAREA | REFLENG |
| Type | F | I | I | F | F | F | F | F |
| Default | 0.0 | 0 | 0 | none | none | none | none | none |

**Directions Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DRAGDIRX | DRAGDIRY | DRAGDIRZ | LIFTDIRX | LIFTDIRY | LIFTDIRZ | | |
| Type | F | F | F | F | F | F | | |
| Default | 1.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | | |

**Moment Options Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DRGAREA | MOMNTD | MOMNTL | MOMNTC | | | | |
| Type | I | I | I | I | | | | |
| Default | 0 | 0 | 0 | 0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| DT | Time interval between outputs. If DT is zero, no output is generated. DT is ignored if LCUR > 0. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve. The abscissa is time, and the ordinate is the time interval between outputs. |
| IOOPT | Flag to govern the behavior of the output frequency load curve defined by LCUR: |

EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) \, .$$

This is the default behavior.

EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \, .$$

EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

| | |
|---|---|
| REFDENS | An appropriate reference density |
| REFVEL | An appropriate reference velocity |
| REFPRESS | An appropriate reference pressure |
| REFAREA | An appropriate reference area |
| REFLENG | An appropriate reference length |
| DRAGDIRX | $x$-component of the drag direction |
| DRAGDIRY | $y$-component of the drag direction |
| DRAGDIRZ | $z$-component of the drag direction |
| LIFTDIRX | $x$-component of the lift direction |
| LIFTDIRY | $y$-component of the lift direction |
| LIFTDIRZ | $z$-component of the lift direction |

| VARIABLE | DESCRIPTION |
|---|---|
| DRGAREA | Flag specifying how to obtain the drag area needed for finding the drag-related coefficients: |
| | **EQ.0:** Use REFAREA in all the calculations requiring an enclosing surface area |
| | **NE.0:** Use LS-DYNA's dynamic calculation of the surface area of each piece/part to compute the various drag-related coefficients. REFAREA scales the computed surface area before being used to calculate the drag-related coefficients. |
| MOMNTD | Flag determining whether to compute the torque in the drag direction: |
| | **EQ.0:** Do not compute the torque. |
| | **NE.0:** Compute the torque. |
| MOMNTL | Flag determining whether to compute the torque in the lift direction: |
| | **EQ.0:** Do not compute the torque. |
| | **NE.0:** Compute the torque. |
| MOMNTC | Flag determining whether to compute the torque in the direction that is the cross product of the drag and lift directions: |
| | **EQ.0:** Do not compute the torque. |
| | **NE.0:** Compute the torque. |

### \*DUALCESE_DATABASE_HISTORY_ELEMENT_SET

Purpose: Enable output of dual CESE solver data at the element centroids of the selected dual CESE mesh elements. This element output goes to binary database binout. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-----|------|-------|---|---|---|---|
| Variable | ESID | DT | LCUR | IOOPT | | | | |
| Type | I | F | I | I | | | | |
| Default | 0 | 0. | 0 | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ESID | ID of a dual CESE element set (see \*DUALCESE_ELEMENTSET) |
| DT | Time interval between outputs. If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve. The abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

      EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) .$$

      This is the default behavior.

      EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) .$$

      EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

## *DUALCESE_DATABASE_HISTORY_GLOBALS

Purpose: Enable output of global dual CESE solver data. The output goes to binary database binout. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-------|---|---|---|---|---|
| Variable | DT | LCUR | I0OPT | | | | | |
| Type | F | I | I | | | | | |
| Default | 0.0 | 0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DT | Time interval between outputs. If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use *DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

    EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) \,.$$

    This is the default behavior.

    EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \,.$$

    EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

## \*DUALCESE_DATABASE_HISTORY_NODE_SET

Purpose: Enable output of dual CESE solver data at the selected dual CESE mesh nodes. This nodal output goes to binary database **binout**. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|------|------|------|------|
| Variable | NSID | DT | LCUR | IOOPT | | | | |
| Type | I | F | I | I | | | | |
| Default | 0 | 0. | 0 | 0. | | | | |

|  VARIABLE  |  DESCRIPTION  |
|------------|---------------|

NSID  ID of a dual CESE node set (see \*DUALCESE_NODESET)

DT  Time interval between outputs. If DT is zero, no output is generated.

LCUR  Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs.

IOOPT  Flag to govern behavior of the output frequency load curve defined by LCUR:

  EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) .$$

    This is the default behavior.

  EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) .$$

  EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

### *DUALCESE_DATABASE_HISTORY_POINT_SET

Purpose: Enable output of dual CESE solver data at the selected points inside the dual CESE mesh. This point-based output goes to binary database binout. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|----|------|------|---|---|---|---|
| Variable | PNTSID | DT | LCUR | IOOPT | | | | |
| Type | I | F | I | I | | | | |
| Default | 0 | 0. | 0 | 0. | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PNTSID | ID of a dual CESE point set (see *DUALCESE_POINTSET) |
| DT | Time interval between outputs. If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use *DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_n) \,.$$

This is the default behavior.

EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as

$$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \,.$$

EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored.

## \*DUALCESE_DATABASE_HISTORY_SEGMENT_SET

Purpose: Enable output of dual CESE solver data averaged on each of the specified dual CESE segment sets. This segment set-based output goes to binary database binout. At most, one instance of this keyword may appear in the input deck.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | LCUR | IOOPT | | | | | |
| Type | F | I | I | | | | | |
| Default | 0.0 | 0 | 0 | | | | | |

**Segment Sets Card.** Define as many cards as necessary. Input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSID1 | SSID2 | SSID3 | SSID4 | SSID5 | SSID6 | SSID7 | SSID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| DT | Time interval between outputs. If DT is zero, no output is generated. |
| LCUR | Optional curve ID specifying the time interval between outputs. Use \*DEFINE_CURVE to define the curve; the abscissa is time, and the ordinate is time interval between outputs. |
| IOOPT | Flag to govern behavior of the output frequency load curve defined by LCUR: |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as $$t_{n+1} = t_n + \text{LCUR}(t_n) \ .$$ This is the default behavior. |
| | EQ.2: When output is generated at time $t_n$, the next output time $t_{n+1}$ is computed as $$t_{n+1} = t_n + \text{LCUR}(t_{n+1}) \ .$$ |
| | EQ.3: Output is generated for each abscissa point in the load curve definition. The actual value of the load curve is ignored. |
| SSID*i* | $i^{\text{th}}$ dual CESE segment set ID (see \*DUALCESE_SEGMENTSET). For each of these segment sets, an average value of each dual CESE output variable is output to the binout file at the times selected by the fields in Card 1. |

**\*DUALCESE_D3PLOT**

Purpose:  Specify the flow variables to be added to the dual CESE d3plot output.

Provide as many cards as necessary.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FLOW_VAR | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FLOW_VAR | Name of a flow variable to output to the d3plot file.  The currently supported variables are listed in the table below. |

**Flow Variables:**

This table lists the supported flow variables.

| FLOW_VAR | DESCRIPTION |
|----------|-------------|
| DENSITY | Density |
| VELOCITY | Velocity |
| MOMENTUM | Momentum |
| VORTICITY | Vorticity |
| TOTAL_ENERGY | Total energy |
| INTERNAL_ENERGY | Internal energy |
| PRESSURE | Pressure |
| TEMPERATURE | Temperature |
| MACH_NUMBER | Flow Mach number |
| SCHLIEREN_NUMBER | Quantity for capturing or highlighting the shock structure in a compressible flow |

| FLOW_VAR | DESCRIPTION |
|---|---|
| VOID_FRACTION | Void fraction (only for the dual CESE cavitation solver) |
| VOLUME_FRACTION | Volume fraction of the different materials in a hybrid or two-phase multiphase model |
| REACTANT_MASS_FRAC-TION | Mass fraction of the reactant (material $\alpha$) with respect to the explosive material (material 2) in a hybrid multiphase model |
| LIQUID_MASS_FRACTION | Mass fraction of the liquid component of the fluid in the phase change model |
| VAPOR_MASS_FRACTION | Mass fraction of the vapor component of the fluid in the phase change model |
| OTHER_GASES_MASS_FRAC-TION | Mass fraction of the other gases in the fluid in the phase change model |

## \*DUALCESE_D3PLOT_FLUID_SSID

Purpose: Generate surface d3plot output for the dual CESE solver on a specified dual CESE mesh segment set. These surfaces may be on the outside of the dual CESE fluid mesh that is in contact with the structural volume element parts.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | SSID | | | | |
| Type | | | | I | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | ID of a segment set created with \*DUALCESE_SEGMENTSET |

**Dual CESE variables to output**. Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | FLOW_VAR | | | | |
| Type | | | | A | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FLOW_VAR | Name of a flow variable to output to the d3plot file. The currently supported variables are listed in the table below. |

**Flow Variables:**

This table lists the supported flow variables.

| FLOW_VAR | DESCRIPTION |
|----------|-------------|
| DENSITY | Density |
| VELOCITY | Velocity |
| MOMENTUM | Momentum |

| FLOW_VAR | DESCRIPTION |
|---|---|
| VORTICITY | Vorticity |
| TOTAL_ENERGY | Total energy |
| INTERNAL_ENERGY | Internal energy |
| PRESSURE | Pressure |
| TEMPERATURE | Temperature |
| MACH_NUMBER | Flow Mach number |
| SCHLIEREN_NUMBER | Quantity for capturing or highlighting the shock structure in a compressible flow |
| VOID_FRACTION | Void fraction (only for the dual CESE cavitation solver) |
| VOLUME_FRACTION | Volume fraction of the different materials in a hybrid or two-phase multiphase model |
| REACTANT_MASS_FRAC-TION | Mass fraction of the reactant (material $\alpha$) with respect to the explosive material (material 2) in a hybrid multiphase model |

**\*DUALCESE_ELE2D**

Purpose: Define three and four node elements.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|-----|-----|-----|-----|-----|-----|---|---|---|----|
| Variable | EID | PID | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | I | I | | | | |
| Default | none | none | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EID | Element ID. Choose a unique number with respect to other elements. |
| PID | Part ID, see *DUALCESE_MESH_PART. |
| N1 | Nodal point 1 |
| N2 | Nodal point 2 |
| N3 | Nodal point 3 |
| N4 | Nodal point 4 |

## \*DUALCESE_ELE3D

Purpose: Define three-dimensional fluid volume elements. These can be 4 node tetrahedra, 5 node pyramids, 6 node wedges (prisms), and 8 node hexahedra.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Variable | EID | PID | N1 | N2 | N3 | N4 | N5 | N6 | N7 | N8 |
| Type | I | I | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none | none | none |
| Remarks | 1 | | | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EID | Element ID. A unique number must be chosen. |
| PID | Part ID, see *DUALCESE_MESH_PART. |
| N1 | Nodal point 1 |
| N2 | Nodal point 2 |
| N3 | Nodal point 3 |
| ⋮ | ⋮ |
| N8 | Nodal point 8 |

**Remarks:**

1.  **Node numbering.** Four, five, six, and eight node elements are allowed as numbered below. This ordering must be followed, or code termination will occur during the initialization phase with a negative volume message. In the case of a pyramid element, the base of the pyramid must follow the ordering used for the hexahedron. See \*ELEMENT_SOLID for a figure showing the positions of the nodes in 4, 6, and 8 node elements.

    | 4-noded tetrahedron | N1, N2, N3, N4, N4, N4, N4, N4 |
    |---|---|
    | 5-noded pyramid | N1, N2, N3, N4, N5, N5, N5, N5 |

6-noded pentahedron          N1, N2, N3, N4, N5, N5, N6, N6

8-noded hexahedron           N1, N2, N3, N4, N5, N6, N7, N8

## \*DUALCESE_ELEMENTSET

Purpose:  Define a set of dual CESE mesh elements.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | ESID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Element ID Cards.** List of elements in the set, where the element IDs are defined with \*DUALCESE_ELE2D or \*DUALCESE_ELE3D cards.  Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|------|------|------|------|
| Variable | EID1 | EID2 | EID3 | EID4 | EID5 | EID6 | EID7 | EID8 |
| Type | I | I | I | I | I | I | I | I |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ESID | Set ID.  All dual CESE element sets should have a unique set ID. |
| EID$i$ | Element ID $i$ |

## \*DUALCESE_EOS_CAV_HOMOG_EQUILIB

Purpose: Define the coefficients in the equation of state (EOS) for the homogeneous equilibrium cavitation model.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | RHOVAP | RHOLIQ | AVAP | ALIQ | MUVAP | MULIQ | PSATVAP |
| Type | I | F | F | F | F | F | F | F |
| Default | none | 0.8 | 880.0 | 334.0 | 1386.0 | 1.435e-5 | 1.586e-4 | 1.2e+4 |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state ID |
| RHOVAP | Density of the saturated vapor, $\rho_{\text{vap}}$ |
| RHOLIQ | Density of the saturated liquid, $\rho_{\text{liq}}$ |
| AVAP | Sound speed of the saturated vapor, $a_{\text{vap}}$ |
| ALIQ | Sound speed of the saturated liquid, $a_{\text{liq}}$ |
| MUVAP | Dynamic viscosity of the vapor, $\mu_{\text{vap}}$ |
| MULIQ | Dynamic viscosity of the liquid, $\mu_{\text{liq}}$ |
| PSATVAP | Pressure of the saturated vapor, $P_{\text{SatVap}}$ |

**Remarks:**

1.  **EOS Validity.** In this homogeneous equilibrium cavitation model, a barotropic equation of state is used. This model can be used in small scale and high-speed cavitation flows, but it is not good for large-scale, low-speed cavitation calculations.

## \*DUALCESE_EOS_COCHRAN_CHAN

Purpose: Define a Cochran-Chan type of EOS that provides a means to represent a condensed phase explosive in a dual CESE multiphase model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|------|------|--------|------|------|
| Variable | EOSID | A | B | EPS1 | EPS2 | GAMMA0 | RHO0 | E0 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | 0.0 |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | CV | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | Equation of state ID for the dual CESE solver |
| A | Model parameter (in pressure units), $A$ |
| B | Model parameter (in pressure units), $B$ |
| EPS1 | Model constant (dimensionless), $\varepsilon_1$ |
| EPS2 | Model constant (dimensionless), $\varepsilon_2$ |
| GAMMA0 | Gruneisen coefficient |
| RHO0 | Initial or reference density, $\rho_0$ |
| E0 | Represents the heat of detonation released during the reactions, or the constant rate of afterburn energy added (E0 = 0.0 is the default), $e_0$ |
| CV | Heat capacity, $C_v$ |

**Remarks:**

The Cochran-Chan EOS like the JWL EOS (*DUALCESE_EOS_JWL) is a type of Mie-Gruneisen EOS. The equations of state of a Mie-Gruneisen form are given by:

$$P(\rho, e) = P_{\text{ref}} + \Gamma(\rho)\rho[e - e_{\text{ref}}(\rho)]$$

Here $\Gamma(\rho)$ is the Gruneisen coefficient. For the Cochran-Chan EOS reference pressure and energy are given by:

$$P_{ref}(\rho) = A\left(\frac{\rho_0}{\rho}\right)^{-\varepsilon_1} - B\left(\frac{\rho_0}{\rho}\right)^{-\varepsilon_2}$$

$$e_{\text{ref}}(\rho) = \frac{A}{\rho_0(1-\varepsilon_1)}\left(\frac{\rho_0}{\rho}\right)^{1-\varepsilon_1} + \frac{B}{\rho_0(1-\varepsilon_2)}\left(\frac{\rho_0}{\rho}\right)^{1-\varepsilon_2} - e_0$$

## \*DUALCESE_EOS_COOLPROP

Purpose: Define an equation of state (EOS) to be evaluated using the COOLPROP EOS library.

> **WARNING:** This feature is currently not working.

Note that the COOLPROP library is not provided by ANSYS. You need to download a 64-bit version of the shared library from a public repository, such as:

https://sourceforge.net/projects/coolprop/files/CoolProp/6.3.0/shared_library/Linux/64bit/

> **WARNING:** Since the \*MODULE capability is not yet working in the Windows build of LS-DYNA, do *not* attempt to use a Windows DLL version of the COOLPROP shared library.

To use the COOLPROP shared library with this keyword card, load this shared library into LS-DYNA using the \*MODULE capability. The following \*MODULE card needs to appear before a \*DUALCESE_MODEL card (not inside the file hierarchy of any file specified with a \*DUALCESE_MODEL card):

```
*MODULE_LOAD
UserA                   DUALCESE COOLPROP
 < path to installed COOLPROP shared library >
```

### Card Summary:

**Card 1.** This card is required.

| EOSID | NCOMP | TYPE | PHASE | TABULAR | | | |
|-------|-------|------|-------|---------|--|--|--|

**Card 2.** Include as many cards as needed to specify mole fractions for the NCOMP components of the fluid.

| MOL_FR1 | MOL_FR2 | MOL_FR3 | MOL_FR4 | MOL_FR5 | MOL_FR6 | MOL_FR7 | MOL_FR8 |
|---------|---------|---------|---------|---------|---------|---------|---------|

**Card 3.** Include this card when the TABULAR field is active on Card 1.

| N_T | N_DEN | DEN_LOW | DEN_HIGH | T_LOW | T_HIGH | | |
|-----|-------|---------|----------|-------|--------|--|--|

**Card 4.** This card is required.

| FLUIDNAME |
|-----------|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | NCOMP | TYPE | PHASE | TABULAR | | | |
| Type | I | I | A | A | A | | | |
| Default | none | none | none | GAS | optional | | | |

| VARIABLE | DESCRIPTION |
|---|---|

EOSID      ID for this EOS

NCOMP      Number of components in the fluid composition

TYPE      Fluid type:

       EQ.PURE:        A single component fluid (default)

       EQ.PSEUDOPURE: A predefined fluid mixture

       EQ.MIXTURE:      A fluid mixture with NCOMP components

PHASE      Phase of the fluid.

       EQ.GAS:     Gas phase

       EQ.LIQUID: Liquid phase

TABULAR      Type of lookup tables to build for this EOS:

       EQ.<BLANK>: No table lookup (default)

       EQ.P_EIN:     Build tables of pressure and internal energy, both as a function of density and temperature.

**COOLPROP Parameters by Fluid Component.** Repeat this card as many times as needed to input mole fractions for the NCOMP components of the fluid.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MOL_FR1 | MOL_FR2 | MOL_FR3 | MOL_FR4 | MOL_FR5 | MOL_FR6 | MOL_FR7 | MOL_FR8 |
| Type | F | F | F | F | F | F | F | F |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MOL_FR$i$ | Mole fraction of the $i^{\text{th}}$ component |

**COOLPROP EOS Table Density and Temperature Ranges.** This card is included when the TABULAR option on Card 1 is active.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | N_T | N_DEN | DEN_LOW | DEN_HIGH | T_LOW | T_HIGH | | |
| Type | I | I | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |
| Remarks | 1 | 1 | 2 | 2 | 2 | 2 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N_T | Number of temperature values in the tables |
| N_DEN | Number of density values (on a log scale) in the tables |
| DEN_LOW | Minimum density available in the tables (in model units) |
| DEN_HIGH | Maximum density available in the tables (in model units) |
| T_LOW | Minimum temperature available in the tables (in model units) |
| T_HIGH | Maximum temperature available in the tables (in model units) |

**Name of CoolProp fluid.** This card is required.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FLUIDNAME | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| FLUIDNAME | Name of a fluid that has an EOS in CoolProp. For a list of the supported pure and pseudo-pure fluids, see: |

> http://www.coolprop.org/fluid_properties/PurePseudo-Pure.html#list-of-fluids

Note that the predefined fluid mixtures are not supported at this time.

**Remarks:**

1. **Number of Values in the Lookup Tables.** The number of density and temperature values in the tables should not be too few to give good resolution of the EOS. Note that the cost of building the EOS from these tables rises with these numbers, as well as the computer memory required. Nevertheless, if these numbers are too small (< 20), then the accuracy may suffer, while larger numbers of density and temperature points improves the accuracy.

2. **Valid Value Ranges for the Lookup Tables.** For many equations of state in the CoolProp library, there is a range of valid densities and temperatures. Thus, the low and high limits for the table densities and temperatures should not lie outside these ranges. Please refer to the CoolProp documentation for that information.

## *DUALCESE_EOS_IDEAL_GAS

Purpose: Define the coefficients $C_v$ and $C_p$ in the equation of state for an ideal gas in the dual CESE fluid solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|--------|------|---|---|---|---|
| Variable | EOSID | CV | CP | E0 | | | | |
| Type | I | F | F | F | | | | |
| Default | none | 717.5 | 1004.5 | 0.0 | | | | |
| Remarks | | 1 | 1 | 2 | | | | |

|  VARIABLE  |  DESCRIPTION  |
|------------|---------------|
| EOSID | Equation of state ID |
| CV | Specific heat at constant volume, $C_v$ |
| CP | Specific heat at constant pressure, $C_p$ |
| E0 | Represents the heat of detonation released during the reactions, or the constant rate of afterburn energy added (E0 = 0.0 is the default), $e_0$ |

**Remarks:**

1.  **Units.** As with other solvers in LS-DYNA, you are responsible for unit consistency. For example, if you want to use dimensionless variables, CV and CP should also be replaced by the corresponding dimensionless ones. If the dual CESE model has a specified system of units either directly from the *DUALCESE_MODEL card or inherited from the overall problem input, then these values need to be given in that unit system.

2.  **E0.** E0 is used only with the hybrid multiphase solver where the EOS of the reactant is specified by this ideal gas EOS in the *DUALCESE_EOS_SET card.

### \*DUALCESE_EOS_INFLATOR1

Purpose: Define an EOS using $C_p$ and $C_v$ thermodynamic expansions for an inflator gas mixture with a single temperature range.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CP0 | CP1 | CP2 | CP3 | CP4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CV0 | CV1 | CV2 | CV3 | CV4 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state ID for the dual CESE solver |
| CP0, …, CP4 | Coefficients of temperature-dependent specific heat at constant pressure $$C_p(T) = C_{p_0} + C_{p_1}T + C_{p_2}T^2 + C_{p_3}T^3 + C_{p_4}T^4$$ |

| VARIABLE | DESCRIPTION |
|---|---|
| CV0, …, CV4 | Coefficients of temperature-dependent specific heat at constant volume |

$$C_v(T) = C_{v0} + C_{v1}T + C_{v2}T^2 + C_{v3}T^3 + C_{v4}T^4$$

**Remarks:**

These coefficient expansions for the specific heats over the entire temperature range are generated by the zero-dimensional inflator model solver. See \*CHEMISTRY_CON-TROL_INFLATOR and \*CHEMISTRY_INFLATOR_PROPERTIES for details related to running that solver.

## *DUALCESE_EOS_INFLATOR2

Purpose: Define an EOS using $C_p$ and $C_v$ thermodynamic expansions for an inflator gas mixture with two temperature ranges, one below 1000 Kelvin, and the other above 1000 Kelvin.

### Card Summary:

**Card 1.** This card is required.

| EOSID | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.** This card is required. This card with Card 3 specifies $C_p$. This card gives the coefficients for T < 1000 K.

| CP10 | CP11 | CP12 | CP13 | CP14 | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 3.** This card is required. This card gives the coefficients for T > 1000 K.

| CP20 | CP21 | CP22 | CP23 | CP24 | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 4.** This card is required. This card with Card 5 defines $C_v$. This card gives the coefficients for T < 1000 K.

| CV10 | CV11 | CV12 | CV13 | CV14 | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 5.** This card is required. This card gives the coefficients for T > 1000 K.

| CV20 | CV21 | CV22 | CV23 | CV24 | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

### Data Card Definitions:

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state ID for the dual CESE solver |

Coefficients for the expansion to determine specific heat at constant pressure for T < 1000 K.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CP10 | CP11 | CP12 | CP13 | CP14 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

Coefficients for the expansion to determine specific heat at constant pressure for T > 1000 K.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CP20 | CP21 | CP22 | CP23 | CP24 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CP10, …, CP14 | Coefficients of temperature-dependent specific heat at constant pressure valid for T < 1000 K |
| CP20, …, CP24 | Coefficients of temperature-dependent specific heat at constant pressure valid for T > 1000 K |

Cards 2 and 3 give $C_p$ over the two temperature ranges:

$$C_p(T) = \begin{cases} \text{CP10} + \text{CP11} \times T + \text{CP12} \times T^2 + \text{CP13} \times T^3 + \text{CP14} \times T^4 & \text{for } T < 1000 \text{ K} \\ \text{CP20} + \text{CP21} \times T + \text{CP22} \times T^2 + \text{CP23} \times T^3 + \text{CP24} \times T^4 & \text{for } T > 1000 \text{ K} \end{cases}$$

**Card for the Expansion of Specific Heat at Constant Volume.** Valid for T < 1000 K

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CV10 | CV11 | CV12 | CV13 | CV14 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

**Card for the Expansion of Specific Heat at Constant Volume.** Valid for T > 1000 K

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CV20 | CV21 | CV22 | CV23 | CV24 | | | |
| Type | F | F | F | F | F | | | |
| Default | 0. | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CV10, …, CV14 | Coefficients of temperature-dependent specific heat at constant volume valid for T < 1000 K |
| CV20, …, CV24 | Coefficients of temperature-dependent specific heat at constant volume valid for T > 1000 K |

Cards 4 and 5 give $C_v$ over the two temperature ranges:

$$C_v(T) = \begin{cases} CV10 + CV11 \times T + CV12 \times T^2 + CV13 \times T^3 + CV14 \times T^4 & \text{for } T < 1000 \text{ K} \\ CV20 + CV21 \times T + CV22 \times T^2 + CV23 \times T^3 + CV24 \times T^4 & \text{for } T > 1000 \text{ K} \end{cases}$$

**Remarks:**

These coefficient expansions for the specific heats over two temperature ranges are generated by the zero-dimensional inflator model solver. See \*CHEMISTRY_CONTROL_-INFLATOR and \*CHEMISTRY_INFLATOR_PROPERTIES for details related to running that solver.

## *DUALCESE_EOS_JWL

Purpose: Define a JWL-type EOS that provides a means to represent a condensed phase explosive in a dual CESE multiphase model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | A | B | R1 | R2 | GAMMA0 | RHO0 | E0 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | 0.0 |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CV | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state ID for the dual CESE solver. |
| A | Model parameter, $A$ (in pressure units) |
| B | Model parameter, $B$ (in pressure units) |
| R1 | Model constant, $R_1$ (dimensionless) |
| R2 | Model constant, $R_2$ (dimensionless) |
| GAMMA0 | Gruneisen coefficient |
| RHO0 | Initial or reference density, $\rho_0$ |
| E0 | Represents the heat of detonation released during the reactions or the constant rate of afterburn energy added (E0 = 0.0 for standard JWL EOS), $e_0$ |
| CV | Heat capacity, $C_v$ |

**Remark:**

The equations of state of a Mie-Gruneisen form are given by:

$$P(\rho, e) = P_{\text{ref}} + \Gamma(\rho)\rho[e - e_{\text{ref}}(\rho)]$$

Here $\Gamma(\rho)$ is the Gruneisen coefficient. Equations of state of this type are very popular in condensed phase explosive modeling. Depending on the form of the reference pressure and energy functions, different EOS types can be retrieved. The JWL EOS is one type with reference pressure and energy given by:

$$P_{\text{ref}}(\rho) = A\exp\left(\frac{-R_1\rho_0}{\rho}\right) + B\exp\left(\frac{-R_2\rho_0}{\rho}\right)$$

$$e_{\text{ref}}(\rho) = \frac{A}{\rho_0 R_1}\exp\left(\frac{-R_1\rho_0}{\rho}\right) + \frac{B}{\rho_0 R_2}\exp\left(\frac{-R_2\rho_0}{\rho}\right) - e_0$$

## \*DUALCESE_EOS_NASG

Purpose: Define a Noble-Abel Stiffened-Gas (NASG) type fluid EOS for use in the phase-change dual CESE solver. See M'etayer and Saurel [2016] for details.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | GAMMA | CV | PINF | Q | QP | B | W |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state ID |
| GAMMA | Ratio of specific heats, $\gamma$ |
| CV | Specific heat at constant volume |
| PINF | Parameter for a given phase, $p_\infty$ (dimensions: $\left[\frac{M}{LT^2}\right]$). See Le M'etayer and Saurel [2016]. |
| Q | Parameter for a given phase, $q$ (dimensions: $\left[\frac{L^2}{T^2}\right]$). $q$ is the heat bond for the phase. See Le M'etayer and Saurel [2016]. |
| QP | Parameter for a given phase, $q'$ (dimensions: $\left[\frac{L^2}{T^2\theta}\right]$, where $\theta$ represents the dimension of temperature). See Le M'etayer and Saurel [2016]. |
| B | Parameter for a given phase, $b$ (dimensions: $\left[\frac{L^3}{M}\right]$). $b$ indicates the fluid's covolume. See Le M'etayer and Saurel [2016]. |
| W | Molar mass of this fluid |

**Remarks:**

The NASG EOS given by M'etayer and Saurel [2016] has the following form:

$$p(v,e) = \frac{(\gamma - 1)(e - q)}{v - b} - \gamma p_\infty$$

$$T(p,v) = \frac{(v - b)(p + p_\infty)}{C_v(\gamma - 1)}$$

$$g(p,T) = (\gamma C_v - q')T - C_v T \ln\left[\frac{T^\gamma}{(p + p_\infty)^{\gamma-1}}\right] + bp + q$$

$$c(p,v) = \sqrt{\gamma v(p + p_\infty)}$$

where $\gamma, C_v, p_\infty, q, q'$ and $b$ are parameters needed for each phase. $v, e, g$ and $c$ are for each fluid phase the specific volume, the specific internal energy, the specific Gibbs free energy, and the sound speed, respectively. $g = h - Ts$ with $h$ and $s$ as the specific enthalpy and specific entropy, respectively.

**References:**

[1]    Le M'etayer, O. and R. Saurel, "The Nobel-Abel Stiffened-Gas equation of state," *Physics of Fluids*, 28 (4), (2016).

**\*DUALCESE_EOS_REFPROP**

Purpose: Define an equation of state (EOS) to be evaluated using the REFPROP EOS library

Note that the REFPROP library is provided by ANSYS; it is REFPROP v10.0 from NIST.

> **WARNING:** Since the \*MODULE capability is not yet working in the Windows build of LS-DYNA, do *not* attempt to use a Windows DLL version of the REFPROP shared library that comes with REFPROP v10.0.

To use the REFPROP shared library with this keyword card, load this shared library into LS-DYNA using the \*MODULE capability. The following \*MODULE card needs to appear before a \*DUALCESE_MODEL card (not inside the file hierarchy of any file specified with a \*DUALCESE_MODEL card):

```
*MODULE_LOAD
UserA                   DUALCESE REFPROP
 < path to the installed REFPROP shared library >
```

In addition, for REFPROP to be able to find the appropriate EOS data, \*DUALCESE_-EOS_REFPROP_PATH must also be given somewhere inside a \*DUALCESE_MODEL file hierarchy to point to the place in your filesystem where REFPROP has been installed.

**Card Summary:**

**Card 1.** This card is required.

| EOSID | NCOMP | TYPE | PHASE | TABULAR | | | |
|-------|-------|------|-------|---------|---|---|---|

**Card 2.** Include as many cards as needed to specify mole fractions for the NCOMP components of the fluid.

| MOL_FR1 | MOL_FR2 | MOL_FR3 | MOL_FR4 | MOL_FR5 | MOL_FR6 | MOL_FR7 | MOL_FR8 |
|---------|---------|---------|---------|---------|---------|---------|---------|

**Card 3.** This card is included when the TABULAR field is active on Card 1.

| N_T | N_DEN | DEN_LOW | DEN_HIGH | T_LOW | T_HIGH | | |
|-----|-------|---------|----------|-------|--------|---|---|

**Card 4.** This card is required.

| FLUIDNAME |
|-----------|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|------|---------|---|---|---|
| Variable | EOSID | NCOMP | TYPE | PHASE | TABULAR | | | |
| Type | I | I | A | A | A | | | |
| Default | none | none | none | GAS | optional | | | |

|          VARIABLE          |                          DESCRIPTION                          |
|----------------------------|---------------------------------------------------------------|

EOSID       ID for this EOS

NCOMP       Number of components in the fluid composition

TYPE        Fluid type:

    EQ.PURE:           A single component fluid (default)

    EQ.PSEUDOPURE:  A predefined fluid mixture

    EQ.MIXTURE:       A fluid mixture with NCOMP components

PHASE       Phase of the fluid:

    EQ.GAS:    Gas phase

    EQ.LIQUID:  Liquid phase

TABULAR     Type of lookup tables to build for this EOS:

    EQ.<BLANK>: No table lookup (default)

    EQ.P_EIN:    Build tables of pressure and internal energy, both as a function of density and temperature.

**REFPROP Parameters by Fluid Component.** Repeat this card as many times as needed to input mole fractions for the NCOMP components of the fluid.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | MOL_FR1 | MOL_FR2 | MOL_FR3 | MOL_FR4 | MOL_FR5 | MOL_FR6 | MOL_FR7 | MOL_FR8 |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MOL_FR$i$ | Mole fraction of the $i^{th}$ component of the fluid. |

.

**REFPROP EOS Table Density and Temperature Ranges.** This card is included when the TABULAR field is active on Card 1.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | N_T | N_DEN | DEN_LOW | DEN_HIGH | T_LOW | T_HIGH | | |
| Type | I | I | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |
| Remarks | 1 | 1 | 2 | 2 | 2 | 2 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N_T | Number of temperature values in the tables |
| N_DEN | Number of density values (on a log scale) in the table |
| DEN_LOW | Minimum density available in the tables (in model units) |
| DEN_HIGH | Maximum density available in the tables (in model units) |
| T_LOW | Minimum temperature available in the tables (in model units) |
| T_HIGH | Maximum temperature available in the tables (in model units) |

**Name of REFPROP fluid.** This card is required.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FLUIDNAME | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FLUID-<br>NAME | Name of a fluid that has an EOS in REFPROP. For a list of the supported pure and pseudo-pure fluids, see the directory of supported fluids that comes with the REFPROP v10.0 library from ANSYS.<br><br>Note that the predefined fluid mixtures are not supported at this time. |

**Remarks:**

1. **Number of Values in the Lookup Table.** The number of values of density and temperature axes of the tables should not be too few to give good resolution of the EOS. Note that the cost of building the EOS from these tables rises with these numbers, as well as the computer memory required. Nevertheless, if these numbers are too small (< 20), then the accuracy may suffer, while larger numbers of density and temperature points improves the accuracy.

2. **Valid Value Ranges for the Lookup Tables.** For many equations of state in the REFPROP library, a range of densities and temperatures are valid. Thus, the low and high limits for the table densities and temperatures should not lie outside these ranges. Please refer to the REFPROP documentation for that information.

**\*DUALCESE_EOS_REFPROP_PATH**

Purpose: Provide the file path to the directory where the REFPROP EOS system is installed.

Note that in any problem where a \*DUALCESE_EOS_REFPROP card is used, you must also provide a \*DUALCESE_EOS_REFPROP_PATH card somewhere inside a \*DUALCESE_MODEL file hierarchy to point to the place in your filesystem where REFPROP has been installed so that the appropriate EOS data can be loaded.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PATH | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PATH | Path giving the directory where the REFPROP data is installed. |

**\*DUALCESE_EOS_SET**

Purpose: Define a set of equations of state that are used together to compute the thermo-dynamic state of a multiphase fluid for the dual CESE solver.

> **WARNING:** As of version R14, this keyword is deprecated. Instead, use \*DUALCESE_SOLVER_HYBRID_MULTIPHASE for the hybrid multiphase case and \*DUALCESE_-SOLVER_TWO-PHASE_MULTIPHASE for the two-phase multiphase case.

Include one card for each dual CESE multiphase mesh. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|---|---|---|---|
| Variable | EOSSID | EOSINID | EOSRCTID | EOSPRDID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSSID | Set ID of the EOS mixture of a given multiphase fluid |
| EOSINID | EOS ID of the inert component of the multiphase mixture |
| EOSRCTID | EOS ID of the reactant phase of the multiphase mixture |
| EOSPRDID | EOS ID of the product phase of the multiphase mixture |

## \*DUALCESE_EOS_STIFFENED_GAS

Purpose: Define a stiffened gas type fluid EOS for use by the dual CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|---|---|---|---|---|
| Variable | EOSID | GA | BT | | | | | |
| Type | I | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | Equation of state ID for this dual CESE solver EOS |
| GA | Adiabatic exponent, $\gamma$. Must be > 1.0. |
| BT | Reference pressure, $\beta$. Must be $\geq$ 0.0 |

**Remark:**

The stiffened gas equation of state:

$$p(\rho, e) = (\gamma - 1)\rho e - \gamma\beta$$

provides a fundamental characterization of material properties of fluids. Here $e$ is the internal energy per unit mass, $\rho$ is the density, and $\gamma$ and $\beta$ are two thermodynamic constants. $\gamma$ and $\beta$ can be determined by a fitting procedure from laboratory data. A typical set of parameter values for water are: $\gamma = 7$ and $\beta = 3000$ atm while for human blood are: $\gamma = 5.527$ and $\beta = 614.6$ MPa. In addition to the modelling of a liquid, it is often used to describe other type of materials, including many compressible solids of practical importance.

## \*DUALCESE_EOS_VAN_DER_WAALS_GENERALIZED

Purpose:  Define a Van Der Waals generalized type fluid EOS for use in the dual CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|------|------|---|---|---|
| Variable | EOSID | A | B | GA | BT | | | |
| Type | I | F | F | F | F | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | Equation of state ID |
| A | van der Waals gas constant for molecular cohesive forces, $a$ |
| B | van der Waals gas constant for the finite size of molecules, $b$ |
| GA | Ratio of specific heats, $\gamma$. Must be > 1.0. |
| BT | Reference pressure, $\beta$. Must be ≥ 0.0. See \*DUALCESE_EOS_-STIFFENED_GAS. |

**Remark:**

The generalized Van der Waals equation of state can be written as:

$$p(\rho, e) = \frac{(\gamma - 1)}{1 - b\rho}\left(\rho e - \beta + a\rho^2\right) - \left(\beta + a\rho^2\right)$$

Here $e$ denotes the specific internal energy, $\gamma$ is the ratio of specific heats ($\gamma > 1$), $\beta$ is a reference pressure, and the quantities $a$ and $b$ are the van der Waals gas constants for molecular cohesive forces and the finite size of molecules, respectively (a ≥ 0, 0 ≤ b < $1/\rho$). This EOS is often used to deal with possible real-gas effect (without phase transition) when both the temperature and pressure are high.  When $\beta = 0$, the generalized van der Waals equation of state becomes a standard Van der Waals equation of state.  If $a = b = 0$, the stiffened gases EOS will be recovered.

**References:**

[1]    G. Allaire, S. Clerc, S. Kokh, A five-equation model for the simulation of interfaces between compressible fluids. J. Comp. Phys. 181 (2) (2002) 577-616.

[2]    K.M. Shyue, A fluid-mixture type algorithm for compressible multicomponent flow with van der Waals equation of state, J. Comp. Phys. 156, 43 (1999)

## \*DUALCESE_FSI_EXCLUDE

Purpose: Provide a list of mechanics solver parts that are not involved in the dual CESE FSI calculation. This keyword is intended for increasing computational efficiency by excluding parts that will not involve significant FSI interactions with the dual CESE compressible fluid solver.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PID*n* | IDs of mechanics parts that will be excluded from the FSI interaction calculation with the dual CESE solver |

## \*DUALCESE_FSI_EXCLUDE_PARTSET

Purpose: Provide a list of mechanics solver part sets for parts that are not involved in the dual CESE FSI calculation.  This keyword is intended for increasing computational efficiency by excluding parts that will not involve significant FSI interactions with the dual CESE compressible fluid solver.

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PSID1 | PSID2 | PSID3 | PSID4 | PSID5 | PSID6 | PSID7 | PSID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PSID*n* | IDs of mechanics part sets that will be excluded from the FSI interaction calculation with the dual CESE solver |

**\*DUALCESE_GRAVITY**

Purpose: Apply a gravity load to the dual CESE fluid. It is only avilable for single fluid solvers (meaning EQNS = EULER or NS) for both FSI (including FSI-IBM and FSI-MMM) and no FSI. Please note that this keyword must be accompanied by \*LOAD_BODY_VECTOR, \*LOAD_BODY_X, \*LOAD_BODY_Y, or \*LOAD_BODY_Z. However, these \*LOAD_BODY_... keywords cannot be in the dual CESE model portion of the input deck (see Dual CESE Keyword Deck Structure for details).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IGRAV | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IGRAV | Flag for applying a gravity load: |
| | EQ.0: No gravity load applied (default) |
| | EQ.1: Apply gravity load |

**Remarks:**

1. **Including gravity.** In most compressible cases, the gravity terms are not needed (the default is no gravity). Including gravity only has a significant effect for certain cases, such as buoyancy driven flow, stratified flow, etc.

## \*DUALCESE_INCLUDE_MODEL

Purpose: Provide the filename of a file containing additional keywords belonging to a dual CESE model. Any number of these \*DUALCESE_INCLUDE_MODEL keywords may be used in a single dual CESE model, where at the top level the overall model begins with a \*DUALCESE_MODEL card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FILENAME | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FILENAME | Filename of the keyword file containing more of the dual CESE model. This card is only allowed inside a file that is given in one instance of a \*DUALCESE_MODEL keyword card. |

**\*DUALCESE_INITIAL**

Purpose: Specify constant initial conditions for flow variables at the centroid of each dual CESE fluid element.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | U | V | W | RH | P | T | | IFUNC |
| Type | F | F | F | F | F | F | | I |
| Default | 0 | 0.0 | 0.0 | 1.225 | 0.0 | 0.0 | | none |

| VARIABLE | DESCRIPTION |
|---|---|
| U, V, W | $x$, $y$, and $z$ velocity components, respectively |
| RHO | Density, $\rho$ |
| P | Pressure, $P$ |
| T | Temperature, $T$ |
| IFUNC | Option to define initial conditions using \*DEFINE_FUNCTION cards: |

    EQ.0: Not in use.

    EQ.1: All values for initial velocity, pressure, density, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position.

**Remarks:**

1.  **Required input.** Usually, only two of $\rho$, $P$, and $T$ are needed to be specified (besides the velocity). If all three are given, only $\rho$ and $P$ will be used.

2.  **Applicable elements.** These initial conditions will be applied in those elements that have not been assigned a value by \*DUALCESE_INITIAL_*OPTION* cards for individual elements or sets of elements.

## \*DUALCESE_INITIAL_REGION

Purpose: Specify initial conditions for the flow variables at the centroid of each element in a region of the dual CESE mesh specified with \*DEFINE_REGION. This initialization method is only used by the single-fluid dual CESE solvers.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | REGID | IFUNC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | U | V | W | RHO | P | T | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|

REGID        Region ID (see \*DEFINE_REGION).

IFUNC        Flag to specify initial conditions using \*DEFINE_FUNCTION:

        EQ.0: Not in use.

        EQ.1: All values for initial velocity, pressure, temperature, etc. now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x, y, z). Thus, each variable's initial profile is a function of position.

U, V, W        $x$, $y$, and $z$ components of velocity, respectively

RHO        Density, $\rho$

P        Pressure, $P$

| VARIABLE | DESCRIPTION |
| --- | --- |
| T | Temperature, $T$ |

**Remarks:**

1.  **Required input.** Usually, only two of $\rho$, $P$, and $T$ are needed to be specified (besides the velocity). If all three are given, only $\rho$ and $P$ will be used.

2.  **Keyword priority.** The priority of this card is higher than \*DUALCESE_INITIAL. Thus, if an element is assigned an initial value by this keyword, \*DUALCESE_INITIAL will no longer apply to that element. However, the priority of \*DUALCESE_INITIAL_SET is higher than this keyword, meaning any element initialized by \*DUALCESE_INITIAL_SET will not be initialized by this keyword.

## \*DUALCESE_INITIAL_SET

Purpose: Specify initial conditions for the flow variables at the centroid of each element in an element subset of the dual CESE mesh.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ESID | IFUNC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | U | V | W | RHO | P | T | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ESID | Element set ID (see \*DUALCESE_ELEMENTSET) |
| IFUNC | Option to define initial conditions using \*DEFINE_FUNCTION cards: |

> EQ.0: Not in use.
>
> EQ.1: All values for initial velocity, pressure, density, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| U, V, W | $x$, $y$, and $z$ velocity components, respectively |
| RHO | Density, $\rho$ |
| P | Pressure, $P$ |

| VARIABLE | DESCRIPTION |
|---|---|
| T | Temperature, $T$ |

**Remarks:**

1. **Required input.** Usually, only two of $\rho$, $P$ and $T$ are needed to be specified (besides the velocity). If all three are given, only $\rho$ and $P$ will be used.

2. **Keyword priority.** The priority of this card is higher than \*DUALCESE_INITIAL. Thus, if an element is assigned an initial value by this card, \*DUALCESE_INITIAL will no longer apply to that element.

## \*DUALCESE_INITIAL_HYBRID

Purpose: Specifies values to use for velocity, pressure, etc. for problem initialization of a hybrid multiphase model on the dual CESE mesh. Note that these values can be overridden in some mesh elements by use of the \*DUALCESE_INITIAL_HYBRID_SET card.

The hybrid multiphase model involves two materials, separated by a material surface. These materials do not mix. The first material is inert while the second material is an explosive mixture, composed of reactants and products. This model is useful for simulations with high explosives. See Michael and Nikiforakis 2016 for details about this model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Z1 | RA | UIC | VIC | WIC | RHO1 | RHO_A | RHO_B |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PIC | TIC | | IFUNC | | | | |
| Type | F | F | | I | | | | |
| Default | none | none | | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| Z1 | Volume fraction of material 1 (or color function). This is usually a value of 0 or 1. For numerical stability, however, use a very small value instead of zero. |
| RA | Mass fraction of the reactant (material $\alpha$) with respect to material 2 (the explosive mixture) |
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions, respectively |
| RHO1 | Density of material 1 |

| VARIABLE | DESCRIPTION |
|---|---|
| RHO_A | Density of the reactant (material $\alpha$) |
| RHO_B | Density of the product (material $\beta$) |
| PIC | Equilibrium multifluid pressure |
| TIC | Equilibrium multifluid temperature |
| IFUNC | Option to define initial conditions using \*DEFINE_FUNCTION cards: |

                                     EQ.0: Not in use.

                                     EQ.1: All values for initial velocity, pressure, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position.

## \*DUALCESE_INITIAL_HYBRID_SET

Purpose: Specifies values to use for velocity, pressure, etc. for problem initialization of a hybrid multiphase model in an element subset of the dual CESE mesh. The values specified here override the values set on \*DUALCESE_INITIAL_HYBRID for the element subset.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ESID | IFUNC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Z1 | RA | UIC | VIC | WIC | RHO1 | RHO_A | RHO_B |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PIC | TIC | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ESID | Element set ID (see \*DUALCESE_ELEMENTSET) |
| IFUNC | Option to define initial conditions using \*DEFINE_FUNCTION cards: |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: Not in use. |
| | EQ.1: All values for initial velocity, pressure, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position. |
| Z1 | Volume fraction of material 1 (or color function). This is usually a value of 0 or 1. For numerical stability, however, use a small value instead of 0. |
| RA | Mass fraction of the reactant (material $\alpha$) with respect to material 2 (the explosive mixture) |
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions, respectively |
| RHO1 | Density of material 1 |
| RHO_A | Density of the reactant (material $\alpha$) |
| RHO_B | Density of the product (material $\beta$) |
| PIC | Equilibrium multifluid pressure |
| TIC | Equilibrium multifluid temperature |

## \*DUALCESE_INITIAL_PHASE_CHANGE

Purpose: Specify values to use for velocity, pressure, etc. for problem initialization of a phase-change multiphase model on the dual CESE mesh. Note that these values can be overridden in some mesh elements by use of the \*DUALCESE_INITIAL_PHASE_CHANGE_SET card.

The phase-change multiphase model involves three fluids: a liquid, its vapor, and other gases.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHO | PIC | TIC | Y1 | Y2 |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Y3 | | | IFUNC | | | | |
| Type | F | | | I | | | | |
| Default | none | | | 0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions, respectively |
| RHO | Mixture density |
| PIC | Equilibrium multifluid pressure |
| TIC | Equilibrium multifluid temperature |
| Y1 | Mass fraction of fluid 1 |
| Y2 | Mass fraction of fluid 2 |

| VARIABLE | DESCRIPTION |
|---|---|
| Y3 | Mass fraction of fluid 3 |
| IFUNC | Option to define initial conditions with \*DEFINE_FUNCTION: |

EQ.0: Not in use.

EQ.1: All values for initial velocity, pressure, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x, y, z). Thus, each variable's initial profile is a function of position.

## \*DUALCESE_INITIAL_PHASE_CHANGE_SET

Purpose: Specify values to use for velocity, pressure, etc. for problem initialization of a phase- change multiphase model in an element subset of the dual CESE mesh. The values specified here override the values set on \*DUALCESE_INITIAL_PHASE_CHANGE for the element subset.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ESID | IFUNC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | 0 | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | UIC | VIC | WIC | RHO | PIC | TIC | Y1 | Y2 |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | Y3 | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ESID | Element set ID (see \*DUALCESE_ELEMENTSET) |
| IFUNC | Option to define initial conditions with \*DEFINE_FUNCTION: |

      EQ.0: Not in use.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: All values for initial velocity, pressure, and temperature now refer to \*DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x, y, z). Thus, each variable's initial profile is a function of position. |
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions, respectively |
| RHO | Mixture density |
| PIC | Equilibrium multifluid pressure |
| TIC | Equilibrium multifluid temperature |
| Y1 | Mass fraction of fluid 1 |
| Y2 | Mass fraction of fluid 2 |
| Y3 | Mass fraction of fluid 3 |

## *DUALCESE_INITIAL_TWO-PHASE

Purpose: Specify values to use for velocity, pressure, etc. for problem initialization of a two-phase multifluid model on the dual CESE mesh. Note that these values can be over-ridden in some mesh elements by use of the *DUALCESE_INITIAL_TWO-PHASE_SET card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Z1 | UIC | VIC | WIC | RHO_1 | RHO_2 | PIC | TIC |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | 0. | 0. | 0. | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IFUNC | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| Z1 | Volume fraction of material 1 (or color function) |
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions respectively. |
| RHO_1 | Density of fluid 1 |
| RHO_2 | Density of fluid 2 |
| PIC | Equilibrium multifluid pressure |
| TIC | Equilibrium multifluid temperature |
| IFUNC | Option to define initial conditions using *DEFINE_FUNCTION cards: |

VARIABLE                                    DESCRIPTION

EQ.0: Not in use.

EQ.1: All values for initial velocity, pressure, and temperature now refer to *DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position.

## *DUALCESE_INITIAL_TWO-PHASE_SET

Purpose: Specify values to use for velocity, pressure, etc. for problem initialization of a two-phase multifluid model in an element subset of the dual CESE mesh.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ESID | IFUNC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Z1 | UIC | VIC | WIC | RHO_1 | RHO_2 | PIC | TIC |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| ESID | Element set ID (see *DUALCESE_ELEMENTSET) |
| IFUNC | Option to define initial conditions using *DEFINE_FUNCTION cards: |

    EQ.0: Not in use.

    EQ.1: All values for initial velocity, pressure, and temperature now refer to *DEFINE_FUNCTION IDs. In these functions, the following parameters are allowed: f(x,y,z), meaning that each variable's initial profile is a function of position.

| | |
|---|---|
| Z1 | Volume fraction of material 1 (or color function) |
| UIC, VIC, WIC | Multiphase flow velocity components in the $x$, $y$, and $z$-directions, respectively |

| VARIABLE | DESCRIPTION |
| --- | --- |
| RHO_1 | Density of material 1 |
| RHO_2 | Density of material 2 |
| PIC | Equilibrium multiphase flow pressure |
| TIC | Equilibrium multiphase flow temperature |

**\*DUALCESE_MAT_GAS**

Purpose: Define the fluid (gas) properties in a viscous flow for the dual CESE solver. In this model, the dynamic viscosity is determined using Sutherland's formula for viscosity, and the thermal conductivity is determined using the Prandtl Number.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | C1 | C2 | PRND | | | | |
| Type | I | F | F | F | | | | |
| Default | none | 1.458E-6 | 110.4 | 0.72 | | | | |

|        VARIABLE        |                    DESCRIPTION                    |
|---|---|

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID |
| C1, C2 | Two coefficients in the Sutherland's formula for viscosity: $$\mu = \frac{C_1 T^{3/2}}{T + C_2} \ .$$ Here $C_1$ and $C_2$ are constants for a given gas. For example, for air at moderate temperatures $$C_1 = 1.458 \times 10^{-6} \, \text{kg/msK}^{1/2}, \quad C_2 = 110.4 \text{ K}$$ |
| PRND | Prandtl Number (used to determine the coefficient of thermal conductivity). It is approximately constant for most gases. For air at standard conditions PRND = 0.72. |

**Remarks:**

1.  **Inviscid flows.** C1 and C2 are only used to calculate the viscosity in viscous flows, so for inviscid flows, this material card is not needed.

2.  **Thermal coupling.** The Prandtl number is used to extract the thermal conductivity. It is only needed when thermal coupling with the structure is being done. However, the dual CESE does not include a conjugate heat transfer capability in the Dual CESE solver.

3.    **Unit consistency.** As with other solvers in LS-DYNA, you are responsible for unit consistency.  For example, if dimensionless variables are used, $C_1$ and $C_2$ should be replaced by the corresponding dimensionless ones.  If the dual CESE model has a specified system of units either directly from the \*DUALCESE_-MODEL card or inherited from the overall problem input, then these values need to be given in that unit system.  Also, note that the formulas here require the temperature be given in either Kelvin or Rankine units.

## *DUALCESE_MAT_GAS_0

Purpose: Define the fluid (gas) properties in a viscous flow for the dual CESE solver. In this model, the dynamic viscosity and thermal conductivity are specified constants.

**Material Definition Cards.** Include one card for each instance of this material type. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | MU | K | | | | | |
| Type | I | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID |
| MU | Fluid dynamic viscosity. $MU = 1.81 \times 10^{-5}$ kg/ms for air at 15°C. |
| K | Thermal conductivity of the fluid |

**Remarks:**

1.  **Fields that depend on the problem's physics.** The viscosity is only used in viscous flows, so it is not necessary to define it for inviscid flows. The thermal conductivity is only used when coupling is activated between the structure and thermal solver to calculate the heat transfer. However, the Dual CESE solver does not include a conjugate heat transfer capability.

2.  **Unit consistency.** As with other solvers in LS-DYNA, you are responsible for unit consistency. For example, if dimensionless variables are used, MU should be replaced by the corresponding dimensionless one. If the dual CESE model has a specified system of units either directly from the *DUALCESE_MODEL card or inherited from the overall problem input, then these values need to be given in that unit system.

**\*DUALCESE_MAT_GAS_2**

Purpose: Define the fluid (gas) properties in a viscous flow for the dual CESE solver. This model determines dynamic viscosity and thermal conductivity by combining Sutherland's formula with the Power law for dilute gases.

**Material Definition Cards.** Include one card for each instance of this material type. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-----|------|------|-------|---|---|
| Variable | MID | MU0 | SMU | K0 | SK | T0 | | |
| Type | I | F | F | F | F | F | | |
| Default | none | 1.716E-5 | 111. | 0.0241 | 194.0 | 273.0 | | |

|  VARIABLE  | DESCRIPTION |
|------------|-------------|

MID     Material ID

MU0 / SMU     Two coefficients appearing in the equation derived by combining Sutherland's formula with the Power law for dilute gases:

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S_\mu}{T + S_\mu} \ .$$

Here $\mu$ is the dynamic viscosity, $\mu_0$ is a reference value, and $S_\mu$ is an effective temperature called the Sutherland constant which is characteristic of the gas. For air at moderate temperatures,

$$\mu_0 = 1.716 \times 10^{-5}\,\text{Ns/m}^2, \qquad S_\mu = 111\,\text{K}$$

K0/SK     Two coefficients appearing in the equation derived by combining Sutherland's formula with the Power law for dilute gases:

$$\frac{k}{k_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S_k}{T + S_k} \ .$$

Here $k$ is the thermal conductivity, $k_0$ is a reference value, and $S_k$ is the Sutherland constant, which is characteristic of the gas. For air at moderate temperatures,

$$k_0 = 0.0241\ \text{W/m}, \qquad S_k = 194\,\text{K}$$

T0     Reference temperature, $T_0$. The default value (273.0) is for air in K.

**Remarks:**

1.  **Fields that depend on the problem's physics.**  The viscosity is only used for viscous flows, so it is not necessary to define it for inviscid flows.  The thermal conductivity is only used to calculate the heat transfer between the structure and the thermal solver when coupling is activated.  However, the dual CESE solver does not include a conjugate heat transfer capability.

2.  **Unit consistency.**  As with other solvers in LS-DYNA, you are responsible for unit consistency.  For example, if dimensionless variables are used, MU should be replaced by the corresponding dimensionless one.  If the dual CESE model has a specified system of units either directly from the \*DUALCESE_MODEL card or inherited from the overall problem input, then these values need to be given in that unit system.  Also, note that the formulas here require the temperature be given in either Kelvin or Rankine units.

## \*DUALCESE_MAT_LIQUID

Purpose: Define the fluid (liquid) properties in a viscous flow for the dual CESE solver. The parameters are used to calculate the viscosity of the liquid. This material model is usually accompanied by a liquid EOS (see \*DUALCESE_EOS_NASG). This keyword is only available for single fluid, viscous flows for either no FSI or FSI-IBM.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---------|------|---|---|-------|---|---|
| Variable | MID | A | B | | | K | | |
| Type | I | F | F | | | F | | |
| Default | none | 1.732E-6 | 1863 | | | 0.579 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID |
| A, B | Two coefficients in the Andrade's formula for the liquid's viscosity: |

$$\mu = A \exp\left(\frac{B}{T}\right)$$

Here $T$ is the absolute temperature of the liquid. See Remark 1. The default values taken from the values for water at 10°C: $A = 1.732 \times 10^{-6}$ N·s/m² and $B = 1863$ K.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| K | Thermal conductivity of the liquid. The default value is taken from that for water at 10°C: 0.579 W/m·K. |

**Remarks:**

1. **Properties in Andrade's formula.** The values of $A$ and $B$ need to be determined for the liquid by fitting the equation to experimental viscosity data at different temperatures.

## \*DUALCESE_MESH_GEOMETRY

Purpose:  Set general purpose control variables for the dual CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | GEOM | IDC | | | | | | |
| Type | A | F | | | | | | |
| Default | none | 0.25 | | | | | | |
| Remarks | 1 | 2 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| GEOM | Sets the geometric dimension: |
| | EQ.2D:  Two-dimensional (2D) problem |
| | EQ.3D:  Three-dimensional (3D) problem |
| | EQ.AXI: 2D axisymmetric |
| IDC | Contact interaction detection coefficient (for FSI problems) |

**Remarks:**

1.  **Mesh and Boundary Conditions for 2D Problems.** If you want to use the 2D (GEOM = 2D) or 2D axisymmetric (GEOM=AXI) solver, the mesh should only be distributed in the *xy*-plane with the boundary conditions given only at the *xy* domain boundaries.  Otherwise, a warning message will be given, and the 3D solver will be triggered instead.

    The 2D axisymmetric case will work only if the 2D mesh and corresponding boundary conditions are properly defined with the *x* and *y* coordinates corresponding to the radial and axial directions, respectively.

2.  **Contact Interaction Detection Coefficient.** IDC is the same type of variable that is input on the \*ICFD_CONTROL_FSI card.  For an explanation, see Remark 1 for the \*ICFD_CONTROL_FSI card.

3.  **Dual CESE Solver and Restarts.** The dual CESE solver will support restarts beginning with release R17.

## \*DUALCESE_MESH_PART

Purpose: Define dual CESE solver mesh parts, that is, specify the dual CESE FSI algorithm to use for a mesh part. In other words, this keyword allows you to restrict the type of solver (immersed boundary FSI, moving mesh FSI, or non-FSI Eulerian) used on a region of a dual CESE mesh. The part ID specified with this keyword corresponds to the part ID specified on \*DUALCESE_ELE2D, \*DUALCESE_ELE3D, or \*DUALCESE_BLOCK-MESH.

**Part Cards.** Include one card for each dual CESE part. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | FSITYPE | MMSHID | | | | | |
| Type | I | A | I | | | | | |
| Default | none | optional | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID (must be different from any other \*DUALCESE_MESH_-PART part ID). It is important to note that \*DUALCESE_PART and \*DUALCESE_PART_MULTIPHASE cards should not be used when the newer \*DUALCESE_MESH_PART card is used. |
| FSITYPE | FSI type to use on this part:<br><br>EQ.<BLANK>: If left blank, no FSI performed.<br><br>EQ.IBM: Immersed boundary FSI solver<br><br>EQ.MOVMESH: Moving mesh FSI solver (FSITYPE = MMM may also be used for the same effect) |
| MMSHID | ID for the mesh motion algorithm to use for the moving mesh FSI solver on this part (region of the current dual CESE mesh). This ID refers to the ID of an instantiation of \*DUALCESE_CONTROL_-MESH_MOV. |

## \*DUALCESE_MODEL

Purpose: Set the units used by a dual CESE compressible flow problem, along with the name of the file specifying the dual CESE model. There can be any number of such models (each with a separate mesh), and each such model must be in a different file.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|---|---|---|---|---|---|---|
| Variable | UNITSYS | FILENAME | | | | | | |
| Type | A | A | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| UNITSYS | Name of the unit system of this dual CESE model (defined with \*UNIT_SYSTEM). |
| | EQ.<BLANK>: Use same units as the presumed units of the entire problem. |
| FILENAME | Filename of the keyword file containing the dual CESE model. Note that only \*DUALCESE_... keyword cards are allowed in this file. |

## *DUALCESE_NODE2D

Purpose: Define a node and its coordinates in the global coordinate system. The nodal point ID must be unique relative to other nodes defined with \*DUALCESE_NODE2D or \*DUALCESE_NODE3D cards.

**Node Cards.** Include as many cards in the following format as desired. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | NID | X | | Y | | | | | | |
| Type | I | F | | F | | | | | | |
| Default | none | 0. | | 0. | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Node number |
| X | $x$ coordinate |
| Y | $y$ coordinate |

**\*DUALCESE_NODE3D**

Purpose: Define a node and its coordinates in the global coordinate system. The nodal point ID must be unique relative to other nodes defined with \*DUALCESE_NODE3D or \*DUALCESE_NODE2D cards.

**Node Cards.** Include as many cards in the following format as desired. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Variable | NID | X | | Y | | Z | | | | |
| Type | I | F | | F | | F | | | | |
| Default | none | 0. | | 0. | | 0. | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| NID | Node number |
| X | $x$ coordinate |
| Y | $y$ coordinate |
| Z | $z$ coordinate |

## *DUALCESE_NODESET

Purpose:  Define a nodal set of dual CESE mesh nodes.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | NSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Node ID Cards.** Set one value per node in the set.  Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|------|------|------|------|
| Variable | NID1 | NID2 | NID3 | NID4 | NID5 | NID6 | NID7 | NID8 |
| Type | I | I | I | I | I | I | I | I |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NSID | Set ID of new node set.  All dual CESE node sets should have a unique set ID. |
| NID$i$ | Node ID $i$ |

**\*DUALCESE_PART**

Purpose: Define dual CESE solver parts, that is, specify the dual CESE material and EOS information for a part. It also provides a means to restrict the type of solver used on a region of a dual CESE mesh, meaning an immersed boundary FSI solver, a moving mesh FSI solver, or a non-FSI Eulerian solver can be specified for just this part.

> **WARNING:** As of version R14, this keyword is deprecated. Instead, for the part ID and FSI solver details, use \*DUALCESE_MESH_PART. For the material properties, use the \*DUALCESE_SOLVER_... card corresponding to the choice made with \*DUALCESE_SOLVER_SELECTION.

**Part Cards.** Include one card for each dual CESE part. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | MID | EOSID | FSITYPE | MMSHID | | | |
| Type | I | I | I | A | I | | | |
| Default | none | none | none | optional | 0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID (must be different from any other \*DUALCESE_PART, \*DUALCESE_PART_MULTIPHASE, \*DUALCESE_MESH_PART part ID) |
| MID | Material ID referring to a \*DUALCESE_MAT_… material (see Remark 1) |
| EOSID | Equation of state ID referring to a \*DUALCESE_EOS_… EOS |
| FSITYPE | FSI type to use on this part: |

        EQ.<BLANK>:  If left blank, no FSI performed.

        EQ.IBM:       Immersed boundary FSI solver

        EQ.MOVMESH: Moving mesh FSI solver (FSITYPE = MMM may also be used for the same effect)

| VARIABLE | DESCRIPTION |
| --- | --- |
| MMSHID | ID for the mesh motion algorithm to use for the moving mesh FSI solver on this part (region of the current dual CESE mesh). This ID refers to a \*DUALCESE_CONTROL_MESH_MOV card ID. |

**Remarks:**

1.  **MID for Inviscid Flows.** Since material coefficients are only used in viscous flows, MID can be left blank for inviscid flows.

## *DUALCESE_PART_MULTIPHASE

Purpose: Define dual CESE multiphase solver parts, that is, specify the dual CESE material and EOS information for a part. It also provides a means to restrict the type of solver used on a region of a dual CESE mesh, meaning an immersed boundary FSI solver, a moving mesh FSI solver, or a non-FSI Eulerian solver can be specified for just this part.

> **WARNING:** As of version R14, this keyword is deprecated. Instead, for the part ID and FSI solver details, use \*DUAL-CESE_MESH_PART. For the material properties, use the \*DUALCESE_SOLVER_... card corresponding to the choice made with \*DUALCESE_SOLVER_SELEC-TION.

**Part Cards.** Include one card for each dual CESE multiphase solver part. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | REACT_ID | EOSSID | MID | FSITYPE | MMSHID | | |
| Type | I | I | I | I | A | I | | |
| Default | none | none | none | none | optional | 0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID (must be different from any PID on a \*DUALCESE_PART, \*DUALCESE_PART_MULTIPHASE, \*DUALCESE_MESH_-PART card) |
| REACT_ID | ID of chemical reaction rate model (see \*DUALCESE_REAC-TION_RATE_... cards) |
| EOSSID | Set ID of multiphase EOS set specification (see \*DUALCESE_-EOS_SET) |
| MID | Material ID defined by a \*DUALCESE_MAT_… card |

| VARIABLE | DESCRIPTION |
|---|---|
| FSITYPE | FSI type to use on this part: |
| | EQ.&lt;BLANK&gt;:   If left blank, no FSI is performed. |
| | EQ.IBM:   Immersed boundary FSI solver |
| | EQ.MOVMESH: Moving mesh FSI solver (FSITYPE = MMM may also be used for the same effect) |
| MMSHID | ID of the mesh motion algorithm to use for the moving mesh FSI solver on this part (region of the current dual CESE mesh). This ID refers to a \*DUALCESE_CONTROL_MESH_MOV card ID. |

## \*DUALCESE_POINTSET

Purpose: Define a list of points used to output at specified sample times variables from the chosen dual CESE solver to binary database binout.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PNTSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Point Cards.** Provide as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | X | Y | Z | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PNTSID | ID for this point set which can be used by \*DUALCESE_DATA-BASE_HISTORY_POINT_SET |
| X, Y, Z | Coordinates of a point. As many points as desired can be specified |

## \*DUALCESE_POINT_SOURCE

Purpose:  For the dual CESE compressible flow solver, define values at a point source (inside the fluid mesh) for mass flow rate, magnitude of velocity, density, pressure, and temperature.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1.  Card 1 specifies the position and direction where an injected point source is to be applied.

2.  Card 2 reads in load curve IDs.

3.  Card 3 reads in scale factors.

For each point source to be specified include one set of cards.  This input ends at the next keyword ("\*") card.

**Card Summary:**

**Card 1.** This card is required.

| NSID | | | | | | | |
|------|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.** This card is required.

| LC_MRTE | LC_V | LC_RHO | LC_P | LC_T | | | |
|---------|------|--------|------|------|---|---|---|

**Card 3.** This card is required.

| SF_MRTE | SF_V | SF_RHO | SF_P | SF_T | | | |
|---------|------|--------|------|------|---|---|---|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | NSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NSID | The ID of a \*DUALCESE_POINT_SOURCE_STRUCTNODE_SET card to determine where the point source values in this card should be set. |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---------|------|--------|------|------|---|---|---|
| Variable | LC_MRTE | LC_V | LC_RHO | LC_P | LC_T | | | |
| Type | I | I | I | I | I | | | |
| Default | 0 | 0 | 0 | 0 | 0 | | | |
| Remarks | 1 | 1 | 1 | 1 | 1 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| LC_MRTE | Load curve ID (see \*DEFINE_CURVE) to describe the mass flow rate as a function of time. |

        EQ.0:  Mass flow rate is a constant with value SF_MRTE.

        EQ.-1: Mass flow rate is computed by the solver.

| | |
|----------|-------------|
| LC_V | Load curve ID to describe the magnitude of the velocity as a function of time. |

        EQ.0:  The magnitude of velocity is a constant with value SF_V.

        EQ.-1: The magnitude of velocity is computed by the solver.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_RHO | Load curve ID to describe the density as a function of time. |
| | EQ.0:  Density is a constant with value SF_RHO. |
| | EQ.-1: Density is computed by the solver. |
| LC_P | Load curve ID to describe the pressure as a function of time. |
| | EQ.0:  Pressure is a constant with value SF_P. |
| | EQ.-1: Pressure is computed by the solver. |
| LC_T | Load curve ID to describe the temperature as a function of time. |
| | EQ.0:  Temperature is a constant with value SF_T. |
| | EQ.-1: Temperature is computed by the solver. |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_MRTE | SF_V | SF_RHO | SF_P | SF_T | | | |
| Type | F | F | F | F | F | | | |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_MRTE | Scale factor for LC_MRTE |
| SF_V | Scale factor for LC_V |
| SF_RHO | Scale factor for LC_RHO |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1. **Consistent flow injection values.** On each point source, the variables ($mrate$, $v$, $\rho$, $P$, $T$) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

**\*DUALCESE_POINT_SOURCE_TWO-PHASE**

Purpose: For the dual CESE compressible two-phase multiphase flow solver, this keyword specifies values at a point source (inside the fluid mesh) for the mass flow rate, volume fraction of material 1, magnitude of the velocity, density of material 1, density of material 2, pressure, and temperature.

**Card Sets:**

A set of data cards for this keyword consists of 3 of the following cards:

1. Card 1 specifies the position and direction where an injected point source is to be applied.

2. Card 2 reads in load curve IDs.

3. Card 3 reads in scale factors.

For each point source to be specified, include one set of cards. This input ends at the next keyword ("*") card.

**Card Summary:**

**Card 1.** This card is required.

| NSID | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |

**Card 2.** This card is required.

| LC_MRTE | LC_Z1 | LC_V | LC_D1 | LC_D2 | LC_P | LC_T | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| SF_MRTE | SF_Z1 | SF_V | SF_D1 | SF_D2 | SF_P | SF_T | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| NSID | ID of a *DUALCESE_POINT_SOURCE_STRUCTNODE_SET where the point source values in this card should be set. |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LC_MRTE | LC_Z1 | LC_V | LC_D1 | LC_D2 | LC_P | LC_T | |
| Type | I | I | I | I | I | I | I | |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Remarks | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |

| VARIABLE | DESCRIPTION |
|---|---|
| LC_MRTE | Load curve ID (see *DEFINE_CURVE) to describe the mass flow rate as a function of time. |

> EQ.0:  Constant mass flow rate with value SF_MRTE
>
> EQ.-1: The solver computes the mass flow rate.

| | |
|---|---|
| LC_Z1 | Load curve ID to describe the magnitude of the volume fraction of material 1 as a function of time. |

> EQ.0:  Constant volume fraction for material 1 with value SF_Z1
>
> EQ.-1: The solver computes the volume fraction of material 1.

| VARIABLE | DESCRIPTION |
|---|---|
| LC_V | Load curve ID to describe the magnitude of the velocity as a function of time. |
| | EQ.0: Constant magnitude of velocity with value SF_V |
| | EQ.-1: The solver computes the magnitude of velocity. |
| LC_D1 | Load curve ID to describe the density of material 1 as a function of time. |
| | EQ.0: Constant density for material 1 with value SF_D1 |
| | EQ.-1: The solver computes the density of material 1. |
| LC_D2 | Load curve ID to describe the density of material 2 as a function of time. |
| | EQ.0: Constant density for material 2 with value SF_D2 |
| | EQ.-1: The solver computes the density of material 2. |
| LC_P | Load curve ID to describe the pressure as a function of time. |
| | EQ.0: Constant pressure is a constant with value SF_P |
| | EQ.-1: The solver computes the pressure. |
| LC_T | Load curve ID to describe the temperature as a function of time. |
| | EQ.0: Constant temperature with value SF_T |
| | EQ.-1: The solver computes the temperature. |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SF_MRTE | SF_Z1 | SF_V | SF_D1 | SF_D2 | SF_P | SF_T | |
| Type | F | F | F | F | F | F | F | |
| Default | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_MRTE | Scale factor for LC_MRTE |
| SF_Z1 | Scale factor for LC_Z1 |

| VARIABLE | DESCRIPTION |
|---|---|
| SF_V | Scale factor for LC_V |
| SF_D1 | Scale factor for LC_D1 |
| SF_D2 | Scale factor for LC_D2 |
| SF_P | Scale factor for LC_P |
| SF_T | Scale factor for LC_T |

**Remarks:**

1. **Consistent flow injection values.** On each point source, the variables (*mrate*, $z1, v, \rho1, \rho2, P, T$) that are given values must be consistent and make the model well-posed (meaning be such that the solution of the model exists, is unique, and is physical).

## \*DUALCESE_POINT_SOURCE_STRUCTNODE_SET

Purpose: Provide the position, direction, and size (area of the orifice) of a flow to be injected into a background flow field.

**Node Set ID Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | NSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Orifice Definition Card.** Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|-------|---|---|---|---|---|
| Variable | NID | VID | ORIFA | | | | | |
| Type | I | I | F | | | | | |
| Default | none | none | 1.0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NSID | ID of this set of orifice definitions |
| NID | Structural node that gives the position of the orifice |
| VID | ID of a vector defined by \*DEFINE_VECTOR that gives the direction of the flow away from the position defined by NID |
| ORIFA | Surface area of the orifice |

## \*DUALCESE_POROUS_MODEL

Purpose: Specify the method for treating porous media flow in porous media fluid-structure interaction. Although the literature contains several methods, currently only the jump condition method is available. Other methods may be added in the future.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | METHOD | | | | | | | |
| Type | C | | | | | | | |
| Default | JUMP | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| METHOD | Method for modeling the porous-media interface: |
| | EQ.JUMP: Jump method (default). See *DUALCESE_POROUS_SPECIFY_JUMP. |

**Remarks:**

1.  **Availability.** The porous media flow capability is available for single-fluid FSI-IBM and two-phase FSI-IBM solvers including for viscous and inviscid flows.

**\*DUALCESE_POROUS_SPECIFY_JUMP**

Purpose: Specify the properties of the porous media used in the jump method (see \*DU-ALCESE_POROUS_MODEL).  These properties include the structural part or part set of the porous medium, the thickness of the medium, and the model for mimicking the porosity of the materials.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---------|------|---|---|---|---|---|
| Variable | PID | THICKNSS | EQID | | | | | |
| Type | I | F | I | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Structural part ID of the porous medium |
| THICKNSS | Thickness of the medium |
| EQID | ID of the equation used to model the porous medium (see \*DUAL-CESE_DARCY-FORCHHEIMER_EQ) |

## \*DUALCESE_REACTION_RATE_IG

Purpose: Define a reaction rate law for the Ignition and Growth model to describe the conversion of reactants to products in the modeling of a condensed phase explosive in a dual CESE multiphase model. See Michael and Nikiforakis 2016 and Tarver 2005 for details about this law.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | REACT_ID | IGN | AA | BB | XX | GROW1 | CC | DD |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | YY | GROW2 | EE | GG | ZZ | IGMAX | G1MAX | G2MAX |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| REACT_ID | ID of reaction rate law |
| IGN | Reaction ignition term parameter, $I$ |
| AA | Reaction ignition term parameter, $a$ |
| BB | Reaction ignition term parameter, $b$ |
| XX | Reaction ignition term parameter, $x$ |
| GROW1 | Reaction growth term parameter, $G_1$ |
| CC | Reaction growth term parameter, $c$ |
| DD | Reaction growth term parameter, $d$ |
| YY | Reaction growth term parameter, $y$ |

| VARIABLE | DESCRIPTION |
|---|---|
| GROW2 | Reaction completion term parameter, $G_2$ |
| EE | Reaction completion term parameter, $e$ |
| GG | Reaction completion term parameter, $g$ |
| ZZ | Reaction completion term parameter, $z$ |
| IGMAX | Maximum mass fraction of the product for reaction ignition term, $\Phi_{\text{IGmax}}$ |
| G1MAX | Maximum mass fraction of the product for reaction growth term, $\Phi_{\text{G1max}}$ |
| G2MAX | Maximum $\Phi$ for reaction completion term, $\Phi_{\text{G2max}}$ |

**Remarks:**

Using the notation of Michael and Nikiforakis 2016, the reaction rate law can be given as:

$$\frac{d\Phi}{dt} = I(1-\Phi)^b(\rho - 1 - a)^x H(\Phi_{\text{IGmax}} - \Phi)$$
$$+ G_1(1-\Phi)^c \Phi^d p^y H(\Phi_{\text{G1max}} - \Phi) + G_2(1-\Phi)^e \Phi^g p^z H(\Phi - \Phi_{\text{G2max}})$$

where $H$ is the Heaviside function. Here $\Phi$ is the mass fraction of the products, $p$ is the pressure, and $\rho$ is the density of the explosive mixture. Note that the pressure is assumed to be in equilibrium between the phases. $I$, $G_1$, $G_2$, $a$, $b$, $c$, $d$, $e$, $g$, $x$, $y$, and $z$ are constants. They depend on the explosive as well as the part of the detonation process being modeled; see Michael and Nikiforakis 2016 for details.

The constants $\Phi_{\text{IGmax}}$, $\Phi_{\text{G1max}}$, and $\Phi_{\text{G2max}}$ in the Heavyside functions indicate when each of the three stages of the reaction are dominant. It was developed by Tarver 2005 to describe the reaction of pressed solid explosives during shock initiation and detonation. Tarver 2005 developed this reaction law for pressed solid explosives to describe the observed reaction stages during shock initiation and detonation See Tarver 2005 for a description of each stage of the reaction.

## \*DUALCESE_REACTION_RATE_IG_REDUCED

Purpose: Define a reduced form reaction rate law compared to that defined with \*DUALCESE_REACTION_RATE_IG for describing the conversion of reactants to products in the modeling of a condensed phase explosive in a dual CESE multiphase model. See Michael and Nikiforakis 2016 for details about this reaction rate law.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | REACT_ID | GROW1 | CC | DD | YY | PHI0 | | |
| Type | I | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|
| REACT_ID | ID of reaction rate law |
| GROW1 | Reaction growth term parameter, $G_1$ |
| CC | Reaction growth term parameter, $c$ |
| DD | Reaction growth term parameter, $d$ |
| YY | Reaction growth term parameter, $y$ |
| PHI0 | Additional parameter to account for the non-zero amount of reaction when the mass fraction of the products, $\phi$, is zero |

**Remarks:**

Michael and Nikiforakis 2016 simplified the Ignition and Growth model reaction law to a pressure dependent law with a single stage to make the reduced model. They excluded the first and third terms from the Ignition and Growth model to makes this law. However, to account for a finite amount of reaction from ignition when $\phi$ is zero, they added a constant $\phi_0$. This reduced law has the form:

$$\frac{d\phi}{dt} = G_1(1-\phi)^c(\phi+\phi_0)^d p^y \ .$$

All the parameters are the same as the Ignition and Growth model except $\Phi_0$. See \*DUALCESE_REACTION_RATE_IG and Michael and Nikiforakis 2016 for details.

## \*DUALCESE_REACTION_RATE_P_DEPEND

Purpose: Define an explicitly pressure-dependent reaction rate law for describing the conversion of reactants to products in the modeling of a condensed phase explosive in a dual CESE multiphase model. This law is from Banks et al 2008.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | REACT_ID | SIGMA | NU | N | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| REACT_ID | ID of reaction rate law |
| SIGMA | A positive constant, $\sigma$ |
| NU | A positive constant, $\nu$ |
| N | A positive constant, $n$ |

**Remarks:**

Using the notation of Michael and Nikiforakis 2016, this simple pressure dependent reaction rate law by Banks et al 2008 can be stated as:

$$\frac{d\phi}{dt} = \sigma \phi^{\nu} p^{n}$$

Here $\phi$ is the mass fraction of the products, $p$ is the pressure, and $\sigma$, $\nu$, and $n$ are positive constants found from experimental data. As discussed by Banks et al 2008, this type of reaction rate law that depends explicitly on pressure is often preferred for modeling the detonation of solid explosives because the constants can be found by fitting experimental data and other physical variables are difficult to measure.

## \*DUALCESE_SEGMENTSET

Purpose: Define a set of segments. For three-dimensional geometries, a segment can be triangular or quadrilateral. For two-dimensional geometries, a segment is a line defined by two nodes.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

**Segment Cards.** For each segment in the set include one card of this format. Include as many cards as necessary. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SID | Set ID. All segment sets should have a unique set ID. |
| N1 | Nodal point $n_1$ |
| N2 | Nodal point $n_2$ |
| N3 | Nodal point $n_3$. To define a line segment, set N3 = N2. |
| N4 | Nodal point $n_4$. To define a triangular segment, set N4 = N3. To define a line segment, set N4 = N2. |

**Table 5-1.** Face definitions for volume dual CESE elements

| FACE | Hexahedron | Pentahedron | Pyramid | Tetrahedron |
|---|---|---|---|---|
| 1 | N1, N5, N8, N4 | N1, N2, N5 | N1, N4, N3, N2 | N1, N2, N4 |
| 2 | N2, N3, N7, N6 | N4, N6, N3 | N1, N2, N5 | N2, N3, N4 |

| FACE | Hexahedron | Pentahedron | Pyramid | Tetrahedron |
|------|------------|-------------|---------|-------------|
| 3 | N1, N2, N6, N5 | N1, N4, N3, N2 | N2, N3, N5 | N1, N3, N2 |
| 4 | N4, N8, N7, N3 | N2, N3, N6, N5 | N3, N4, N5 | N1, N4, N3 |
| 5 | N1, N4, N3, N2 | N1, N5, N6, N4 | N4, N1, N5 | |
| 6 | N5, N6, N7, N8 | | | |

## *DUALCESE_SOLVER_SELECTION

Purpose: Set general purpose control variables for the dual CESE compressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | EQNS | | | | | | | |
| Type | A | | | | | | | |
| Default | EULER | | | | | | | |
| Remark | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EQNS | Select the equations being solved with the dual CESE solver: |

        EQ.CAVITATION:   Cavitation solver

        EQ.EULER:        Euler equations

        EQ.HYBRID:       Hybrid multiphase model

        EQ.NS:           Navier-Stokes equations

        EQ.PHASE-CHNG: Phase change model

        EQ.TWO-PHASE:   Two-phase multiphase model

**Remarks:**

1. **Dual CESE Solver and Restarts.** The dual CESE solver will support restarts beginning with release R17.

## \*DUALCESE_SOLVER_CAV_EQNS

Purpose: Set the properties of the cavitating flow mixture being solved with the cavitation solver.

**Property Card.** Include one card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state (EOS) ID that must refer to an EOS defined with \*DUALCESE_EOS_CAV_HOMOG_EQUILIB |

### \*DUALCESE_SOLVER_EULER_EQNS

Purpose: Set the properties of the gas flow being solved with the Euler equations solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state (EOS) ID that refers to an EOS defined by one of the following keywords: \*DUALCESE_EOS_IDEAL_GAS, \*DUALCESE_EOS_INFLATOR1, or \*DUALCESE_EOS_INFLATOR2. |

**\*DUALCESE_SOLVER_HYBRID_MULTIPHASE**

Purpose: Define the properties of the fluid and condensed phase materials via equations-of-state that are used together to compute the thermodynamic state in the hybrid multiphase dual CESE solver.  Also, specify the single-step reaction rate model for the chemical reactions.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSINID | EOSRCTID | EOSPRDID | REACT_ID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |
| Remark | 1 | 1 | 1 | 2 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSINID | EOS ID of the inert component of the multiphase mixture |
| EOSRCTID | EOS ID of the reactant phase of the multiphase mixture |
| EOSPRDID | EOS ID of the product phase of the multiphase mixture |
| REACT_ID | ID of chemical reaction rate model |

**Remarks:**

1. **Supported EOS Types.**  Each EOS can be one of the following types:

   \*DUALCESE_EOS_IDEAL_GAS

   \*DUALCESE_EOS_STIFFENED_GAS

   \*DUALCESE_EOS_VAN_DER_WAALS_GENERALIZED

   \*DUALCESE_EOS_COCHRAN_CHAN

   \*DUALCESE_EOS_JWL.

2. **Supported Reaction Rate Types.**  The reaction rate can be one of the following types:

\*DUALCESE_REACTION_REAT_IG

\*DUALCESE_REACTION_RATE_IG_REDUCED

\*DUALCESE_REACTION_RATE_P_DEPEND

**\*DUALCESE_SOLVER_NAVIER_STOKES**

Purpose: Set the properties of the fluid flow being solved with the Navier-Stokes equations solver.  That is, specify the dual CESE material and EOS information to be used.

**Property Card.**  Include one card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | MID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | Equation of state (EOS) ID referring to an EOS defined by one of the following card types: \*DUALCESE_EOS_IDEAL_GAS, \*DUALCESE_EOS_INFLATOR1, or \*DUALCESE_EOS_INFLATOR2. |
| MID | Material ID referring to a \*DUALCESE_MAT_… material card (see Remark 1) |

**Remarks:**

1.  **MID for Inviscid Flows.** Since material coefficients are only used in viscous flows, MID can be left blank for inviscid flows.

## *DUALCESE_SOLVER_PHASE_CHANGE

Purpose:  Define the properties of the fluid and condensed phase materials via equations of state that are used together to compute the thermodynamic state in the phase change multiphase dual CESE solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSIDL | EOSIDV | EOSIDO | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |
| Remarks | 1 | 1 | 1 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSIDL | Equation of state (EOS) ID of the liquid component in the multiphase mixture |
| EOSIDV | Equation of state (EOS) ID of the vapor component in the multiphase mixture |
| EOSIDO | Equation of state (EOS) ID of the other gases in the multiphase mixture |

**Remarks:**

1.  **Available EOS models.** Each EOS can be one of the following types:

    *DUALCESE_EOS_NASG

**\*DUALCESE_SOLVER_TWO-PHASE_MULTIPHASE**

Purpose: Define the properties of the fluid phase materials through equations-of-state that are used together to compute the thermodynamic state in the two-phase multiphase dual CESE solver. This solver does not compute phase changes.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID1 | EOSID2 | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |
| Remarks | 1 | 1 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID1 | EOS ID of the first inert component of the multiphase mixture |
| EOSID2 | EOS ID of the second inert component of the multiphase mixture |

**Remarks:**

1.   **Supported EOS Types.**  Each EOS can be one of the following types:

     \*DUALCESE_EOS_IDEAL_GAS

     \*DUALCESE_EOS_STIFFENED_GAS

     \*DUALCESE_EOS_VAN_DER_WAALS_GENERALIZED

     \*DUALCESE_EOS_COCHRAN_CHAN

     \*DUALCESE_EOS_JWL

# \*EM

The \*EM keyword cards provide input for the electromagnetism module. This module is for solving 3D eddy-current, inductive heating or resistive heating problems. It can be coupled with the mechanical and thermal solvers. Typical applications include magnetic metal forming and welding. This module also includes coupling the boundary element method to the finite element method coupling. We intend this coupling for simulations involving a conductor interacting with air so that the air does not need to be meshed. The conductor is modeled with finite elements while the air is modeled with boundary elements.

    \*EM_2DAXI

    \*EM_BOUNDARY

    \*EM_BOUNDARY_PRESCRIBED

    \*EM_CIRCUIT

    \*EM_CIRCUIT_CONNECT

    \*EM_CIRCUIT_ROGO

    \*EM_CIRCUIT_SOURCE

    \*EM_CONTACT

    \*EM_CONTACT_RESISTANCE

    \*EM_CONTACT_SUBDOM

    \*EM_CONTROL

    \*EM_CONTROL_CONTACT

    \*EM_CONTROL_COUPLING

    \*EM_CONTROL_EROSION

    \*EM_CONTROL_MAGNET

    \*EM_CONTROL_SOLUTION

    \*EM_CONTROL_SWITCH

    \*EM_CONTROL_SWITCH_CONTACT

\*EM_CONTROL_TIMESTEP

\*EM_DATABASE_CIRCUIT

\*EM_DATABASE_CIRCUIT0D

\*EM_DATABASE_CIRCUITSOURCE

\*EM_DATABASE_ELOUT

\*EM_DATABASE_FIELDLINE

\*EM_DATABASE_GLOBALENERGY

\*EM_DATABASE_NODOUT

\*EM_DATABASE_PARTDATA

\*EM_DATABASE_POINTOUT

\*EM_DATABASE_ROGO

\*EM_DATABASE_TIMESTEP

\*EM_EP_CELLMODEL_DEFINE_FUNCTION

\*EM_EP_CELLMODEL_FENTONKARMA

\*EM_EP_CELLMODEL_FIZHUGHNAGUMO

\*EM_EP_CELLMODEL_TENTUSSCHER

\*EM_EP_CELLMODEL_TOMEK

\*EM_EP_CELLMODEL_TOR_ORD

\*EM_EP_CELLMODEL_USERMAT

\*EM_EP_CREATEFIBERORIENTATION

\*EM_EP_ECG

\*EM_EP_EIKONAL

\*EM_EP_ISOCH

\*EM_EP_LAPLACE_DIRICHLET

\*EM_EP_PURKINJE_NETWORK

\*EM_EP_TENTUSSCHER_STIMULUS

\*EM_EOS_BURGESS

\*EM_EOS_MEADON

\*EM_EOS_PERMEABILITY

\*EM_EOS_TABULATED1

\*EM_EOS_TABULATED2

\*EM_EXTERNAL_ECVEL

\*EM_EXTERNAL_FIELD

\*EM_ISOPOTENTIAL

\*EM_ISOPOTENTIAL_CONNECT

\*EM_ISOPOTENTIAL_ROGO

\*EM_MAT_001

\*EM_MAT_002

\*EM_MAT_003

\*EM_MAT_004

\*EM_MAT_005

\*EM_MAT_006

\*EM_OUTPUT

\*EM_OUTPUT_FORCES

\*EM_OUTPUT_VTK

\*EM_PERMANENT_MAGNET

\*EM_POINT_SET

\*EM_RANDLES_BATMAC

\*EM_RANDLES_EXOTHERMIC_REACTION

\*EM_RANDLES_MESHLESS

\*EM_RANDLES_TSHELL

\*EM_RANDLES_SHORT

    \*EM_RANDLES_SOLID

    \*EM_ROTATION_AXIS

    \*EM_SOLVER_BEM

    \*EM_SOLVER_BEM_REASSEMBLY

    \*EM_SOLVER_BEMMAT

    \*EM_SOLVER_FEM

    \*EM_SOLVER_FEMBEM

    \*EM_SOLVER_FEMBEM_MONOLITHIC

**\*EM_2DAXI**

Purpose: Sets up the electromagnetism solver as 2D axisymmetric instead of 3D, on a given part, in order to save computational time as well as memory.

The electromagnetism is solved in 2D on a given cross section of the part (defined by a segment set), with a symmetry axis defined by its direction (at this time, it can be the *x*, *y*, or *z* axis). The EM forces and Joule heating are then computed over the full 3D part by rotations. The part needs to be compatible with the symmetry, i.e. each node in the part needs to be the child of a parent node on the segment set, by a rotation around the axis. Only the conductor parts (with a \*EM_MAT_… of type 2 or 4) should be defined as 2D axisymmetric.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | SSID | | | STARSSID | ENDSSID | NUMSEC | |
| Type | I | I | | | I | I | I | |
| Default | none | none | | | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the part to be solved using 2D axisymmetry |
| SSID | Segment Set ID : Segment that will define the 2D cross section of the part where the EM field is solved |
| STARSSID, ENDSSID | Used by the 2D axisymmetric solver to make the connection between two corresponding boundaries on each side of a slice when the model is a slice of the full 360 circle. |
| NUMSEC | Number of Sectors. This field gives the ratio of the full circle to the angular extension of the mesh. This has to be a power of two. For example, NUMSEC = 4 means that the mesh of the part represents one fourth of the total circle. If this value is set to 0, then the value from *EM_ROTATION_AXIS is used instead. |

**Remarks:**

1.   At this time, *either* all or none of the conductor parts should be 2D axisymmetric. In the future, a mix between 2D axisymmetric and 3D parts will be allowed.

**\*EM_BOUNDARY**

Purpose: Define some boundary conditions for the electromagnetism problems.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | SSID | BTYPE | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SSID | Segment Set Id |
| BTYPE | EQ.9: The faces of this segment set are eliminated from the BEM calculations (used for example for the rear or side faces of a workpiece). |

## \*EM_BOUNDARY_PRESCRIBED

Purpose: Prescribe a local boundary condition applied on nodes.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|--------|---------|-------|-----|------|---|---------|
| Variable | BPID | BPTYPE | SETTYPE | SETID | VAL | LCID | | SYSTYPE |
| Type | I | I | I | I | F | I | | I |
| Default | none | none | none | none | 0. | 0 | | 0 |

**Optional Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|--------|---|---|------|-------|---|---|
| Variable | BIRTHT | DEATHT | | | VAL2 | LCID2 | | |
| Type | F | F | | | F | I | | |
| Default | 0. | 1.e28 | | | 0. | 0 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ISOID | ID of the prescribed boundary |
| BPTYPE | Prescribed boundary type: |
| |     EQ.1: Short (scalar potential set to 0.) |
| |     EQ.2: Prescribed resistance (Robin B.C.) |
| |     EQ.3: Prescribed scalar potential (Dirichlet B.C.) |
| |     EQ.4: Prescribed current density (Neumann B.C.) |
| SETTYPE | Set type: |
| |     EQ.1: Segment set |
| |     EQ.2: Node set |
| |     EQ.3: Fluid part (see \*ICFD_PART) |
| SETID | Set ID |

| VARIABLE | DESCRIPTION |
|---|---|
| VAL | Value of the resistance, current density or potential depending on BPTYPE. Ignored if LCID is defined. |
| LCID | Load curve ID defining the value of the resistance, voltage, or current as a function of time.  If a negative value is entered, a \*DEFINE_FUNCTION will be expected.  The following parameters are allowed: f(time, emdt, curr, pot, cond, temp, potglob, currglob, areaglob, area, x, y, z). Pot/curr/area and potglob/currglob/areaglob are the local value of the scalar potential/current/area and the global averaged value on the prescribed boundary, respectfully.  Cond is the local electrical conductivity, and x, y, and z are the local coordinates. |
| SYSTYPE | Flag for the type of system on which the boundary condition is applied (applies only for cardiac electrophysiology when \*EM_BOUNDARY_PRESCRIBED is used with EMSOL = 11 or 12):<br><br>EQ.0:  Applied on extracellular potential<br><br>EQ.1:  Applied on transmembrane potential |
| BIRTHT / DEATHT | Birth and death times for that prescribed boundary |
| VAL2 | Value of the impedance in radiofrequency problems to be used in conjunction with BPTYE = 2. |
| LCID2 | Load curve ID for defining the impedance value as a function of time.  It is only available in radiofrequency problems with BPTYPE = 2. |

**Remarks:**

1. **Supported solvers.**  This keyword is currently only available for the resistive heating solver (EMSOL = 3) and the electrophysiology solvers (EMSOL = 11, 12, and 13).

**\*EM_CIRCUIT**

Purpose: Define an electrical circuit.

The solver type, set with EMSOL of \*EM_CONTROL, determines how the current density in a circuit is modeled. For example, for an eddy current solver, the diffusion of the current in the circuit is considered. To model a circuit with uniform current through its cross-section, see \*EM_CIRCUIT_SOURCE.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CIRCID | CIRCTYP | LCID | R/F | L/A | C/T0 | V0 | T0 |
| Type | I | I | I | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | 0. |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SIDCURR | SIDVIN | SIDVOUT | PID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

**Optional Card.** This card is only read if CIRCTYP = 30.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VCUT | R3 | L3 | R2 | | | | |
| Type | F | F | F | F | | | | |
| Default | 0. | 0. | 0. | 0. | | | | |

|   VARIABLE   |   DESCRIPTION   |
|---|---|
| CIRCID | Circuit ID |

| VARIABLE | DESCRIPTION |
|---|---|
| CIRCTYP | Circuit type : |

> **EQ.1:** Imposed current as a function of time set by a load curve.
>
> **EQ.2:** Imposed voltage as a function of time specified by a load curve. If a negative value is entered for LCID, its absolute value will refer to a DEFINE FUNCTION for a user-defined circuit equation. If a DEFINE_FUNCTION is used, the following parameters are accepted: f(time, emdt, curr, curr1, curr2, pot1, pot2). emdt is the current timestep; curr, curr1, and curr2 refer to the current value at $t$, $t-1$, and $t-2$, respectfully; and pot1 and pot2 refer to the scalar potential at $t-1$ and $t-2$, respectfully.
>
> **EQ.3:** R, L, C, V0 circuit.
>
> **EQ.11:** Imposed current defined by an amplitude $A$, frequency $F$ and initial time $t_0$: $I = A\sin[2\pi F(t-t_0)]$
>
> **EQ.12:** Imposed voltage defined by an amplitude $A$, frequency $F$ and initial time $t_0$: $V = A\sin[2\pi F(t-t_0)]$
>
> **EQ.21:** Imposed current defined by a load curve over one period and a frequency $F$. See Remark 3.
>
> **EQ.22:** Imposed voltage defined by a load curve over one period and a frequency $F$. See Remark 3.
>
> **EQ.30:** Modified version of R, L, C, V0 circuit that includes a diode. See Figure 6-1.

| VARIABLE | DESCRIPTION |
|---|---|
| LCID | Load curve ID for CIRCTYP = 1, 2, 21, and 22 |
| R/F | Value of the circuit resistance for CIRCTYP = 3 and 30. For CIRCTYP = 30, this part of the circuit is labeled R1 in Figure 6-1. |
| | Value of the frequency for CIRCTYP = 11, 12, 21, and 22. For CIRCTYP = 11 and 12, to have the frequency specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID. |
| L/A | Value of the circuit inductance for CIRCTYP = 3 and 30. For CIRCTYP = 30, this part of the circuit is labeled L1 in Figure 6-1. |
| | Value of the amplitude for CIRCTYP = 11 and 12. To have the amplitude specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID. |
| C/T0 | Value of the circuit capacity for CIRCTYP = 3 and 30. For CIRC- |

| VARIABLE | DESCRIPTION |
|---|---|
| | TYP = 30, this part of the circuit is labeled C1 in Figure 6-1. |
| | Value of the initial time $t_0$ for CIRCTYP = 11 and 12. |
| V0 | Value of the circuit initial voltage for CIRCTYP = 3 and 30. |
| T0 | Starting time for CIRCTYP = 3. The default is the beginning of the run. |
| SIDCURR | Segment set ID for the current. It uses the orientation given by the normal of the segments. To use the opposite orientation, use a '–' (minus) sign in front of the segment set ID. |
| | CIRCTYP.EQ.1/11/21: The current is imposed through this segment set. |
| | CIRCTYP.EQ.3/30: The current needed by the circuit equations is measured through this segment set. |
| | CIRCTYP.EQ.2/12/22: Optional segment set that the current is forced through. See Remark 2. |
| SIDVIN | Segment set ID for input voltage when CIRCTYP = 2, 3, 30, 12, or 22 or for input current when CIRCTYP = 1, 11, or 21. The input voltage or current is oriented to enter the structural mesh, irrespective of the orientation of the segments. |
| SIDVOUT | Segment set ID for output voltage when CIRCTYP = 2, 3, 30, 12, or 22 or for output current when CIRCTYP = 1, 11, or 21. The output voltage or current is oriented to leave the structural mesh, irrespective of the orientation of the segment. |
| PID | Part ID associated with the circuit. It is only mandatory when including the second line of \*EM_ROTATION_AXIS for the EM 2D axisymmetric solver. |
| VCUT | Cut off voltage for the diode, allowing the current to flow or not. Setting this field to a very large negative value effectively means that the diode circuit branch is never triggered, causing CIRCTYP = 30 to revert to an R, L, C circuit with behavior similar to CIRCTYP = 3. See Figure 6-1. |
| R3/L3/R2 | Optional circuit resistance and inductance values for the different branches for CIRCTYP = 30. See Figure 6-1. |

**Table 6-1.** Correspondence between circuit type and card entries. "M" indicates mandatory, "M\*" mandatory with exceptions (see Remark 1), "O" optional, and "-" ignored.

| Variable | 1: Imposed current | 2: Imposed voltage | 3: R, L, C | 11: F, A, t0 | 12: F, A, t0 |
|---|---|---|---|---|---|
| LCID | M | M | - | - | - |
| R/L/C/V0 | - | - | M | - | - |
| F | - | - | - | M | M |
| A/T0 | - | - | - | M | M |
| SIDCURR | M | O | M | M | O |
| SIDVIN | M\* | M | M | M\* | M |
| SIDVOUT | M\* | M | M | M\* | M |

| Variable | 21: LCID, F | 22: LCID, F | 30: R, L, C with diode |
|---|---|---|---|
| LCID | M | M | - |
| R/L/C/V0 | - | - | M |
| F | M | M | - |
| A/T0 | - | - | - |
| SIDCURR | M | O | M |
| SIDVIN | M\* | M | M |
| SIDVOUT | M\* | M | M |
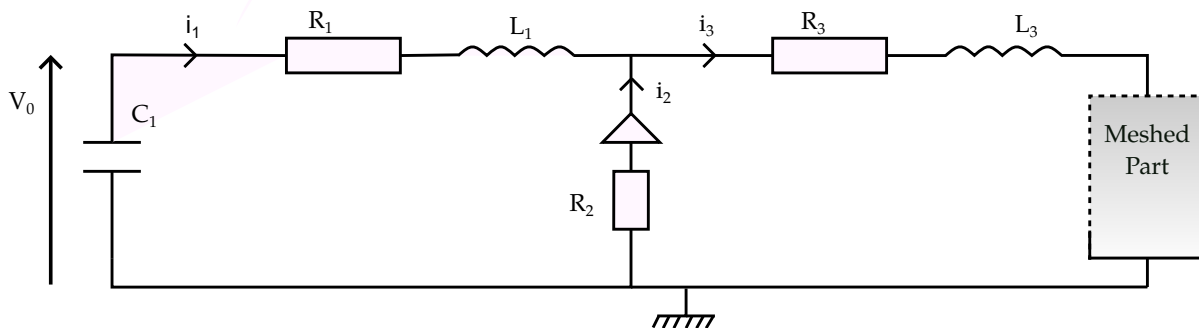


**Figure 6-1.** CIRCTYP = 30 circuit sketch

**Remarks:**

1.  **Imposed current with closed loop geometry.** For a circuit with an imposed current (CIRCTYP 1, 11, or 21) in a closed loop geometry (torus), SIDVIN and SIDVOUT cannot be specified. Thus, only SIDCURR is necessary.

2.  **SIDCURR with imposed tension.** For a circuit with an imposed tension (CIRC-TYP 2, 12, 22), it is also possible to set SIDCURR. This can be useful in circuits where various flow paths are possible for the current to force the entire current to go through SIDCURR.

3.  **CIRCTYP = 21 and 22.** Circuit types 21 and 22 are for cases where the periodic current/tension does not exactly follow a perfect sinusoidal. You must provide the frequency and the shape of the current/tension over one period through a load curve.

4.  **EMSOL = 4.** Only CIRCTYP = 1 and 2 are available for the frequency-based Eddy current solver. The values in the load curve represent the norm of the amplitude. A time shift can optionally be defined using T0.

5.  **CIRCTYP = 30.** This circuit type is only available for the Eddy current solver. When used, the output includes the current and voltage values of the different branches.

## \*EM_CIRCUIT_CONNECT

Purpose: Connect several circuits together by imposing a linear constraint on the global currents of circuit pairs.

$$c_1 i_1 + c_2 i_2 = 0.$$

This feature is especially useful for 2D axisymmetric models involving spiral or helical coils.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CONID | CONTYPE | CIRC1 | CIRC2 | C1 | C2 | | |
| Type | I | I | I | I | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CONID | ID of the circuit connect |
| CONTYPE | Connection type between circuits: |

> EQ.1: If CIRC2 already has a global condition on its current, $i_2$, (see \*EM_CIRCUIT), that global condition takes precedence over the constraint defined by the circuit connect.

> EQ.2: The condition defined by circuit connect takes precedence in the case of conflicting constraints (for example CIRC2 also has an imposed current defined by \*EM_CIRCUIT).

| VARIABLE | DESCRIPTION |
|---|---|
| CIRC1 | ID of the first circuit |
| CIRC2 | ID of the second circuit |
| C1/C2 | Values of the linear constraints |

**\*EM_CIRCUIT_ROGO**

Purpose: Define Rogowsky coils to measure a global current versus time through a segment set or a node set.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---------|--------|-----|---|---|---|
| Variable | ROGID | SETID | SETTYPE | CURTYP | PID | | | |
| Type | I | I | I | I | I | | | |
| Default | 0 | 0 | 0 | 0 | 0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ROGID | Rogowsky coil ID |
| SETID | Segment or node set ID |
| SETTYPE | Type of set: |
| |     EQ.1: Segment set |
| |     EQ.2: Node set (not available yet} |
| CURTYP | Type of current measured: |
| |     EQ.1: Volume current |
| |     EQ.2: Surface current (not available yet} |
| |     EQ.3: Magnetic field flux (B field times Area) |
| PID | Part ID. It is only available for 2D axisymmetric Eddy current cases. See Remark 2. |

**Remarks:**

1. **Output.** An ASCII file em_rogo_*xxx*, with *xxx* being the ROGID, is generated for each \*EM_CIRCUIT_ROGO card. This file contains the value of the current or the magnetic field versus time for that Rogowsky coil.

2. **Special input for 2D axisymmetric Eddy current problems.** When the second line of \*EM_ROTATION_AXIS is used, a simplified input for 2D axisymmetric

Eddy current problems becomes available. This case does not require specifying segment sets through the cross sections. Instead, if segment sets are unavailable, provide the part ID of the 2D axisymmetric part as PID to associate it with a Rogowsky coil.

## *EM_CIRCUIT_SOURCE

Purpose: Define a circuit with uniform current through its cross-section.

This feature generally helps model stranded conductors carrying a source current (in which case Amperes become Ampere-turns). This feature can also help save computational time in models with a low-frequency current and where the diffusion of the EM fields is a very fast process. In contrast, when using *EM_CIRCUIT, the current density in a circuit is modeled in accordance with the solver type defined in EMSOL of *EM_-CONTROL. For example, using an eddy current solver causes considering the diffusion of the current in the circuit. See Remark 2 for a discussion of the available circuit types for source circuits.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CIRCID | CIRCTYP | LCID | R/F | T/A | T0 | | |
| Type | I | I | I | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SIDCURR | SIDVIN | SIDVOUT | PARTID | IFREQST | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | 1 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CIRCID | Circuit ID |
| CIRCTYP | Circuit type : |

        EQ.1:   Imposed current as a function of time specified by a load curve.

        EQ.2:   Imposed voltage as a function of time given by a load curve.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.11: Imposed current defined by an amplitude $A$, frequency $F$ and initial time $t_0$: $I = A\sin[2\pi F(t - t_0)]$ |
| LCID | Load curve ID for CIRCTYP = 1 or 2. See Remark 3. |
| R/F | Value of the frequency for CIRCTYP = 11. To have the frequency specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID. |
| | Value of the resistance when using an imposed voltage (CIRCTYPE = 2). |
| T/A | Value of the amplitude for CIRCTYP = 11. To have the amplitude specified as a function of time with a load curve, a negative value can be entered with the absolute value corresponding to the load curve ID. See Remark 3. |
| | Number of turns when using an imposed voltage (CIRCTYPE = 2). |
| T0 | Value of the initial time, $t_0$, for CIRCTYP = 11 |
| SIDCURR | Segment set ID for the current. It uses the orientation given by the normal of the segments. To use the opposite orientation, use a '−' (minus) sign in front of the segment set ID or reorient the face normals. |
| SIDVIN | Segment set ID for input voltage when CIRCTYP = 2 or for input current when CIRCTYP = 1 or 11. This field must be left blank if the stranded conductor is a torus shape (see Remark 1). |
| SIDVOUT | Segment set ID for output voltage when CIRCTYP = 2 or for output current when CIRCTYP = 1 or 11. This field must be left blank if the stranded conductor is a torus shape (see Remark 1). |
| PARTID | Part ID associated with the circuit |
| IFREQST | Frequency for recomputing the source terms. The source terms are recalculated every IFREQST time steps. By default, the source terms are recomputed every EM time step. See Remark 4. |
| | LT.0: \|IFREQST\| is a load curve ID giving the frequency for recomputing as a function of time. |

**Remarks:**

1.  **Imposed current with closed loop geometry.** For a closed loop geometry (to-rus), SIDVIN and SIDVOUT cannot be defined. Thus, only SIDCURR is necessary.

2.  **Circuit types for source circuits.** Source circuits with imposed currents (CIRCTYP = 1 or 11) can be associated with an insulator material (MTYPE = 1) in \*EM_MAT_001. In this case, the solver relies on the Biot-Savart integration method to retrieve the influence of the source circuit on other conductors. This method is fast, but it is not possible to calculate the force on the coil. Circuits conforming to these conditions can be used with both the Richardson (\*EM_-SOLVER_FEMBEM) and Monolithic solvers (\*EM_SOLVER_FEMBEM_MON-OLITHIC) for coupling the FEM-BEM solvers.

    To extract the magnetic force on the coil when using imposed current, the source circuit must be associated with a conductor material (MTYPE = 2) that has a 0. value for the conductivity. In this case, the stranded circuit becomes part of the FEM/BEM system, and resolution might be slower. This approach is only valid with the monolithic solver (see \*EM_SOLVER_FEMBEM_MONOLITHIC).

    Source circuits also support imposed voltage with CIRCTYP = 2 (associated to a resistance value and a number of turns or windings). The source circuit must be used with the monolithic solver (\*EM_SOLVER_FEMBEM_MONOLITHIC) and become part of the FEM/BEM system. Therefore, it must be associated with a conductor material (MTYPE = 2) with a 0. value for the conductivity in its associated EM material (see \*EM_MAT_001). Defining source circuits by their voltage instead of their current is very useful in cases where the current is unknown, such as for actuators or electric motors.

3.  **Ampere versus Ampere-turns.** For an imposed current (CIRCTYP = 1 or 11), the number of windings can be directly applied by multiplying the current value by the number of turns. The imposed current value corresponds to Ampere-turns. For example, a stranded coil with ten turns and a current of two Amperes means that imposing a value of twenty in the load curve (if CIRCTYP = 1) or its periodic amplitude (if CIRCTYP = 11). For imposed voltage, providing Ampere-turns is not available. Thus, the number of turns must be specified directly in the keyword (as well as the total resistance of the circuit).

4.  **When to change IFREQST.** In cases where conductors are not moving with respect to one another, using high values of IFREQST avoids recomputing the source fields which can save some calculation time.

5.  **EMSOL = 4.** For the frequency-based Eddy current solver, only CIRCTYPE = 1 and 2 are available. The values contained in the load curve represent the norm of the amplitude while a time shift can optionally be defined using T0.

## \*EM_CONTACT

Purpose: To optionally define and specify options on electromagnetic contacts between two sets of parts. Generally, it is used with the \*EM_CONTACT_RESISTANCE. Fields left empty on this card default to the value of the equivalent field for \*EM_CONTROL_-CONTACT.

**Contact Definition Cards.** Include one card for each contact definition. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CONTID | DTYPE | PSIDR | PSIDT | EPS1 | EPS2 | EPS3 | D0 |
| Type | I | I | I | I | F | F | F | F |
| Default | none | 0 | none | none | 0.3 | 0.3 | 0.3 | none |

| VARIABLE | DESCRIPTION |
|---|---|
| CONTID | Electromagnetic contact ID |
| DTYPE | Detection type (see remarks):<br>EQ.0: Contact type 0 (default)<br>EQ.1: Contact type 1 |
| PSIDR | Reference surface part set ID |
| PSIDT | Tracked surface part set ID |
| EPS$i$ | Contact coefficients for contact detection conditions. See the discussion below. |
| D0 | Parameter for contact condition 3 when DTYPE = 1 (see remarks) |

**Remarks:**

In these remarks, we discuss the conditions for contact detection. For reference, Figure 0-1 illustrates which geometric values help determine contact. In this figure and discussion, $f_r$ is a face of the reference surface, and $f_t$ is a face of the tracked surface. Contact is detected when *all of the following three conditions are satisfied*:
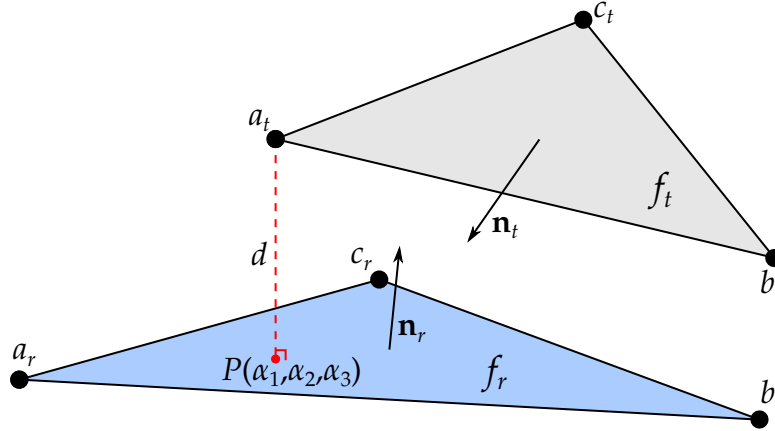
**Figure 0-1.** Contact detection conditions between two faces.

1. Contact condition 1:

$$\mathbf{n}_r \cdot \mathbf{n}_t \leq -1 + \varepsilon_1$$

Here $\mathbf{n}_r$ and $\mathbf{n}_t$ are the normal vectors of faces $f_r$ and $f_t$, respectively, and $\varepsilon_1$ is an input parameter. See Figure 0-1.

2. Contact condition 2:

$$-\varepsilon_2 \leq \alpha_1 \leq 1 + \varepsilon_2$$
$$-\varepsilon_2 \leq \alpha_2 \leq 1 + \varepsilon_2$$
$$-\varepsilon_2 \leq \alpha_3 \leq 1 + \varepsilon_2$$

$(\alpha_1, \alpha_2, \alpha_3)$ are the local coordinates of point $P$ (see Figure 0-1). $P$ is the projection of point $a_2$ on face $f_r$. $\varepsilon_2$ is an input parameter.

3. Contact condition 3 depends on the contact type. For either possible condition, let $d$ be the distance between $P$ and $a_t$ (see Figure 0-1).

   a) For contact type 0:

   $$d \leq \varepsilon_3 S_r \ ,$$

   where $\varepsilon_3$ is an input parameter and $S_r$ is the minimum side length for $f_r$:

   $$S_r = \min[d(a_r, b_r), d(b_r, c_r), d(c_r, a_r)] \ .$$

   b) For contact type 1:

   $$d \leq D_0 \ ,$$

   where $D_0$ is an input parameter.

## *EM_CONTACT_RESISTANCE

Purpose: Calculate the electric contact resistance of a previously defined EM contact in *EM_CONTACT or as a general contact resistance if not associated with any specific contact (see Remark 2 and CONTID = 0).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CRID | CONTID | CRTYPE | | JHRTYPE | | | |
| Type | I | I | I | | I | | | |
| Default | none | none | none | | none | | | |

| Cards 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DFID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CRID | Resistive contact ID |
| CONTID | EM contact ID defined in *EM_CONTACT. |
| | EQ.0: This contact resistance applies to all detected contacts that are not part of any *EM_CONTACT. See Remark 2. |
| CRTYPE | Contact resistance type: |
| | EQ.1: Electric contact resistance defined with a *DEFINE_-FUNCTION. |
| DFID | *DEFINE_FUNCTION ID (see Remark 1) |
| JHRTYPE | Indicates how the Joule heating calculated by the contact resistance shall be taken into account: |
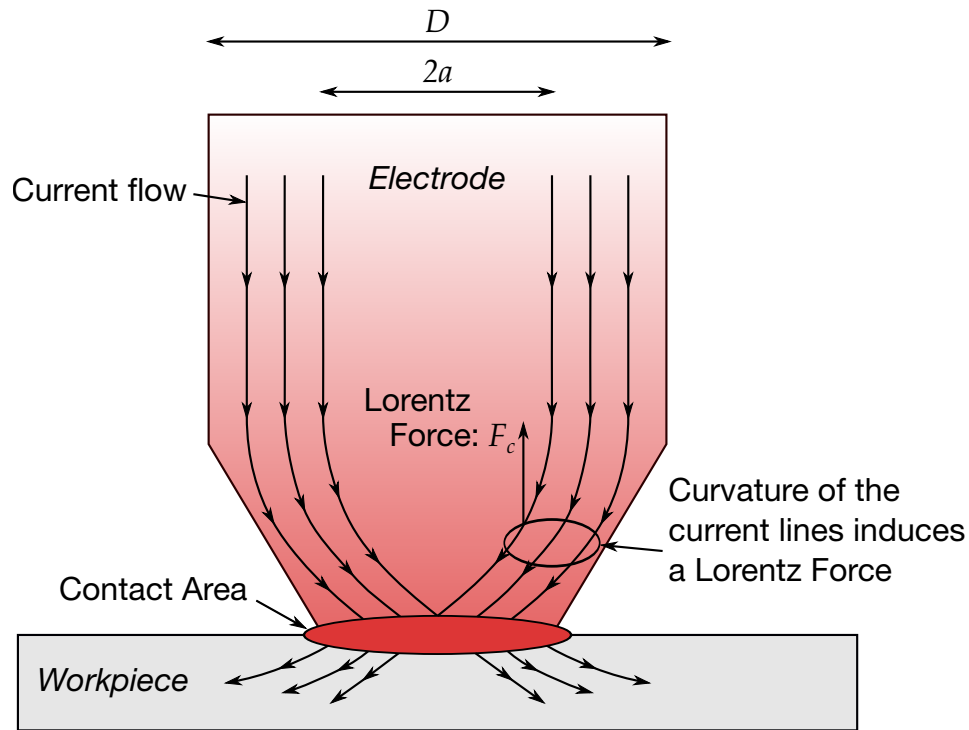
**Figure 6-2.** Electrode coming into contact with workpiece (RSW application).

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: No addition. The Joule heating calculated by the contact resistance is not taken into account. |
| | EQ.1: The Joule heating coming from the contact resistance is divided and distributed evenly among all elements neighboring the contact surface. |

**Remarks:**

1.  **\*DEFINE_FUNCTION parameters.** In the \*DEFINE_FUNCTION, the following parameters are allowed: f(time, emdt, arealoc, areatot, ctdist, currloc, currglob, rho_mst, rho_slv, cond_mst, cond_slv, ctpress_mst, ctpress_slv, temp_mst, temp_slv, vmstress_mst, vmstress_slv, press_mst, press_slv). Here,

| | |
|---|---|
| time | current time step |
| emdt | EM time step |
| arealoc | Local area associated with each face in contact |
| areatot | Total contact area |
| ctdist | Contact distance between the two faces in contact |

| | |
|---|---|
| rho_mst | Density of the elements associated with the reference surface side of the contact |
| rho_slv | Density of the elements associated with the tracked surface side of the contact |
| cond_mst | Electrical conductivity of the elements associated with the reference surface side of the contact |
| cond_slv | Electrical conductivity of the elements associated with the tracked surface side of the contact |
| ctpress_mst | Contact pressure of the elements associated with the reference surface side of the contact |
| ctpress_slv | Contact pressure of the elements associated with the tracked surface side of the contact |
| temp_mst | Temperature of the elements associated with the reference surface side of the contact |
| temp_slv | Temperature of the elements associated with the tracked surface side of the contact |
| vmstress_mst | von Mises stress of the elements associated with the reference surface side of the contact |
| vmstress_slv | von Mises stress of the elements associated with the tracked surface side of the contact |
| press_mst | Pressure of the elements associated with the reference surface side of the contact |
| press_slv | Pressure of the elements associated with the tracked surface side of the contact |

2. **General contact resistance.** If CONTID is 0, this \*EM_CONTACT_RESISTANCE applies to all detected EM contacts that are not part of any \*EM_CONTACT. This feature can be helpful in cases where a given part comes into contact with itself (self-contact). Note that CCONLY must be set to 0 on \*EM_CONTROL_CONTACT for contacts not part of a \*EM_CONTACT to be detected.

3. **Supported contact types.** CTYPE on \*EM_CONTROL_CONTACT must be greater than or equal to 0 for the contact resistance to apply because contact resistance is only supported for penalty contacts.

**\*EM_CONTACT_SUBDOM**

Purpose: Optional card used for defining a specific region where EM contact will be active. This allows saving some calculation time by limiting the contact search area. Must be used in conjunction with \*EM_CONTROL_CONTACT.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SDTYPE | MVTYPE | LCIDX/NID | LCIDY | LCIDZ | | | |
| Type | I | I | I | I | I | | | |
| Default | none | 0 | none | none | none | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| SDTYPE | Subdomain definition type : |

> EQ.1: Defined by box.
>
> EQ.2: Defined by cylinder.
>
> EQ.3: Defined by sphere.

| | |
|---|---|
| MVTYPE | Movement type of subdomain : |

> EQ.0: Static subdomain (Default).
>
> EQ.1: Domain translates in the three directions by the velocities given by LCIDX,LCIDY,LCIDZ.
>
> EQ.2: Domain follows the displacements of the node ID given by NID.

| VARIABLE | DESCRIPTION |
|---|---|
| LCIDX/NID | Time dependent load curve ID for the translational velocity in the X direction for MVTYPE = 1, Node ID for MVTYPE = 2. |
| LCIDY/Z | Time dependent load curve IDs for MVTYPE = 1 in the Y and Z directions. |
| R | Radius of the sphere if SDTYPE = 3 or the cylinder if SDTYPE = 2. |
| PMINX/Y/Z | Point of minimum coordinates if SDTYPE = 1. Origin point if SDTYPE = 3. Axis head point if SDTYPE = 2. |
| PMAXX/Y/Z | Point of maximum coordinates if SDTYPE = 1. Axis tail point if SDTYPE = 2. |

## \*EM_CONTROL

Purpose: Enable the EM solver and set its options.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---------|--------|---|---------|---------|
| Variable | EMSOL | NUMLS | | DIMTYPE | NPERIO | | NCYLFEM | NCYLBEM |
| Type | I | I | | I | I | | I | I |
| Default | none | 100 | | 0 | 2 | | 5000 | 5000 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EMSOL | Electromagnetism solver selector: |

      EQ.-1:  Turns the EM solver off after reading the EM keywords.

      EQ.1:  Eddy current solver

      EQ.2:  Periodic inductive heating solver (see Remark 3)

      EQ.3:  Resistive heating solver

      EQ.4:  Frequency-based Eddy current solver (see Remark 3)

      EQ.5:  Periodic resistive heating solver (see Remark 3)

      EQ.11: Electrophysiology monodomain

      EQ.12: Electrophysiology bidomain

      EQ.13: Electrophysiology monodomain coupled with bidomain

      EQ.14: Pure eikonal model. Activation times are computed and output in VTK format to the /vtk directory. See \*EM_-EP_EIKONAL.

      EQ.15: Reaction eikonal (RE) model based on [1]. See \*EM_EP_-EIKONAL.

| NUMLS | Number of local EM steps in a whole period for EMSOL = 2. Global frequency for EMSOL = 4. If a negative value is entered, it gives the value as a function of the macro time. |

| DIMTYPE | EM dimension type: |

      EQ.0:  3D solve

      EQ.1:  2D planar with zero thickness shell elements

| VARIABLE | DESCRIPTION |
| --- | --- |
| | EQ.2: 2D axisymmetric ($Y$-axis only) with zero thickness elements |
| NPERIO | Number of periods for which the last is used to calculate the average Joule heat rate when EMSOL = 2. NPERIO = 2 means that two periods of NUMLS steps will be calculated. Only the last period of NPERIO is used for the average Joule heat calculation. See Remark 1. |
| NCYLFEM | Number of electromagnetism cycles between the recalculation of FEM matrices. If negative, the absolute value refers to a load curve that gives the number of electromagnetism cycles as a function of time. See Remark 2. |
| NCYLBEM | Number of electromagnetism cycles between the recalculation of BEM matrices. If negative, the absolute value refers to a load curve that gives the number of electromagnetism cycles as a function of time. See Remark 2. |

**Remarks:**

1. **Number of periods and the average Joule heating calculation.** The purpose of using more than one period to calculate the average Joule heating is to allow the different fields to adopt the correct amplitude and time shift when starting from 0.0 at $t = 0$. NPERIO = 2 means that two periods are calculated, of which only last one, being the second one in this case, is used for the average Joule heat calculation. In some cases, larger values might be required to achieve good accuracy, and conversely, in others, NPERIO = 1 might yield sufficient accuracy.

2. **Order of precedence for NCYLFEM and NCYLBEM.** You can set NCYLFEM and NCYLBEM with \*EM_CONTROL_SOLUTION, \*EM_SOLVER_FEM/BEM, or \*EM_CONTROL. \*EM_CONTROL_SOLUTION has the highest priority for setting these fields, while \*EM_CONTROL has the lowest priority. If a field is left as the default on \*EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of that field on \*EM_SOLVER_FEM/BEM. If left as default on \*EM_-SOLVER_FEM/BEM, LS-DYNA looks at the setting on \*EM_CONTROL. When the conductor parts are deforming or undergoing changes in their EM material properties (conductivity for example), the FEM matrices should be recalculated more often, so NCYLFEM may need to be changed. NCYCLBEM controls the BEM matrices recomputation frequency as well as the EM contact detection. It is therefore important to use the field in Eddy current cases when conductors are moving respective to one another as well as in case involving changing EM contact.

3.    **Solver for inductive heating.** Both EMSOL = 2 and 4 can be used for inductive heating problems. EMSOL = 4 requires using the monolithic solver. It is a frequency-based solver, so the solve is usually faster than solving EM quantities in the time domain over the full period. However, only EMSOL = 2 is available for nonlinear magnetic permeability cases. EMSOL = 5 is similar to EMSOL = 2 but restricted to resistive-heating-type applications because it does not consider inductive-diffusive effects.

**References:**

[1]    A. Neic et al, " Efficient computation of electrograms and ECGs in human whole heart simulations using a reaction-eikonal model", Journal of Computational Physics 346 (2017) 191–211

## \*EM_CONTROL_CONTACT

Purpose: Activate the electromagnetism contact algorithms, which detect contact between conductors. Electromagnetic fields flow from one conductor to another when found to be in contact.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|--------|-------|-------|------|------|------|------|
| Variable | EMCT | CCONLY | CTYPE | DTYPE | EPS1 | EPS2 | EPS3 | D0 |
| Type | I | I | I | I | F | F | F | F |
| Default | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.3 | none |

|            VARIABLE             |                    DESCRIPTION                    |
|---|---|

EMCT      EM contact activation flag:

       EQ.0: No contact detection

       EQ.1: Contact detection

CCONLY      Determines parts for which EM contact is active:

       EQ.0: Contact detection between all active parts associated with a conducting material. (Default)

       EQ.1: Only look for EM contact between parts associated through the \*EM_CONTACT card. In some cases, this option can reduce the calculation time.

CTYPE      Contact type:

       EQ.-1: Node-to-node contact based on constraints on the scalar potential. See Remark 1.

       EQ.0: Node-to-node penalty-based contact on the scalar potential.

       EQ.1: Discrete mortar penalty contact on the scalar potential.

       EQ.2: Continuous mortar penalty contact on the scalar potential and the vector potential (when active).

DTYPE      Detection type. If \*EM_CONTACT is not defined, the solver will look for global contact options in \*EM_CONTROL_CONTACT. See \*EM_CONTACT for details.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: Contact type 0 (default). |
| | EQ.1: Contact type 1. |
| EPS*i* | Global contact coefficients used if the equivalent fields in \*EM_-CONTACT are empty. See \*EM_CONTACT for details. |
| D0 | Global parameter for contact condition 3 when DTYPE = 1. See \*EM_CONTACT for details. |

**Remarks:**

1. **Contact types.** In versions prior to R12, CTYPE = 0 was the default EM contact for the resistive heating solver, while CTYPE = -1 was the default EM contact for the Eddy current solver. In versions R12 and later, CTYPE = 0 became the default for all solvers. We recommend CTYPE = 1 and 2 for the best accuracy.

2. **Contact between BEM surfaces with the Eddy current solver.** When the Eddy current solver is active and contact occurs between BEM surfaces, the solver automatically removes the faces on the contact surface and internally stitches the two BEM surfaces together to achieve a continuous closed BEM mesh.

## \*EM_CONTROL_COUPLING

Purpose: Control couplings between various solvers with the EM solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | THCPL | SMCPL | THLCID | SMLCID | THCPLFL | SMCPLFL | | |
| Type | I | I | I | I | I | I | | |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | | |

**Optional Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SMMOD | DFX | DFY | DFZ | | FSIB | INTERP | |
| Type | I | I | I | I | | I | I | |
| Default | 0 | none | none | none | | 0 | 0 | |

**Optional Card.**

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NID1 | NID2 | NID3 | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| THCPL | Coupling to the thermal solver. When turned on, the EM solver will transfer the Joule heating terms to the solid mechanics thermal solver.<br><br>EQ.0: Coupling on. |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: Coupling off. |
| | EQ.2: Coupling on. It forces all EM heating terms to be expressed at the element level. See Remark 2. |
| SMCPL | Coupling to the solid mechanics solver. When turned on, the EM solver will transfer forces to the solid mechanics solver. |
| | EQ.0: Coupling on. Lorentz force density is transferred. |
| | EQ.1: Coupling off. |
| | EQ.2: Coupling on. Magnetic force surface density is transferred. More accurate representation of EM forces in cases involving magnets or nonlinear ferromagnets. See \*EM_SOLVER_FEMBEM_MONOLITHIC. |
| | EQ.3: Coupling on. Magnetic force surface density is transferred to magnets and ferromagnets, while Lorentz force density is transferred to regular conductors. |
| THLCID | Optional load curve ID. When defined, the heat rate transferred to the thermal solver will be scaled by the value returned by THLCID. |
| SMLCID | Optional load curve ID. When defined, the forces transferred to the solid mechanics solver will be scaled by the value returned by SMLCID. |
| THCPLFL | Coupling to the heat equation when EM quantities are solved on fluid elements. When turned on, the EM solver will transfer the Joule heating terms to the ICFD solver. |
| | EQ.0: Coupling off. |
| | EQ.1: Coupling on. |
| SMCPLFL | Interaction between the solid mechanics solver and the ICFD solver when EM quantities are solved on fluid elements. |
| | EQ.0: The fluid pressure will be passed to the solid mechanics solver (default). |
| | EQ.1: The fluid pressure is replaced by the electrostatic pressure. |
| | EQ.2: The fluid and electrostatic pressure are passed on to the solid mechanics solver. |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.4: The EM solver will send the Lorentz Force as a volumetric source term to the fluid solver. |
| SMMOD | Coupling to the solid mechanics solver. When turned on, the EM solver will transfer forces to the solid mechanics solver. |
| | EQ.0: Off. |
| | EQ.1: Force calculation at the element level is decided by \*DEFINE_FUNCTION. See DFX, DFY and DFZ. |
| | EQ.2: Force calculation at the element level is decided by the usermat routine. See dyn21em.f and user_getEMForceArray routine. |
| DFX/DFY/DFZ | \*DEFINE_FUNCTION IDs for the force three components if SMMOD = 1. Arguments for the \*DEFINE_FUNCTIONs are the same as in \*EM_EOS_TABULATED2. See Remark 2 of \*EM_EOS_TABULATED2. |
| FSIB | Solid mechanics – ICFD FSI boundaries. When turned on, the EM solver uses the coupled FSI interface to impose the continuity of the scalar potential between the two domains. See Remark 1. |
| | EQ.0: Off |
| | EQ.1: On |
| INTERP | Flag for EM force interpolation by the solid mechanics solver. By default, the solid mechanics solver interpolates at each time the EM force from the last two EM steps. See Remark 3. |
| | EQ.0: Time interpolation on (default) |
| | EQ.1: No time interpolation. Use the force from the last EM solve. |
| NID1/NID2/NID3 | Three node IDs defining a local coordinate system. See Remark 4. |

**Remarks:**

1.  **FSI coupling.** \*ICFD_CONTROL_FSI and \*ICFD_BOUNDARY_FSI control the coupling between the ICFD and the solid mechanics solvers. When FSI exists and the FSIB flag is turned on, the EM solver reuses those boundaries to impose the necessary constraints on the scalar potential to ensure continuity. The solid

and fluid domains must have been previously defined as conductors (see \*EM_-MAT_001).

2.  **Heating term at the element level.** By default, the EM-thermal heat rate is expressed at the node level before being sent to the thermal solver. However, for some applications where sharp gradients are present, such as battery applications involving Randles circuits, an alternative approach is to express the heat rate term at the element level using THCPL = 2. THCPL = 2 results in a smoother and more diffusive solution.

3.  **Force interpolation.** In typical EM Eddy current applications, such as magnetic metal forming or welding, the mechanical time step is much smaller than the EM time step. The EM solver completes its solve with its larger time step and waits for the mechanical solver to catch up. During each of its solves, the mechanical solver interpolates the force between the two last EM steps. However, for specific magnetostatic problems (specifically rotating problems), this time interpolation can introduce errors. INTERP, therefore, exists to turn off the time interpolation and have the mechanical solver use the force from the last EM solve.

4.  **Rotating problems.** In conjunction with INTERP = 1 described in Remark 3, optional Card 3 enables defining a local reference frame. If the frame is rotating, the mechanical solver applies the corresponding rotation to the force vectors obtained from the EM solver. This feature was developed specifically for magnetostatic rotating problems and is subject to further development.

## \*EM_CONTROL_EROSION

Purpose:  Allows the EM solver to take eroded elements into account

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | ECTRL | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ECTRL | Erosion search : |

       EQ.0: Off. This means that the EM solver will ignore eroded elements and still consider them part of the EM problem.

       EQ.1: On. The EM solver will look for potential elements that are eroded and remove them from the EM solve by updating its matrix system.

**\*EM_CONTROL_MAGNET**

Purpose: Control how often the magnetization vector for magnets is recomputed. By default, the magnetization vector for each magnet is computed only once at the beginning of the calculation (see Remark 1).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MCOMP | NCYCM | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MCOMP | Flag controlling whether the magnetization vector is recomputed. |
| | EQ.0: Magnetization vector not recomputed (see Remark 1). |
| | EQ.1: Magnetization vector recomputed at the frequency controlled by NCYCM. |
| NCYCM | Magnetization vector recomputation frequency. A value of 1 means recomputation at every EM time step. If a negative value is entered, \|NCYCM\| is the ID of a load curve giving the value as a function of time. |

**Remark:**

1. **MCOMP.** In most applications involving magnets, the magnetization vector associated to each magnet needs only to be calculated once at the beginning of the analysis. The magnetization direction is then scaled by the Coercive force value (See EM_PERMANENT_MAGNET) to correctly estimate the contribution of each magnet. In certain specific applications, for examples in cases involving magnet deformations or changes in magnet boundary conditions, it may be needed to periodically update the initially computed magnetization vector. This can be achieved by setting MCOMP to 1 and defining NCYCM.

## \*EM_CONTROL_SOLUTION

Purpose: Specify different conditions under which reassembly of the FEM and BEM matrices occurs.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | NCYLFEM | NCYLBEM | AUTOFEM | AUTOBEM | TOL1FEM | TOL2FEM | TOL1BEM | TOL2BEM |
| Type | I | I | I | I | F | F | F | F |
| Default | 5000 | 5000 | 0 | 0 | 0.3 | 0.1 | 0.3 | 0.1 |

**Optional Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | NID1 | NID2 | NID3 | NID4 | NID5 | NID6 | ANG | DIST |
| Type | I | I | I | I | I | I | F | F |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 1.e16 | 1.e16 |

|         VARIABLE          |         DESCRIPTION          |
|---------------------------|------------------------------|

NCYLFEM      Number of electromagnetism cycles between the recalculation of FEM matrices. See Remark 1.

  LT.0: |NCYLFEM| refers to a load curve, giving the number of cycles as a function of time.

NCYLBEM      Number of electromagnetism cycles between the recalculation of BEM matrices. See Remark 1.

  LT.0: |NCYLBEM| refers to a load curve, giving the number of cycles as a function of time.

AUTOFEM      In addition to NCYLFEM, AUTOFEM triggers an automatic recomputation of the FEM matrices based on an error calculation of the conductors' relative deformation and electrical conductivity changes. See TOL1FEM and TOL2FEM. See Remark 2.

  EQ.0: Autorecomputation off

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: Autorecomputation on |
| AUTOBEM | In addition to NCYLBEM, AUTOBEM triggers an automatic recomputation of the BEM matrices based on an error calculation of the conductors' relative displacements.  See TOL1BEM and TOL2BEM. See Remark 2. |
| | EQ.0: Autorecomputation off |
| | EQ.1: Autorecomputation on |
| | EQ.2: Autorecomputation on.  Skip EM solve.  See Remark 4. |
| TOL1FEM | Only used if AUTOFEM = 1. If a conducting element experiences a deformation or a conductivity change that reaches an error larger than TOL1FEM, the solver reassembles the FEM matrices.  If negative, the absolute value refers to a load curve that gives the tolerance as a function of time. |
| TOL2FEM | Only used if AUTOFEM = 1. If (number of conducting elements) × TOL2FEM elements experience a deformation or a conductivity change that reaches an error larger than TOL2FEM, the solver recomputes the FEM matrices.  If negative, the absolute value refers to a load curve that gives TOL2FEM as a function of time. |
| TOL1BEM | Only used if AUTOBEM = 1. If a conducting element experiences a displacement that reaches an error larger than TOL1BEM, then LS-DYNA reassembles the BEM matrices.  If negative, the absolute value refers to a load curve that gives the tolerance as a function of time. |
| TOL2BEM | Only used if AUTOBEM = 1. If (number of conducting elements) × TOL2BEM elements experience a displacement that reaches an error larger than TOL2BEM, then the BEM matrices are recomputed. If negative, the absolute value refers to a load curve that gives TOL2BEM as a function of time. |
| NID1, NID2, NID3 | Local coordinate system specified with NID1, NID2, and NID3. See Remark 3. |
| NID4, NID5, NID6 | Local coordinate system specified with NID4, NID5, and NID6. See Remark 3. |
| ANG | Angle (in degrees) tolerance criterion that triggers a BEM matrix recomputation.  See Remark 3. |
| | LT.0.0: |ANG| is a load curve ID giving the angle tolerance |

| VARIABLE | DESCRIPTION |
|---|---|
| | criterion as a function of time. |
| DIST | Distance tolerance criterion that triggers a BEM matrix recomputation.  See Remark 3. |
| | LT.0.0:  \|DIST\|  is a load curve ID giving the distance tolerance criterion as a function of time. |

**Remarks:**

1.  **Order of precedence for NCYLFEM and NCYLBEM.**  You can set NCYLFEM and NCYLBEM with \*EM_CONTROL_SOLUTION, \*EM_SOLVER_FEM/BEM, or \*EM_CONTROL. \*EM_CONTROL_SOLUTION has the highest priority for setting these fields, while \*EM_CONTROL has the lowest priority.  If you leave one of these fields as the default value on \*EM_CONTROL_SOLUTION, LS-DYNA then looks at the setting of that field on \*EM_SOLVER_FEM/BEM. If left as the default on \*EM_SOLVER_FEM/BEM, LS-DYNA looks at the setting on \*EM_CONTROL.

2.  **EM contact with recomputation.**  When EM contact occurs and you have enabled automatic FEM or BEM matrix recomputation, LS-DYNA simultaneously reassembles both the FEM and BEM matrices when any criterion is reached to maintain consistency.  When you do not enable automatic recomputation, we recommend the FEM and BEM systems have the same value for the recomputation cycle.

3.  **Rotating and translating parts.** The optional second line triggers a BEM matrix recomputation only if the rotation or distance between the system composed of NID1/NID2/NID3 and NID4/NID5/NID6 exceeds ANG (in degrees) or DIST. This feature is useful in cases when one conductor part rotates or translates based on another part and an automatic criterion is desired.

4.  **AUTOBEM = 2.** Selecting this option causes skipping the EM solve entirely when no BEM matrix recomputation is triggered.  This option is especially useful in magnetostatic cases, meaning the EM solution is independent of previous EM stages and a solve needs to occur only once a certain BEM matrix recomputation threshold is met (usually in combination with the use of NID1/NID2/NID3 and NID4/NID5/NID6).  This option provides significant calculation gains in magnetostatic problems that involve moving pieces.

## \*EM_CONTROL_SWITCH

Purpose: Create a control "switch" that will shut down the solver based on information from a load curve. LS-DYNA supports complex types of curves (See \*DEFINE_CURVE_-FUNCTION) that allow the setting up of complex on/off switches, for instance, by using a nodal temperature value.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---------|---------|---|---|---|---|---|
| Variable | LCID | FEMCOMP | BEMCOMP | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

|  VARIABLE  |  DESCRIPTION  |
|------------|---------------|
| LCID | Load curve or define curve function ID. Negative values switch the solver off; positive values switch it back on. |
| FEMCOMP | Flag to determine if LS-DYNA recomputes the FEM matrices each time the EM solver is turned back on: |
| | EQ.0: Recompute FEM matrices. |
| | EQ.1: Do not recompute FEM matrices. |
| BEMCOMP | Flag to determine if LS-DYNA recomputes the BEM matrices each time the EM solver is turned back on: |
| | EQ.0: Recompute BEM matrices. |
| | EQ.1: Do not recompute the BEM matrices. |

## \*EM_CONTROL_SWITCH_CONTACT

Purpose: It is possible to active a control "switch" that will shut down the electromagnetic contact detection. This can be useful in order to save some calculation time in cases where the user knows when contact between conductors will occur or stop occurring.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | LCID | NCYLFEM | NCYLFEM | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| LCID | Load Curve ID. |
| | Negative values switch the contact detection off, positive values switch it back on. |
| NCYLFEM | Determines the number of cycles before FEM matrix recomputation. If defined this will overwrite the previous NCYCLFEM as long as the contact detection is turned on. |
| NCYLBEM | Determines the number of cycles before BEM matrix recomputation. If defined this will overwrite the previous NCYCLBEM as long as the contact detection is turned on. |

## \*EM_CONTROL_TIMESTEP

Purpose: Controls the EM time step and its evolution.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|--------|------|--------|-------|-------|------|--------|
| Variable | TSTYPE | DTCONST | LCID | FACTOR | TSMIN | TSMAX | RLCSF | MECATS |
| Type | I | F | I | F | F | F | I | I |
| Default | none | none | none | 1.0 | none | none | 25 | 0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TSTYPE | Time step type: |

> EQ.1: Constant time step given in DTCONST
>
> EQ.2: Time step as a function of time given by a load curve specified in LCID
>
> EQ.3: Automatic time step computation, depending on the solver type. This time step is then multiplied by FACTOR
>
> EQ.5: EM time step forced to be the same as the thermal time step in problems with the EM solver coupled to the thermal solver. In other words, the thermal solver determines the EM time step.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DTCONST | Constant value for the time step for TSTYPE = 1 |
| LCID | Load curve ID giving the time step as a function of time for TSTYPE = 2 |
| FACTOR | Multiplicative factor applied to the time step for TSTYPE = 3 |
| TSMIN | Minimum time step. When TSMIN is defined, the EM time step cannot drop below TSMIN. A negative value will refer to a time-dependent load curve. |
| TSMAX | Maximum time step. When TSMAX is defined, the EM time step cannot increase beyond TSMAX. A negative value will refer to a time-dependent load curve. |
| RLCSF | RLC Circuit time step scale factor. See Remark 2. |

| VARIABLE | DESCRIPTION |
|---|---|
| MECATS | Mechanical time step handling in cases where the EM solver time step becomes smaller (see Remark 3): |

> EQ.0: Default. The EM time step will go below the solid mechanics timestep, and several EM solves will occur between two solid mechanics time steps to ensure time consistency.

> EQ.1: The solid mechanics time step will adapt and decrease to the EM time step value so that only one EM solve occurs between two solid mechanics solves.

**Remarks:**

1. **Automatic time step for Eddy current solvers.** For eddy current solvers, the automatic time step is based on the diffusion equation for the magnetic field:

$$\sigma \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} \times \frac{1}{\mu} \vec{\nabla} \times \vec{A} + \sigma \vec{\nabla} \varphi = \vec{j}_S \ .$$

   It is computed as the minimal elemental diffusion time step over the elements. For a given element, the elemental diffusion time step is given as $dt_e = l_e^2/(2D)$, where:

   - $D$ is the diffusion coefficient $D = 1/(\mu_0 \sigma_e)$,
   - $\sigma_e$ is the element's electrical conductivity,
   - $\mu_0$ is the permeability of free space,
   - $l_e$ is the minimal edge length of the element (minimal size of the element).

2. **Automatic time step with RLC circuit.** When an automatic time step is defined and an RLC circuit is present, the EM solver will perform an additional check and calculate an approximation of the first current period based on a 0-D circuit solve. It will then limit the timestep by a factor $T_{\text{period}}/(4 \times \text{RLCSF})$. The default value of RLCSF ensures that 25 EM timesteps will be calculated for the first quarter period.

3. **MECATS.** In general, we recommend avoiding scenarios where the EM time step becomes smaller than the solid mechanics time step, a situation often resulting from ill-defined input decks and parameters. However, this can happen when conducting elements have large deformations and an automatic EM time step is selected. For this case, choose between the two MECATS options.

4. **Macro time step.** If EMSOL = 2 or 4 in \*EM_CONTROL, the EM time step defined here represents a "macro" time step, meaning the time when new time-

averaged quantities such as Joule heating Power or Magnetic Forces are updated. If material properties are constant and no displacement of parts is expected, this macro time step can be equal to the termination time.

## \*EM_DATABASE_CIRCUIT

Purpose:  Enable the output of EM data for every circuit defined.

Output options card

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 1 | 0. | | | | | | |

|  VARIABLE  |  DESCRIPTION  |
|-----------|---------------|

OUTLV         Determines if LS-DYNA creates the output file:

                EQ.0: Do not generate the output file.

                EQ.1: Generate the output file.

DTOUT         Time interval to print the output.  If DTOUT is equal to 0.0, LS-DYNA uses the EM timestep.

**Remarks:**

1.  **File name.** The file name for this database is em_circuit_*XXX*.dat with *XXX* as the circuit ID.

2.  **ResistanceD.** LS-DYNA calculates *ResistanceD* in the following way:

    a)  Imposes a scalar potential difference of 1 at the circuit's boundaries SIDVIN and SIDVOUT.

    b)  Solves $\nabla^2 \varphi = 0$ with $\varphi_{\text{SIDVIN}} = 1$ and $\varphi_{\text{SIDVOUT}} = 0$ at SIDCURR. We do not consider diffusive effects, meaning the current density can be written as $\mathbf{j} = \nabla \varphi$ and the total current as $I = \mathbf{j} \cdot \mathbf{n} dA$.

    c)  Estimates the resistance using $R_D = U/I$. $U$ is the potential difference between $\varphi_{\text{SIDVIN}}$ and and $\varphi_{\text{SIDVOUT}}$, that is, equal to 1.  The circuit's geometry and conductivity solely determine this $R_D$ resistance.  It is, therefore, equivalent to the resistance as commonly defined in the circuit equations:

    $$R_D = L/\sigma S \ ,$$

where $L$ is the length of the circuit and $S$ is its surface area.

3.  **ResistanceJ.** LS-DYNA calculates *ResistanceJ* with the data provided during the EM solve: $R_J = J/I^2$ where $J$ and $I$ are, respectively, the joule heating and the current. Compared with *ResistanceD, ResistanceJ* is not so much a resistance calculation since it accounts for the resistive effects (when using the Eddy current solver). Rather, it corresponds to the resistance that the circuit would need in order to get the same Joule heating in the context of a circuit equation. If all EM fields are diffused or you are using the resistive heating solver, *ResistanceJ* should be close to *ResistanceD*.

4.  **Mutual inductances.** Only the mutual inductances between the first three circuits defined are output.

## \*EM_DATABASE_CIRCUIT0D

Purpose: Enable the output of 0D EM data for every circuit defined.

Output options card

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if LS-DYNA creates the output file. |
| | EQ.0: Does not generate the output file. |
| | EQ.1: Generates the output file. |
| DTOUT | Time interval to print the output. If DTOUT equals 0.0, then LS-DYNA uses the EM time step. |

**Remarks:**

1.  **File name.** The file name for this database is em_circuit0D_*XXX*.dat with *XXX* as the circuit ID.

2.  **0D solution.** At the start of the run, based on the initial values of the meshes resistances and inductances, the solver calculates the results for a so-called "0D" solution, which does not consider the current's diffusion, the part's displacements, or the EM material property changes. It is, therefore, a crude approximation. LS-DYNA extrapolates the initial results through time which it outputs at DTOUT intervals. This result can be useful in some cases, especially in RLC circuits if you need a rough idea of how the source current will behave.

3.  **Cost.** Since the calculation of this 0D circuit can take time depending on the size of the problem, you should only use it in cases where the output results help with comprehension of the analysis.

4.  **Effect of this keyword.** This keyword does not influence the results of the EM run itself.

## \*EM_DATABASE_CIRCUITSOURCE

Purpose: Output additional data specific to source circuits.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|-----|---|---|---|---|---|---|
| Variable | CIRCID | IMP | | | | | | |
| Type | I | I | | | | | | |
| Default | none | 0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| CIRCID | Source circuit ID for which total magnetic flux is calculated and output to em_CircuitSource_CIRCID.dat. See Remark 1. |
| IMP | Include the source circuit with ID CIRCID in the impedance matrix calculation and output: |
| | EQ.0: Not included. |
| | EQ.1: Included. See Remark 2. |

**Remarks:**

1. **Magnetic flux.** This keyword causes an additional vector product operation on the current density and vector potential to give the magnetic flux for the specified source circuits. For the frequency domain solver, the output is decomposed into its real and imaginary components. This output is useful for retrieving coil inductance variations and resistance variations or induced voltage. It is frequently used in crack detection problems in conjunction with the frequency domain Eddy current solver. Since it relies on the vector potential output, the source circuit coil must be defined as a conductor. See Remark 2 in \*EM_CIRCUIT_SOURCE).

2. **Impedance matrix.** IMP = 1 only applies when the frequency domain solver is also activated (EMSOL = 4 in \*EM_CONTROL). For each CIRCID for which IMP = 1, the solver performs a separate solve with each CIRCID considered in turn as an emissive and receptive coil. This method enables establishing the complete impedance matrix. Its real and imaginary parts are output in ASCII files em_indMtx.dat and em_resMtx.dat, respectively. The results of em_resMtx.dat are multiplied by $\omega$, where $\omega = 2\pi F$, for convenience purposes.

## \*EM_DATABASE_ELOUT

Purpose: Enable the output of EM data on elements.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | ELSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if LS-DYNA creates the output file: |
| | EQ.0: Does not generate the output file. |
| | EQ.1: Generates the output file. |
| DTOUT | Time interval to print the output. If DTOUT equals 0.0, LS-DYNA uses the EM time step. |
| ELSID | Solid elements set ID |

**Remarks:**

1.  **File name.** The file name for this database is em_elout.dat.

**\*EM_DATABASE_FIELDLINE**

Purpose: The EM solver uses a BEM method to calculate the EM fields between conductors. With this method, the magnetic field in the air or vacuum between conductors is therefore not explicitly computed. However, in some cases, it may be interesting to visualize some magnetic field lines for a better analysis. This keyword allows the output of field line data. It has no influence on the results of the EM solve.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FLID | PSID | DTOUT | NPOINT | | | | |
| Type | I | I | F | I | | | | |
| Default | none | none | 0. | 100 | | | | |

**Remaining cards are optional.**[†]

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | INTEG | H | HMIN | HMAX | TOLABS | TOLREL | | |
| Type | I | F | F | F | F | F | | |
| Default | 2 | 0. | 0. | 1E10 | 1E-3 | 1E-5 | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | BTYPE | | | | | | | |
| Type | I | | | | | | | |
| Default | 2 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| FLID | Field line set ID |
| PSID | Point Set ID associated to the field line set (See \*EM_POINT_SET). The coordinates given by the different points will be the starting points of the field lines. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the EM time step will be used. |
| NPOINT | Number of points per field line. The points are regularly spaced. |
| INTEG | Type of numerical integrator used to compute the field lines : |
| |     EQ.1: RK4, Runge Kutta 4. See Remark 2. |
| |     EQ.2: DOP853, Dormand Prince 8(5,3). See Remark 2. |
| H | Value of the step size. In case of an integrator with adaptive step size, it is the initial value of the step size. |
| HMIN | Minimal step size value. Only used in the case of an integrator with adaptive step size. |
| HMAX | Maximal step size value. Only used in the case of an integrator with adaptive step size. |
| TOLABS | Absolute tolerance of the integrator. Only used in the case of an integrator with adaptive step size. |
| TOLREL | Relative tolerance of the integrator. Only used in the case of an integrator with adaptive step size. |
| BTYPE | Method to compute the magnetic field : |
| |     EQ.1: Direct method (every contribution is computed by the Biot Savart Law and summed up : very slow). |
| |     EQ.2: Multipole method (approximation of the direct method using the multipole expansion). |
| |     EQ.3: Multicenter method (approximation of the direct method using a weighted subset of points only in order to compute the magnetic field). |

**Remarks:**

1.  **File Names.**  The file name for this database is em_fieldLine_*XX_YYY*.dat where *XX* is the field line ID and *YYY* is the point set ID defined in \*EM_POINT_SET.

2.  **Integrators.**  The Runge Kutta 4 integrator is an explicit iterative method for solving ODEs.  It is a fourth order method with a constant step size.  The Dormand Prince 8(5,3) integrator is an explicit iterative method for solving IDEs.  Particularly, this integrator is an embedded Runge Kutta integrator of order 8 with an adaptive step size.  This integrator allows a step size control which is done though an error estimate at each step.  The Dormand Prince 8(5,3) is a Dormand Prince 8(6) for which the 6$^{th}$ order error estimator has been replaced by a 5$^{th}$ order estimator with 3$^{rd}$ order correction in order to make the integrator more robust.

## \*EM_DATABASE_GLOBALENERGY

Purpose:  Enable the output of global EM energies.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

|          VARIABLE          |          DESCRIPTION          |
|------------|------------|

OUTLV          Determines if the output file should be dumped.

    EQ.0: No output file is generated.

    EQ.1: The output file is generated.

DTOUT          Time interval to print the output.  If DTOUT is equal to 0.0, then the EM timestep will be used.

**Remarks:**

1.  **Database Name.** The file name for this database is em_globEnergy.dat.

2.  **Output Data.**  The output file includes the global EM energies of the mesh, the air, and the source circuit.  It also includes the global kinetic energy and the global plastic work energy.

**\*EM_DATABASE_NODOUT**

Purpose:  This keyword enables the output of EM data on nodes.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | NSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be dumped. |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |
| DTOUT | Time interval to print the output.  If DTOUT is equal to 0.0, then the EM timestep will be used. |
| NSID | Node Set ID. |

**Remarks:**

1.    The file name for this database is em_nodout.dat.

**\*EM_DATABASE_PARTDATA**

Purpose:  This keyword enables the output of EM data for every part defined.  .

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

|         VARIABLE         |                  DESCRIPTION                  |
|--------------------------|-----------------------------------------------|

OUTLV           Determines if the output file should be dumped.

     EQ.0: No output file is generated.

     EQ.1: The output file is generated.

DTOUT           Time interval to print the output.  If DTOUT is equal to 0.0, then the EM timestep will be used.

**Remarks:**

1.  The file name for this database is em_partData_*XXX*.dat with *XXX* the part ID.

2.  Outputs the part EM energies of the part as well as the Lorentz force.  Also outputs the part kinetic energy and the part plastic work energy.

**\*EM_DATABASE_POINTOUT**

Purpose:  Enable the output of EM data on point sets.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|---|---|---|---|---|---|---|
| Variable | PTSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if LS-DYNA creates the output file: |
| | EQ.0:  Do not generate the output file. |
| | EQ.1:  Generate the output file. |
| DTOUT | Time interval to print the output.  If DTOUT equals 0.0, LS-DYNA uses the ICFD time step. |
| PTSID | Point set ID (See \*EM_POINT_SET card). |

**Remarks:**

1.  **File name.** The file name for this database is em_pointout.dat.

## *EM_DATABASE_ROGO

Purpose:  This keyword enables the output of EM data for every circuit defined.  .

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 1 | 0. | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| OUTLV | Determines if the output file should be dumped. |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |
| DTOUT | Time interval to print the output.  If DTOUT is equal to 0.0, then the EM timestep will be used. |

**Remarks:**

1.  The file name for this database is em_rogoCoil_*XXX*.dat  where *XXX* is the rogo Coil ID.

**\*EM_DATABASE_TIMESTEP**

Purpose:  This keyword enables the output of EM data regarding the EM timestep.

Output options card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | OUTLV | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be dumped. |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |

**Remarks:**

1.  The file name for this database is em_timestep.dat.

2.  Outputs the run's EM tim estep versus the time step calculated using the EM CFL condition as criteria (autotimestep).  This can be useful in cases with big deformations and/or material property changes and a fixed time step is being used in case that time step becomes to big compared to the stability time step.

## \*EM_EP_CELLMODEL_DEFINE_FUNCTION

Purpose: Define a user-defined ionic cell model for Electro-Physiology.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | NSTATE | FSWITCH | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DVDT | DU1DT | DU2DT | DU3DT | DU4DT | DU5DT | DU6DT | DU7DT |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | V0 | U1 | U2 | U3 | U4 | U5 | U6 | U7 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID defined in the \*MAT section. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |
| FSWITCH | Flag for the ODE definition (see Remark 1): |
| | EQ.0: Functions |
| | EQ.1: Derivatives |

| VARIABLE | DESCRIPTION |
|---|---|
| NSTATE | Number of state variables $u_1, u_2, \ldots, u_n$. The maximum value is 7 (see Cards 2 and 3). |
| DVDT | Function ID (see \*DEFINE_FUNCTION) for evolution of $V$ (function $g$ in the equations in Remark 1). |
| DU*i*DT | Function ID (see \*DEFINE_FUNCTION) for evolution of $u_i$ (function $f_i$ in the equations in Remark 1) |
| V0 | Function ID (see \*DEFINE_FUNCTION) for initial value of $V(x, y, z)$ |
| U*i* | Function ID (see \*DEFINE_FUNCTION) for initial value of $u_i(x, y, z)$ |

**Remarks:**

1. **Model.** This keyword enables specifying a user-defined cell model through defined functions (see \*DEFINE_FUNCTION). This model traces the evolution of the transmembrane potential, $V$, and $n$ state variables: $u_1, u_{2,} \ldots u_n$. Their temporal evolution depends upon FSWITCH.

   a) If FSWITCH = 0:

   $$V(t) = g\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$u_1(t) = f_1\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$u_2(t) = f_2\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\vdots$$
   $$u_n(t) = f_n\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$

   b) If FSWITCH = 1:

   $$\frac{\partial V(t)}{\partial t} = g\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\frac{\partial u_1(t)}{\partial t} = f_1\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\frac{\partial u_2(t)}{\partial t} = f_2\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$
   $$\vdots$$
   $$\frac{\partial u_n(t)}{\partial t} = f_3\big(t, dt, V(t-1), u_1(t-1), u_2(t-1), \ldots, u_n(t-1)\big)$$

2. **Benchmarks.** You can use this model to perform the electrophysiology benchmarks presented in Pathmanathan and Gray [2014].

**References:**

[1]    Pathmanathan, P. and R.A. Gray, "Verification of computational models of cardiac electro-physiology," Int J Numer Method Biomed Eng, vol. 30, No. 5, pp. 524-544, (2014).

## **\*EM_EP_CELLMODEL_FENTONKARMA**

Purpose: Define a Fenton-Karma ionic cell model for Electro-Physiology.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | MID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|-------|------|-------|-------|-------|-------|
| Variable | TAUD | TAUR | TAUSI | TAU0 | TAUVP | TAUVM | TAUWP | TAUWM |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|---|---|---|---|---|
| Variable | UC | UCSI | K | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|---|---|---|---|---|
| Variable | U0 | V0 | W0 | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID defined in \*MAT. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |
| TAUD | Time constant $\tau_d$ described in Equation 5 |
| TAUR | Time constant $\tau_r$ described in Equation 6 |
| TAUSI | Time constant $\tau_{si}$ described in Equation 7 |
| TAU0 | Time constant $\tau_0$ described in Equation 6 |
| TAUVP | Time constant $\tau_{vp}$ described in Equation 3 |
| TAUVM | Time constant $\tau_{vm}$ described in Equation 3 |
| TAUWP | Time constant $\tau_{wp}$ described in Equation 4 |
| TAUWM | Time constant $\tau_{wm}$ described in Equation 4 |
| UC | Threshold potential, $u_c$ for activation of $J_{\text{fi}}$ (the fast inward current) in Equations 3, 4, 5, and 6 |
| UCSI | Threshold potential $u_c^{\text{si}}$ for activation of $J_{\text{si}}$ (the slow inward current) in Equation 7 |
| K | Constant $k$ in Equation 7 |
| U0/V0/W0 | Initial values of $u$, $v$, and $w$, respectively |

**Remarks:**

The Fenton-Karma model is a simplified ionic model with three membrane currents that approximates well the restitution properties and spiral wave behavior of more complex ionic models of cardiac action potential (Beeler-Reuter and others). It was introduced in [1].

The total current flowing through the membrane is given by:

$$I_{\text{ion}} = -C_m \frac{\partial V}{\partial t} = -J_{\text{fi}} \qquad (1)$$

where $V$ is the transmembrane potential, $C_m$ is the specific capacitance of the cell membrane, and $J_{\text{fi}}$ is the fast inward current.

The model depends on three state variables, $u$, $v$, and $w$, and three membrane currents, $J_{fi}$, $J_{so}$ (slow outward current), and $J_{si}$ (slow inward current), through the following equations:

$$\frac{du}{dt} = -J_{fi} - J_{so} - J_{si} \tag{2}$$

$$\frac{dv}{dt} = \frac{\Theta(u_c - u)(1 - v)}{\tau_{vm}} - \frac{\Theta(u - u_c)v}{\tau_{vp}} \tag{3}$$

$$\frac{dw}{dt} = \frac{\Theta(u_c - u)(1 - w)}{\tau_{wm}} - \frac{\Theta(u - u_c)w}{\tau_{wp}} \tag{4}$$

$$J_{fi} = -\frac{\Theta(u_c - u)(1 - u)(u - u_c)}{\tau_d} \tag{5}$$

$$J_{so} = \frac{u\,\Theta(u_c - u)}{\tau_o} + \frac{u\,\Theta(u - u_c)}{\tau_r} \tag{6}$$

$$J_{si} = -\frac{w(1 + \tanh[k(u - u_c^{si})])}{2\tau_{si}} \tag{7}$$

In the above $\Theta$ is the Heaviside step function.

## References:

[1]    Fenton, F. & A. Karma, "Vortex dynamics in three-dimensional continuous myocardium with fiber rotation. Filament instability and fibrillations," *Chaos, Solitons, and Fractals*, Vol. 8, No. 1, pp. 661-686, (1998).

[2]    https://www.ibiblio.org/e-notes/html5/fk.html

## \*EM_EP_CELLMODEL_FITZHUGHNAGUMO

Purpose:  Define a Fitzhugh-Nagumo ionic cell model for Electro-Physiology.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | MID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|------|-------|------|------|------|---|---|
| Variable | ALPHA | BETA | GAMMA | C | MU1 | MU2 | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|---|---|---|---|---|---|
| Variable | V | R | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID defined in \*MAT. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |
| ALPHA | Excitation constant $\alpha$ described in Equation 1 |
| BETA | Excitation constant $\beta$ described in Equation 2 |

| VARIABLE | DESCRIPTION |
|---|---|
| GAMMA | Excitation constant $\gamma$ described in Equation 2 |
| C | Excitation constant $c$ described in Equation 1 |
| MU1 | Excitation constant $\mu_1$ described in Equation 2 |
| MU2 | Excitation constant $\mu_2$ described in Equation 2 |
| V | Initial value of $V$ |
| R | Initial value of $r$ |

**Remarks:**

In the Fitzhugh-Nagumo model, the excitation is defined by a cubic polynomial along with one recovery variable, $r$. The transmembrane current, $I_{\text{ion}}$, is given by:

$$I_{\text{ion}} = -C_m \frac{\partial V}{\partial t} = -cV(V - \alpha)(V - 1) - rV \tag{1}$$

Here $V$ is the transmembrane potential, $C_m$ is the specific capacitance of the cell membrane, and $c$ and $\alpha$ are excitation constants.

The recovery variable $r$ evolves according to:

$$\frac{dr}{dt} = (\gamma + \frac{r\mu_1}{\mu_2 + V})(-r - cV(V - \beta - 1)) \tag{2}$$

where $\beta$, $\gamma$, $\mu_1$ and $\mu_2$ are excitation constants.

**References:**

[1] Aliev, R.R. and Panfilov, A.V., "A simple two-variable model of cardiac excitation," *Chaos, Solitons, and Fractals*, Vol 7, No 3, pp 293-301, (1996).

[2] Pullan, A.J., Cheng, L.K., and Buist, M.L., Mathematically Modelling the Electrical Activity of the Heart, World Scientific Publishing Co. Pte. Ltd., Singapore, pp 132-133, (2005).

[3] Baillargeon, B. et al., "The Living Heart Project: A robust and integrative simulator for human heart function," *European Journal of Mechanics - A/Solids*. Vol 48, pp 38-47, (2014).

## \*EM_EP_CELLMODEL_TENTUSSCHER

Purpose:  Define a ten Tusscher ionic cell model for Electro-Physiology.

**Card Summary:**

**Card 1.**  This card is required.

| MID | | | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|
| | | | | | | | |

**Card 2.**  This card is required.

| R | T | F | CM | VC | VSR | VSS | PKNA |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 3.**  This card is required.

| KO | NAO | CAO | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 4.**  This card is required.

| GK1 | GKR | GKS | GNA | GBNA | GCAL | GBCA | GTO |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 5.**  This card is required.

| GPCA | GPK | | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 6.**  This card is required.

| PNAK | KMK | KMNA | KNACA | KSAT | ALPHA | GAMMA | KMCA |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 7.**  This card is required.

| KMNAI | KPCA | | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 8.**  This card is required.

| K1 | K2 | K3 | K4 | EC | MAXSR | MINSR | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 9.**  This card is required.

| VREL | VLEAK | VXFER | VMAXUP | KUP | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 10.**  This card is required.

| BUFC | KBUFC | BUFSR | KBUFSF | BUFSS | KBUFSS | | |
|-----|-----|-----|-----|-----|-----|-----|-----|

**Card 11.** This card is required.

| V | KI | NAI | CAI | CASS | CASR | RPRI | |
|---|---|---|---|---|---|---|---|

**Card 12.** This card is required.

| XR1 | XR2 | XS | M | H | J | D | F |
|---|---|---|---|---|---|---|---|

**Card 13.** This card is required.

| F2 | FCASS | S | R | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID defined in \*MAT section.  If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R | T | F | CM | VC | VSR | VSS | PKNA |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| R | Gas constant ($J \times K^{-1} \times Mol^{-1}$) |

| VARIABLE | DESCRIPTION |
|---|---|
| T | Temperature (K) |
| F | Faraday constant (C × mmol$^{-1}$) |
| CM | Cell capacitance for unit surface area ($\mu$F × Cm$^{-2}$) |
| VC | Cytoplasmic volume ($\mu$m$^3$) |
| VSR | Sarcoplasmic reticulum volume ($\mu$m$^3$) |
| VSS | Subspace volume ($\mu$m$^3$) |
| PKNA | Relative $I_{Ks}$ permeability to Na$^+$ |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | K0 | NAO | CAO | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| KO | Extracellular K$^+$ concentration (mM) |
| NAO | Extracellular Na$^+$ concentration (mM) |
| CAO | Extracellular Ca$^{2+}$ concentration (mM) |

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | GK1 | GKR | GKS | GNA | GBNA | GCAL | GBCA | GTO |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | GPCA | GPK | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| GK1, GKR, GKS, GNA, GBNA, GCAL, GB-CA, GTO, GPCA, GPK | Maximal $I_{K1}$, $I_{Kr}$, $I_{Ks}$, $I_{Na}$, $I_{bNa}$, $I_{CaL}$, $I_{bCa}$, $I_{to}$, $I_{pCa}$, and $I_{pK}$ conductance, respectively (units: nS × pF$^{-1}$) |

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PNAK | KMK | KMNA | KNACA | KSAT | ALPHA | GAMMA | KMCA |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 7 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | KMNAI | KPCA | | | | | | |
| Type | F | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PNAK | $P_{NaK}$, parameter for calculating the Na$^+$/K$^+$ pump current (units: pA × pF$^{-1}$). See Reference [1]. |

| VARIABLE | DESCRIPTION |
|---|---|
| KMK, KMNA | $K_{mK}$ and $K_{mNa}$, parameters for calculating the $Na^+/K^+$ pump current (units: millimolar). See Reference [1]. |
| KNACA, KSAT, ALPHA, GAMMA, KMNAI | $k_{NaCa}$, $k_{sat}$, $\alpha$, $\gamma$, and $K_{mNai}$, parameters for calculating the $Na^+/Ca^{2+}$ exchanger current (units: millimolar). See Reference [1]. |
| KPCA | $K_{pCa}$, parameter for calculating $Ca^{2+}$ pump current (units: millimolar). See Reference [1]. |

| Card 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | K1 | K2 | K3 | K4 | EC | MAXSR | MINSR | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |
| Ref | 2 | 2 | 2 | 2 | 2 | 2 | 2 | |

| VARIABLE | DESCRIPTION |
|---|---|
| K1 | R to O and RI to I $I_{rel}$ transition rate ($mM^{-2} \times ms^{-1}$) |
| K2 | O to I and R to RI $I_{rel}$ transition rate ($mM^{-1} \times ms^{-1}$) |
| K3 | O to R and I to RI $I_{rel}$ transition rate ($ms^{-1}$) |
| K4 | I to O and RI to I $I_{rel}$ transition rate ($ms^{-1}$) |
| EC | $Ca_{SR}$ half-saturation constant of $k_{casr}$ (mM) |
| MAXSR/MINSR | Maximum and minimum values of $k_{casr}$ |

| Card 9 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VREL | VLEAK | VXFER | VMAXUP | KUP | | | |
| Type | F | F | F | F | F | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|---|---|

VREL, VLEAK, VXFER, VMAXUP — Maximal $I_{rel}$, $I_{leak}$, $I_{xfer}$, and $I_{up}$ conductance (mM × ms$^{-1}$), respectively. See Reference [2].

KUP — Half-saturation constant of $I_{up}$ (mM). See Reference [2].

| Card 10 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | BUFC | KBUFC | BUFSR | KBUFSF | BUFSS | KBUFSS | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |
| Ref | 2 | 2 | 2 | 2 | 2 | 2 | | |

| VARIABLE | DESCRIPTION |
|---|---|

BUFC — Total cytoplasmic buffer concentration (mM)

KBUFC — $Ca_i$ half-saturation constant for cytoplasmic buffer (mM)

BUFSR — Total sarcoplasmic buffer concentration (mM)

KBUFSR — $Ca_{SR}$ half-saturation constant for sarcoplasmic buffer (mM)

BUFSS — Total subspace buffer concentration (mM)

KBUFSS — $Ca_{SS}$ half-saturation constant for subspace buffer (mM)

| Card 11 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | V | KI | NAI | CAI | CASS | CASR | RPRI | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |
| Ref | 2 | 1 | 1 | 2 | 2 | 2 | 2 | |

| VARIABLE | DESCRIPTION |
|---|---|
| V | Initial value of transmembrane potential (mV) |
| KI | Initial value of $K_i$, used in potassium dynamics (mM) |
| NAI | Initial value of $Na_i$, used in sodium dynamics (mM) |
| CAI | Initial value of $Ca_i$. used in calcium dynamics (mM) |
| CASS | Initial value of $Ca_{SS}$, used in calcium dynamics (mM) |
| CASR | Initial value of $Ca_{SR}$, used in calcium dynamics (mM) |
| RPRI | Initial value of R′, used in calcium dynamics |

| Card 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | XR1 | XR2 | XS | M | H | J | D | F |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |
| Ref | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |

| VARIABLE | DESCRIPTION |
|---|---|
| XR1 | Initial value of $x_{r1}$, used to compute the rapid time dependent $K^+$ current |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| XR2 | Initial value of $x_{r2}$, used to compute the rapid time dependent K$^+$ current |
| XS | Initial value of $x_s$, used to compute slow time dependent K$^+$ current |
| M | Initial value of $m$, used to compute the fast Na$^+$ current |
| H | Initial value of $h$, used to compute the fast Na$^+$ current |
| J | Initial value of $j$, used to compute the fast Na$^+$ current |
| D | Initial value of $d$, used to compute the L-type Ca$^{2+}$ current |
| F | Initial value of $f$, used to compute the L-type Ca$^{2+}$ current |

| Card 13 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | F2 | FCASS | S | R | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |
| Ref | 2 | 2 | 1 | 1 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| F2 | Initial value of $f_2$, used to compute the L-type Ca$^{2+}$ current |
| FCASS | Initial value of $f_{cass}$, used to compute the L-type Ca$^{2+}$ current |
| S | Initial value of $s$, used to compute the transient outward current |
| R | Initial value of $r$, used to compute the transient outward current |

**Remarks:**

This is a model of the action potential of human ventricular cells that, while including a high level of electrophysiological detail, is computationally cost-effective enough to be applied in large-scale spatial simulations for the study of reentrant arrhythmias. Please see the references for details. This model is based on [2].

**References:**

[1]    ten Tusscher, K.H.W.J., D. Noble, P.J. Noble, and A.V. Panfilov, "A model for human ventricular tissue," Am J Physiol Heart Circ Physiol, vol 286, no 4, pp H1573-H1589, (2004).

[2]    ten Tusscher, K.H.W.J. and A.V. Panfilov, "Alternans and spiral breakup in human ventricular tissue model," Am J Physiol Heart Circ Physiol, vol 291, no 3, pp H1088-H1100, (2006).

## \*EM_EP_CELLMODEL_TOMEK

Purpose:  Define a ToR-ORd model for cardiac electrophysiology [1].

> **WARNING:**  As of version R15, this keyword is deprecated.  Instead, use  \*EM_EP_CELLMODEL_TOR_ORD  which  is  an updated version of this keyword.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | PHIEND | PHIMYO | | | | | |
| Type | I | F | F | | | | | |
| Default | none | 0.0 | 0.0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID: refers to MID in the \*PART card.  If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |
| PHIEND | Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered endocardial in the ToR-Ord cell model. |
| PHIMYO | Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered myocardial in the ToR-Ord cell model. |

**References:**

[1]  Tomek J., Bueno-Orovio A., Passini E., Zhou X., Minchole A., Britton O., Bartolucci C., Severi S., Shrier A., Virag L., Varro A., and Rodriguez B., "Development, calibration, and validation of a novel human ventricular myocyte model in health, disease, and drug block," Elife (2019).

**\*EM_EP_CELLMODEL_TOR_ORD**

Purpose: Define a ToR-ORd model for cardiac electrophysiology [1].

> **NOTE:** This keyword is an updated version of \*EM_EP_CELLMODEL_-
> TOMEK. For versions R15 and later, \*EM_EP_CELLMODEL_-
> TOR_ORD is the preferred keyword, and \*EM_EP_CELLMOD-
> EL_TOMEK is deprecated.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | LDID | PHIEND | PHIMYO | | | | |
| Type | I | I | F | F | | | | |
| Default | none | none | 0.0 | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID. It refers to MID in the \*PART card. If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |
| LDID | ID of the \*EM_EP_LAPLACE_DIRICHLET solution to be used for transmural depth definition |
| PHIEND | Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered endocardial in the ToR-Ord cell model. |
| PHIMYO | Value between 0.0 and 1.0 giving the ratio of the cardiac tissue to be considered myocardial version in the ToR-Ord cell model. |

**References:**

[1]    Tomek J., Bueno-Orovio A., Passini E., Zhou X., Minchole A., Britton O., Bartolucci C., Severi S., Shrier A., Virag L., Varro A., and Rodriguez B., "Development, calibration, and validation of a novel human ventricular myocyte model in health, disease, and drug block," Elife (2019).

## \*EM_EP_CELLMODEL_USERMAT

Purpose:  Specify a user material for an ionic cell model to be used in electrophysiology simulations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | MID | | | | | | | |
| Type | I | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID.  A unique number must be specified (see \*PART).  If a negative value is entered, the cell model is defined on a node set instead of a part, and -MID is the node set where the cell model is defined. |

## \*EM_EP_CREATEFIBERORIENTATION

Purpose: Define fiber orientation by solving a Laplace-Dirichlet system defined by \*EM_-EP_LAPLACE_DIRICHLET. This feature is based on [1].

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|-------|-------|------|---------|---------|---|
| Variable | PSID | LDID1 | LDID2 | ALPHA | BETA | IEXPORT | IPRERUN | |
| Type | I | I | I | F | F | I | I | |
| Default | none | none | none | 0.0 | 0.0 | 0 | 0 | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PSID | Part set ID of the part set on which the system is solved |
| LDID1 | ID of the Laplace system that is solved in the transmural direction |
| LDID2 | ID of the Laplace system that is solved in the apicobasal direction |
| ALPHA | Helical angle with respect to the counterclockwise circumferential direction in the heart when looking from the base towards the apex. |

> LT.0: |ALPHA| is the ID for the \*DEFINE_FUNCTION giving the helical angle. See Remark 1 for available arguments.

| BETA | Angle with respect to the outward transmural axis of the heart. |

> LT.0: |BETA| is the ID for the \*DEFINE_FUNCTION giving the angle. See Remark 1 for available arguments.

| IEXPORT | Selects whether result files (ELEMENT_SOLID_ORTHO.k and vtk files) are exported: |

> EQ.0: Not exported
>
> EQ.1: Exported

| IPRERUN | Select whether the run is stopped after creating fibers: |

> EQ.0: Do not stop after fiber creation
>
> EQ.1: Stop after fiber creation

**Remarks:**

1.    **\*DEFINE_FUNCTION Arguments.** The arguments for the function defined with \*DEFINE_FUNCTION may include the following: f(x_ele, y_ele, z_ele, phi_len, phi_thi). Here phi_len and phi_thi are the potentials corresponding to the potentials solved in LDID1 and LDID2, respectively.

**References:**

[1]    Bayer, J.D., Blake, R. C., Plank, G., and Trayanova, N. A., "A novel rule-based algorithm for assigning myocardial fiber orientation to computational heart models," Annals of biomedical engineering, 40(10), 2243-2254 (2012).

**\*EM_EP_ECG**

Purpose: Compute pseudo-ECGs on a set of virtual points. LS-DYNA exports a file named em_ECG_{ECGID}.dat.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ECGID | PSID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ECGID | ID of the ECG computation |
| PSID | Point set ID containing the list of virtual points on which the pseudo-ECGs are computed |

**\*EM_EP_EIKONAL**

Purpose:  Set up the eikonal (EMSOL = 14) or reaction eikonal, RE, (EMSOL = 15) models.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EIKID | EIKPST | EIKSNS | EIKSDF | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | 0 | | | | |

**RE Card.** Additional parameters for the RE model (EMSOL = 15)

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FTYPE | FT | FA | | | | | |
| Type | I | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EIKID | ID of the eikonal solver |
| EIKPST | Part set ID on which the eikonal solve is performed |
| EIKSNS | Node set ID where the seed (meaning initial activation time values) is set |
| EIKSDF | *DEFINE_FUNCTION ID for defining the seed value.  Accepted arguments by the *DEFINE_FUNCTION are the node coordinates using the names "x_node, y_node, z_node." If no *DEFINE_-FUNCTION is used (EIKSDF = 0), the activation time is set to 0.0 on EIKSNS. |
| FTYPE | Type of foot current: |

> EQ.1: Neic model.  FA gives the foot current between the activation time and the activation time plus FT.

| VARIABLE | DESCRIPTION |
| --- | --- |
| FT | Duration of the foot current |
| FA | Amplitude of the foot current |

**References:**

[1]  A. Neic et al., "Efficient computation of electrograms and ECGs in human whole heart simulations using a reaction-eikonal model," Journal of Computational Physics, 346 (2017), 191–211.

**\*EM_EP_ISOCH**

Purpose: Compute isochrones of activation/repolarization of a cardiac electrophysiology wave of one or several beats.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ISOCHID | IDEPOL | DPLTHR | IREPOL | RPLTHR | CYCLEMIN | APDMIN | |
| Type | I | I | F | I | F | F | F | |
| Default | none | 0 | none | 0 | none | 0.0 | 0.0 | |

|   VARIABLE   |   DESCRIPTION   |
|--------------|-----------------|
| ISOCHID | ID of the isochrone |
| IDEPOL | Flag to activate the computation of depolarization:<br>EQ.0: Off<br>EQ.1: On |
| DPLTHR | Amplitude threshold used for measuring depolarization |
| IREPOL | Flag to activate the computation of repolarization times:<br>EQ.0: Off<br>EQ.1: On |
| RPLTHR | Amplitude threshold used for measuring repolarization |
| CYCLEMIN | Minimum time between two consecutive depolarizations (used in the EP eikonal model with time stepping) |
| APDMIN | Minimum time between depolarization and repolarization (used in the EP eikonal model with time stepping) |

## \*EM_EP_LAPLACE_DIRICHLET

Purpose: Define the boundary conditions of the Laplace-Dirichlet system to be solved to define fiber orientation, based on [1]. The system is solved by using \*EM_EP_CREATE-FIBERORIENTATION. This keyword was formerly called \*EM_EP_FIBERINITIAL in versions R14 and earlier.

Include as many of this card as needed. The next keyword ("*") card terminates this input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LDID | PID | STYPE | SID1 | SID0 | | | |
| Type | I | I | I | I | I | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LDID | ID of the Laplace system to solve (define a new ID with each new card) |
| PID | Part ID on which the system is solved |
| STYPE | Set type for the boundary condition:<br>EQ.1: Segment set<br>EQ.2: Node set |
| SID1 | Set on which a potential of value 1 is prescribed |
| SID0 | Set on which a potential of value 0 is prescribed |

**References:**

[1]    Bayer, J.D., Blake, R. C., Plank, G., and Trayanova, N. A., "A novel rule-based algorithm for assigning myocardial fiber orientation to computational heart models," Annals of biomedical engineering, 40(10), 2243-2254 (2012).

**\*EM_EP_PURKINJE_NETWORK**

Purpose: Define a Purkinje network that consists of conductive beams and lies on a given surface, based on Costabal et al [2016].

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PURKID | BUILDNET | SSID | MID | POINTSTX | POINTSTY | POINTSTZ | EDGELEN |
| Type | I | I | I | I | F | F | F | F |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NGEN | NBRINIT | NSPLIT | INODEID | IEDGEID | | | |
| Type | I | I | I | I | I | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PURKID | ID for the Purkinje network |
| BUILDNET | Flag to create Purkinje network: |
| | EQ.0: Purkinje network not created. |
| | EQ.1: New Purkinje network created. |
| SSID | Segment set on which the Purkinje network is lying |
| MID | Material ID defined in the \*MAT section. |
| POINTSTX | $X$ coordinate of the tree origin |
| POINTSTY | $Y$ coordinate of the tree origin |
| POINTSTZ | $Z$ coordinate of the tree origin |
| EDGELEN | Edge length |
| NGEN | Number of generations of branches |
| NBRINIT | Number of branches attached to the tree origin |
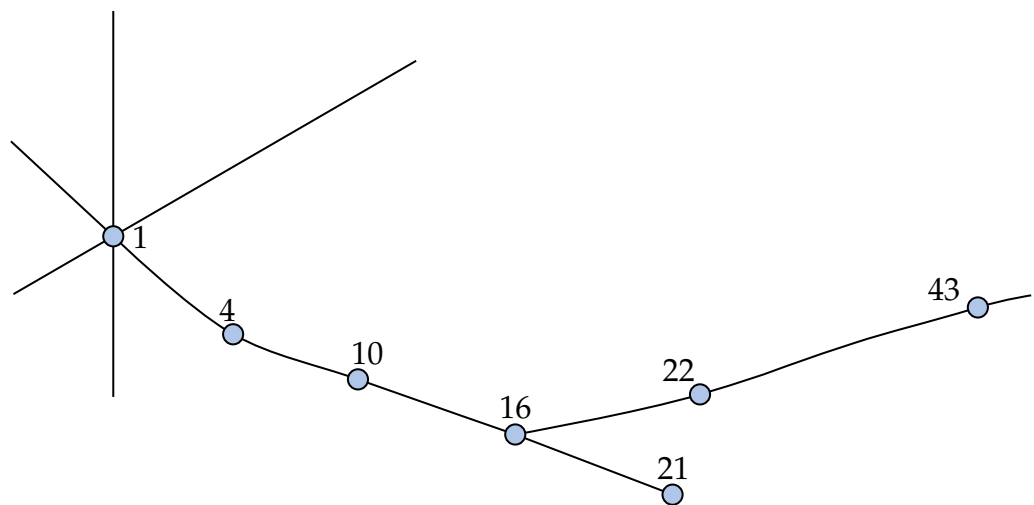
**Figure 6-3.** Example of part of a network. For this network, NSPLIT = 4.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NSPLIT | Number of nodes between two consecutive branchings as shown in Figure 6-3 |
| INODEID | Initial node ID |
| IEDGEID | Initial edge ID. These edges are internally generated by LS-DYNA. |

**References:**

Costabal, F.S., D. E. Hurtado, and E. Kuhl, "Generating Purkinje networks in the human heart," Journal of Biomechanics, vol. 49, issue 12, pp. 2455–2465, (2016).

## **\*EM_EP_TENTUSSCHER_STIMULUS**

Purpose: Define a stimulation pattern of a Tentusscher cell model (requires the use of \*EM_EP_CELLMODEL_TENTUSSCHER).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | STIMID | SETTYPE | SETID | | | | | |
| Type | I | I | I | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | STIMSTRT | STIMT | STIMDUR | STIMAMP | | | | |
| Type | F | F | F | F | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| STIMID | ID of the stimulation |
| SETTYPE | Set type: <br> EQ.1: Segment set <br> EQ.2: Node set |
| SETID | Node set or segment set ID to be stimulated |
| STIMSTRT | Starting time of the stimulation |
| STIMT | Stimulation period |
| STIMDUR | Stimulation duration |
| STIMAMP | Stimulation amplitude (picoA/picoF) |

## \*EM_EOS_BURGESS

Purpose: Define the parameters for a Burgess model giving the electrical conductivity as as a function of the temperature and the density, see:

*T.J. Burgess, "Electrical resistivity model of metals", 4th International Conference on Megagauss Magnetic-Field Generation and Related Topics, Santa Fe, NM, USA, 1986*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-------|-------|------|------|------|------|
| Variable | EOSID | V0 | GAMMA | THETA | LF | C1 | C2 | C3 |
| Type | I | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-------|---------|---------|--------|--------|---|
| Variable | C4 | K | EXPON | LGTUNIT | TIMUNIT | TEMUNI | ADJUST | |
| Type | F | F | I | F | F | I | I | |
| Default | none | none | none | none | none | none | none | |

In the following, UUS stands for User Units System and BUS for Burgess Units

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | ID of the EM_EOS (specified by an \*EM_MAT card) |
| V0 | Reference specific volume $V_0$ (UUS). |
| GAMMA0 | Reference Gruneisen value $\gamma_0$.(no units). |
| THETA | Reference melting temperature $\theta_{m,0}$ in eV (BUS). |
| LF | Latent heat of fusion $L_F$ in kJoule/mol (BUS). |
| C1 | C1 constant (BUS) |
| C2 | C2 constant (no units) |

| VARIABLE | DESCRIPTION |
|---|---|
| C3 | C3 constant (no units) |
| C4 | C4 constant (no units) |
| K | Parameter k (no units). |
| EXPON | Exponent in equations (2) (see remarks) |
| LGTUNIT | Length units for UUS (relative to meter, i.e. = 1.e-3 if UUS in mm). |
| TIMUNIT | Time units for UUS (relative to seconds). |
| TEMUNIT | Temperature units<br><br>EQ.1: temperature in Celsius<br><br>EQ.2: temperature in Kelvins |
| ADJUST | Conductivity modification<br><br>EQ.0: (default) The conductivity is given by the Burgess formula.<br><br>EQ.1: The conductivity is adjusted so that it is equal to the conductivity defined in \*EM_MAT card $\sigma_{\text{mat}}$ at room temperature:<br><br>$$\sigma(\theta) = \sigma_{\text{Burgess}}(\theta)\frac{\sigma_{\text{mat}}}{\sigma_{\text{Burgess}}(\theta_{\text{room}})}$$ |

**Remarks:**

1. The Burgess model gives the electrical resistivity vs temperature and density for the solid phase, liquid phase and vapor phase. At this time, only the solid and liquid phases are implemented. To check which elements are in the solid and in the liquid phase, a melting temperature is first computed by:

$$\theta_m = \theta_{m,0}\left(\frac{V}{V_0}\right)^{-\frac{1}{3}} e^{(2\gamma_0 - 1)(1 - \frac{V}{V_0})}$$

   a) If $T < \theta_m$: solid phase model applies.

   The solid phase electrical resistivity corresponds to the Meadon model:

$$\eta_S = (C_1 + C_2\theta^{C_3})f_c\left(\frac{V}{V_0}\right), \tag{1}$$

where $\theta$ is the temperature, V is the specific volume, and $V_0$ is the reference specific volume (zero pressure, solid phase). In (1), the volume dependence is given by:

$$f_c\left(\frac{V}{V_0}\right) = \begin{cases} \left(\dfrac{V}{V_0}\right)^{2\gamma-1} & \text{EXPON.EQ.} -1 \quad \text{(most materials)} \\[2ex] \left(\dfrac{V}{V_0}\right)^{2\gamma+1} & \text{EXPON.EQ.} +1 \quad\quad \text{(tungsten)} \\[2ex] \left(\dfrac{V}{V_0}\right)^{2\gamma} & \text{EXPON.EQ.} 0 \quad\quad \text{(stainless steel)} \end{cases} \tag{2}$$

with

$$\gamma = \gamma_0 - \left(\gamma_0 - \frac{1}{2}\right)\left(1 - \frac{V}{V_0}\right) \tag{3}$$

b) If $T > \theta_m$: liquid phase model:

$$\eta_L = (\eta_L)_{\theta_m}\left(\frac{\theta}{\theta_m}\right)^{C_4} \tag{4}$$

with

$$(\eta_L)_{\theta_m} = \Delta\eta(\eta_S)_{\theta_m}$$

where

$$\Delta\eta = \begin{cases} ke^{0.69L_F/\theta_m} & k > 0 \\ 1 + 0.0772(2 - \theta_m) & k = -1 \quad\quad \text{(tungsten)} \\ 1 + 0.106(0.846 - \theta_m) & k = -2 \quad \text{(stainless steel SS-304)} \end{cases} \tag{5}$$

The following table reports some sets of parameters given by Burgess in his paper:

| Parameter | Cu | Ag | Au | W | Al(2024) | SS(304) |
|---|---|---|---|---|---|---|
| $V_0$(cm³/gm) | 0.112 | 0.0953 | 0.0518 | 0.0518 | 0.370 | 0.1265 |
| $\gamma_0$ | 2.00 | 2.55 | 3.29 | 1.55 | 2.13 | 2.00 |
| $\theta_{m,0}$ (BUS) | 0.117 | 0.106 | 0.115 | 0.315 | 0.0804 | 0.156 |
| $L_F$ (BUS) | 0.130 | 0.113 | 0.127 | 0.337 | 0.107 | 0.153 |
| $C_1$ (BUS) | -4.12e-5 | -3.37e-5 | -4.95e-5 | -9.73e-5 | -5.35e-5 | 0 |

| Parameter | Cu | Ag | Au | W | Al(2024) | SS(304) |
|---|---|---|---|---|---|---|
| $C_2$ | 0.113 | 0.131 | 0.170 | 0.465 | 0.233 | 0.330 |
| $C_3$ | 1.145 | 1.191 | 1.178 | 1.226 | 1.210 | 0.4133 |
| EXPON | -1 | -1 | -1 | +1 | -1 | 0 |
| $C_4$ | 0.700 | 0.672 | 0.673 | 0.670 | 0.638 | 0.089 |
| k | 0.964 | 0.910 | 1.08 | -1. | 0.878 | -2. |

### \*EM_EOS_MEADON

Purpose:  Define the parameters for a Meadon model, giving the electrical conductivity as a function of the temperature and the density; see:

*T.J. Burgess, "Electrical resistivity model of metals", 4th International Conference on Megagauss Magnetic-Field Generation and Related Topics, Santa Fe, NM, USA, 1986*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | C1 | C2 | C3 | TEMUNI | V0 | GAMMA | EXPON |
| Type | I | F | F | F | I | F | F | I |
| Default | none | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LGTUNIT | TIMUNIT | ADJUST | | | | | |
| Type | F | F | I | | | | | |
| Default | none | none | none | | | | | |

In the following, UUS stands for User Units System and BUS for Burgess Units.

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | ID of the EM_EOS |
| C1 | C1 constant (BUS) |
| C2 | C2 constant (no units) |
| C3 | C3 constant (no units) |
| TEMUNIT | Temperature units |
| |     EQ.1: temperature in Celsius |
| |     EQ.2: temperature in Kelvins |

| VARIABLE | DESCRIPTION |
| --- | --- |
| V0 | Reference specific volume V0 (UUS). |
| GAMMA0 | Reference Gruneisen value $\gamma_0$.(no units). |
| EXPON | Exponent in equations (7) |
| LGTUNIT | Length units for UUS (relative to meter, i.e. = 1.e-3 if UUS in mm). |
| TIMUNIT | Time units for UUS (relative to seconds). |
| ADJUST: | EQ.0: (default) the conductivity is given by the Burgess formula.<br><br>EQ.1: The conductivity is adjusted so that it is equal to the conductivity defined in the \*EM_MAT card $\sigma_{\text{mat}}$ at room temperature: |

$$\sigma(\theta) = \sigma_{\text{Burgess}}(\theta)\frac{\sigma_{\text{mat}}}{\sigma_{\text{Burgess}}(\theta_{\text{room}})}$$

**Remarks:**

1. The Meadon model is a simplified Burgess model with the solid phase equations only.

   The electrical resistivity is given by:

   $$\eta_S = \left(C_1 + C_2\theta^{C_3}\right)f_c\left(\frac{V}{V_0}\right) \tag{6}$$

   where $\theta$ is the temperature, V is the specific volume, and $V_0$ is the reference specific volume (zero pressure, solid phase).

   In (6), the volume dependence is given by:

   $$f_c\left(\frac{V}{V_0}\right) = \begin{cases} \left(\frac{V}{V_0}\right)^{2\gamma-1} & \text{EXPON.EQ.}-1 & \text{(most materials)} \\ \left(\frac{V}{V_0}\right)^{2\gamma+1} & \text{EXPON.EQ.}+1 & \text{(tungsten)} \\ \left(\frac{V}{V_0}\right)^{2\gamma} & \text{EXPON.EQ.0} & \text{(stainless steel)} \\ 1 & \text{VO.EQ.0} & \text{(default value for } V_0 \text{ is zero)} \end{cases} \tag{7}$$

   (In this last case, only EOSID, C1, C2, C3, TEMUNIT, TIMUNIT and LGTUNIT need to be defined)

   with,

$$\gamma = \gamma_0 - \left(\gamma_0 - \frac{1}{2}\right)\left(1 - \frac{V}{V_0}\right) \tag{8}$$

The following table reports some sets of parameters given by Burgess in his paper:

| Parameter | Cu | Ag | Au | W | Al(2024) | SS(304) |
|---|---|---|---|---|---|---|
| $V_0$(cm³/gm) | 0.112 | 0.0953 | 0.0518 | 0.0518 | 0.370 | 0.1265 |
| $\gamma_0$ | 2.00 | 2.55 | 3.29 | 1.55 | 2.13 | 2.00 |
| $C_1$ (BUS) | -4.12e-5 | -3.37e-5 | -4.95e-5 | -9.73e-5 | -5.35e-5 | 0 |
| $C_2$ | 0.113 | 0.131 | 0.170 | 0.465 | 0.233 | 0.330 |
| $C_3$ | 1.145 | 1.191 | 1.178 | 1.226 | 1.210 | 0.4133 |
| EXPON | -1 | -1 | -1 | +1 | -1 | 0 |

## *EM_EOS_PERMEABILITY

Purpose: Define the parameters for the behavior of a material's permeability.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | EOSTYPE | LCID | BS/POLY | MUR0 | C | TC | |
| Type | I | I | I | F | F | F | F | |
| Default | none | none | none | 0. | 0. | 0. | 0. | |

| VARIABLE | DESCRIPTION |
|---|---|

EOSID      ID of the EM_EOS

EOSTYPE      Define the type of EOS:

> EQ.1: Permeability defined by $B$ as a function of $H$ curve ($B = \mu H$). The abscissa of the curve is $H$, and the ordinate is $B$.

> EQ.2: Permeability defined by a $H$ function of $B$ curve ($H = B/\mu$). The abscissa of the curve is $B$, and the ordinate is $H$.

> EQ.3: Permeability defined by a load curve where $B$-$H$ curves ($B = \mu H$) may be defined as a function of von Mises stress. The abscissa of the curve is von Mises stress, and the ordinate is a load curve ID for the $B$-$H$ load curves. The abscissa for each $B$-$H$ load curve is $H$, and the ordinate is $B$.

> EQ.4: Permeability defined by a load curve where $B$-$H$ load curves ($B = \mu H$) may be defined as a function of temperature. The abscissa of the curve is temperature, and the ordinate is load curve ID for the $B$-$H$ load curves. The abscissa for each $B$-$H$ load curve is $H$, and the ordinate is $B$.

> EQ.7: Permeability given by an analytical arctan law defining $B$ as a function of $H$ and optionally temperature. See Remark 1.

> EQ.8: Permeability given by the Froelich law defining $B$ as a function of $H$ and optionally temperature. See

| VARIABLE | DESCRIPTION |
|---|---|
| | Remark 2. |
| LCID | Load curve ID for EOSTYPE = 1, 2, 3, and 4. Ignored if EOSTYPE = 7 or 8. |
| BS/MUR0/C/TC | Saturation magnetic flux ($B_s$), relative permeability at a reference temperature ($\mu_{r0}$), constant value ($C$), and Curie temperature ($T_c$), respectively. These parameters are used by the analytical laws (EOSTYPE = 7 and 8). See Remarks 1 and 2. |
| POLY | Applies a polynomial smoothing on the input load curve for EOSTYPE = 1 and 2. See Remark 3. |
| | EQ.0: Off |
| | EQ.1: On |

**Remarks:**

1.  **Arctan analytical law.** For EOSTYPE = 7, the solver applies the following analytical law:

$$B(H, T) = \mu_0 H + \frac{2 B_s}{\pi} \operatorname{atan} \left( \frac{\pi}{2 B_s} H \mu_0 (\mu_{r0} - 1.) \right) \times F(T) \times \mathrm{SF}$$

SF is an optional coefficient defined by the material properties (see Remark 3 on \*EM_MAT_002). $F(T)$ provides temperature dependence. $B_s$ and $\mu_{r0}$ are input parameters. $\mu_0$ is the permeability of free space and is hard-coded in the solver. By default, $\mathrm{SF} = 1$ and $F(T) = 1$. If $C$ is defined, $F(T)$ becomes:

$$F(T) = \max \left( 0., 1. - \exp \left( \frac{T - T_c}{C} \right) \right)$$

$T_c$ is an input parameters.

2.  **Froelich analytical law.** For EOSTYPE = 8, the solver applies the following analytical law:

$$B(H, T) = \mu_0 H + H \frac{B_s}{1. + \mu_{r0} H} \times F(T) \times \mathrm{SF}$$

SF is an optional coefficient defined by material properties (see Remark 3 on \*EM_MAT_002). $F(T)$ provides temperature dependence. By default, $\mathrm{SF} = 1$ and $F(T) = 1$. If $C$ is defined, $F(T)$ becomes:

$$F(T) = \max \left( 0., 1. - \exp \left( \frac{T - T_c}{C} \right) \right)$$

$T_c$ is an input parameters.

3.  **Polynomial approach.**   For EOSTYPE = 1 or 2, in some cases the input *B-H* curve contains few points or has some ill-defined areas.  In such scenarios, it can be useful to reconstruct the curve using a polynomial approach.  Accuracy can increase with reduced computational time.  The smoothed load curve is output to a keyword file em_polyCurve_LCID.dat for reference.  It is not necessarily recommended to use this feature if the original *B-H* curve is well defined.

## \*EM_EOS_TABULATED1

Purpose:  Define the electrical conductivity or permeability depending on the material referencing this EOS as a function of temperature by using a load curve.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | EOSID | LCID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EOSID | ID of the EM EOS |
| LCID | Load curve ID.  See Remark 1. |

**Remarks:**

1. **Suggestions for the Load Curve.** The load curve describes the electrical conductivity or permeability (ordinate) as a function of the temperature (abscissa). You need to make sure the temperature and the electrical conductivity / permeability given by the load curve are in the correct units.  Also, we advise giving some bounds to the load curve (conductivities / permeabilities at very low and very high temperatures) to avoid bad extrapolations of the conductivity if the temperature gets out of the load curve bounds.

## \*EM_EOS_TABULATED2

Purpose: Define the electrical conductivity or permeability (depending on the material model referencing this EOSID) as a function of time by using a load curve.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | EOSID | LCID | IFLAG | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EOSID | ID of the EM EOS |
| LCID | Load curve ID (see Remark 1), function ID (see \*DEFINE_FUNC-TION), table ID or 2D table ID. For the arguments for the \*DE-FINE_FUNCTION, see Remark 2. |
| IFLAG | If LCID is a table ID or 2D table ID, conductivity / permeability is a function of temperature and material density. This flag dictates how LS-DYNA interprets the table. In other words, it specifies which property (temperature or material density) is the value for the table and which is the ordinate for load curves in the table: |

> EQ.0: Temperature (value) indexes each conductivity/permeability (ordinate) versus material density (abscissa) load curve.
>
> EQ.1: Material density indexes each conductivity/permeability (ordinate) versus temperature (abscissa) load curve.

**Remarks:**

1. **Suggestions for the Load Curve.** The load curve describes the electrical conductivity / permeability (ordinate) as a function of time (abscissa). You need to make sure the time and the electrical conductivity / permeability given by the load curve are in the correct units. Also, we advise giving some bounds to the load curve (conductivities / permeabilities at $t = 0$ and after a long time) to avoid bad extrapolations of the conductivity / permeability if the run time gets out of the load curve bounds.

2.  **\*DEFINE_FUNCTION Arguments.**  LCID can also refer to a \*DEFINE_FUNC-TION ID. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(vx, vy, vz, temp, pres, vol, mass, Ex, Ey, Ex, Bx, By, Bz, Fx, Fy, Fz, JHrate, time, x, y, z). (Fx, Fy, Fz) refers to the Lorentz force vector.

**\*EM_EXTERNAL_ECVEL**

Purpose: Add an inertial velocity term to the vector potential FEM formulation to add velocity effects on Eddy currents. See Remarks 1 and 2.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | NID1 | NID2 | OMEGA | VX | VY | VZ |
| Type | I | | I | I | F | F | F | F |
| Default | none | | none | none | 0. | 0. | 0. | 0. |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID on which the velocity term will be added |
| NID1/NID2 | Node IDs defining the origin (NID1) and rotation axis (pointing from NID2 to NID1) |
| OMEGA | Rotation velocity term (given in radians) |

> **GE.0.0:** Constant value
>
> **LT.0.0:** |OMEGA| points to a load curve ID for a load curve giving the rotation velocity as a function of time.

| | |
|---|---|
| V[X,Y,Z] | Translational velocity components: |

> **GE.0.0:** Constant value
>
> **LT.0.0:** The absolute value of V[X,Y,Z] refers to a load curve ID for the load curve giving the translational velocity component as a function of time.

**Remarks:**

1.  **Eddy current velocity effects.** In a typical EM solver application, the effects of velocity on Eddy currents are automatically taken into account by the translations and rotations of the different conductors in a Lagrangian formulation (thanks to the coupling with the mechanical solvers). However, it may be convenient to use an Eulerian formulation for certain applications, such as the study of homopolar generators (like a Faraday disk) or default detection in pipes (like

a Lenz's law apparatus). In this case, the conductors are static, and this keyword directly applies the velocity effects on the relevant conductors.

2.  **Vector potential formulation.** When present, the velocity term appears in the FEM formulation for the vector potential **a**:

$$\sigma \frac{\partial \mathbf{a}}{\partial t} + \nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{a} \right) + \sigma \nabla \varphi - \sigma \mathbf{u} \times \mathbf{a} = \mathbf{J}_s$$

Here, $\sigma$ is the material's conductivity, $\varphi$ is the scalar potential, **u** is the Eulerian velocity, and $\mathbf{J}_s$ is the surface current.

**\*EM_EXTERNAL_FIELD**

Purpose: Define the components of a time-dependent exterior field uniform in space applied on the conducting parts.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | FIELDID | FTYPE | FDEF | LCIDX | LCIDY | LCIDZ | | |
| Type | I | I | F | I | I | I | | |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | | |

**Optional Card.** Additional input for frequency-based Eddy current cases (EMSOL = 4 in \*EM_CONTROL).

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | | | LCIDXI | LCIDYI | LCIDZI | | |
| Type | | | | I | I | I | | |
| Default | | | | optional | optional | optional | | |

| VARIABLE | DESCRIPTION |
|---|---|
| FIELDID | External Field ID |
| FTYPE | Field type: |
| | EQ.1: Magnetic field |
| | EQ.2: Electric field (not available yet) |
| | EQ.3: Charge density (resistive heating solver only). See Remark 1. |
| FDEF | Field defined by: |
| | EQ.1: Load curves |
| | EQ.2: Define function (see \*DEFINE_FUNCTION). If a define function is used, the following parameters are accepted: x, y, z, time. See Remark 2. For FTYPE = 3, the additional |

| VARIABLE | DESCRIPTION |
|---|---|
| | following parameters are accepted: emdt, pot, curr, sigma. |
| | EQ.4: Subroutine `usermat_getextfield` in the usermat package. See Remark 3. |
| LCID[X,Y,Z] | Load curve ID defining the $(X, Y, Z)$ component of the field function of time for FTYPE = 1. For FTYPE = 3, only LCIDY is used and should be a simple a load curve or define function ID. |
| LCIDI[X,Y,Z] | Only available for EMSOL = 4 in \*EM_CONTROL. Load curve ID defining the $(X, Y, Z)$ component of the optional phase shift function of time for FTYPE = 1. Unit is in degrees. |

**Remarks:**

1. **Electrostatic problems.** FTYPE = 3 is mostly used in electrostatic problem configurations. The material's conductivity then represents the permittivity.

2. **Spatially varying magnetic fields.** Using FTYPE = 1 and FDEF = 2 enables defining a spatially varying field. The coordinates given as arguments by the \*DEFINE_FUNCTION represent the coordinates at the midpoint of the BEM edges.

3. **Defining field with usermat.** Using FTYPE = 1 and FDEF = 4 allows defining a spatially varying field in even greater detail by accessing the routine called `usermat_getextfield` in dyn21em.f when compiling LS-DYNA in usermat mode. With this subroutine, the user can implement his own law and rules.

## *EM_ISOPOTENTIAL

Purpose: Define an isopotential. In other words, constrain nodes so that they have the same scalar potential value. This keyword card can only be used with the type 3 EM solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---------|-------|---------|---|---|---|---|
| Variable | ISOID | SETTYPE | SETID | RDLTYPE | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ISOID | ID of the isopotential |
| SETTYPE | Set type: |
| | EQ.1: Segment Set |
| | EQ.2: Node Set |
| | EQ.3: Fluid surface part. See *ICFD_PART. |
| SETID | Set ID |
| RDLTYPE | Used for the battery application (see *EM_RANDLES_BATMAC or *EM_RANDLES_TSHELL). Selects which layers of the underlying battery cell are associated with the isopotential: |
| | EQ.0: Default. No specific treatment. |
| | EQ.1: Current Collector Positive |
| | EQ.2: Positive Electrode |
| | EQ.3: Separator |
| | EQ.4: Negative Electrode |
| | EQ.5: Current Collector Negative |
| | The function of a layer is defined in *EM_MAT_001. |

## \*EM_ISOPOTENTIAL_CONNECT

Purpose:  Define a connection between two isopotentials or between an isopotential and the ground.

**Card Summary:**

**Card 1a.**  Include this card for CONTYPE = 1 (short circuit).

| CONID | CONTYPE | ISOID1 | ISOID2 | | | | |
|---|---|---|---|---|---|---|---|

**Card 1b.**  Include this card for CONTYPE = 2, 3, 4, 6, or 7.

| CONID | CONTYPE | ISOID1 | ISOID2 | VAL | LCID | | |
|---|---|---|---|---|---|---|---|

**Card 1c.**  Include this card for CONTYPE = 5 (meshless Randles circuit).

| CONID | CONTYPE | ISOID1 | ISOID2 | | RDLID | PSID | |
|---|---|---|---|---|---|---|---|

**Card 2.**  Include this card for CONTYPE = 6 (RLC circuit).

| L | C | V0 | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

**Short Circuit Connection Card.**  Include this card if CONTYPE= 1.

| Card 1a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CONID | CONTYPE | ISOID1 | ISOID2 | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | 0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CONID | Connection ID |
| CONTYPE | Connection type:<br>EQ.1: Short circuit |
| ISOID1 | ID of the first isopotential to be connected |

| VARIABLE | DESCRIPTION |
|---|---|
| ISOID2 | Optional ID of the second isopotential to be connected |

**Resistance, Voltage Source, Current Source, and RLC Circuit Connection Card.**
Include this card if CONTYPE= 2, 3, 4, 6, or 7.

| Card 1b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CONID | CONTYPE | ISOID1 | ISOID2 | VAL | LCID | | |
| Type | I | I | I | I | F | I | | |
| Default | none | none | none | 0 | none | 0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CONID | Connection ID |
| CONTYPE | Connection type: |

> EQ.2: Resistance
>
> EQ.3: Voltage source
>
> EQ.4: Current source
>
> EQ.6: RLC circuit
>
> EQ.7: Power (See Remark 1)

| | |
|---|---|
| ISOID1 | ID of the first isopotential to be connected |
| ISOID2 | Optional ID of the second isopotential to be connected |
| VAL | Value of the resistance, voltage, or current depending on CONTYPE. Ignored for CONTYPE = 2 through 4 if LCID ≠ 0. |
| LCID | Load curve ID giving the value of resistance, voltage, or current as a function of time. Only available for CONTYPE = 2 through 4. |

> LT.0: |LCID| is a \*DEFINE_FUNCTION ID. The following arguments are allowed: f(time, emdt, curr1, curr2, pot1, pot2, rmesh). pot1 and pot2 are the potential at the previous time step and at two previous time steps. curr1 and curr2 are the current at the previous time step and two previous time steps. rmesh is the mesh resistance calculated

| VARIABLE | DESCRIPTION |
|---|---|

by the solver at this isopotential.

**Meshless Randles Circuit Connection Card.** Include this card if CONTYPE = 5.

| Card 1c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CONID | CONTYPE | ISOID1 | ISOID2 | | RDLID | PSID | |
| Type | I | I | I | I | | I | I | |
| Default | none | none | none | 0 | | none | 0 | |

| VARIABLE | DESCRIPTION |
|---|---|
| CONID | Connection ID |
| CONTYPE | Connection type:<br><br>    **EQ.5:** Meshless Randles circuit (used to represent a cell by one lumped Randles circuit) |
| ISOID1 | ID of the first isopotential to be connected |
| ISOID2 | Optional ID of the second isopotential to be connected |
| VAL | Value of the resistance, voltage, or current depending on CONTYPE |
| RDLID | ID of the Randles circuit defined by \*EM_RANDLES_MESHLESS |
| PSID | Used if the variable R0TOTH of \*EM_RANDLES_MESHLESS equals 1. Part set ID where LS-DYNA adds the joule heating corresponding to the resistance $r_0$ in \*EM_RANDLES_MESHLESS, averaged over the part set. |

**RLC Circuit Parameters Card.** Only defined if CONTYPE = 6.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|---|---|---|---|---|
| Variable | L | C | V0 | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| L/C/V0 | Circuit inductance, capacity, and initial voltage.  VAL gives the resistance. |

**Remarks:**

1.  **Power boundary condition.**  This condition is only available when using the EM resistive heating solver (EMSOL = 3 in \*EM_CONTROL_SOLVER).  When active, the solver solves the resistive heating problem in two steps per time step. In the first solve, it applies a Dirichlet boundary condition with an imposed voltage of 1 to each power boundary condition.  Once the first solve is complete, it retrieves the current on the boundary in order to update the voltage boundary condition to the value corresponding to the user-defined expected value for power and solves again.

    In classic resistive heating applications, the classic Ohm's law is used to determine the relationship between power, voltage, and current:

    $$P = VI$$

    In radiofrequency applications (meaning when complex numbers are present), power is found by calculating the sum of the real and imaginary parts:

    $$P = V_r I_r + V_i I_i$$

## \*EM_ISOPOTENTIAL_ROGO

Purpose: measures the total current flowing through a given section of the conductor and outputs it in an ASCII file called em_rogoCoil.dat

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ISOID | SETTYPE | SETID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

|          VARIABLE          |                          DESCRIPTION                          |
|---|---|

ISOID          ID of the Rogo coil.

SETTYPE      Set type:

                EQ.1: Segment Set.

SETID          Set ID

## *EM_MAT_001

Purpose: Define the electromagnetic material type and properties for a material whose permeability equals the free space permeability. Electromagnetic materials act like a \*MAT_ADD, so they must be associated with a \*MAT material or an ICFD part. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | MTYPE | SIGMA | EOSID | | EPLAMDA | DEATHT | RDLTYPE |
| Type | I | I | F | I | | F | F | I |
| Default | none | none | none | optional | | optional | $10^{28}$ | 0 |

**Optional RF Heating Card.** Additional material parameters for radio-frequency heating (RF) cases.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | FREQ | EPSRR | EOSID2 | EPSRI | EOSID3 | EPS0 | |
| Type | | F | F | I | F | I | F | |
| Default | | 0. | 0. | optional | 0. | optional | ↓ | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID. For all MTYPE except MTYPE = 3, MID must reference a \*MAT material since the electromagnetic properties are added onto the \*MAT properties. If MTYPE = 3, MID can be left blank for the electromagnetic properties to apply to the ICFD entire fluid or it can be the PID of a \*ICFD_PART_VOL to apply to an ICFD fluid part. See Remark 1. |
| MTYPE | Defines the electromagnetism type of the material:<br><br>EQ.0: Air or vacuum<br><br>EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.<br><br>EQ.2: Conductor carrying a source. In these conductors, the |

| VARIABLE | DESCRIPTION |
|---|---|
| | eddy current problem is solved, which gives the actual current density. Typically, this material would correspond to the coil. |
| | EQ.3: Fluid conductor. In this case, MID refers to the ID given in \*ICFD_PART_VOL. See Remark 2. |
| | EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this material would correspond to the workpiece. |
| SIGMA | Initial electrical conductivity of the material. For the eikonal solvers (EMSOL = 14 and 15 on \*EM_CONTROL), SIGMA is the wave velocity. |
| EOSID | Optional ID of the EOS to be used for the electrical conductivity (see \*EM_EOS cards). |
| EPLAMDA | Optional. When defined, this field activates the computation of extracellular potentials in the purkinje network with the anisotropy ratio given by EPLAMDA. |
| DEATHT | Death time for the material. After DEATHT, the material will no longer be considered a conductor and removed from the EM solve. If a negative value is entered, a \*DEFINE_FUNCTION will be expected. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, Fz refers to the Lorentz force vector. A negative value returned by the \*DEFINE_FUNCTION corresponds to a "dead" or inactive element. Once an element has been removed from the EM solve, it cannot return. |
| RDLTYPE | Used for composite Tshell batteries modeled with \*EM_RANDLES_TSHELL. RDLTYPE specifies the function of the layer associated to MID: |
| | EQ.0: Default. Conductor which is not part of a battery cell. |
| | EQ.1: Current Collector Positive |
| | EQ.2: Positive Electrode |
| | EQ.3: Separator |
| | EQ.4: Negative Electrode |
| | EQ.5: Current Collector Negative |

| VARIABLE | DESCRIPTION |
|---|---|
| FREQ | Frequency used for the RF solve. |
| EPSRR/EPSRI | Real and imaginary part of the relative permeability (dielectric constant and dielectric loss terms). |
| EOSID2/EOSID3 | Optional IDs defining equation of states for EPSRR and EPSRI respectfully. |
| EPS0 | Vacuum permittivity. The default is $8.8541878128 \times 10^{-12}$ |

**Remarks:**

1. **Input decks with EM materials.** EM materials must be associated with a \*MAT material for MTYPE ≠ 3 or an ICFD fluid for MTYPE = 3. These EM properties are added onto the normal material properties like \*MAT_ADD material properties. Thus, when added onto a \*MAT material, MID here must refer to the MID of the \*MAT material. For example, an input deck can have the following to define a conductor:

   ```
   *PART
   2,1,20
   *MAT_RIGID
   20,&dens,&young,$nu
   *EM_MAT_001
   20,2,&cond
   ```

   In this case, if \*MAT_RIGID is not included, the conduction properties are not applied.

   For MTYPE = 3, MID can refer to the PID of a \*ICFD_PART_VOL or be left blank. If it is left blank, the EM properties apply to the entire ICFD fluid.

2. **Coupling ICFD to EM.** Only the resistive heating solver is currently available when coupling the ICFD solver with the EM solver (see \*EM_CONTROL).

3. **Eikonal solvers.** For the eikonal solvers (EMSOL = 14 and 15 on \*EM_CONTROL), this material is supported for beam elements.

## *EM_MAT_002

Purpose: Define an electromagnetic material type and properties with a permeability different than the free space permeability. Electromagnetic materials act like a *MAT_-ADD, so they must be associated with a *MAT material. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | MTYPE | SIGMA | EOSID | MUREL | EOSMU | DEATHT | |
| Type | I | I | F | I | F | I | F | |
| Default | none | none | none | none | none | optional | $10^{28}$ | |

Optional card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | EOSIDSF | | | | | | |
| Type | | I | | | | | | |
| Default | | optional | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material identification. MID must reference a *MAT material since the electromagnetic properties are added onto the *MAT properties. See Remark 1. |
| MTYPE | Electromagnetism type of the material: |

    EQ.0: Air or vacuum

    EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

    EQ.2: Conductor carrying a source. In these conductors, the eddy current problem is solved, which gives the actual current density. Typically, this would correspond to the coil.

    EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this

| VARIABLE | DESCRIPTION |
|---|---|
| | would correspond to the workpiece. |
| SIGMA | Initial electrical conductivity of the material |
| EOSID | ID of the EOS to be used for the electrical conductivity (see \*EM_-EOS cards) |
| MUREL | Relative permeability which is the ratio of the permeability of a specific medium to the permeability of free space ($\mu_r = \mu/\mu_0$). See Remark 2. |
| EOSMU | ID of the EOS to be used to define the nonlinear behavior of $\mu$. It is optional.  Note: if EOSMU is defined, MUREL will be used for the initial value only.  See \*EM_EOS_PERMEABILITY. |
| DEATHT | Death time for the material.  After DEATHT, the material will no longer be considered a conductor and will be removed from the EM solve.  If a negative value is entered, a \*DEFINE_FUNCTION will be expected.  The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, and Fz refer to the components of the Lorentz force vector.  A negative value returned by the \*DEFINE_FUNCTION corresponds to a 'dead' or inactive element.  Once an element has been removed from the EM solve, it cannot return. |
| EOSIDSF | Optional ID of the EOS for specifying a scale factor to the permeability EOS defined in EOSMU. This field only applies if EOSMU is defined, but it is optional.  If used, the EOS must be either \*EM_-EOS_TABULATED1 or \*EM_EOS_TABULATED2. See Remark 3. |

**Remarks:**

1.  **Input decks with EM materials.** EM materials must be associated with a \*MAT material.  These EM properties are added onto the normal material properties like \*MAT_ADD material properties.  Thus, MID here must refer to the MID of the \*MAT material.  For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_002
    20,2,&cond,&eosid,&murel
    ```

In this case, if \*MAT_RIGID is not included, the conduction properties are not applied.

2. **Solver recommendations.** If $\mu \neq \mu_0$, then it is recommended to switch to the monolithic solver (See \*EM_SOLVER_FEMBEM_MONOLITHIC) for better stability.

3. **Scale factor applied on permeability.** EOSIDSF is an equation of state for specifying a scale factor to the permeability specified with EOSMU. The scale factor is applied in the following way:

$$B(H, T) = \mu_0 H + G(H) \times \text{SF}$$

In other words, the nonlinear behavior of $B(H, T)$ is decomposed into a linear part ($\mu_0 H$) and a nonlinear part ($G(H) \times \text{SF}$). The linear part represents what happens at very high $H$ values, such as when saturation is reached. $G(H)$ in the nonlinear term depends on the curve or law specified with EOSMU. The scale factor, SF, is determined with EOSIDSF. In general, this scale factor is a function of temperature, but the capability is not limited to it (see options available in \*EM_EOS_TABULATED1 and \*EM_EOS_TABULATED2).

## \*EM_MAT_003

Purpose: Define an electromagnetic material type whose electromagnetic conductivity is defined by a (3 × 3) tensor matrix. Applications include composite materials. This material only applies to solid elements. Electromagnetic materials act like a \*MAT_ADD, so they must be associated with a \*MAT material. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|---------|---------|---------|------|-----|---|
| Variable | MID | MTYPE | SIGMA11 | SIGMA22 | SIGMA33 | BETA | CM | |
| Type | I | I | F | F | F | F | F | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---------|---------|---------|---------|---------|---------|------|--------|
| Variable | SIGMA12 | SIGMA13 | SIGMA21 | SIGMA23 | SIGMA31 | SIGMA32 | AOPT | LAMBDA |
| Type | F | F | F | F | F | F | F | F |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|----|----|----|----|----|----|------|---|
| Variable | XP | YP | ZP | A1 | A2 | A3 | MACF | |
| Type | F | F | F | F | F | F | I | |

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|----|----|----|----|----|----|---|---|
| Variable | V1 | V2 | V3 | D1 | D2 | D3 | | |
| Type | F | F | F | F | F | F | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID. . MID must reference a \*MAT material since the electromagnetic properties are added onto the \*MAT properties. See Remark 1. |
| MTYPE | Defines the electromagnetism type of the material: |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: Air or vacuum |
| | EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0. |
| | EQ.2: Conductor carrying a source. For these conductors, the EM solver solves the eddy current problem, which gives the actual current density. Typically, this type would correspond to the coil. In electrophysiology (EP), it corresponds to the tissue where the monodomain equations are solved for EMSOL = 11 or EMSOL = 13. For this case, an \*EM_EP_CELLMODEL must be associated with this \*EM_MAT_003. |
| | EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this type would correspond to the workpiece. In electrophysiology (EP), for EMSOL = 11, 12 or 13, it corresponds to the bath surrounding the tissue for which only the external potential is found. In the case of electrophysiology, no \*EM_EP_CELLMODEL should be associated with this material. |
| SIGMA11 | The 1, 1 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on \*EM_CONTROL), this is the 1, 1 term in the 3 × 3 wave velocity tensor. Note that 1 corresponds to the **a** material direction. |
| | LT.0.0: \|SIGMA11\| corresponds to the ID of a \*DEFINE_FUNCTION. See Remark 3 for available parameters. |
| SIGMA12 | The 1, 2 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on \*EM_CONTROL), this is the 1, 2 term in the 3 × 3 wave velocity tensor. Note that 2 corresponds to the **b** material direction. |
| | LT.0.0: \|SIGMA12\| corresponds to the ID of a \*DEFINE_FUNCTION. See Remark 3 for available parameters. |
| $\vdots$ | $\vdots$ |
| SIGMA33 | The 3, 3 term in the 3 × 3 electromagnetic conductivity tensor matrix. For the eikonal solvers (EMSOL = 14 and 15 on \*EM_CONTROL), this is the 3, 3 term in the 3 × 3 wave velocity tensor. Note that 3 corresponds to the **c** material direction. |
| | LT.0.0: \|SIGMA33\| corresponds to the ID of a \*DEFINE_ |

| VARIABLE | DESCRIPTION |
|---|---|
| | FUNCTION. See Remark 3 for available parameters. |
| BETA | Surface to volume ratio of the cell membrane (to be used only when EMSOL = 11 or 12 in *EM_CONTROL). |
| CM | Membrane capacitance per unit area (to be used only when EM-SOL = 11 or 12 in *EM_CONTROL). |
| AOPT | Material axes option (see *MAT_002 for a more detailed description): |

      **EQ.0.0:** Locally orthotropic with material axes determined by element nodes. The **a**-direction is from node 1 to node 2 of the element. The **b**-direction is orthogonal to the **a**-direction and is in the plane formed by nodes 1, 2, and 4.

      **EQ.1.0:** Locally orthotropic with material axes determined by a point in space, $P$, and the global location of the element center; this is the **a**-direction.

      **EQ.2.0:** Globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR.

      **EQ.3.0:** Locally orthotropic material axes determined by a vector **v** and the normal vector to the plane of the element. The plane of a solid element is the midsurface between the inner surface and outer surface defined by the first four nodes and the last four nodes of the connectivity of the element, respectively. Thus, for solid elements, AOPT = 3 is only available for hexahedrons. **a** is determined by taking the cross product of **v** with the normal vector, **b** is determined by taking the cross product of the normal vector with **a**, and **c** is the normal vector. Then **a** and **b** are rotated about **c** by an angle BETA. BETA may be set in the keyword input for the element.

      **EQ.4.0:** Locally orthotropic in cylindrical coordinate system with the material axes determined by a vector, **v**, and an originating point, $P$, which define the centerline axis.

| XP, YP, ZP | Coordinates of point, $P$, for AOPT = 1 and 4 |
|---|---|
| A1, A2, A3 | Components of vector, **a**, for AOPT = 2 |

| VARIABLE | DESCRIPTION |
|---|---|
| MACF | Material axes change flag for solid elements: <br><br> EQ.1: No change, default |
| V1, V2, V3 | Components of vector, **v**, for AOPT = 3 and 4. |
| D1, D2, D3 | Components of vector, **d**, for AOPT = 2 |
| LAMBDA | Intra-to-extracellular conductivity ratio. When non-empty, the elliptic equation is solved to compute extracellular potentials (to be used only when EMSOL = 11 in *EM_CONTROL). |

**Remarks:**

1.  **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_003
    20,2,&cond11,&cond22,&cond33
    &cond12,&cond13,&cond21,&cond23,&cond31,&cond32
    ```

    In this case, if *MAT_RIGID is not included, the conduction properties are not applied.

2.  **Material directions.** See the manual page for *MAT_002 for a description of how the principal material directions, {**a**, **b**, **c**}, are determined with AOPT. Note that *EM_MAT_003 only works for solid elements. The AOPT options illustrated in the AOPT figure of *MAT_002 can define the material directions for all elements of the parts that use the material.

3.  **Function parameters.** The available parameters for the *DEFINE_FUNCTIONs are: f(time, emdt, x_ele, y_ele, z_ele, ieleuser). Here, time is the current EM time; emdt is the current EM time step; x_ele, y_ele, and z_ele are the location of the element; and ieleuser is the element ID.

4.  **Eikonal solvers.** For the eikonal solvers (EMSOL = 14 and 15 on *EM_CONTROL), this material is supported for tetrahedral elements.

**\*EM_MAT_004**

Purpose: Define the electromagnetic material type and properties for conducting shells in a 3D problem or in a 2D resistive heating problem. Electromagnetic materials act like a \*MAT_ADD, so they must be associated with a \*MAT material or an ICFD part. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | MID | MTYPE | SIGMA | EOSID | NELE | MUREL | EOSMU | DEATHT |
| Type | I | I | F | I | I | F | I | F |
| Default | none | none | none | none | 1 | 1. | optional | $10^{28}$ |

**Optional RF heating Card.** Additional material parameters for radio-frequency heating (RF) cases.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | FREQ | EPSRR | EOSID2 | EPSRI | EOSID3 | EPS0 | |
| Type | | F | F | I | F | I | F | |
| Default | | 0. | 0. | 0 | 0. | 0 | ↓ | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MID | Material ID. For all MTYPE except MTYPE = 3, MID must reference a \*MAT material since the electromagnetic properties are added onto the \*MAT properties. If MTYPE = 3, MID can be left blank for the electromagnetic properties to apply to the ICFD entire fluid or it can be the PID of a \*ICFD_PART_VOL to apply to an ICFD fluid part. See Remark 1. |
| MTYPE | Defines the electromagnetism type of the material: |

        EQ.0: Air or vacuum

        EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

        EQ.2: Conductor carrying a source. In these conductors, the

| VARIABLE | DESCRIPTION |
|---|---|
| | eddy current problem is solved, which gives the actual current density. Typically, this would correspond to the coil. |
| | EQ.3: Fluid conductor. In this case, MID refers to the ID given in \*ICFD_PART_VOL. Note that this is only available for ICFD in 2D. See Remark 2. |
| | EQ.4: Conductor not connected to any current or voltage source, where the Eddy current problem is solved. Typically, this would correspond to the workpiece. |
| SIGMA | Initial electrical conductivity of the material |
| EOSID | ID of the EOS to be used for the electrical conductivity (see \*EM_-EOS cards). |
| NELE | Number of elements in the thickness of the shell. Note that you must make sure your mesh fine enough to correctly capture the inductive-diffusive effects (see skin depth definition). |
| MUREL | Relative permeability which is the ratio of the permeability of a specific medium to the permeability of free space ($\mu_r = \mu/\mu_0$). |
| EOSMU | ID of the EOS to be used to define the nonlinear behavior of $\mu$. Note that if EOSMU is defined, MUREL will be used for the initial value only. See \*EM_EOS_PERMEABILITY. |
| DEATHT | Death time for the material. After DEATHT, the material will no longer be considered a conductor and will be removed from the EM solve. If a negative value is entered, a \*DEFINE_FUNCTION will be expected. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). Fx, Fy, and Fz refer to the components of the Lorentz force vector. A negative value returned by the \*DEFINE_FUNCTION corresponds to a 'dead' or inactive element. Once an element has been removed from the EM solve, it cannot return. |
| FREQ | Frequency used for the RF solve. |
| EPSRR/EPSRI | Real and imaginary part of the relative permeability (dielectric constant and dielectric loss terms). |
| EOSID2/EO-SID3 | Optional IDs defining equations of state for EPSRR and EPSRI, respectfully |

| VARIABLE | DESCRIPTION |
|----------|-------------|

EPS0         Vacuum permittivity.  The default is $8.8541878128 \times 10^{-12}$.

**Remarks:**

1.  **Input decks with EM materials.** EM materials must be associated with a \*MAT material for MTYPE $\neq$ 3 or an ICFD fluid for MTYPE = 3. These EM properties are added onto the normal material properties like \*MAT_ADD material properties.  Thus, when added onto a \*MAT material, MID here must refer to the MID of the \*MAT material.  For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_004
    20,2,&cond,&eosid
    ```

    In this case, if \*MAT_RIGID is not included, the conduction properties are not applied.

    For MTYPE = 3, MID can refer to the PID of a \*ICFD_PART_VOL or be left blank.  If it is left blank, the EM properties apply to the entire ICFD fluid.

2.  **Coupling ICFD to EM.**  Only the resistive heating solver is currently available when coupling the ICFD solver with the EM solver (see \*EM_CONTROL).

## \*EM_MAT_005

Purpose: Define an electromagnetic material for which two material conductivities are specified per EM node and electromagnetic conductivities are defined by a (3 × 3) tensor matrix. Applications of this material include the Randles Batmac model (see Remark 2) and the electrophysiology bidomain model. This material is only supported for solid elements. Electromagnetic materials act like a \*MAT_ADD, so they must be associated with a \*MAT material. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | MTYPE | SIGMAXXA | SIGMAYYA | SIGMAZZA | | | |
| Type | I | I | F | F | F | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SIGMAXYA | SIGMAXZA | SIGMAYXA | SIGMAYZA | SIGMAZXA | SIGMAZYA | | |
| Type | F | F | F | F | F | F | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | | SIGMAXXB | SIGMAYYB | SIGMAZZB | | | |
| Type | | | F | F | F | | | |

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SIGMAXYB | SIGMAXZB | SIGMAYXB | SIGMAYZB | SIGMAZXB | SIGMAZYB | | |
| Type | F | F | F | F | F | F | | |

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | AOPT | XP | YP | ZP | A1 | A2 | A3 | MACF |
| Type | F | F | F | F | F | F | F | I |

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | V1 | V2 | V3 | D1 | D2 | D3 | | |
| Type | F | F | F | F | F | F | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID. MID must reference a \*MAT material since the electromagnetic properties are added onto the \*MAT properties. See Remark 1. |
| MTYPE | Defines the electromagnetism type of the material: |

    EQ.0: Air or vacuum

    EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

    EQ.2: In electrophysiology, it corresponds to the tissue, where the bidomain equations will be solved for EMSOL = 12 or EMSOL = 13. An \*EM_EP_CELLMODEL must be associated with this material.

    EQ.4: In electrophysiology, it corresponds to the bath where only the external potential is solved for. No \*EM_EP_CELLMODEL should be associated with this material.

    EQ.5: Material associated with \*EM_RANDLES_BATMAC. See Remark 2.

SIGMAXXA/B      The 1, 1 term in the $3 \times 3$ electromagnetic conductivity tensor matrix for the two conductivities. For the BatMac model, A is for the potential on the positive current collector, and B is for the potential on the negative current collector. For the bidomain model in Electrophysiology, A is for the intracellular potential, and B is for the extracellular potential. Note that 1 corresponds to the **a** material direction.

| VARIABLE | DESCRIPTION |
|---|---|
| | LT.0.0: \|SIGMAXXA/B\| corresponds to the ID of a \*DEFINE_FUNCTION. See Remark 4 for available parameters. |
| SIGMAXYA/B | The 1, 2 term in the 3 × 3 electromagnetic conductivity tensor matrix for the two conductivities. Note that 2 corresponds to the **b** material direction. |
| | LT.0.0: \|SIGMAXYA/B\| corresponds to the ID of a \*DEFINE_FUNCTION. See Remark 4 for available parameters. |
| ⋮ | ⋮ |
| SIGMAZZA/B | The 3, 3 term in the 3 × 3 electromagnetic conductivity tensor matrix for the two conductivities. Note that 3 corresponds to the **c** material direction. |
| | LT.0.0: \|SIGMAZZA/B\| corresponds to the ID of a \*DEFINE_FUNCTION. See Remark 4 for available parameters. |
| AOPT | Material axes option (see \*MAT_002 for a more detailed description): |
| | EQ.0.0: Locally orthotropic with material axes determined by element nodes. The **a**-direction is from node 1 to node 2 of the element. The **b**-direction is orthogonal to the **a**-direction and is in the plane formed by nodes 1, 2, and 4. |
| | EQ.1.0: Locally orthotropic with material axes determined by a point in space, $P$, and the global location of the element center; this is the **a**-direction. |
| | EQ.2.0: Globally orthotropic with material axes determined by vectors defined below, as with \*DEFINE_COORDINATE_VECTOR. |
| | EQ.3.0: Locally orthotropic material axes determined by a vector **v** and the normal vector to the plane of the element.The plane of a solid element is the midsurface between the inner surface and outer surface defined by the first four nodes and the last four nodes of the connectivity of the element, respectively. Thus, for solid elements, AOPT = 3 is only available for hexahedrons. **a** is determined by taking the cross product of |

| VARIABLE | DESCRIPTION |
|---|---|
| | **v** with the normal vector, **b** is determined by taking the cross product of the normal vector with **a**, and **c** is the normal vector. Then **a** and **b** are rotated about **c** by an angle BETA. BETA may be set in the keyword input for the element. |
| | EQ.4.0: Locally orthotropic in cylindrical coordinate system with the material axes determined by a vector, **v**, and an originating point, $P$, which define the centerline axis. |
| XP, YP, ZP | Define coordinates of point **p** for AOPT = 1 and 4. |
| A1, A2, A3 | Define components of vector **a** for AOPT = 2. |
| MACF | Material axes change flag for solid elements: |
| | EQ.1: No change, default |
| V1, V2, V3 | Define components of vector **v** for AOPT = 3 and 4. |
| D1, D2, D3 | Define components of vector **d** for AOPT = 2. |

**Remarks:**

1.  **Input decks with EM materials.** EM materials must be associated with a \*MAT material. These EM properties are added onto the normal material properties like \*MAT_ADD material properties. Thus, MID here must refer to the MID of the \*MAT material. For example, an input deck can have the following to define a conductor:

    ```
    *PART
    2,1,20
    *MAT_RIGID
    20,&dens,&young,$nu
    *EM_MAT_005
    20,2,&cond11a,&cond22a,&cond33a
    &cond12a,&cond13a,&cond21a,&cond23a,&cond31a,&cond32a
    ,,&cond11b,&cond22b,&cond33b
    &cond12b,&cond13b,&cond21b,&cond23b,&cond31b,&cond32b
    ```

    In this case, if \*MAT_RIGID is not included, the conduction properties are not applied.

2.  **Using this material with BatMac.** When this material is used in conjunction with the battery BatMac model, then the conductivities must be adjusted by the current collector thickness ratio over the total thickness of the cell. For example, if $n_p$ is the number of positive current collectors, $t_p$ the thickness of each

individual positive current collector and Th the total thickness of the cell, then the conductivity for the positive current collector must be scaled by:

$$\frac{n_p \times t_p}{\text{Th}} \; .$$

3.  **Material directions.** See the manual page for \*MAT_002 for a description of how the principal material directions, $\{\mathbf{a}, \mathbf{b}, \mathbf{c}\}$, are determined with AOPT. Note that \*EM_MAT_005 only works for solid elements. The AOPT options illustrated in the AOPT figure of \*MAT_002 can define the material directions for all elements of the parts that use the material.

4.  **Function parameters.** The available parameters for the \*DEFINE_FUNCTIONs are: f(time, emdt, x_ele, y_ele, z_ele, ieleuser). Here, time is the current EM time; emdt is the current EM time step; x_ele, y_ele, and z_ele are the location of the element; and ieleuser is the element ID.

**\*EM_MAT_006**

Purpose: Define two conductivities per EM node for special applications (Randles Batmac). Electromagnetic materials act like a \*MAT_ADD, so they must be associated with a \*MAT material. See Remark 1.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|------|------|------|------|--------|---|
| Variable | MID | MTYPE | SIGP | EOSP | SIGN | EOSN | DEATHT | |
| Type | I | I | F | I | F | I | F | |
| Default | none | none | none | none | none | none | $10^{28}$ | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

MID        Material identification. MID must reference a \*MAT material since the electromagnetic properties are added onto the \*MAT properties. See Remark 1.

MTYPE      Defines the electromagnetism type of the material:

　　　　EQ.0: Air or vacuum

　　　　EQ.1: Insulator material. These materials have the same electromagnetism behavior as MTYPE = 0.

　　　　EQ.5: Material associated to \*EM_RANDLES_BATMAC

SIGP/SIGN  Conductivities of the positive / negative current collector materials

EOSP/EOSN  Optional ID of the EOS to be used for the two conductivities

DEATHT     Death time for the material. After DEATHT, the material will no longer be considered a conductor and removed from the EM solve. If a negative value is entered, a |DEATHT| is a \*DEFINE_FUNCTION ID. The following parameters are allowed: (vx, vy, vz, temp, vol, mass, Ex, Ey, Ez, Bx, By, Bz, Fx, Fy, Fz, JHrate, time). The vector (Fx, Fy, Fz) refers to the Lorentz force vector. A negative value returned by the \*DEFINE_FUNCTION corresponds to a "dead" or inactive element. Once an element has been removed from the EM solve, it cannot return.

**Remarks:**

1. **Input decks with EM materials.** EM materials must be associated with a *MAT material. These EM properties are added onto the normal material properties like *MAT_ADD material properties. Thus, MID here must refer to the MID of the *MAT material. For example, an input deck can have the following to define an insulator:

   ```
   *PART
   2,1,20
   *MAT_RIGID
   20,&dens,&young,$nu
   *EM_MAT_006
   20,1,&condp,&eosp,&condn,&eosn
   ```

   In this case, if *MAT_RIGID is not included, the insulator properties are not applied.

2. **BatMac Model.** When this material is used in conjunction with the battery BatMac model, the conductivities must be adjusted by the current collector thickness ratio over the total thickness of the cell. For example, if $n_p$ is the number of positive current collectors, $t_p$ is the thickness of each individual positive current collector, and Th is the total thickness of the cell, the conductivity for the positive current collector must be scaled by: $n_p \times t_p/\text{Th}$.

**\*EM_OUTPUT**

Purpose:  Define the level of EM related output on the screen and in the messag file.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|------|------|-----|--------|---|
| Variable | MATS | MATF | SOLS | SOLF | MESH | MEM | TIMING | |
| Type | I | I | I | I | I | I | I | |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MATS | Level of matrix assembly output to the screen: |
| | EQ.0: No output |
| | EQ.1: Basic assembly steps |
| | EQ.2: Basic assembly steps + percentage completed + final statistics |
| | EQ.3: Basic assembly steps + percentage completed + statistics at each percentage of completion |
| MATF | Level of matrix assembly output to the messag file: |
| | EQ.0: No output |
| | EQ.1: Basic assembly steps |
| | EQ.2: Basic assembly steps + percentage completed + final statistics |
| | EQ.3: Basic assembly steps + percentage completed + statistics at each percentage of completion |
| SOLS | Level of solver output on the screen: |
| | EQ.0: No output |
| | EQ.1: Global information at each FEM iteration |
| | EQ.2: Detailed information at each FEM iteration |
| SOLF | Level of solver output to the messag file: |
| | EQ.0: No output |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: Global information at each FEM iteration |
| | EQ.2: Detailed information at each FEM iteration |
| MESH | Controls the output of the mesh data to the d3hsp file: |
| | EQ.0: No mesh output written. |
| | EQ.1: Mesh info written. |
| MEMORY | Controls the output of information about the memory used by the EM solve to the messag file: |
| | EQ.0: No memory information written. |
| | EQ.1: Memory information written. |
| TIMING | Controls the output of information about the time spent in the different parts of the EM solver to the messag file |
| | EQ.0: No timing information written. |
| | EQ.1: Timing information written. |

**\*EM_OUTPUT_FORCES**

Purpose: Cause the output of a binary file (emforcout) containing the node IDs, the coordinates, and the EM forces at each node. Additionally, ASCII files in keyword format containing these forces can be output.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|-------|-----|---|---|---|---|
| Variable | IOUT | OUTDT | LCOFF | SF | | | | |
| Type | I | F | I | F | | | | |
| Default | 0 | 0.0 | 0 | 1. | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| IOUT | Type of the output: |

        EQ.1: Outputs the binary file only.

        EQ.2: Outputs the binary file and generates a set of keyword files em_loadnid and em_loadlcid giving the EM forces at each node at the given output time.

        EQ.3: Same as 2 except the forces are output as function of time.

| OUTDT | Time period at which the keyword files are generated. Setting OUTDT to 0.0 causes the output to be generated at each EM time step. The absolute value of a negative value refers to a time-dependent load curve. See Remark 2. |
| LCOFF | Optional offset in the load curve IDs that are associated with the forces at each node when generating the keyword files. |
| SF | Optional scaling factor that can be applied to the output forces when generating the keyword files. |

**Remarks:**

1. **2-step EM coupling.** This feature can be used to perform a coupled analysis in two steps. The first step solves the magnetostatic EM problem and outputs the forces. The second step loads those forces in a transient mechanical analysis. This capability enables quickly gaining a good understanding of the model before turning to a fully coupled transient EM solid mechanics analysis.

2.    **Memory cost.** The computational cost to generate the ASCII files can become high in large cases. When OUT=3 is used, there is also a memory cost associated to the output which can again become problematic in large cases. For this reason, it can recommended to use an OUTDT that is larger than the EM timestep to reduce the amount of times those ASCII files are output.

## \*EM_OUTPUT_VTK

Purpose: Cause the output of vtk files. It can be used in applications that require two material conductivities per EM node and whose electromagnetic conductivities are defined by a (3 × 3) tensor matrix. These applications include the Randles Batmac model and the Electrophysiology Bidomain model.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VTKTYPE | VTKT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

VTKTYPE    Type of the vtk files output.

        EQ.1: A single .vtk file

        EQ.2: Parallel unstructured points data (.pvtu files), recommended in mpp executions.

VTKT    Time period at which vtk files are exported.

## \*EM_PERMANENT_MAGNET

Purpose:  Defines a permanent magnet.

**Card Summary:**

**Card 1.**  This card is required.

| ID | PID | MTYPE | NORTH | SOUTH | HC | | |
|----|-----|-------|-------|-------|----|----|----|

**Card 2a.**  This card is included if MTYPE = 3.

| X | Y | Z | | | | | |
|---|---|---|---|---|---|---|---|

**Card 2b.**  This card is included if MTYPE = 4.

| NID1 | NID2 | | | | | | |
|------|------|---|---|---|---|---|---|

**Card 2c.**  This card is included if MTYPE = 5, 6, or 7.

| X | Y | Z | NDIVIS | AXIS | DIR/X2 | Y2 | Z2 |
|---|---|---|--------|------|--------|----|----|

**Card 3.**  This card is optional.

| TTYPE | OX | OY | OZ | NX | NY | NZ | |
|-------|----|----|----|----|----|----|----|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ID | PID | MTYPE | NORTH | SOUTH | HC | | |
| Type | I | I | I | I | I | I | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ID | ID of the magnet |
| PID | Part ID |

| VARIABLE | DESCRIPTION |
| --- | --- |
| MTYPE | Magnet definition type: |

        EQ.0: Magnet defined by two node sets for North and South Poles.

        EQ.1: Magnet defined by two segments sets for North and South Poles.

        EQ.3: Magnet defined by a global vector orientation.

        EQ.4: Magnet defined by a global vector orientation given by two node IDs

        EQ.5: Magnetic gear with NDIVIS magnets oriented around an axis given by AXIS and centered at point (X, Y, Z). The pole orientations alternate for each magnet in the gear, meaning they alternate at increments of 360/NDIVIS around the gear starting along the vector given by (X2, Y2, Z2). See Figure 6-4.

        EQ.6: Magnetic gear with NDIVIS magnets oriented around an axis given by AXIS and centered at point (X, Y, Z). The pole orientations alternate for each magnet in the gear, meaning they alternate at increments of 360/NDIVIS around the gear starting along the vector given by DIR. See Figure 6-4.

        EQ.7: Same as 5 except the North and South orientation of the magnets follows the gear rotation axis (see AXIS in Card 2c) rather than its radial direction.

        EQ.8: Same as 6 except the North and South orientation of the magnets follows the gear rotation axis (see AXIS in Card 2c) rather than its radial direction.

| VARIABLE | DESCRIPTION |
| --- | --- |
| NORTH | Set ID of the magnet north face for MTYPE = 0 and 1 |
| SOUTH | Set ID of the magnet south face for MTYPE = 0 and 1 |
| HC | Coercive force, $H_c$. See Remark 1. |

        LT.0.0: |HC| refers to a load curve ID giving the coercive force as a function of time.

**MTYPE = 3 Card.** This card is only included for MTYPE = 3.

| Card 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | X | Y | Z | | | | | |
| Type | F | F | F | | | | | |
| Default | 0. | 0. | 0. | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| X, Y, Z | Orientation of magnetization vector |

**MTYPE = 4 Card.** This card is only included for MTYPE = 4.

| Card 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | NID1 | NID2 | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID1 / NID2 | Two node IDs defining the magnetization vector |

**Magnetic Gear Card.** This card is only included if MTYPE = 5, 6, or 7. See Figure 6-4.

| Card 2c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| Variable | X | Y | Z | NDIVIS | AXIS | DIR/X2 | Y2 | Z2 |
| Type | F | F | F | I | I | I/F | F | F |
| Default | 0. | 0. | 0. | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| X, Y, Z | Origin / center point of the magnetic gear |
| NDIVIS | Number of subdivisions, that is, number of magnets around the circle |
| AXIS | Normal vector to the magnets: |
| | EQ.1: Global $X$ axis |
| | EQ.2: Global $Y$ axis |
| | EQ.3: Global $Z$ axis |
| DIR | Directional vector giving the location of the starting magnet / starting magnetic orientation if MTYPE = 6: |
| | EQ.1: Global $X$ axis |
| | EQ.2: Global $Y$ axis |
| | EQ.3: Global $Z$ axis |
| X2, Y2, Z2 | Directional vector coordinates giving the starting magnet / starting magnetic orientation if MTYPE = 5 or 7. |

**Optional Card.**    This card is only useful to change some magnet-related output quantities.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TTYPE | 0X | 0Y | 0Z | NX | NY | NZ | |
| Type | I | F | F | F | I | I | I | |
| Default | 0 | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| TTYPE | Torque calculation type: |
| | EQ.0: Default. Magnet torque is output as a vector based on the cross product of the EM force and the relative position of a given node with respect to the center of gravity. |
| | EQ.1: The position vector is based on a user-defined origin point and the result of the aforementioned cross product |
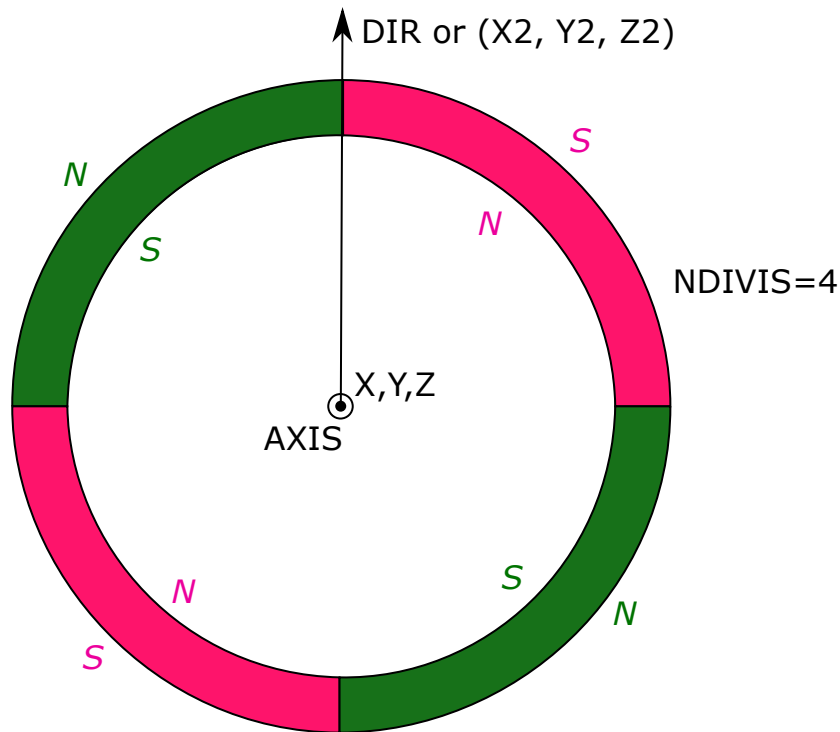
**Figure 6-4.** Example of Magnetic Gear (MTYPE = 5 or 6)

| VARIABLE | DESCRIPTION |
|---|---|
| | operation is projected onto a user-defined axis. As a result, the torque output becomes a scalar quantity. |
| OX/OY/OZ | Origin point for the magnet torque calculation if TTYPE = 1. |
| NX/NY/NZ | Axis on which the torque is projected if TTYPE = 1. |

**Remark:**

1. **Coercive Force.** The absolute value of coercive force $H_c$ applied to the magnet (A/m) relates to the Residual induction $B_r$ by the following relation:

$$H_c = B_r / \mu$$

Here, $\mu$ is the magnet's permeability defined in \*EM_MAT_002 using a constant relative permeability $\mu = \mu_r \mu_0$.

The coercive force can also be expressed using the energy product $BH_{\max}$ :

$$H_c = 2\sqrt{\frac{BH_{\max}}{\mu}}$$

**\*EM_POINT_SET**

Purpose:  Create a set of points that can be used by \*EM_DATABASE_POINTOUT.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PTSID | PTSTYPE | VX | VY | VZ | | | |
| Type | I | I | F | F | F | | | |
| Default | 0 | 0 | 0. | 0. | 0. | | | |

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PTID | X | Y | Z | IPOS | | | |
| Type | I | F | F | F | I | | | |
| Default | none | none | none | none | 0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PSID | Point set ID |
| PTSTYPE | Point set type : |
| | EQ.0: Fixed points |
| | EQ.1: Tracer points using prescribed velocity |
| VX, VY, VZ | Constant velocities used when PTSTYPE = 1 |
| PTID | Point ID |
| X, Y, Z | Point initial coordinates |
| IPOS | Position flag (for 2D, see Remark 1): |
| | EQ.0: The solver determines if the point is inside or outside of the conductors. |

| VARIABLE | DESCRIPTION |
| --- | --- |
| | EQ.1: The point is outside of the conductors during the entire simulation. The solver does not check; hence a gain in computation time. |

**Remarks:**

1.  **2D axisymmetric.** If using \*EM_2DAXI, notice that the conductors represent the corresponding 3D conductors.

# *EM_RANDLES

The keywords in this section facilitate defining Randles circuit parameters for Randles cells.  The available keywords in alphabetical order are as follows:

      *EM_RANDLES_BATMAC

      *EM_RANDLES_EXOTHERMIC_REACTION

      *EM_RANDLES_MESHLESS

      *EM_RANDLES_SHORT

      *EM_RANDLES_SOLID

      *EM_RANDLES_TSHELL

We have implemented four models for the Randles cell: *EM_RANDLES_BATMAC, *EM_RANDLES_MESHLESS, *EM_RANDLES_SOLID, and *EM_RANDLES_TSHELL. *EM_RANDLES_BATMAC is for defining the parameters for the Randles cell when using the batmac model. *EM_RANDLES_MESHLESS, *EM_RANDLES_SOLID, and *EM_-RANDLES_TSHELL are for defining the parameters when the cell is not associated with a mesh, the cell is associated with a solid mechanical model, and the cell is associated with a composite tshell mechanical model, respectively. *EM_RANDLES_EXOTHER-MIC_REACTION and *EM_RANDLES_SHORT enable adding additional parameters to the Randles cell for modeling thermal runaway and shorts, respectively.

**Using *DEFINE_FUNCTION for Randles Cell Parameters:**

**Table 6-2.**  Many of the parameters for these models can be specified with a *DEFINE_-FUNCTION. This table indicates the available arguments, depending on the kind of model.  The first column lists the arguments in single quotes with a description.  The second column gives what is available for the Randles circuit parameters.  The third column indicates what is available for R0CHA and R0DIS for user-defined Equivalent Circuit models, depending on the model chosen.  The fourth and fifth columns give the availability for parameters in *EM_RANDLES_SHORT and *EM_RANDLES_EXOTHER-MIC_REACTION.

| | Parameters with *DEFINE_FUNCTIONs | | | |
|---|---|---|---|---|
| Variable names | Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$ | RDLTYPE = -1 | Internal short | Exothermic reaction |
| *'time'*: Current EM time | All models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |

| | Parameters with \*DEFINE_FUNCTIONs | | | |
|---|---|---|---|---|
| Variable names | Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$ | RDLTYPE = -1 | Internal short | Exothermic reaction |
| *'emdt'*: Current EM time step | All models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'x_sep, y_sep, z_sep'*: Positive electrode coordinates | Solid/tshell models | Solid/tshell models | Solid/tshell models | Solid/tshell models |
| *'x_sen, y_sen, z_sen'*: Negative electrode coordinates | Solid/tshell models | Solid/tshell models | Solid/tshell models | Solid/tshell models |
| *'x_ccp, y_ccp, z_ccp'*: Positive Current collector coordinates | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'x_ccn, y_ccn, z_ccn'*: Negative Current collector coordinates | Solid/tshell models | Solid/tshell models | Solid/tshell models | Solid/tshell models |
| *'pres'*: Local pressure | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'rho'*: Local density | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'vmstress'*: Local von Mises stress | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'cond'*: Local electrical conductivity | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'temp'*: Local temperature | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'tempRand'*: Temperature associated to Randles circuit | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'efstrain'*: Local effective strain | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/batmac models | Solid/batmac models |
| *'strainLocX/Y/Z'*: Local strain in the X/Y/Z directions | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/batmac models | Solid/batmac models |
| *'soc,soceff'*: Local state of charge, effective state of charge | All models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'current'*: Transverse Randles current | All models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'ocv, vc, volt, r0'*: Open charge voltage, damping voltage, total voltage, r0 resistance. | All models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'H_ex'*: Exothermal heating power integrated over time | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |

| Variable names | Parameters with *DEFINE_FUNCTIONs | | | |
| --- | --- | --- | --- | --- |
| | Randles circuit parameters $(r_0, r_{10}, c_{10},$ etc.$)$ | RDLTYPE = -1 | Internal short | Exothermic reaction |
| (= exothermal heating energy) when exothermic reaction keyword is present. | | | | |
| *'short':* Short gives the state of the Randles circuit. If short = 0, then the circuit is not shorted, if short = 1, then it is shorted. | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'ero':* Ero gives the state of the erosion. If ero = 1, then the circuit is adjacent to an element that has been eroded, ero = 0 otherwise. | Solid/batmac models | Solid/batmac models | Solid/batmac models | Solid/batmac models |
| *'areaCircuit, areaCell, areashortGlob':* Local Randles circuit area, total Randles cell area, total cell shorted area. | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models | Solid/tshell/batmac models |
| *'save1, save2, save3…, save10':* Ten local variables that the user can define and that will be saved during the run and associated with each local Randles circuits. | No models | Solid/tshell/batmac models | No models | No models |

## \*EM_RANDLES_BATMAC

Purpose:  Define the distributed Randles circuit parameters for a Randles cell when using the batmac model.  The batmac model is a macro battery model where solid elements are retained for the solid mechanics and thermal solve, and each conducting node has its own Randles circuit associated with it.  It must be used with \*EM_MAT_005 or \*EM_MAT_-006.

**Card Summary:**

**Card 1.** This card is required.

| RDLID | RDLTYPE | RDLAREA | PSID | | | | |
|---|---|---|---|---|---|---|---|

**Card 2.** This card is required.

| Q | CQ | SOCINIT | SOCTOU | | | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| ROCHA | RODIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
|---|---|---|---|---|---|---|---|

**Card 4.** This card is only read if RDLTYPE > 1. It is optional.

| R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
|---|---|---|---|---|---|---|---|

**Card 5.** This card is optional.

| TEMP | FRTHER | ROTOTH | DUDT | TEMPU | | | |
|---|---|---|---|---|---|---|---|

**Card 6.** This card is optional

| USESOCS | TAU | FLCID | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RDLID | RDLTYPE | RDLAREA | PSID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| RDLID | ID of the Randles cell |
| RDLTYPE | Type of Randles cell: |

RDLTYPE — Type of Randles cell:

EQ.-1: User-defined equivalent circuit model. See Remark 3.

EQ.0: 0-order Randles Cell

EQ.1: 1-order Randles Cell

EQ.2: 2-order Randles Cell

EQ.3: 3-order Randles Cell

RDLAREA — Randles area:

EQ.1: The parameters are per unit area and are scaled in each Randle circuit by a factor depending on the local area of the circuit. Unit consistency in SI: Ohms times square meters.

EQ.2: The parameters are defined for the whole cell and are scaled in each Randle circuit by a factor depending on the local area of the circuit and the global area of the cell (default). Unit consistency in SI: Ohms.

EQ.3: The parameters are not scaled by area factors. Unit consistency in SI: Ohms.

EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

PSID — Part set ID of all the parts composing the cell

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Q | CQ | SOCINIT | SOCTOU | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

Q             Cell capacity

CQ            SOC conversion factor (%/s).  It is known to be equal to 1/36 in SI units.

SOCINIT       Initial state of charge of the cell

SOCTOU        Equilibrium voltage (OCV):

      GE.0.0: Constant value

      LT.0.0: |SOCTOU| can refer to a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC) or to a table ID with temperature indexing load curves that give OCV as a function of SOC.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|

R0CHA/         $r_0/r_{10}/c_{10}$ when the current flows in the charge direction:
R10CHA/
C10CHA               GE.0.0: Constant value

      LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments.  For a table, the circuit

| VARIABLE | DESCRIPTION |
|---|---|
| | parameters can be made a function of the SOC and temperature. |
| R0DIS/ R10DIS/ C10DIS | $r_0/r_{10}/c_{10}$ when the current flows in the discharge direction: <br><br> GE.0.0: Constant value <br><br> LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Card for RDLTYPE > 1.** This card is only read for RDLTYPE > 1. It is optional.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
| Type | F | F | F | F | F | F | F | F |
| Default | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |

| VARIABLE | DESCRIPTION |
|---|---|
| R20CHA/ R30CHA/ C20CHA/ C30CHA | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: <br><br> GE.0.0: Constant value <br><br> LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |
| R20DIS/ R30DIS/ C20DIS/ C30DIS | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: <br><br> GE.0.0: Constant value <br><br> LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Thermal Card.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|--------|--------|------|-------|---|---|---|
| Variable | TEMP | FRTHER | R0TOTH | DUDT | TEMPU | | | |
| Type | F | I | I | F | I | | | |
| Default | 0. | 0 | 0 | 0.0 | 0 | | | |

|   VARIABLE   |   DESCRIPTION   |
|---|---|

TEMP            Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0)

FRTHER       Flag setting where the temperature is coming from:

        EQ.0: The temperature used in the Randles circuit parameters is TEMP.

        EQ.1: The temperature used in the Randles circuit parameter is the temperature from the thermal solver.

R0TOTH       Flag for adding joule heating from $r_0$ to the thermal solve:

        EQ.0: The joule heating in the resistance $r_0$ is not added to the thermal solve.

        EQ.1: The joule heating in the resistance $r_0$ is added to the thermal solve.

DUDT           Reversible heat:

        GE.0.0: Constant value

        LT.0.0: |DUDT| is a load curve ID for the curve giving the reversible heat as a function of SOC.

TEMPU        Temperature unit:

        EQ.0: Celsius

        EQ.1: Kelvin

**Optional SOCShift Card.**

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | USESOCS | TAU | FLCID | | | | | |
| Type | I | F | I | | | | | |
| Default | 0 | 0.0 | 0 | | | | | |

|        VARIABLE        |                     DESCRIPTION                     |
|------------------------|-----------------------------------------------------|

| VARIABLE | DESCRIPTION |
|----------|-------------|
| USESOCS | Use SOC shift (see Remark 2):<br><br>EQ.0: Do not use the added SOCshift<br><br>EQ.1: Use the added SOCshift |
| TAU | Damping time in the SOCshift equation (see Remark 2) |
| FLCID | Load curve giving $f(i)$ where $i$ is the total current in the unit cell (see Remark 2) |

**Remarks:**

1. **Model combinations.** The batmac model cannot be mixed with the solid or thick shell Randles models. It can, however, be used in conjunction with the meshless model.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

   with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose

of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a \*DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a \*DEFINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

## \*EM_RANDLES_EXOTHERMIC_REACTION

Purpose: Add an extra heat source term to the Randles circuit nodes to account for thermal runaway situations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|----------|---------|---|---|---|---|---|---|
| Variable | AREATYPE | FUNCTID | | | | | | |
| Type | I | I | | | | | | |
| Default | 2 | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| AREATYPE | Works the same way as RDLAREA in \*EM_RANDLES_SOLID or \*EM_RANDLES_TSHELL: |

> EQ.1: The heat source in FUNCTID is per unit area so that, for each local Randles circuit, the result returned by FUNCTID is multiplied by a factor areaLoc. areaLoc is the local area associated with each Randles circuit while areaGlob is the area of the whole cell. Unit consistency in SI: W*m2.

> EQ.2: The heat source in FUNCTID is for the whole cell (the whole cell is shorted), so that, for each Randles circuit, the result returned by FUNCTID is multiplied by a factor areaLoc/areaGlob (default). Unit consistency in SI: W.

> EQ.3: The heat source returned by FUNCTID is taken as is in each Randles circuit. Unit consistency in SI: W.

> EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

> EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

| | |
|----------|-------------|
| FUNCTID | DEFINE_FUNCTION ID giving the local heat source as a function of local parameters for the local Randles circuit. See Table 6-2 in \*EM_RANDLES. |

## \*EM_RANDLES_MESHLESS

Purpose: Define the distributed Randles circuit parameters for a Randles cell that is not associated with a mesh (lumped Randles circuit).

**Card Summary:**

**Card 1.** This card is required.

| RDLID | RDLTYPE | | | | | | |
|---|---|---|---|---|---|---|---|

**Card 2.** This card is required.

| Q | CQ | SOCINIT | SOCTOU | | | | |
|---|---|---|---|---|---|---|---|

**Card 3.** This card is required.

| R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
|---|---|---|---|---|---|---|---|

**Card 4.** This card is only read if RDLTYPE > 1. It is optional.

| R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
|---|---|---|---|---|---|---|---|

**Card 5.** This card is optional.

| TEMP | | | DUDT | TEMPU | | | |
|---|---|---|---|---|---|---|---|

**Card 6.** This card is optional.

| USESOCS | TAU | FLCID | | | | | |
|---|---|---|---|---|---|---|---|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RDLID | RDLTYPE | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RDLID | ID of the Randles cell |
| RDLTYPE | Type of Randles cell: |

                EQ.0: 0-order Randles cell

                EQ.1: 1-order Randles cell

                EQ.2: 2-order Randles cell

                EQ.3: 3-order Randles cell

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | Q | CQ | SOCINIT | SOCTOU | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| Q | Cell capacity |
| CQ | SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units. |
| SOCINIT | Initial state of charge of the cell |
| SOCTOU | Equilibrium voltage (OCV): |

                GE.0.0: Constant value

                LT.0.0: |SOCTOU| is a load curve ID defining the equilibrium voltage (OCV) as a function of the state of charge (SOC).

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|-------|-------|--------|--------|---|---|
| Variable | R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| R0CHA/ R10CHA/ C10CHA | $r_0/r_{10}/c_{10}$ when the current flows in the charge direction: <br> **GE.0.0:** Constant value <br> **LT.0.0:** Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |
| R0DIS/ R10DIS/ C10DIS | $r_0/r_{10}/c_{10}$ when the current flows in the discharge direction: <br> **GE.0.0:** Constant value <br> **LT.0.0:** Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Card for RDLTYPE > 1.** This card is only read if RDLTYPE is greater than 1. It is optional.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Variable | R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
| Type | F | F | F | F | F | F | F | F |
| Default | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |

| VARIABLE | DESCRIPTION |
|---|---|
| R20CHA/ R30CHA/ C20CHA/ C30CHA | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction:<br><br>**GE.0.0:** Constant value<br><br>**LT.0.0:** Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |
| R20DIS/ R30DIS/ C20DIS/ C30DIS | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction:<br><br>**GE.0.0:** Constant value.<br><br>**LT.0.0:** Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Thermal Card.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TEMP | | | DUDT | TEMPU | | | |
| Type | F | | | F | I | | | |
| Default | 0. | | | none | 0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| TEMP | Constant temperature value used for the Randles circuit parameters |
| DUDT | Reversible heat:<br><br>**GE.0.0:** Constant value<br><br>**LT.0.0:** \|DUDT\| is a load curve ID for the curve giving the reversible heat as a function of SOC. |
| TEMPU | Temperature unit:<br><br>**EQ.0:** Celsius |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: Kelvin |

**SOC shift Optional card.**

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | USESOCS | TAU | FLCID | | | | | |
| Type | I | F | I | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| USESOCS | Use SOCshift (see Remark 1): |
| |     EQ.0: Do not use the added SOCshift. |
| |     EQ.1: Use the added SOCshift. |
| TAU | Damping time in the SOCshift equation (see Remark 1) |
| FLCID | Load curve giving $f(i)$ where $i$ is the total current in the unit cell (see Remark 1) |

**Remarks:**

1. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

with $\text{SOCshift}(t = 0) = 0$.

## \*EM_RANDLES_TSHELL

Purpose: Define the distributed Randles circuit parameters for a Randles cell when using a composite tshell mechanical model.

**Card Summary:**

**Card 1.** This card is required.

| RDLID | RDLTYPE | RDLAREA | PSID | | | | |
|-------|---------|---------|------|--|--|--|--|

**Card 2.** This card is required.

| Q | CQ | SOCINIT | SOCTOU | | | | |
|---|----|---------|--------|--|--|--|--|

**Card 3.** This card is required.

| R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
|-------|-------|--------|--------|--------|--------|--|--|

**Card 4.** This is only read if RDLTYPE > 1. It is optional.

| R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
|--------|--------|--------|--------|--------|--------|--------|--------|

**Card 5.** This card is optional.

| TEMP | FRTHER | R0TOTH | DUDT | TEMPU | | | |
|------|--------|--------|------|-------|--|--|--|

**Card 6.** This card is optional.

| USESOCS | TAU | FLCID | | | | | |
|---------|-----|-------|--|--|--|--|--|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | RDLID | RDLTYPE | RDLAREA | PSID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | 2 | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

RDLID      ID of the Randles Cell

RDLTYPE      Type of Randles Cell:

      EQ.-1: User-defined equivalent circuit model. See Remark 3.

      EQ.0:  0-order Randles Cell

      EQ.1:  1-order Randles Cell

      EQ.2:  2-order Randles Cell

      EQ.3:  3-order Randles Cell

RDLAREA      Randles Area:

      EQ.1: The parameters are per unit area and will be scaled in each Randles circuit by a factor depending on the local area of the circuit. Unit consistency in SI: Ohms times square meters.

      EQ.2: The parameters are defined for the whole cell and will be scaled in each Randles circuit by a factor depending on the local area of the circuit and the global area of the cell (default). Unit consistency in SI: Ohms.

      EQ.3: The parameters are not scaled by area factors. Unit consistency in SI: Ohms.

PSID      Part set ID of all the parts composing the cell (see Remark 1)

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Q | CQ | SOCINIT | SOCTOU | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

Q      Cell capacity

CQ      SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SOCINIT | Initial state of charge of the cell |
| SOCTOU | Equilibrium voltage (OCV): |

GE.0.0: Constant value

LT.0.0: |SOCTOU| is a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC).

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| R0CHA/ R10CHA/ C10CHA | $r_0/r_{10}/c_{10}$ when the current flows in the charge direction: |

GE.0.0: Constant value

LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

R0DIS/ R10DIS/ C10DIS — $r_0/r_{10}/c_{10}$ when the current flows in the discharge direction:

GE.0.0: Constant value

LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

**Optional Card for RDLTYPE > 1.** This card is only read if RDLTYPE > 1. It is optional.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
| Type | F | F | F | F | F | F | F | F |
| Default | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |

| VARIABLE | DESCRIPTION |
|---|---|
| R20CHA/ R30CHA/ C20CHA/ C30CHA | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction: <br><br> GE.0.0: Constant value <br><br> LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |
| R20DIS/ R30DIS/ CDIS/ C30DIS | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction: <br><br> GE.0.0: Constant value <br><br> LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Thermal Card.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TEMP | FRTHER | R0TOTH | DUDT | TEMPU | | | |
| Type | F | I | I | F | I | | | |
| Default | 0. | 0 | 0 | 0.0 | 0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| TEMP | Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0) |
| FRTHER | Flag about where the temperature is coming from: |
| | EQ.0: The temperature used in the Randles circuit parameters is TEMP. |
| | EQ.1: The temperature used in the Randle circuit parameter is the temperature from the thermal solver. |
| R0TOTH | Flag for adding joule heating from $r_0$ to the thermal solve: |
| | EQ.0: The joule heating in the resistance $r_0$ is not added to the thermal solve. |
| | EQ.1: The joule heating in the resistance $r_0$ is added to the thermal solve. |
| DUDT | Reversible heat: |
| | GE.0.0: Constant value |
| | LT.0.0: |DUDT| is a load curve ID for the curve givig the reversible heat as a function of SOC. |
| TEMPU | Temperature unit: |
| | EQ.0: Celsius |
| | EQ.1: Kelvin |

**Optional SOCShift Card.**

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | USESOCS | TAU | FLCID | | | | | |
| Type | I | F | I | | | | | |
| Default | 0 | 0.0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| USESOCS | Use SOCshift (see Remark 2): |
|  | EQ.0: Do not use the added SOCshift. |
|  | EQ.1: Use the added SOCshift. |
| TAU | Damping time in the SOCshift equation (see Remark 2) |
| FLCID | Load curve giving $f(i)$ where $i$ is the total current in the unit cell (see Remark 2) |

**Remarks:**

1. **Sectioning of a circuit.** \*PART_COMPOSITE_TSHELL defines each part of PSID. With this keyword for defining the part, each layer of a part can serve a different function, namely, as a current collector positive, current collector negative, separator, negative electrode, or positive electrode. The RDLTYPE field of \*EM_MAT_001 sets a given layer's function.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOCshift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

   with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a \*DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a \*DEFINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

## *EM_RANDLES_SHORT

Purpose: For a battery cell internal short, define conditions to turn on a Randles short (replace one or several Randles circuits by resistances). Also, define the value of the short resistance.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | AREATYPE | FUNCTID | | | | | | |
| Type | I | I | | | | | | |
| Default | 2 | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| AREATYPE | Works the same way as RDLAREA in *EM_RANDLES_SOLID or *EM_RANDLES_TSHELL: |

EQ.1: The resistance inverse in FUNCTID is per unit area so that, for each local Randles circuit, the result returned by FUNCTID is multiplied by a factor 1./areaLoc (areaLoc is the local area associated with each Randles circuit, while areaGlob is the area of the whole cell). Unit consistency in SI: Ohms times square meters.

EQ.2: The resistance in FUNCTID is for the whole cell (the whole cell is shorted), so that, for each Randles circuit, the result returned by FUNCTID is multiplied by a factor areaGlob/areaLoc (default). Unit consistency in SI: Ohms.

EQ.3: The resistance returned by FUNCTID is taken as is for each Randles circuit. Unit consistency in SI:Ohms.

EQ.11: Same as 1, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

EQ.22: Same as 2, except the parameters are defined for the whole cell and are scaled in each Randles circuit by a factor depending on the local volume of the circuit and the global volume of the cell.

| VARIABLE | DESCRIPTION |
|----------|-------------|
| FUNCTID | Function ID (see \*DEFINE_FUNCTION) for the function giving the local resistance function of local parameters for the local Randles circuit. See Remark 1. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. |

**Remarks:**

1. **Short criterion.** If the return value of the function is zero, there is no short. The Randles circuit is maintained. A positive returned value causes replacing the Randles circuit with the returned short resistance. To ensure that the short is maintained even after the original criterion is no longer met, the default positive value may be replaced by a negative value. The solver then takes the absolute value returned and adopts it as the new short resistance in case the original short criterion is no longer met rather than reverting to a Randles circuit.

2. **\*Example \*DEFINE_FUNCTION.** The following partial input provides an example of a function:

```
*DEFINE_FUNCTION
FID (Function Id)
Float resistance_short_randle(
float time,
float x_ccp,float y_ccp,float z_ccp,
float x_sep,float y_sep,float z_sep,
float x_sem,float y_sem,float z_sem,
float x_ccm,float y_ccm,float z_ccm)
{
  float seThick0;
  seThick0=1.e-5;
  seThick=(sqrt(x_sep-x_sem)^2+(y_sep-y_sem)^2+(z_sep-z_sem)^2);
  if (seThick >= seThick0) then
  return 1.e-2;
  else
  return -1.e-3;
  endif
}
```

In this example, as long as seThick is smaller than seThick0, no short occurs. Once seThick becomes larger than seThick0, a short occurs, and the short resistance is 1.e-2. If during the run, seThick once again becomes smaller than seThick0, the short is maintained and the short resistance becomes 1.e-3. Replacing 1.e-3 by 0.0 causes the short to revert to the original Randles circuit.

3. **Erosion.** For the solid model (see \*EM_RANDLES_SOLID), when an erosion-based criterion is defined, the erosion variable, ero, enables distinguishing which component of the battery has been eroded and adjusts the short resistance law accordingly:

a)  ero = 1 when the eroded element comes from the positive current collector.

b)  ero = 10 when the eroded element comes from the negative current collector.

c)  ero = 100 when the eroded element comes from the separator.

d)  ero = 1000 when the eroded element comes from the positive electrode.

e)  ero = 10000 when the eroded element comes from the negative electrode.

When multiple components have eroded elements, ero is the sum of the indicators. For example, a returned value of 1001 indicates that both the elements coming from the positive electrode and the positive current collector have been eroded.

## \*EM_RANDLES_SOLID

Purpose: Define the distributed Randles circuit parameters for a Randles cell when using a solid mechanical model.

### Card Summary:

**Card 1.** This card is required.

| RDLID | RDLTYPE | RDLAREA | CCPPART | CCNPART | SEPPART | PELPART | NELPART |
|-------|---------|---------|---------|---------|---------|---------|---------|

**Card 2.** This card is required.

| Q | CQ | SOCINIT | SOCTOU | | | | |
|---|----|---------|--------|---|---|---|---|

**Card 3.** This card is required.

| R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
|-------|-------|--------|--------|--------|--------|---|---|

**Card 4.** This card is only read for RDLTYPE > 1. It is optional.

| R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
|--------|--------|--------|--------|--------|--------|--------|--------|

**Card 5.** This card is optional.

| TEMP | FRTHER | R0TOTH | DUDT | TEMPU | | | |
|------|--------|--------|------|-------|---|---|---|

**Card 6.** This card is optional.

| USESOCS | TAU | FLCID | | | | | |
|---------|-----|-------|---|---|---|---|---|

### Data Card Definitions:

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | RDLID | RDLTYPE | RDLAREA | CCPPART | CCNPART | SEPPART | PELPART | NELPART |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| RDLID | ID of the Randles Cell |
| RDLTYPE | Type of Randles Cell:<br><br>EQ.-1: User-defined equivalent circuit model.  See Remark 3.<br><br>EQ.0:  0-order Randles Cell<br><br>EQ.1:  1-order Randles Cell<br><br>EQ.2:  2-order Randles Cell<br><br>EQ.3:  3-order Randles Cell |
| RDLAREA | Randles Area:<br><br>EQ.1: The parameters are per unit area and will be scaled in each Randles circuit by a factor depending on the local area of the circuit.  Unit consistency in SI: Ohms times square meters.<br><br>EQ.2: The parameters are defined for the whole cell and will be scaled in each Randles circuit by a factor depending on the local area of the circuit and the global area of the cell (default).  Unit consistency in SI: Ohms.<br><br>EQ.3: The parameters are not scaled by area factors.  Unit consistency in SI: Ohms. |
| CCPPART | Current collector positive (CCP) part ID |
| CCNPART | Current collector negative (CCN) part ID |
| SEPPART | Separator part ID |
| PELPART | Positive electrode part ID |
| NELPART | Negative electrode part ID |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Q | CQ | SOCINIT | SOCTOU | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| Q | Cell capacity |
| CQ | SOC conversion factor (%/s). It is known to be equal to 1/36 in SI units. |
| SOCINIT | Initial state of charge of the cell |
| SOCTOU | Equilibrium voltage (OCV): |

           GE.0.0: Constant value

           LT.0.0: |SOCTOU| can refer to a load curve ID defining equilibrium voltage (OCV) as a function of the state of charge (SOC) or to a table ID with temperature indexing load curves that give OCV as a function of SOC.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R0CHA | R0DIS | R10CHA | R10DIS | C10CHA | C10DIS | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|
| R0CHA/ R10CHA/ C10CHA | $r_0/r_{10}/c_{10}$ when the current flows in the charge direction: |

           GE.0.0: Constant value

           LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature.

| | |
|---|---|
| R0DIS/ R10DIS/ C10DIS | $r_0/r_{10}/c_{10}$ when the current flows in the discharge direction: |

           GE.0.0: Constant value

           LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit

| VARIABLE | DESCRIPTION |
|---|---|
| | parameters can be made a function of the SOC and temperature. |

**Optional Card for RDLTYPE > 1.** This card is only read for RDLTYPE greater than 1. It is optional.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | R20CHA | R20DIS | C20CHA | C20DIS | R30CHA | R30DIS | C30CHA | C30DIS |
| Type | F | F | F | F | F | F | F | F |
| Default | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |

| VARIABLE | DESCRIPTION |
|---|---|
| R20CHA/ R30CHA/ C20CHA/ C30CHA | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the charge direction:<br><br>GE.0.0: Constant value<br><br>LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |
| R20DIS/ R30DIS/ C20DIS/ C30DIS | $r_{20}/r_{30}/c_{20}/c_{30}$ when the current flows in the discharge direction:<br><br>GE.0.0: Constant value<br><br>LT.0.0: Absolute value is a function (see \*DEFINE_FUNCTION) or table ID. See Table 6-2 in \*EM_RANDLES for the accepted function arguments. For a table, the circuit parameters can be made a function of the SOC and temperature. |

**Optional Thermal Card.**

| Card 5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|--------|--------|------|-------|---|---|---|
| Variable | TEMP | FRTHER | R0TOTH | DUDT | TEMPU | | | |
| Type | F | I | I | F | I | | | |
| Default | 0. | 0 | 0 | 0.0 | 0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TEMP | Constant temperature value used for the Randles circuit parameters when there is no coupling with the thermal solver (FRTHER = 0) |
| FRTHER | Flag about where the temperature is coming from: |
| | EQ.0: The temperature used in the Randles circuit parameters is TEMP. |
| | EQ.1: The temperature used in the Randle circuit parameter is the temperature from the thermal solver. |
| R0TOTH | Flag for adding joule heating from $r_0$ to the thermal solve: |
| | EQ.0: The joule heating in the resistance $r_0$ is not added to the thermal solve. |
| | EQ.1: The joule heating in the resistance $r_0$ is added to the thermal solve. |
| DUDT | Reversible heat: |
| | GE.0.0: Constant value |
| | LT.0.0: $|DUDT|$ is a load curve ID for the curve giving the reversible heat as a function of SOC. |
| TEMPU | Temperature unit: |
| | EQ.0: Celsius |
| | EQ.1: Kelvin |

**Optional SOC Shift Card.**

| Card 6 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-------|---|---|---|---|---|
| Variable | USESOCS | TAU | FLCID | | | | | |
| Type | I | F | I | | | | | |
| Default | 0 | 0.0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

USESOCS    Use SOCshift (see Remark 2):

       EQ.0: Do not use the added SOCshift.

       EQ.1: Use the added SOCshift.

TAU    Damping time in the SOCshift equation (see Remark 2)

FLCID    Load curve giving $f(i)$ where $i$ is the total current in the unit cell (see Remark 2)

**Remarks:**

1. **Element normal vector orientation.** The solid element normal vectors must all be oriented in the direction pointing from the positive current collector to the negative current collector to detect which current collector nodes are connected to one another. Furthermore, any number of layers can be modeled, but the meshes of the CCP, anode, separator, cathode, and CCN must be continuous and have merged nodes at the boundaries.

2. **Accounting for diffusion limitations.** Sometimes, an extra term called SOC-shift (or SocS) can be added to high-rate discharges to account for diffusion limitations. The SOCshift is added to SOC for the calculation of the OCV, $u(\text{SOC} + \text{SOCshift})$, and $r_0(\text{SOC} + \text{SOCshift})$. SOCshift satisfies the following equation:

$$\frac{d(\text{SOCshift})}{dt} + \frac{\text{SOCshift}}{\tau} = \frac{f(i(t))}{\tau}$$

with $\text{SOCshift}(t = 0) = 0$.

3. **User-defined ECMs.** Randles circuits are based on the finite element Robin boundary condition, acting similarly to a convection boundary condition for the heat equation. As such, the circuit equation is decomposed into a term that

enters the left-hand side of the stiffness matrix and a term that is added to the right-hand side. Changing the definition of those terms permits replacing the Randles circuits with any type of Equivalent Circuit model (ECM). This is the purpose of RDLTYPE = -1 where the term entering the left-hand side is defined by a negative integer referring to a \*DEFINE_FUNCTION ID in R0CHA (unit consistency: resistance) while a negative integer in R0DIS associated with a \*DE-FINE_FUNCTION gives the term entering in the right-hand side (unit consistency: current).

## \*EM_ROTATION_AXIS

Purpose: Define a rotation axis for the EM solver. This keyword is used with the 2D axisymmetric solver. The axis is defined by a point and a direction.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | XP | YP | ZP | XD | YD | ZD | NUMSEC | |
| Type | F | F | F | F | F | F | I | |
| Default | none | none | none | none | none | none | none | |

**Optional Card.** Define an additional vector normal to the rotation vector that gives the rotation direction. See Remark 1.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | XT | YT | ZT | XH | YH | ZH | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|
| XP, YP, ZP | $x$, $y$, and $z$ coordinates of the point |
| XD, YD, ZD | $x$, $y$, and $z$ components of direction of the axis |
| NUMSEC | Number of sectors. This field gives the ratio of the full circle to the angular extension of the mesh. This has to be a power of two. For example, NUMSEC = 4 means that the mesh of the part represents one-fourth of the total circle. If NUMSEC = 0 for \*EM_2DAXI, the solver replaces it with this value. |
| XT/YT/ZT and XH/YH/ZH | Tail and head coordinates of the additional vector orthogonal to the rotation axis that gives the direction of the rotation. See Remark 1. |

**Remarks:**

1. **Simplified 2D axisymmetric input.** Starting with R15, the EM 2D axisymmetric solver enables specifying an additional vector orthogonal to the rotation axis that provides the rotation direction. When used, \*EM_2DAXI is no longer needed. Also, SIDCUR, SIDVIN, and SIDVOUT in \*EM_CIRCUIT are no longer needed, but PID becomes mandatory. This results in a simplified input deck (fewer segment sets and keywords need to be defined).

**\*EM_SOLVER_BEM**

Purpose: Define the type of linear solver and pre-conditioner as well as tolerance for the EM_BEM solve.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | RELTOL | MAXITE | STYPE | PRECON | USELAST | NCYLBEM | | |
| Type | I | I | I | I | I | I | | |
| Default | $10^{-6}$ | 1000 | 2 | 2 | 1 | 5000 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RELTOL | Relative tolerance for the iterative solvers (PCG or GMRES). If the results are not accurate enough, the user should try to decrease this tolerance. More iterations will then be needed. |
| MAXITER | Maximum number of iterations for the iterative solvers |
| STYPE | Solver type: |

        EQ.1: Direct solve. The matrices are considered dense.

        EQ.2: Pre-conditioned gradient method (PCG). This method allows for block matrices with low-rank blocks and thus reduces the memory used.

        EQ.3: GMRES method. This method allows for block matrices with low-rank blocks and thus reduces the memory used. The GMRES option only works in serial for now.

| PRECON | Preconditioner type for PCG or GMRES iterative solves: |

        EQ.-1: No preconditioner

        EQ.1:  Diagonal line

        EQ.2:  Diagonal block (default)

        EQ.3:  Broad diagonal including all neighbor faces

        EQ.4:  LLT factorization

| USELAST | Only used for iterative solvers (PCG or GMRES). |

        EQ.-1: Start from 0 as the initial guess for the solution of the

| VARIABLE | DESCRIPTION |
|---|---|
| | linear system. |
| | EQ.1: Starts from the previous solution normalized by the RHS change. See Remark 1. |
| NCYLBEM | Number of electromagnetism cycles between the recalculation of BEM matrices. If negative, the absolute value refers to a load curve giving the number of cycles as a function of time. See Remarks 2 and 3. |

**Remarks:**

1.  **USELAST.** Using USELAST = 1 can save many iterations in the subsequent solves if the vector solution of the present solve can be assumed to be nearly parallel to the vector solution of the previous solve, as usually happens in time-domain eddy-current problems.

2.  **Moving conductors.** Since the BEM matrices depend on (and only on) the surface node coordinates of the conductors, recalculating them when the conductors are moving is important. NCYLBEM controls the frequency with which they are updated. Note that very small values, for example, NCYLBEM = 1, should, generally, be avoided since this calculation involves a high computational cost. However, when two conductors are moving and in contact with each other, we recommend recalculating the matrices at *every* time step.

3.  **Order of precedence for NCYLBEM.** You can set NCYLBEM with \*EM_CON-TROL_SOLUTION, \*EM_SOLVER_FEM/BEM, and \*EM_CONTROL. \*EM_-CONTROL_SOLUTION has the highest priority for setting this field. If NCYLBEM is the default value on \*EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of NCYLBEM on \*EM_SOLVER_BEM. If left as default on this keyword, LS-DYNA looks at the setting of NCYLBEM on \*EM_CONTROL.

## \*EM_SOLVER_BEM_REASSEMBLY

Purpose: Specify the domain decomposition method, and for certain domain decomposition methods, request storing portions of the BEM matrices to save calculation time during BEM system recomputations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | IOCT | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PSID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| IOCT | Octree domain decomposition method (see Remark 1): |

      EQ.0: BEM faces are grouped in domains based on their proximity.

      EQ.1: Same as 0 except the BEM faces from a given domain must belong to the same part. In addition, portions of the BEM matrix can be stored by specifying the parts for storage in PSID on Card 2.

| | |
|---|---|
| PSID | Part sets IDs for which BEM information is kept. Ignored for IOCT = 0. See Remark 2. |

**Remarks:**

1.  **IOCT.** The domain decomposition method of the BEM faces is typically handled internally and is not of direct practical use to the user. Switching between IOCT = 0 and IOCT = 1 may slightly impact the calculation times one way or another, depending on the case studied. However, it should not significantly affect any calculation result, as only the order of some operations will vary. Using IOCT = 1 allows for storing in memory BEM information that belongs to certain parts throughout the calculation, which in turn saves calculation time during subsequent BEM matrices reassemblies. The parts are selected with part set IDs specified on Card 2.

2.  **Rigid parts.** The parts that belong to the various PSIDs should only belong to non-deformable structures (typically rigid bodies) that do not move relative to each other.

**\*EM_SOLVER_BEMMAT**

Purpose: Define the type of BEM matrices as well as the way they are assembled.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|--------|
| Variable | MATID | | | | | | | RELTOL |
| Type | I | | | | | | | F |
| Default | none | | | | | | | $10^{-6}$ |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MATID | Defines which BEM matrix the card refers to:<br><br>EQ.1: **P** matrix<br><br>EQ.2: **Q** matrix<br><br>EQ.3: **W** matrix |
| RELTOL | Relative tolerance on the sub-blocks of the matrix when doing low rank approximations. The user should try to decrease these tolerances if the results are not accurate enough. More memory will then be needed. |

**Remarks:**

1. The **W** matrix only exists when the monolithic solver is activated (see \*EM_-SOLVER_FEMBEM_MONOLITHIC).

## \*EM_SOLVER_FEM

Purpose: Define some parameters for the EM FEM solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|--------|-------|--------|---------|---------|---|---|
| Variable | RELTOL | MAXITE | STYPE | PRECON | USELAST | NCYLFEM | | |
| Type | I | I | I | I | I | I | | |
| Default | $10^{-3}$ | 1000 | 1 | 1 | 1 | 5000 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RELTOL | Relative tolerance for the iterative solvers (PCG). If the results are not accurate enough, try decreasing this tolerance. More iterations will then be needed. |
| MAXITER | Maximum number of iterations for iterative solvers |
| STYPE | Solver type:<br>EQ.1: Direct solve<br>EQ.2: Pre-conditioned Gradient Method (PCG) |
| PRECON | Preconditioner type for PCG.<br>EQ.0: No preconditioner<br>EQ.1: Diagonal line |
| USELAST | This is used only for iterative solvers (PCG).<br>EQ.-1: Starts from 0 as the initial solution of the linear system.<br>EQ.1: Starts from the previous solution normalized by the right-hand-side change. See Remark 1. |
| NCYLFEM | Number of electromagnetism cycles between the recalculation of FEM matrices. If negative, the absolute value refers to a load curve giving NCYCLFEM as a function of time. See Remarks 2 and 3. |

**Remarks:**

1. **Starting from the previous solution.** Using USELAST = 1 can save many iterations in the subsequent solves if the vector solution of the present solve can be assumed to be nearly parallel to the vector solution of the previous solve, as usually happens in time-domain eddy-current problems.

2. **NCYLFEM.** When the conductor parts are deforming or undergoing changes in their EM material properties (conductivity for example), the FEM matrices should be recalculated more often, so NCYLFEM may need to be changed.

3. **Order of precedence for NCYLFEM.** You can set NCYLFEM with \*EM_CONTROL_SOLUTION, \*EM_SOLVER_FEM, and \*EM_CONTROL. \*EM_CONTROL_SOLUTION has the highest priority for setting this field. If NCYLFEM is the default value on \*EM_CONTROL_SOLUTION, LS-DYNA looks at the setting of NCYLFEM on \*EM_SOLVER_FEM. If left as default on this keyword, LS-DYNA looks at the setting on \*EM_CONTROL.

**\*EM_SOLVER_FEMBEM**

Purpose: Define some parameters for the standard coupling between the EM_FEM and EM_BEM solvers.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | RELTOL | MAXITE | FORCON | | | | | |
| Type | F | I | I | | | | | |
| Default | $10^{-2}$ | 50 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RELTOL | Relative tolerance for the FEM/BEM system solve. If the results are not accurate enough, try decreasing this tolerance. A smaller tolerance will, however, require more iterations. |
| MAXITER | Maximal number of iterations |
| FORCON | Force convergence:<br><br>EQ.0: The code stops with an error if no convergence.<br><br>EQ.1: The code continues to the next time step even if the REL-TOL convergence criteria has not been reached. |

**Remarks:**

This keyword couples the FEM and BEM systems with the Richardson method. At each time step, the solver will iterate between the FEM and the BEM system until reaching convergence (based on the choice of RELTOL and MAXITER). The cost for this solve is low. However, to ensure stability, we recommend imposing a limit on the timestep based on the characteristic diffusion time (See \*EM_CONTROL_TIMESTEP). Furthermore, it can be unstable whenever magnetic materials are involved (conductor's permeability different than vacuum permeability). The monolithic solver invoked with \*EM_SOLVER_-FEMBEM_MONOLITHIC aims to remove those two limitations by solving both the FEM and BEM systems in one single monolithic bloc. For such cases, it is, therefore, the recommended choice (See \*EM_SOLVER_FEMBEM_MONOLITHIC).

## *EM_SOLVER_FEMBEM_MONOLITHIC

Purpose: Replaces *EM_SOLVER_FEMBEM and turns on the monolithic FEM-BEM solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MTYPE | STYPE | ABSTOL | RELTOL | MAXIT | | | |
| Type | I | I | F | F | I | | | |
| Default | 0 | 0 | $10^{-6}$ | $10^{-4}$ | 500 | | | |

**Optional Card.** Optional card for nonlinear magnetic cases.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | NTSTOL | NTATOL | NTRTOL | NTMIT | | | |
| Type | | F | F | F | I | | | |
| Default | | $10^{-5}$ | $10^{-12}$ | $10^{-4}$ | 20 | | | |

**Optional Card.** Optional card for nonlinear magnetic cases.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LS_ON | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MTYPE | Monolithic solver type: |
| | EQ.0: Direct symmetric solver |

| VARIABLE | DESCRIPTION |
| --- | --- |
| STYPE | Solver type: |
| |     EQ.0: MINRES iterative solver |
| |     EQ.1: GMRES iterative solver |
| ABSTOL | Absolute tolerance |
| RELTOL | Relative tolerance |
| MAXIT | Maximum number of iterations |
| NTSTOL/NTATOL/ NTROL | Solution change tolerance, absolute tolerance, and relative tolerance used during the nonlinear Newton step. These tolerances only apply when the EM model includes nonlinear magnetic materials. |
| NTMIT | Maximum nonlinear iterations |
| LS_ON | Line search: |
| |     EQ.0: Off |
| |     EQ.1: On (only used for nonlinear magnetic materials) |

**Remarks:**

The monolithic solver aims to overcome the limitations of the classic Richardson iterative coupling between the FEM and BEM systems. The monolithic solver offers better stability for large timesteps and for simulations involving ferromagnetic materials. We recommend this method whenever the \*EM_MAT_002 keyword is present.

# *ICFD

The keyword *ICFD covers all the different options available in the incompressible fluid solver. The keyword cards in this section are defined in alphabetical order:

*ICFD_BOUNDARY_CONJ_HEAT

*ICFD_BOUNDARY_CONVECTION_TEMP

*ICFD_BOUNDARY_FLUX_SPECIES

*ICFD_BOUNDARY_FLUX_TEMP

*ICFD_BOUNDARY_FREESLIP

*ICFD_BOUNDARY_FSI

*ICFD_BOUNDARY_FSI_EXCLUDE

*ICFD_BOUNDARY_FSI_FIXED

*ICFD_BOUNDARY_FSI_ONEWAY

*ICFD_BOUNDARY_FSWAVE

*ICFD_BOUNDARY_GROUND

*ICFD_BOUNDARY_NAVIERSLIP

*ICFD_BOUNDARY_NONSLIP

*ICFD_BOUNDARY_PERIODIC

*ICFD_BOUNDARY_PRESCRIBED_LEVELSET

*ICFD_BOUNDARY_PRESCRIBED_MOVEMESH

*ICFD_BOUNDARY_PRESCRIBED_PRE

*ICFD_BOUNDARY_PRESCRIBED_SPTRANSP_CONC

*ICFD_BOUNDARY_PRESCRIBED_TEMP

*ICFD_BOUNDARY_PRESCRIBED_TURBULENCE

*ICFD_BOUNDARY_PRESCRIBED_VEL

*ICFD_BOUNDARY_PRESCRIBED_VISCOELASTIC

# *ICFD

*ICFD_BOUNDARY_WEAKVEL

*ICFD_BOUNDARY_WINDKESSEL

*ICFD_CONTROL_ADAPT

*ICFD_CONTROL_ADAPT_SIZE

*ICFD_CONTROL_ADVECTION

*ICFD_CONTROL_BACKFLOW

*ICFD_CONTROL_CONJ

*ICFD_CONTROL_DEM_COUPLING

*ICFD_CONTROL_EMBEDSHELL

*ICFD_CONTROL_FSI

*ICFD_CONTROL_GAP

*ICFD_CONTROL_GENERAL

*ICFD_CONTROL_IMMERSED

*ICFD_CONTROL_IMPOSED_MOVE

*ICFD_CONTROL_LEVELSET

*ICFD_CONTROL_LOAD

*ICFD_CONTROL_MESH

*ICFD_CONTROL_MESH_MOV

*ICFD_CONTROL_MONOLITHIC

*ICFD_CONTROL_OUTPUT

*ICFD_CONTROL_OUTPUT_SUBDOM

*ICFD_CONTROL_OUTPUT_VAR

*ICFD_CONTROL_PARTITION

*ICFD_CONTROL_POROUS

*ICFD_CONTROL_STEADY

*ICFD_CONTROL_SURFMESH

\*ICFD_CONTROL_TAVERAGE

\*ICFD_CONTROL_TIME

\*ICFD_CONTROL_TRANSIENT

\*ICFD_CONTROL_TURB_SYNTHESIS

\*ICFD_CONTROL_TURBULENCE

\*ICFD_DATABASE_AVERAGE

\*ICFD_DATABASE_DRAG

\*ICFD_DATABASE_FLUX

\*ICFD_DATABASE_FLUXSURF

\*ICFD_DATABASE_FORCE_DEM

\*ICFD_DATABASE_GOA

\*ICFD_DATABASE_HTC

\*ICFD_DATABASE_NODEAVG

\*ICFD_DATABASE_NODOUT

\*ICFD_DATABASE_NTEMPOUT

\*ICFD_DATABASE_POINTAVG

\*ICFD_DATABASE_POINTOUT

\*ICFD_DATABASE_RESIDUALS

\*ICFD_DATABASE_SSOUT

\*ICFD_DATABASE_SSOUT_EXCLUDE

\*ICFD_DATABASE_TEMP

\*ICFD_DATABASE_TIMESTEP

\*ICFD_DATABASE_TPD

\*ICFD_DATABASE_TWINBUILDER

\*ICFD_DATABASE_UINDEX

\*ICFD_DATABASE_WETNESS

# *ICFD

*ICFD_DEFINE_HEATSOURCE

*ICFD_DEFINE_HEMOLYSIS_INDEX

*ICFD_DEFINE_NONINERTIAL

*ICFD_DEFINE_POINT

*ICFD_DEFINE_POROUS_REGION

*ICFD_DEFINE_RESIDENCETIMESOURCE

*ICFD_DEFINE_SOURCE

*ICFD_DEFINE_SPTRANSPSOURCE

*ICFD_DEFINE_TRANSFORM

*ICFD_DEFINE_TURBSOURCE

*ICFD_DEFINE_WAVE_DAMPING

*ICFD_INITIAL

*ICFD_INITIAL_LEVELSET

*ICFD_INITIAL_SPTRANSP

*ICFD_INITIAL_TEMPNODE

*ICFD_INITIAL_TURBULENCE

*ICFD_MAT

*ICFD_MODEL_NONNEWT

*ICFD_MODEL_POROUS

*ICFD_MODEL_SPECIES_TRANSPORT

*ICFD_MODEL_VISCOELASTIC

*ICFD_PART

*ICFD_PART_VOL

*ICFD_SECTION

*ICFD_SET_NODE

*ICFD_SOLVER_SPLIT

\*ICFD_SOLVER_TOL_FSI

\*ICFD_SOLVER_TOL_LSET

\*ICFD_SOLVER_TOL_MMOV

\*ICFD_SOLVER_TOL_MOM

\*ICFD_SOLVER_TOL_MONOLITHIC

\*ICFD_SOLVER_TOL_PRE

\*ICFD_SOLVER_TOL_TEMP

## \*ICFD_BOUNDARY_CONJ_HEAT

Purpose: Specify which boundary of the fluid domain will exchange heat with the solid.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|------|--------|---|---|---|---|
| Variable | PID | CTYPE | VAL | SFLCID | | | | |
| Type | I | I | F | I | | | | |
| Default | none | 0 | 0. | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | PID of the fluid surface in contact with the solid |
| CTYPE | Contact type:<br><br>EQ.0: Constraint approach<br><br>EQ.1: Mortar contact |
| VAL | Optional temperature drop if CTYPE = 0 or interface heat transfer coefficient if CTYPE = 1 (high value by default to ensure perfect contact). |
| SFLCID | Load curve ID used to describe scale factor on VAL value as a function of time; see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |

**\*ICFD_BOUNDARY_CONVECTION_TEMP**

Purpose: Impose a heat transfer coefficient on the boundary expressed as $h = \frac{q}{T_s - T_b}$

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | HLCID | HSF | TBLCID | TBSF | | | |
| Type | I | I | F | I | F | | | |
| Default | none | none | 1. | none | 1.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID for a fluid surface. |
| HLCID | Load curve ID to describe the heat transfer coefficient value versus time, see \*DEFINE_CURVE,\*DEFINE_CURVE_FUNCTION or \*DEFINE_FUNCTION. If a DEFINE_FUNCTION is used, the following parameters are allowed: $f(x, y, z, vx, vy, vz, temp, pres, time)$. |
| HSF | Load curve scale factor applied on the heat transfer coefficient value. (default = 1.0) |
| TBLCID | Load curve ID to describe the environment (i.e bulk) temperature value versus time, see \*DEFINE_CURVE,\*DEFINE_CURVE_-FUNCTION or \*DEFINE_FUNCTION. If a DEFINE_FUNCTION is used, the following parameters are allowed: $f(x, y, z, vx, vy, vz, temp, pres, time)$. |
| TBSF | Load curve scale factor applied on the environment value. (default = 1.0) |

## \*ICFD_BOUNDARY_FLUX_SPECIES

Purpose: Specify the fluxes of concentration for the transported species at the boundaries.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| Variable | LCID1 | LCID2 | LCID3 | LCID4 | LCID5 | LCID6 | LCID7 | LCID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the boundary with the concentrations flux boundary conditions |
| LCID$i$ | Load curve ID for the curve giving the flux of concentration of species $i$ at the boundary as a function of time. Note that all the transported species must have a load curve defined. For instance, in the four-species case, LCID1, LCID2, LCID3, and LCID4 must be specified. |

**\*ICFD_BOUNDARY_FLUX_TEMP**

Purpose: Impose a heat flux on the boundary expressed as $q = -k\nabla T$

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|---------|-------|---|---|---|
| Variable | PID | LCID | SF | DEATH | BIRTH | | | |
| Type | I | I | F | F | F | | | |
| Default | none | none | 1. | 1.E+28 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | PID for a fluid surface. |
| LCID | Load curve ID to describe the temperature flux value versus time, see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION or \*DEFINE_FUNCTION. . If a DEFINE_FUNCTION is used, the following parameters are allowed: $f(x, y, z, vx, vy, vz, temp, pres, time)$. |
| SF | Load curve scale factor. (default = 1.0) |
| DEATH | Time at which the imposed motion/constraint is removed:<br><br>EQ.0.0: default set to 10e28 |
| BIRTH | Time at which the imposed pressure is activated starting from the initial abscissa value of the curve |

## \*ICFD_BOUNDARY_FREESLIP

Purpose: Specify the fluid boundary with free-slip boundary condition.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the fluid surface where a free-slip boundary condition is applied |

## *ICFD_BOUNDARY_FSI

Purpose: Defines which fluid surfaces will be considered in contact with the solid surfaces for fluid-structure interaction (FSI) analysis. This keyword should not be defined if *ICFD_CONTROL_FSI is not defined.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the fluid surface in contact with the solid domain |

### \*ICFD_BOUNDARY_FSI_EXCLUDE

Purpose: Specify which solid part IDs are excluded from the FSI search. No forces coming from the fluid will be transmitted to those parts.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of a part from the solid mechanics problem that is to be excluded from the FSI analysis |

## \*ICFD_BOUNDARY_FSI_FIXED

Purpose: Define fixed fluid surfaces that will be considered for contact with the solid surfaces for FSI. This keyword is similar to \*ICFD_BOUNDARY_FSI, except the fluid surface cannot move. This restriction allows a solid surface to "slide" over the fluid and for the exchange of data, such as temperature in CHT applications. This keyword should not be defined if \*ICFD_CONTROL_FSI is not defined.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the fluid surface that can be considered for contact with the solid domain |

## *ICFD_BOUNDARY_FSI_ONEWAY

Purpose: Specify which solid part IDs experience one-way FSI coupling. These part IDs follow the structural motion to capture the structural deformation.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | IOWC | | | | | | |
| Type | I | I | | | | | | |
| Default | none | 1 | | | | | | |

|          VARIABLE          |                                  DESCRIPTION                                  |
|---|---|

PID             Part ID of a part from the solid mechanics problem for which only one-way FSI coupling occurs

IOWC            Indicates the coupling direction to the solver:

EQ.1:   The solid mechanics solver transfers displacements to the fluid solver.

EQ.2:   The fluid solver transfers stresses to the solid mechanics solver.

## \*ICFD_BOUNDARY_FSWAVE

Purpose: Impose a wave inflow boundary condition.

**Card Summary:**

**Card Sets.** Include as many sets of the following cards as needed. This input ends with the next keyword ("\*") card.

**Card 1.** This card is required.

| PID | WTYPE | H0 | WAMP | WLENG | WMAX | SFLCID | WANG |
|-----|-------|-----|------|-------|------|--------|------|

**Card 2.** This card is included if WTYPE = 7.

| WPEAK | | | | | | | |
|-------|--|--|--|--|--|--|--|

**Data Card Definitions:**

Include as many of this card and/or sets of this card with the next as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|------|------|-------|------|--------|------|
| Variable | PID | WTYPE | H0 | WAMP | WLENG | WMAX | SFLCID | WANG |
| Type | I | I | F | F | F | F | I | F |
| Default | none | none | none | none | none | none | ↓ | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | PID for a fluid surface |
| WTYPE | Wave type: |

       EQ.1: Stokes wave of first order

       EQ.2: Stokes wave of second order

       EQ.3: Stokes wave of fifth order

       EQ.4: Solitary wave

       EQ.5: Irregular waves using JONSWAP spectrum

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.6: Irregular waves using One Parameter Pierson-Moskowitz spectrum |
| | EQ.7: Irregular waves using Two Parameter Pierson-Moskowitz spectrum |
| H0 | Water level (from the bottom of the channel) for the unperturbed condition |
| WAMP | Wave amplitude or height for WTYPE = 1 and 4. Significant wave height for WTYPE = 5, 6, and 7. |
| WLENG | WTYPE.LE.2: Wave length<br><br>WTYPE.EQ.3: Wave period<br><br>WTYPE.EQ.4: Not used<br><br>WTYPE.GE.5: Minimum wave frequency in spectrum (rad/sec) |
| WMAX | Maximum wave frequency in spectrum (rad/sec) for WTYPE = 5, 6, and 7. Angle between the boundary and the incident waves (in degrees) for WTYPE = 3. |
| SFLCID | Scale factor LCID on the wave amplitude for WTYPE = 1, 2 and 3. Number of wave modes (default = 1024) for WTYPE = 5, 6, and 7. |
| WANG | Angle between incoming wave direction and *x*-axis for *z*- and *y*-aligned gravity vector, or angle between incoming wave direction and *y*-axis for *x*-aligned gravity vector. |

Card included for WTYPE = 7 only

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | WPEAK | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| WPEAK | Peak wave frequency in spectrum [rad/sec] for WTYPE = 7. |

**Remarks:**

1.  **Peak Wave Frequency for WTYPE = 6.** For the irregular waves using the One Parameter Pierson-Moskowitz spectrum, the peak wave frequency in the spectrum LS-DYNA calculates the peak wave frequency with:

$$0.4\sqrt{\frac{g}{H_s}}$$

Here $g$ the gravity and $H_s$ is the significant wave height input with WAMP.

## **\*ICFD_BOUNDARY_GROUND**

Purpose: Specify the fluid boundary with a ground boundary condition. The ground boundary condition is similar to the nonslip boundary condition except that it will keep $V = 0$ in all circumstances, even if the surface nodes are moving. This is useful in cases where the nodes are allowed to move or translate (using ICFD_BOUNDARY_PRE-SCRIBED_MOVEMESH for example) but those displacements are only to accommodate for mesh movement and do not correspond to a physical motion.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | PID of the fluid surface where a ground boundary condition is applied. |

## \*ICFD_BOUNDARY_NAVIERSLIP

Purpose: Specify the fluid boundary with the Navier slip boundary condition.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | FRIC | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0. | | | | | | |

|              VARIABLE              |                       DESCRIPTION                       |
|---|---|
| PID | PID of the fluid surface where a Navier boundary condition is applied |
| FRIC | Friction coefficient. If a negative value is entered, it will refer to a load curve ID used to describe the friction coefficient value as a function of time; see \*DEFINE_CURVE, \*DEFINE_CURVE_-FUNCTION, or \*DEFINE_FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |

**Remarks:**

1. **About the Navier condition.** It is similar to the regular free slip condition, except a local source term is added based on the choice of the friction coefficient. Since this extra shear is a function of the fluid's velocity, a smaller time step may be needed to reduce the effects of the introduced nonlinearity.

## *ICFD_BOUNDARY_NONSLIP

Purpose: Specify the fluid boundary with a non-slip boundary condition.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | PID of the fluid surface where a non-slip boundary condition is applied. |

## \*ICFD_BOUNDARY_PERIODIC

Purpose: Impose various kinds of constraints between two fluid surfaces.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|------|--------|------|------|-------|---|
| Variable | PID | PTYPE | PID2 | PDLCID | AXE | PTID | ANGLE | |
| Type | I | I | I | I | I | I | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|

PID       Part ID for a fluid surface

PTYPE       Boundary type:

> EQ.1: Periodic rotation boundary condition
>
> EQ.2: Periodic reflective boundary condition
>
> EQ.3: Sliding mesh boundary condition

PID2       Part ID for the second surface mesh. The boundary condition selected with PTYPE will be applied between PID and PID2. See Remark 1.

PDLCID       Optional load curve ID to describe the pressure drop value between PID and PID2 as a function of time. This curve can be specified with \*DEFINE_CURVE,\*DEFINE_CURVE_FUNCTION, or \*DEFINE_FUNCTION. For \*DEFINE_FUNCTION, the following parameters are allowed: f(x,y,z,vx,vy,temp,pres,time).

AXE       The meaning of AXE depends on PTYPE. It only applies for PTYPE = 1 and 3. For the periodic rotation boundary condition (PTYPE = 1):

> EQ.1: Rotation around X-axis
>
> EQ.2: Rotation around Y-axis
>
> EQ.3: Rotation around Z-axis

For the sliding mesh boundary condition (PTYPE = 3):

> EQ.0: The contact distance between two faces of PID and PID2 is based on the characteristic local element size.

| VARIABLE | DESCRIPTION |
| --- | --- |
| | EQ.1: The contact distance between two faces of PID and PID2 is based on the characteristic local element size scaled by a factor given by ANGLE. |
| | EQ.2: The contact distance between two faces of PID and PID2 is based on the length given by ANGLE. |
| PTID | Origin point ID for PTYPE = 1 and PTYPE = 2. See \*ICFD_DEFINE_POINT. |
| ANGLE | Rotation angle for PTYPE = 1. Characterizes contact distance for PTYPE = 3 and AXE ≠ 0. |

**Remarks:**

1. **Selection of PID and PID2.** When the two meshes are of different densities, we recommend selecting the finer mesh to be PID and the coarser mesh to be PID2.

## \*ICFD_BOUNDARY_PRESCRIBED_LEVELSET

Purpose: Prescribe the fluid height on a boundary.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | PTID | AXE | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID of the fluid surface where a fluid height will be imposed. |
| PTID | Point ID specifying the origin of the fluid surface. See \*ICFD_DEFINE_POINT. |
| AXE | Global axis specifying the direction of the fluid: |

> EQ.1: *X*-axis
>
> EQ.2: *Y*-axis
>
> EQ.3: *Z*-axis

## \*ICFD_BOUNDARY_PRESCRIBED_MOVEMESH_*{OPTION1}*

Available options for *OPTION1* include:

> DR

Purpose:  Allows the fluid surface nodes to translate in specific directions using an ALE approach.  This feature is helpful in piston-type applications or for avoiding large mesh deformation in certain cases.

Include as many cards as needed.  This input ends at the next keyword ("*") card.  If the DR keyword option is active, then only one occurrence of card 1 is allowed.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | DOFX | DOFY | DOFDZ | | | | |
| Type | I | I | I | I | | | | |
| Default | none | 1 | 1 | 1 | | | | |

Include this card for the DR keyword option.  When the dynamic relaxation phase includes the ICFD solver, this second line allows the application of different parameters during that phase.  See IDR of \*ICFD_CONTROL_GENERAL.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | | DRDOFX | DRDOFY | DRDOFZ | | | | |
| Type | | I | I | I | | | | |
| Default | | 1 | 1 | 1 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID for a fluid surface |
| DOFX/DOFY/DOFZ | Degrees of freedom in the $X$, $Y$, and $Z$ directions:<br><br>EQ.0: Degree of freedom left free (surface nodes can translate in the chosen direction)<br><br>EQ.1: Prescribed degree of freedom (surface nodes are restrained) |

| VARIABLE | DESCRIPTION |
|---|---|
| DRDOFX/DRDOFY/ DRDOFZ | Same as DOFX, DOFY, and DOFZ but applies to the mesh displacement during the dynamic relaxation phase. |

## \*ICFD_BOUNDARY_PRESCRIBED_PRE

Purpose:  Impose a fluid pressure on the boundary.

Include as many cards as needed.  This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|--------|--------|------|---|---|
| Variable | PID | LCID | SF | DEATH | BIRTH | ISO | | |
| Type | I | I | F | F | F | I | | |
| Default | none | none | 1. | 1.E+28 | 0.0 | 0 | | |

|       VARIABLE       |                        DESCRIPTION                        |
|----------------------|-----------------------------------------------------------|
| PID | PID for a fluid surface |
| LCID | Load curve ID to describe the pressure value as a function of time.  See \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_FUNCTION. If using a \*DEFINE_FUNCTION, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |
| SF | Load curve scale factor.  The default is 1.0. |
| DEATH | Time at which the imposed motion/constraint is removed: <br> EQ.0.0:  Default set to 1028 |
| BIRTH | Time at which the imposed pressure is activated starting from the initial abscissa value of the curve |
| ISO | Adds an additional isovelocity condition to the system on top of the user-defined imposed pressure (see Remark 1): <br> EQ.0: Off <br> EQ.1: On |

**Remarks:**

1. **Adding an isovelocity condition.** Flow instability is a well known numerical issue that can occur with imposed pressure conditions, particularly in complex FSI cases or when the global flow changes direction during the transient run (inlet transitions into outlet and vice versa).  Using ISO = 1 adds an isovelocity

condition which makes the velocity uniform across that surface. The objective is an attempt to provide an elegant form of constraining the flow and preventing numerical issues in cases where this hypothesis can be considered physically valid. This feature imposes an additional numerical cost.

## \*ICFD_BOUNDARY_PRESCRIBED_SPTRANSP_CONC

Purpose: Specify the concentration of the transported species at the boundaries.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LCID1 | LCID2 | LCID3 | LCID4 | LCID5 | LCID6 | LCID7 | LCID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the boundary with the concentrations boundary conditions |
| LCID$i$ | Load curve ID for the curve giving the concentration of species $i$ at the boundary as a function of time.  Note that all the transported species must have a load curve defined.  For instance, in the 4-species case, LCID1, LCID2, LCID3, and LCID4 must be specified. |

## \*ICFD_BOUNDARY_PRESCRIBED_TEMP

Purpose: Impose a fluid temperature on the boundary.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | LCID | SF | DEATH | BIRTH | | | |
| Type | I | I | F | F | F | | | |
| Default | none | none | 1. | 1.E+28 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID for a fluid surface. |
| LCID | Load curve ID to describe the temperature value versus time; see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION or \*DEFINE_-FUNCTION. . If a DEFINE_FUNCTION is used, the following parameters are allowed: $f(x, y, z, vx, vy, vz, temp, pres, time)$. |
| SF | Load curve scale factor. (default = 1.0) |
| DEATH | Time at which the imposed temperature is removed:<br>EQ.0.0: default set to 10E28 |
| BIRTH | Time at which the imposed temperature is activated starting from the initial abscissa value of the curve |

## \*ICFD_BOUNDARY_PRESCRIBED_TURBULENCE

Purpose: Optional keyword for strongly imposing turbulence quantities when you select a RANS turbulence model. See \*ICFD_CONTROL_TURBULENCE. This keyword is intended for modifying the default boundary conditions at the inlet.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | VTYPE | IMP | LCID | KS | CS | | |
| Type | I | I | I | I | F | F | | |
| Default | none | none | 0 | none | 0. | 0. | | |

| VARIABLE | DESCRIPTION |
|---|---|

PID        PID for a fluid surface

VTYPE        Variable type:

> EQ.1: Turbulence kinetic energy (see Remark 1)
>
> EQ.2: Turbulence dissipation rate (see Remark 2)
>
> EQ.3: Specific dissipation rate (see Remark 3)
>
> EQ.4: Modified turbulence viscosity (see Remark 4)

IMP        Imposition method:

> EQ.0: Direct imposition through value specified by LCID
>
> EQ.1: Using turbulence intensity specified by LCID if VTYPE = 1 (see Remark 1). Using turbulence length scale specified by LCID if VTYPE = 2, 3, or 4 (see Remarks 2, 3, and 4).
>
> EQ.2: Using turbulence viscosity ratio specified by LCID. Only available for VTYPE = 2 and 3. See Remarks 2 and 3.

LCID        Load curve ID to describe the variable value as a function of time; see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION or \*DEFINE_FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time, k, e, mut).

| VARIABLE | DESCRIPTION |
|---|---|
| KS/CS | Roughness physical height and roughness constant.  When defined, the global values of \*ICFD_CONTROL_TURBULENCE are replaced for this surface part. |

**Remarks:**

1.  **Turbulence Kinetic Energy.** At the inlet, the relationship between the turbulence kinetic energy, $k$, and the turbulence intensity, $I$, is given by:

$$k = \frac{3}{2}\left(U_{\text{avg}}^2 I^2\right) \ .$$

   By default, the solver uses an inlet intensity of 0.05 (5%).

2.  **Turbulence Dissipation Rate.** At the inlet, if you specify the turbulent dissipation rate using a length scale, $l$, the following relationship will be used:

$$\epsilon = C_\mu^{\ 3/4} \frac{k^{3/2}}{l} \ .$$

   By default, the solver estimates a length scale based on the total height of the channel.

   If you specify the turbulent viscosity ratio, $r = \mu_t / \mu$, the following relationship will be used:

$$\epsilon = \rho C_\mu \frac{k^2}{\mu\, r} \ .$$

3.  **Specific Dissipation Rate.** At the inlet, if you specify the specific dissipation rate using a length scale, $l$, the following relationship will be used:

$$\omega = C_\mu^{\ -1/4} \frac{k^{1/2}}{l} \ .$$

   By default, the solver estimates a length scale based on the total height of the channel.

   If you specify the turbulence viscosity ratio, $r = \mu_t / \mu$, the following relationship will be used:

$$\omega = \rho \frac{k}{\mu\, r} \ .$$

4.  **Modified Turbulent Viscosity.**  At the inlet, the relationship between the modified turbulent viscosity, $\tilde{\nu}$, and the length scale, $l$, is given by:

$$\tilde{\nu} = 0.05\sqrt{\frac{3}{2}}\left(U_{\text{avg}}\, l\right)\ .$$

## \*ICFD_BOUNDARY_PRESCRIBED_VEL

Purpose: Impose the fluid velocity on the boundary.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | DOF | VAD | LCID | SF | VID | DEATH | BIRTH |
| Type | I | I | I | I | F | I | F | F |
| Default | none | none | 1 | none | 1. | 0 | $10^{28}$ | 0.0 |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID for a fluid surface. |
| DOF | Applicable degrees of freedom: |
| | EQ.1: $x$- degree of freedom |
| | EQ.2: $y$- degree of freedom |
| | EQ.3: $z$ degree of freedom |
| | EQ.4: Normal direction degree of freedom |
| VAD | Velocity flag: |
| | EQ.1: Linear velocity |
| | EQ.2: Angular velocity |
| | EQ.3: Parabolic velocity profile |
| | EQ.4: Activates synthetic turbulent field on part. See \*ICFD_-CONTROL_TURB_SYNTHESIS. |
| LCID | Load curve ID used to describe motion value versus time, see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_-FUNCTION. If a DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). For steady state the motion value is a function of the number of iterations instead of time. |
| SF | Load curve scale factor. (default = 1.0) |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| VID | Point ID for angular velocity application point, see \*ICFD_DE-FINE_POINT. |
| DEATH | Time at which the imposed motion/constraint is removed:<br><br>EQ.0.0: default set to $10^{28}$ |
| BIRTH | Time at which the imposed motion/constraint is activated starting from the initial abscissa value of the curve |

## \*ICFD_BOUNDARY_PRESCRIBED_VISCOELASTIC

Purpose: Specify the conformation tensor at the boundaries.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|--------|--------|--------|--------|--------|--------|---|
| Variable | PID | LCIDXX | LCIDYY | LCIDZZ | LCIDXY | LCIDXZ | LCIDYZ | |
| Type | I | I | I | I | I | I | I | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the boundary with the prescribed conformation tensor |
| LCID*ij* | Load curve IDs for the conformation tensor components |

## \*ICFD_BOUNDARY_WEAKVEL

Purpose: Specify the fluid boundary with a non-slip boundary condition which is imposed in a weak form.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the fluid surface where a weak non-slip boundary condition is applied |

## \*ICFD_BOUNDARY_WINDKESSEL

Purpose: Impose the pressure function with circuit parameters where an analogy is made between pressure and scalar potential and between flow rate and current intensity. Such conditions are frequently encountered in hemodynamics.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | WTYPE | R1 | C1 | R2 | L1/ QPLCID | | |
| Type | I | I | F | F | F | F | | |
| Default | none | none | 0. | 0. | 0. | 0. | | |

**Optional Card.** This card defines additional parameters for the Windkessel circuits depending on WTYPE.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | P2LCID | C2 | R3 | P0 | P1 | | | |
| Type | I | F | F | F | F | | | |
| Default | 0 | 0. | 0. | 0. | 0. | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | PID for a fluid surface |
| WTYPE | Circuit type. See remarks and figures. |
| R1/C1/L1/R 2/C2/R3 | Parameters (resistances, inductances, capacities) for the different circuits. See remarks and figures. |
| P2LCID | ID of load curve describing the behavior of $P_2(t)$ as a function of time when applicable. See Remarks 2, 3, and 4 and Figures 7-2, 7-3, and 7-4. |
| QPLCID | ID of load curve describing the behavior of $Q_p(t)$ as a function of time when applicable. See Remark 4 and Figure 7-4. |

| VARIABLE | DESCRIPTION |
|---|---|
| P0/P1 | Initial pressures at circuit junctions when applicable. See remarks and figures. |

**Remarks:**

1.  **WTYPE = 1 and 2.** See Figure 7-1 for a diagram of the circuit. The equation solved at the boundary is:

$$P(t) = P_0(t) + \text{SF} \times Q \times R_2$$

$$P_0'(t) = -\frac{1.0}{R_1 C_1} P_0(t) + \text{SF} \times \left[ L_1 Q'' + \frac{Q}{C_1} + \frac{L_1}{R_1 C_1} Q' \right]$$

with $Q$, the flow rate calculated by the solve, and $P$, the pressure. Time derivatives are marked using Lagrange notation. By convention, the flow rate has a negative value if the fluid goes out of the fluid domain (outlet) and a positive value if it goes in (inlet). The scale factor, SF, applied on the circuit equation's flow-rate-dependent terms enables recovering the desired behavior of the Windkessel circuit. SF = -1.0 for WTYPE = 1, and SF = 1.0 for WTYPE = 2.

For WTYPE = 1 and 2, $R_1$, $R_2$ and $L_1$ are optional and can be left as 0.



**Figure 7-1.** WTYPE = 1 and 2 circuit

2.  **WTYPE = 3 and 4.** See Figure 7-2 for a diagram of the circuit. The equation solved at the boundary is:

$$P(t) = P_0(t) + \text{SF} \times Q \times R_1$$

$$P_0'(t) = -\frac{1.0}{R_2 C_1} P_0(t) + \frac{1.0}{R_2 C_1} P_1(t) + \text{SF} \times \frac{Q}{C_1}$$

$$P_1'(t) = \frac{1.0}{R_2 C_2} P_0(t) - \frac{R_3 + R_2}{R_3 R_2 C_2} P_1(t) + P_2'(t)$$

with $Q$ and SF as described in Remark 1. SF = -1.0 for WTYPE = 3, and SF = 1.0 for WTYPE = 4. $R_1$ and $R_3$ are optional for this type of circuit. If $R_3$ is set to 0., that branch of the circuit is removed (open circuit). A negative value can be entered for $R_3$ which points to a \*DEFINE_FUNCTION. The function accepts the following parameters: f(time, dt, flux , pre). In the function, flux is the current flow rate, $Q$, and pre is the current pressure, $P(t)$. With this method, $R_3$ can be set to a specific value or left as 0.0 based on the sign of flux, thus modeling diode behavior.
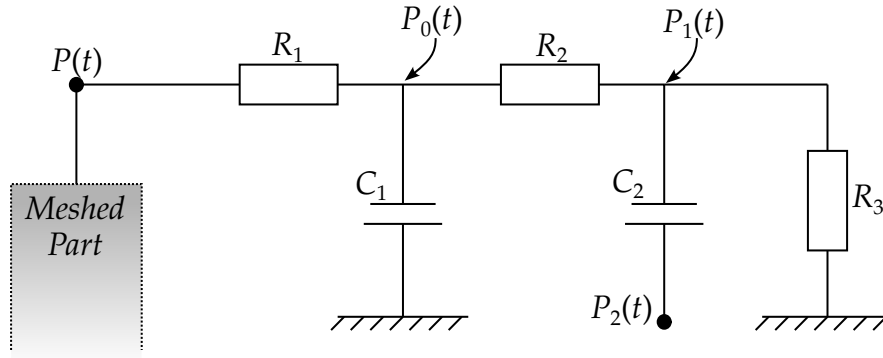


**Figure 7-2.** WTYPE = 3 and 4 circuit

3. **WTYPE = 7 and 8.** See Figure 7-3 for a diagram of the circuit. The equation solved at the boundary is:

$$P(t) = P_0(t) + \text{SF} \times Q \times R_1$$
$$P_0'(t) = -\frac{1.0}{R_2 C_1}P_0(t) + \text{SF} \times \frac{Q}{C_1} + \frac{1.0}{R_2 C_1}P_2(t)$$

with $Q$ and SF as described in Remark 1. SF = -1.0 for WTYPE = 7, and SF = 1.0 for WTYPE = 8. For this type of circuit, $R_1$, $R_2$ , and $P_2(t)$ are optional.
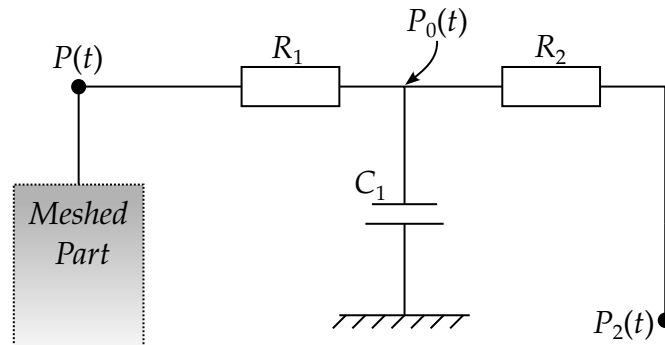


**Figure 7-3.** WTYPE = 7 and 8 circuit

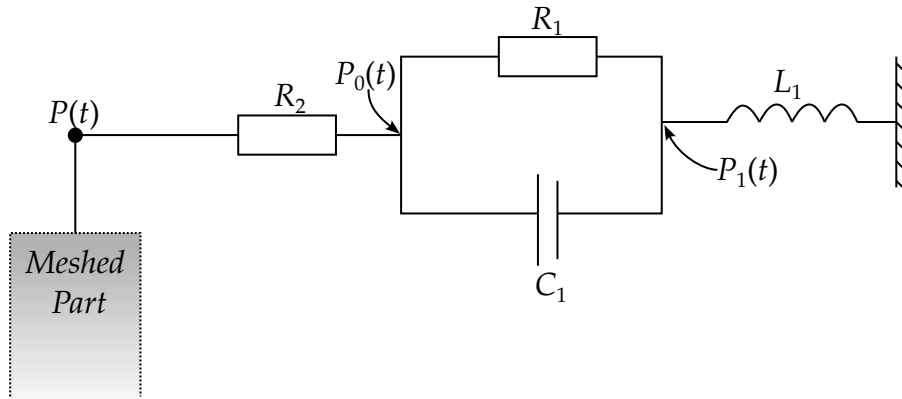4. **WTYPE = 9 and 10.** See Figure 7-4 for a diagram of the circuit. The equation solved at the boundary is:

$$P(t) = \frac{R_3}{R_2 + R_3} P_0(t) + \text{SF} \times Q \times \frac{R_3 R_2}{R_2 + R_3} + \frac{R_2}{R_2 + R_3} P_2(t)$$

$$P_0'(t) = -\frac{R_1 + R_2 + R_3}{(R_2 + R_3) R_1 C_2} P_0(t) + \frac{1.0}{R_1 C_2} P_1(t) + \frac{R_3}{(R_2 + R_3)} \text{SF} \times \frac{Q}{C_2} - \frac{P_2(t)}{C_2} \times \frac{1.0}{R_2 + R_3}$$

$$P_1'(t) = \frac{1.0}{R_1 C_1} P_0(t) - \frac{1.0}{R_1 C_1} P_1(t) + \frac{Q_p(t)}{C_1}$$

with $Q$ and SF as described in Remark 1. SF = -1.0 for WTYPE = 9, and SF = 1.0 for WTYPE = 10. For this type of circuit, $R_2$, $P_2(t)$, $Q_p(t)$, and $R_3$ are optional. If $R_3$ is set to 0.0, that branch of the circuit is removed (open circuit). A negative value can be entered for $R_3$ which points to a \*DEFINE_FUNCTION. The function accepts the following parameters: f(time, dt, flux , pre). In the function, flux is the current flow rate, $Q$, and pre is the current pressure, $P(t)$. With this method, $R_3$ can be set to a specific value or left as 0.0 based on the sign of flux, thus modeling diode behavior.
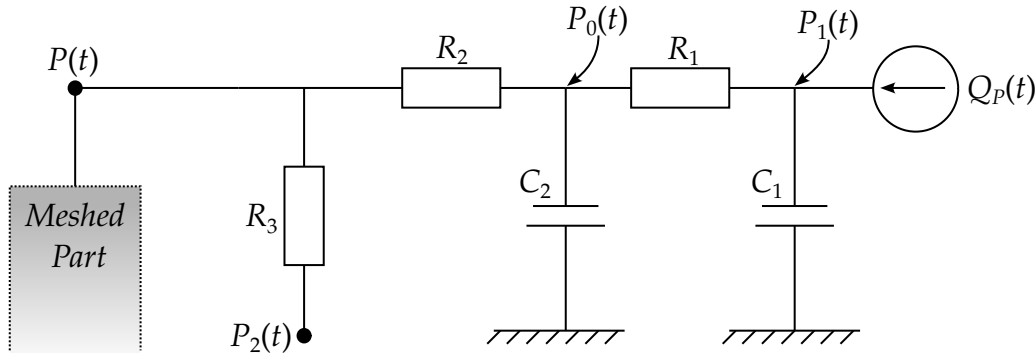


**Figure 7-4.** WTYPE = 9 and 10 circuit

5. **WTYPE = 6.** WTYPE = 6 enables implementing user-defined circuit laws by compiling the usermat versions of LS-DYNA. The routine that can be modified is called icfd_usercircuit and can be found in dyn21icfd.f.

## \*ICFD_CONTROL_ADAPT

Purpose: Activate the adaptive mesh refinement feature. The solver uses an a-posteriori error estimator to compute a new mesh size bounded by the user to satisfy a maximum perceptual global error.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|-----|-----|-----|-----|---|-----|
| Variable | MINH | MAXH | ERR | MTH | NIT | VAR | | KIS |
| Type | F | F | F | I | I | I | | I |
| Default | none | none | 1. | 1 | 0 | 0 | | 0 |

**Optional Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | DT | | | | | | | |
| Type | F | | | | | | | |
| Default | 0.0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MINH | Minimum mesh size allowed to the mesh generator. The resulting mesh will not have an element smaller than MINH even if the minimum size does not satisfy the maximum error. |
| MAXH | Maximum mesh size |
| ERR | Maximum perceptual error allowed in the whole domain |
| MTH | Specify if the mesh size is computed based on function error or gradient error: |

        EQ.1: Function error (default)

        EQ.2: Gradient error

        EQ.3: Relative error

        EQ.4: Gradient relative error

| VARIABLE | DESCRIPTION |
|---|---|
| NIT | Number of iterations before a remeshing is forced: |

        LT.0: $|NIT|$ is a load curve ID giving the number of iterations before a remeshing as a function of time.

        EQ.0: Do not remesh.

        GT.0: Number of iterations before a forced remeshing.

| | |
|---|---|
| VAR | Specify which variable is taken into account for the error calculation: |

        LT.0: Adaptive meshing is based only on the level-set function. Elements of size MINH are targeted over a length $|VAR|$ on each side of the interface.

        EQ.0: Velocity, pressure, and level-set function are taken into account.

        EQ.1: Remove the level-set function from the error calculation.

        EQ.2: Remove the pressure from the error calculation.

        EQ.3: Remove both the pressure and the level-set function from the error calculation. Only the fluid velocity will, therefore, remain.

        EQ.5: For immersed interface methods, adapt the mesh only at the interface of the immersed surfaces.

| | |
|---|---|
| KIS | Keep initial mesh size: |

        EQ.0: Turned off. The remeshing process will ignore the initial mesh size in the volume.

        EQ.1: Turned on. Whenever a remeshing occurs, the new local mesh size will not be allowed to be substantially coarser than the one from the previous mesh. The object is to diminish the excessive coarsening that can occur between two remeshings.

| | |
|---|---|
| DT | Optional time step to control the remeshing frequency. A negative value points to a load curve ID giving the remeshing time step as a function of time. |

## \*ICFD_CONTROL_ADAPT_SIZE

Purpose: Control the remeshing of elements. This keyword enables considering the element quality and distortion instead of only checking for inverted elements.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ASIZE | NIT | KIS | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | none | 0 | | | | | |

**Optional Card.** When including ICFD during the dynamic relaxation phase, this second line enables applying different parameters during that phase. See IDR of \*ICFD_CONTROL_GENERAL.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DRASIZE | DRNIT | DRKIS | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | optional | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

ASIZE       Remesh criteria flag:

      EQ.0: Only remesh in cases where elements invert.

      EQ.1: Remesh if elements invert or if element quality deteriorates.

NIT         Number of iterations before a remeshing is forced. If a negative integer is entered, then a load curve function of time defines NIT.

KIS         Keep initial mesh size:

      EQ.0: Turned off. The remeshing process will ignore the initial mesh size in the volume.

      EQ.1: Turned on. Whenever a remeshing occurs, the new local mesh size will not be allowed to be substantially coarser

| VARIABLE | DESCRIPTION |
|---|---|
| | than the one from the previous mesh. The object is to diminish the excessive coarsening that can occur between two remeshes. |
| DRASIZE | Same as ASIZE but for dynamic relaxation |
| DRNIT | Same as NIT but for dynamic relaxation |
| DRKIS | Same as KIS but for dynamic relaxation |

**\*ICFD_CONTROL_ADVECTION**

Purpose: Modify the default advection schemes for different parts of the solver like Navier Stokes, Level Set, thermal, etc.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|------|------|-----|------|------|
| Variable | | | | SLLS | SLNS | SLT | SLST | SLRT |
| Type | | | | I | I | I | I | I |
| Default | | | | 0 | 0 | 0 | 0 | 0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|

SLLS     Advection scheme for the Level Set solver:

     EQ.0: Default advection scheme

     EQ.1: Changes the default advection scheme in the Level Set solver to use a linear semi-Lagrangian approach (Min and Gibou [2006]).

     EQ.2: Changes the default advection scheme in the Level Set solver to use a higher-order semi-Lagrangian approach.

SLNS     Advection scheme for the Navier-Stokes solver:

     EQ.0: Default advection scheme

     EQ.1: Changes the default advection scheme in the Navier-Stokes solver to use a semi-Lagrangian approach (Min and Gibou [2006]).

SLT     Advection scheme for the Thermal solver:

     EQ.0: Default advection scheme

     EQ.1: Changes the default advection scheme in the Thermal solver to use a semi-Lagrangian approach.

SLST     Advection scheme for the Species Transport solver:

     EQ.0: Default advection scheme

     EQ.1: Changes the default advection scheme in the Species Transport solver to use a semi-Lagrangian approach.

| VARIABLE | DESCRIPTION |
|---|---|
| SLRT | Advection scheme for the Residence Time solver: |

> **EQ.0:** Default advection scheme
>
> **EQ.1:** Changes the default advection scheme in the Residence Time solver to use a semi-Lagrangian approach.

**References:**

Min, Chohong, and Frédéric Gibou. "A second order accurate projection method for the incompressible Navier–Stokes equations on non-graded adaptive grids." Journal of Computational Physics 219.2 (2006): 912-929.

**\*ICFD_CONTROL_BACKFLOW**

Purpose:  Modify default values for backflow stabilization.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | BFOR | SF | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 1.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| BFOR | Set the backflow stabilization formulation: |

      EQ.0: Default stabilization dependent on spatial velocity gradients.

      EQ.1: The stabilization adds a temporal velocity gradient which could be necessary for added stabilization.

SF         Scale factor to increase the stabilization if needed.  A very small value larger than zero minimizes the effect.

## \*ICFD_CONTROL_CONJ

Purpose: This keyword allows to pick between the different coupling methods for conjugate heat transfer applications

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CTYPE | | | | | | | TSF |
| Type | I | | | | | | | F |
| Default | 0 | | | | | | | none |

| VARIABLE | DESCRIPTION |
|---|---|

CTYPE            Indicates the thermal coupling type.

> EQ.0: Robust and accurate monolithic coupling where the temperature field are solved simultaneously between the fluid and the structure.

> EQ.1: Weak thermal coupling. The fluid passes the heat flux to the solid at the fluid-structure interface and the solid returns the temperature which is applied as a Dirichlet condition.

TSF             Thermal Speedup Factor. This factor multiplies all thermal parameters present in the heat equation with units of time in the denominator (e.g., thermal conductivity, convection heat transfer coefficients). It is used to artificially time scale the thermal problem. A negative value will refer to a time dependent load curve.

**Remarks:**

1. The keyword ICFD_BOUNDARY_CONJ_HEAT is ignored if CTYPE = 1 but the keyword ICFD_BOUNDARY_FSI is needed in all thermal coupling cases.

## \*ICFD_CONTROL_DEM_COUPLING

Purpose: Activate coupling between the ICFD and DEM solvers.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | CTYPE | BT | DT | SF | MAXVEL | DTYPE | SFF | FORM |
| Type | I | F | F | F | F | I | F | I |
| Default | 0 | 0. | $10^{28}$ | 1. | none | 0 | 1.0 | 0 |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | NITBS | | | | | | | |
| Type | I | | | | | | | |
| Default | ↓ | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| CTYPE | Indicates the coupling direction of the solvers: |

    EQ.0: Two-way coupling between the fluid and the solid particles.

    EQ.1: One-way coupling. The DEM particles transfer their location to the fluid solver.

    EQ.2: One-way coupling. The fluid solver transfers forces to the DEM particles.

| | |
|----------|-------------|
| BT | Birth time for the DEM coupling |
| DT | Death time for the DEM coupling |
| SF | Scale factor applied to the force transmitted by the fluid to the structure |
| MAXVEL | Maximal fluid velocity that can be used for the calculation of the fluid force passed on to the DEM particle. This is to avoid having spurious velocities in the fluid causing very high and unrealistic |

| VARIABLE | DESCRIPTION |
|---|---|
| | forces on the DEM particles which may lead to a crash. |
| DTYPE | Drag calculation type: |
| |     EQ.0: Constant $C_d$ value 0.5 scaled by SF |
| |     EQ.1: Formula for $C_d$ calculation from Cheng [2009] based on the local Reynolds number value scaled by SF. See Remark 1. |
| SFF | Scale factor applied to the force transmitted by the structure to the fluid |
| FORM | Type of formulation used in the coupling: |
| |     EQ.0: The force at the particle is based on a velocity drag value. |
| |     EQ.2: The force is computed using the fluid pressure gradient. |
| NITBS | Number of time steps between particle searches. The default is 50 in explicit analysis and 1 in implicit. Increasing this number can reduce the computational time at the expense of possible less accurate particle tracking. |

**Remarks:**

1.  **Coefficient of drag by Cheng [2009].** The calculation for $C_d$ is:

$$C_d = \frac{24}{\text{Re}} \times (1 + 0.27 \times \text{Re})^{0.43} + 0.47 \times \left(1 - \exp\left(-0.04 \times \text{Re}^{0.38}\right)\right)$$

See Cheng [2009] for details.

**References:**

[1]  Cheng, N.-S., "Comparison of formulas for drag coefficient and settling velocity of spherical particles," Powder Technology, 189, 395-398 (2009).

## \*ICFD_CONTROL_EMBEDSHELL

Purpose: This keyword allows the user to control specific options related to the use of the keyword MESH_EMBEDSHELL.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | GTYPE | DIST | TPS | | | | | |
| Type | I | F | I | | | | | |
| Default | 0 | 0.1 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| GTYPE | Gap type. Defines the criteria for selecting a distance to build the gap between the embedded nodes and the newly generated : |
| | EQ.0: Automatic and based on the surface mesh size multiplied by a scale factor given by DIST. Default method. |
| | EQ.1: Specific gap size given by the user and defined by DIST. |
| DIST | Distance value if GTYPE = 1 or scale factor value if GTYPE = 0. |
| TPS | Triple Point Seal. Allows to control the fluid escape through triple points |
| | EQ.0: Off. |
| | EQ.1: On. The triple points of embedded shells in contact to walls or among each other are sealed and no flow goes through them. |

## *ICFD_CONTROL_FSI

Purpose: This keyword modifies default values for the fluid-structure interaction coupling algorithm.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | OWC | BT | DT | IDC | LDICSF | XPROJ | | |
| Type | I | F | F | F | I | I | | |
| Default | 0 | 0 | $10^{28}$ | 0.25 | 0 | 0 | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | NSUB | | | IDETEC | VFORC | | | |
| Type | I | | | I | I | | | |
| Default | none | | | 0 | 0 | | | |

|      VARIABLE      |                    DESCRIPTION                    |
|--------------------|--------------------------------------------------|

OWC    Indicates the coupling direction to the solver:

    EQ.0: Two-way coupling. Loads and displacements are transferred across the FSI interface, and the full non-linear problem is solved. It gives weak FSI coupling when coupled to explicit mechanical solver and strong FSI coupling when coupled to implicit mechanical solver.

    EQ.1: One-way coupling. The solid mechanics solver transfers displacements to the fluid solver.

    EQ.2: One-way coupling. The fluid solver transfers stresses to the solid mechanics solver.

    EQ.3: Two-way coupling. It causes weak coupling (no sub-stepping) with the implicit mechanical solver.

BT    Birth time for the FSI coupling. Before BT the fluid solver will not pass any loads to the structure, but it will receive displacements

| VARIABLE | DESCRIPTION |
|---|---|
| | from the solid mechanics solver. |
| DT | Death time for the FSI coupling. After DT the fluid solver will not transfer any loads to the solid mechanics solver, but the fluid will continue to deform with the solid. |
| IDC | Interaction detection coefficient. See Remark 1. |
| LCIDSF | Optional load curve ID to apply a scaling factor on the forces transferred to the solid: |
| | GT.0: Load curve ID for scale factor as a function of iterations |
| | LT.0: \|LCIDSF\| is a load curve ID for scale factor as a function of time. |
| XPROJ | Projection of the nodes of the CFD domain that are at the FSI interface onto the structural mesh (see Remark 2): |
| | EQ.0: No projection |
| | EQ.1: Projection |
| NSUB | Optional limit on the number of FSI fluid subiterations. This avoids the sometimes unneeded excessive number of FSI subiterations when the fluid and very light structures (like parachutes) develop a resonance-like mode inside the FSI subiterations (coupling iterations). |
| IDETEC | Fluid-structure interface detection frequency (see Remark 3): |
| | LT.0: \|IDETEC\| refers to a load curve ID for the curve that gives the detection frequency as a function of time. |
| | EQ.0: The interface detection is performed only once at the beginning of the simulation. |
| | GT.0: The interface is detected every IDETEC time steps. |
| VFORC | Add viscous tangential forces to the FSI coupling: |
| | EQ.0: Only normal pressure forces are used. |
| | EQ.1: Viscous forces are added to normal forces. |
| | EQ.2: Viscous forces are recomputed at every sub-step during the nonlinear iterations and added to normal forces. |
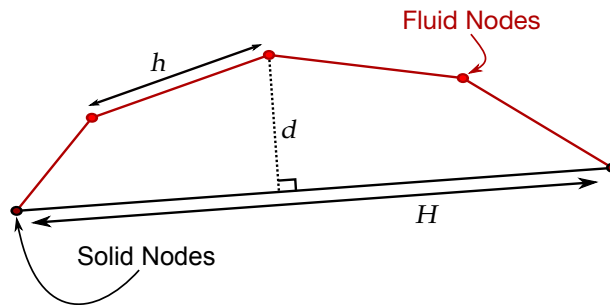
**Figure 0-1.** Geometry of FSI contact.

**Remarks:**

1.  **Detecting fluid-solid interaction.** One of the criteria to automatically detect the fluid and solid surfaces that will interact in FSI problems is the distance $d$ between a fluid (solid) node and a solid (fluid) element, respectively:

    $$d \leq \text{IDC} \times \min(h, H) \,,$$

    where $h$ is the size of the fluid mesh, $H$ is the size of the solid mechanics mesh, and IDC is a detection coefficient criteria with IDC = 0.25 by default. In the majority of cases, this default value is sufficient to ensure FSI interaction. However, it can happen in special cases that the fluid and solid geometries have curvatures that differ too much (such as pipe flows in conjugate heat transfer applications). In such cases, a bigger IDC value may be needed. This flag should be handled with care.

2.  **Rotation and projection of nodes.** XPROJ = 1 is recommended for cases with rotation.

3.  **Fluid-solid interaction detection frequency.** By default, the detection of the fluid and structure surfaces that will interact in FSI or conjugate heat problems is performed only once at the beginning of the analysis. Finding the interface only once is adequate for most cases because the fluid mesh usually follows and is bound to the structure's displacements. One notable exception is for applications using \*ICFD_BOUNDARY_FSI_FIXED. Typically, this boundary condition is used for conjugate heat transfer problems where a solid surface 'slides' over a fluid domain and temperature is exchanged. Thus, the fluid-structure detection must be periodically recomputed with the use of the IDETEC flag.

## \*ICFD_CONTROL_GAP

Purpose: Activate the gap closure treatment that deals with flow blockage when surfaces come into contact. In ICFD, surface meshes are not allowed to collide or penetrate each other. Rather, activation of the gap closure feature triggers a flow blockage between two surfaces in close proximity based on a user defined contact distance. There are two types of flow treatment available. The default is a strong exclusion of the fluid elements within the gap. The second option is a porous media description for the fluid nodes inside the contact gap.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HGAP | PGAP | PERM | | | | | |
| Type | F | I | F | | | | | |
| Default | none | 0 | 1.e-5 | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| HGAP | Threshold distance. If the distance between surfaces is less than this value, the flow motion is blocked in the gap. Currently there is only one universal value of HGAP for all the surfaces listed in Card 2. |
| PGAP | Flag for flow treatment of fluid elements in the gap: |
| | EQ.0: Element exclusion contact treatment |
| | EQ.1: Porous media description |
| PERM | Permeability coefficient. Its value determines the ratio between the fluid and porous representation in the contact region. Low values induce a Darcy description. |

| VARIABLE | DESCRIPTION |
|---|---|
| PID$n$ | Part IDs of the surfaces involved in the gap closure treatment |

**\*ICFD_CONTROL_GENERAL**

Purpose:  Specify the type of ICFD analysis.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ATYPE | MTYPE | DVCL | RDVCL | SOLCL | | IDR | |
| Type | I | I | I | I | I | | I | |
| Default | 0 | 0 | 0 | 0 | 0 | | 0 | |

|  VARIABLE  |  DESCRIPTION  |
|---|---|

ATYPE   Analysis type:

    EQ.-2: Turn off the ICFD solver but leave level set, thermal, etc. Velocities can be set using the define function.  It is useful for debugging models or for simple thermal / level set cases that do not need a full ICFD solution.

    EQ.-1: Turn off the ICFD solver after the initial keyword reading

    EQ.0: Transient analysis (default)

    EQ.1: Steady-state analysis

MTYPE   Solving method type:

    EQ.0: Fractional step method

    EQ.1: Monolithic solve

    EQ.2: Potential flow solve

DVCL   Divergence cleaning flag:

    EQ.0: Initialize the solution with divergence cleaning (default)

    EQ.1: No divergence cleaning

    EQ.2: Initial divergence cleaning using potential flow

    EQ.4: Initial divergence cleaning using steady-state solver

RDVCL   Remeshing divergence cleaning:

    EQ.0: No divergence cleaning after remesh (default)

    EQ.1: Divergence cleaning after each remeshing step

| VARIABLE | DESCRIPTION |
|---|---|
| SOLCL | Solver control: |
| | EQ.0: The solver automatically detects if the analysis is 2D or 3D based on element connectivity (default). |
| | EQ.1: Turns on the 2D axisymmetric solver. |
| | EQ.2: 2D axisymmetric solver for FSI cases that use section shell type 15 for solid parts. |
| IDR | Flag to include ICFD during the structural dynamic relaxation phase: |
| | EQ.0: Off |
| | EQ.1: Include the ICFD solver during the dynamic relaxation phase. The solver only computes the mesh displacement. It does not find pressure/velocity, but the mesh adapts and follows the displacement of the FSI parts. |

## \*ICFD_CONTROL_IMMERSED

Purpose:  Change the default behavior of the immersed interface options.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | IMMTH | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| IMMTH | Method used to represent the immersed interface.  By default, the solver assumes that all interfaces of interest are body-fitted. |

      EQ.0:  Immersed methods are not used in the model.

      EQ.1:  Method based on a discontinuous FEM approximation at the interface

      EQ.2:  Method based on the Resistive Immersed Implicit Surface (RIIS) method

### \*ICFD_CONTROL_IMPOSED_MOVE

Purpose: Impose a velocity on specific ICFD parts or on the whole volume mesh. Global translation, global rotation, and local rotation components can be defined and combined. This keyword can be used to save calculation time in certain applications, such as sloshing, where the modeling of the whole fluid box and the solving of the consequent FSI problem are not necessarily needed.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | LCVX | LCVY | LCVZ | VADT | IDR | | |
| Type | I | I | I | I | I | I | | |
| Default | none | none | none | none | 0 | 0 | | |

**Optional Card.** Rotational velocity components using Euler or Tait-Bryan angles (see Remark 1).

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ALPHAL | BETAL | GAMMAL | ALPHAG | BETAG | GAMMAG | VADR | IANG |
| Type | I | I | I | I | I | I | I | I |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Optional Card.** Local reference frame definition if ALPHAL, BETAL or GAMMAL used.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PTID | X1 | Y1 | Z1 | X2 | Y2 | Z2 | |
| Type | I | F | F | F | F | F | F | |
| Default | 0 | 1. | 0. | 0. | 0. | 1. | 0. | |

**Optional Card.** When defined, Cards 2 and 3 are ignored. With this card, rotation is imposed around a point using the velocity of a second point.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | PTID0 | AXE | NID | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID. This can be any part ID referenced in \*ICFD_PART or \*ICFD_PART_VOL. If PID = 0, then the whole volume mesh will be used. |
| LCVX, LCVY, LCVZ | Load curve IDs for the velocity/displacements in the three global directions $(X, Y, Z)$. To use a \*DEFINE_FUNCTION, see Remark 4. |
| VADT | Velocity/displacements flag for translation components: |
| | EQ.0: Prescribe velocity |
| | EQ.1: Prescribe displacements |
| IDR | Flag determining whether to only impose mesh displacement during dynamic relaxation phase (see IDR of \*ICFD_CONTROL_GENERAL): |
| | EQ.0: Off. |
| | EQ.1: On. Apply imposed mesh movement only during the dynamic relaxation phase. |
| ALPHAL, BETAL, GAMMAL | Load curves IDs for the three angle rotational velocities/displacements in the local reference frame (see Remarks 1 and 2). To use a \*DEFINE_FUNCTION, see Remark 4. |
| ALPHAG, BETAG, GAMMAG | Load curve IDs for the three angle rotational velocities/displacements in the global reference frame (see Remarks 1 and 2). To use a \*DEFINE_FUNCTION, see Remark 4. |

| VARIABLE | DESCRIPTION |
|---|---|
| VADR | Velocity/displacements flag for rotation components:<br><br>EQ.0: Prescribe velocity<br><br>EQ.1: Prescribe displacements |
| IANG | Rotation matrix type:<br><br>EQ.0: Euler angles using $\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Z}(\gamma)$ intrinsic rotations.<br><br>EQ.1: Tait-Bryan angles using $\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Y}(\gamma)$ intrinsic rotations. |
| PTID | Point ID for the origin of the local reference frame. If not defined, the barycenter of the volume mesh will be used |
| X1, Y1, Z1 | Three components of the local reference X1 axis. If not defined, the global $X$ axis will be used. See Remark 2. |
| X2, Y2, Z2 | Three components of the local reference X2 axis. If not defined, the global $Y$ axis will be used. See Remark 2. |
| PTIDO | Point ID (See \*ICFD_DEFINE_POINT) for the center of rotation. |
| AXE | Rotation axis:<br><br>EQ.1: $X$-axis<br><br>EQ.2: $Y$-axis<br><br>EQ.3: $Z$-axis |
| NID | ICFD surface node ID for the rotational velocity. If the node is static, no rotation will occur. See Remark 3. |

**Remarks:**

1. **Rotations.** Any target orientation can be reached starting from a known reference orientation using a specific sequence of intrinsic rotations whose magnitudes are the Euler or Tait Bryan angles $(\alpha, \beta, \gamma)$. Equivalently, any rotation matrix $\mathbf{R}$ can be decomposed as a product of three elemental rotation matrices. For instance:

$$\mathbf{R} = \mathbf{X}(\alpha)\mathbf{Y}(\beta)\mathbf{Z}(\gamma)$$
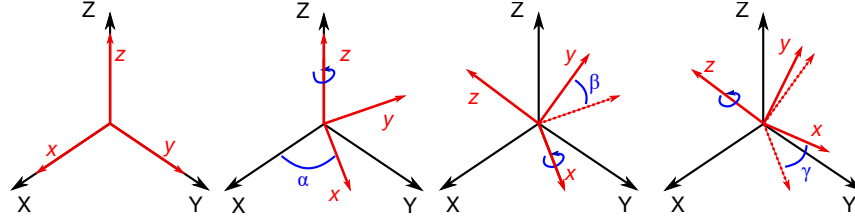
**Figure 7-5.** A rotation represented by Euler angles $(\alpha, \beta, \gamma)$ using $\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Z}(\gamma)$ intrinsic rotations.
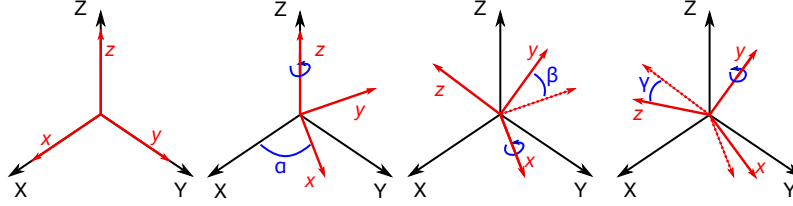


**Figure 7-6.** A rotation represented by Tait-Bryan angles $(\alpha, \beta, \gamma)$ using $\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Y}(\gamma)$ intrinsic rotations

However, a different definition of the elemental rotation matrices and their multiplication order can be adopted. The ICFD solver uses the following approach and rotation matrix for the Euler angles:

$$\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Z}(\gamma) = \begin{bmatrix} c_\alpha c_\gamma - c_\beta s_\alpha s_\gamma & -c_\beta c_\gamma s_\alpha - c_\alpha s_\gamma & s_\alpha s_\beta \\ c_\gamma s_\alpha + c_\alpha c_\beta s_\gamma & c_\alpha c_\beta c_\gamma - s_\alpha s_\gamma & -c_\alpha s_\beta \\ s_\beta s_\gamma & c_\gamma s_\beta & c_\beta \end{bmatrix}$$

Here, $s_\alpha = \sin(\alpha)$, and $c_\beta = \cos(\beta)$.

For the Tait-Bryan approach, the following rotation matrix is used:

$$\mathbf{Z}(\alpha)\mathbf{X}(\beta)\mathbf{Y}(\gamma) = \begin{bmatrix} c_\alpha c_\gamma - s_\alpha s_\beta s_\gamma & -c_\beta s_\alpha & c_\alpha s_\gamma + c_\gamma s_\alpha s_\beta \\ c_\gamma s_\alpha + c_\alpha s_\beta s_\gamma & c_\alpha c_\beta & s_\alpha s_\gamma - c_\alpha c_\gamma s_\beta \\ -c_\beta s_\gamma & s_\beta & c_\beta c_\gamma \end{bmatrix}$$

2.  **Local coordinate systems.** It is possible to have the ICFD parts or ICFD_-PART_VOLs rotate around the global reference frame but also to define and use a local reference frame by defining its point of origin and two of its vectors $\mathbf{v}_1 = $ (X1, Y1, Z1) and $\mathbf{v}_2 = $ (X2, Y2, Z2) (note that $\mathbf{v}_1$ and $\mathbf{v}_2$ should be orthogonal). The third vector is, then, in the direction of $\mathbf{v}_1 \times \mathbf{v}_2$. See Figure 7-5.

3.  **Purpose of NID.** We developed this feature for rotating problems involving FSI and sliding mesh. For example, the airflow can push the blades of a wind turbine and the rotation of the sliding mesh can be prescribed as function of the blade rotation speed.

4.   **\*DEFINE_FUNCTION.** For each of the load curves, a \*DEFINE_FUNCTION can be used.  If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, visc, pres, time, dt).

**\*ICFD_CONTROL_LEVELSET**

Purpose: Modify default values for the level set solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LSRST | LSINL | | LSMTH | | | SGC | AST |
| Type | I | I | | F | | | I | I |
| Default | 20 | 0 | | 0.0 | | | 0 | 0 |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SRL | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| LSRST | Frequency the level set distance function is re-initialized. The default value is every 20 time steps. |
| LSINL | Set the level set to be positive at a velocity inlet: |
| | EQ.0: Let the level set algorithm compute the value (default). |
| | EQ.1: Force a positive level set value at the inlet. |
| LSMTH | Scale factor for level set smoothness. |
| | GT.0.0: Add smoothness to the free surface. Small values like 0.1 are reasonable. The optimal value could be problem dependent. |
| SGC | Smoother approximate of gradient and curvature: |
| | EQ.0: No smoothing added |
| | EQ.1: Linear gradient and curvature |
| | EQ.-1: Least-squares-based gradient and curvature |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.2: Least-squares gradient smoothing |
| AST | Advanced formulation for surface tension: |
| | EQ.0: Smoothed Dirac |
| | EQ.1: Smoothed Heaviside |
| | EQ.2: Laplace-Beltrami |
| SRL | Smoother reinitialization method for the level set: |
| | EQ.0: Standard, geometric-based |
| | EQ.1: Linear closest point algorithm |
| | EQ.2: Higher-order closest point algorithm |

## \*ICFD_CONTROL_LOAD

Purpose: This keyword resets the body load in the ICFD solver to zero, while leaving the body load unchanged for the solid mechanics solver. It is useful in problems where the gravity acceleration may be neglected for the fluid problem, but not for the solid mechanics problem.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ABL | | | | | | | |
| Type | I | | | | | | | |
| Default | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ABL | EQ.0: the body load provided in \*LOAD_BODY is reset to zero only for the fluid analysis. |

## \*ICFD_CONTROL_MESH

Purpose: Modify default values for automatic volume mesh generation.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|--------|---------|-------|---|---|---|
| Variable | MGSF | | MSTRAT | 2DSTRUC | NRMSH | | | |
| Type | F | | I | I | I | | | |
| Default | 1.41 | | 0 | 0 | 0 | | | |

**Optional card.** This card is optional.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|---|---|---|---|---|---|
| Variable | AVER | SFBL | | | | | | |
| Type | I | F | | | | | | |
| Default | 14 | 1.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MGSF | Mesh Growth Scale Factor. It specifies the maximum mesh size that the volume mesher is allowed to use when generating the volume mesh based on the mesh surface element sizes defined in \*MESH_SURFACE_ELEMENT. See Remark 1. |
| MSTRAT | Mesh generation strategy (see Remark 2):<br><br>EQ.0: Mesh generation based on Delaunay criteria<br><br>EQ.1: Mesh generation based on octree |
| 2DSTRUC | Flag to decide between an unstructured mesh generation strategy in 2D or a structured mesh strategy:<br><br>EQ.0: Structured mesh<br><br>EQ.1: Unstructured mesh |

| VARIABLE | DESCRIPTION |
|---|---|
| NRMSH | Flag to turn off any remeshing (see Remark 3):<br><br>EQ.0: Remeshing possible<br><br>EQ.1: Remeshing not allowed |
| AVER | Automatic Volume Mesher version (see Remark 4):<br><br>EQ.14: Version 14<br><br>EQ.16: Version 16 |
| SFBL | Scale factor that controls the speed of boundary layer inflation. If the boundary layer is much larger in size than the surface mesh, we recommend a value less than one. |

**Remarks:**

1. **MGSF.** For MGSF, values between 1 and 2 are allowed. Values closer to 1 will result in a finer volume mesh (1 means the volume mesh is not allowed to be coarser than the element size from the closest surface meshes) and values closer to 2 will result in a coarser volume mesh (2 means the volume can use elements as much as twice as coarse as those from the closest surface mesh). MGSF has a fixed value of 1 in 2D.

2. **Mesh Generation Strategy.** The default mesh generation strategy (based on Delaunay criteria) yields a linear interpolation of the mesh size between two surfaces facing each other whereas the octree-based generation strategy allows for the sizes of the elements to remain close to the element surface mesh size over a longer distance. This octree strategy can be useful for creating a smoother transition in configurations where two surface meshes facing each other have very distinct sizes.

3. **NRMSH.** If you know in advance that no remeshing will occur during the analysis, then setting NRMSH to 1 may be useful as it will free up space used to back up the mesh and consequently lower memory consumption.

4. **Version.** Version 14 is the default version used for the ICFD solver automatic volume mesher. Version 16 is now supported and available as option. In some cases, it can yield an approximatively 20% mesh generation speed gain.

## \*ICFD_CONTROL_MESH_MOV

Purpose: Choose the type of algorithm for mesh movement.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MMSH | LIM_ITER | RELTOL | | | | | |
| Type | I | I | F | | | | | |
| Default | 2 | 100 | $10^{-3}$ | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

**MMSH**

Mesh motion selector:

    EQ.-1: Completely shuts off any mesh movement

    EQ.1: Mesh moves based on the distance to moving walls.

    EQ.2: Mesh moves by solving a linear elasticity problem using the element sizes as stiffness (default).

    EQ.3: Mesh uses a Laplacian smoothing with stiffness on edges and from node to opposite faces. Very robust, but costly.

    EQ.4: Full Lagrangian. The mesh moves with the velocity of the flow.

    EQ.11: Mesh moves using an implicit ball-vertex spring method.

    EQ.20: Mesh moves by solving a linear elasticity problem using a constant size. This can be useful to avoid large distortions in rotating problems that involve large discrepancies in mesh sizes (typically in cases involving boundary layer mesh).

**LIM_ITER**

Maximum number of linear solver iterations for the ball-vertex linear system

**RELTOL**

Relative tolerance to use as a stopping criterion for the ball-vertex method iterative linear solver (conjugate gradient solver with diagonal scaling preconditioner)

## \*ICFD_CONTROL_MONOLITHIC

Purpose: This keyword allows to choose between the Fractional Step Solver and the Monolithic Solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SID | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SID | Solver ID : |
| | EQ.0: Fractional Step Solver. Default. |
| | EQ.1: Monolithic Solver. |

## *ICFD_CONTROL_OUTPUT

Purpose: This keyword modifies default values for screen and file outputs related to this fluid solver only.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|-------|---------|---|------|---|---|
| Variable | MSGL | OUTL | DTOUT | LSPPOUT | | ITOUT | | |
| Type | I | I | F | I | | I | | |
| Default | 0 | 0 | 0 | 0 | | 0 | | |

**Optional Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|---|---|---|---|---|---|---|
| Variable | PITOUT | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSGL | Message level. |

        EQ.0: only time step information is output.

        EQ.1: first level solver information.

        EQ.2: full output information with details about linear algebra and convergence steps.

        EQ.4: full output information is also copied to the messag file.

| VARIABLE | DESCRIPTION |
|---|---|
| OUTL | Output the fluid results in other file formats apart from d3plot. |
| | EQ.0: only d3plot output |
| | EQ.2: output a file with mesh statistics and the fluid results in OpenDX format. A directory named dx will be created in the work directory where the output files will be written. |
| | EQ.6: output a file with mesh statistics and the fluid results in VTK format readable by Paraview. A directory named vtk will be created in the work directory where the output files will be written. |
| | EQ.7: output a file with mesh statistic and the fluid results in VTU format readable by Paraview. A directory named vtk will be created in the work directory where the output files will be written. |
| | EQ.10: output a file with mesh statistic and the fluid results in Fieldview ASCII format. . A directory named fv will be created in the work directory where the output files will be written. Only available in 3D. |
| | EQ.11: output a file with mesh statistic and the fluid results in Fieldview binary format. . A directory named fv will be created in the work directory where the output files will be written. Only available in 3D. |
| DTOUT | Time interval to print the output when OUTL is different than 0. |
| LSPPOUT | EQ.0: no LSPP output is produced. |
| | EQ.1: outputs a file with the automatically created fluid volume mesh in a format compatible for LSPP at each remesh. Also outputs the fluid volume mesh in a format compatible with a subsequent ICFD analysis. |
| | EQ.3: Outputs the fluid volume mesh in a format compatible with a subsequent ICFD analysis at each DTOUT. |
| ITOUT | Iteration interval to print the output, including the d3plot files when the steady state solver is selected (See ICFD_CONTROL_GENERAL). |

| VARIABLE | DESCRIPTION |
| --- | --- |
| PITOUT | Pressure iteration limit output. If the number of pressure iterations in the fractional step solve goes above PITOUT, an extra d3plot will be dumped. This is mainly a debugging feature which can help the user identify problematic areas in the model which often precede a divergence. |

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## \*ICFD_CONTROL_OUTPUT_SUBDOM

Purpose: Defines a specific zone that should be output in the format specified by the ICFD_CONTROL_OUTPUT card rather than the whole domain.

**Shape Control.** First card specifies the shape of the output sub domain.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-------|---|---|---|---|---|---|---|
| Variable | SNAME | | | | | | | |
| Type | A | | | | | | | |
| Default | none | | | | | | | |

**Box Case.** Card 2 for Sname = box

| Cards 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-------|-------|-------|-------|-------|-------|---|---|
| Variable | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ | | |
| Type | F | F | F | F | F | F | | |
| Default | none | none | none | none | none | none | | |

**Sphere Case.** Card 2 for Sname = sphere

| Cards 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|--------|---------|---------|---------|---|---|---|---|
| Variable | RADIUS | CENTERX | CENTERY | CENTERZ | | | | |
| Type | F | F | F | F | | | | |
| Default | none | none | none | none | | | | |

**Cylinder Case.** Card 2 for Sname = cylinder

| Cards 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|------|------|------|------|------|---|
| Variable | Radius | PMINX | PMINY | PMAXZ | PMAXX | PMAXY | PMAXZ | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SNAME | Shape name.  Possibilities include 'box', 'cylinder' and 'sphere' |
| PMINX, Y, Z] | X, Y, Z for the point of minimum coordinates |
| PMAX[X, Y, Z] | X, Y, Z for the point of maximum coordinates |
| CEN-TER[X, Y, Z] | Coordinates of the sphere center in cases where Sname is Sphere |
| RADIUS | Radius of the sphere if SNAME  is *sphere* or of the cross section disk if SNAME is *cylinder*. |

**\*ICFD_CONTROL_OUTPUT_VAR**

Purpose: This keyword allows the user to turn off the output of certain CFD variables to reduce the size of the d3plot files.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | VEL | AVGVEL | VORT | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | PRE | PREAVG | LSET | QC | CFL | | | |
| Type | I | I | I | I | I | | | |
| Default | 0 | 0 | 0 | 0 | 0 | | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | TEMP | TEMPAVG | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0 | | | | | | |

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|---|---|---|
| Variable | KP | EP | MUT | INT | CMU | | | |
| Type | I | I | I | I | I | | | |
| Default | 0 | 0 | 0 | 0 | 0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| VEL/AVGVEL/ VORT | Velocity, average velocity, vorticity : <br> **EQ.0:** Is output. <br> **EQ.1:** Is not output. |
| PRE/PREAVG/ LSET/QC/CFL | Pressure, average pressure, levelset, Q criterion, CFL number : <br> **EQ.0:** Is output. <br> **EQ.1:** Is not output. |
| TEMP/ TEMPAVG | Temperature, average temperature : <br> **EQ.0:** Is output. <br> **EQ.1:** Is not output. |
| KP/EP/MUT /INT/CMU | RANS output variables, kinetic energy, diffusion, turbulent viscosity, turbulent intensity, Cmu variable : <br> **EQ.0:** Is output. <br> **EQ.1:** Is not output. |

.

## \*ICFD_CONTROL_PARTITION

Purpose: This keyword changes the default option for the partition in MPP, thus it is only valid in MPP.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PTECH | | | | | | | |
| Type | I | | | | | | | |
| Default | 1 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PTECH | Indicates the type of partition: |

      EQ.1: the library Metis is used.

      EQ.2: partition along the axis with higher aspect ratio

      EQ.3: partition along $X$-axis

      EQ.4: partition along $Y$-axis

      EQ.5: partition along $Z$-axis

## \*ICFD_CONTROL_POROUS

Purpose: This keyword modifies the porous media solve.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---------|---------|---|---|---|---|---|---|
| Variable | PMSTYPE | VELMETH | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|

PMSTYPE      Indicates the porous media solve type.

         EQ.0: Anisotropic Generalized Navier-Stokes model for porous media (See \*ICFD_MODEL_POROUS) using Fractional step method.

         EQ.1: Anisotropic Darcy-Forcheimer model using a Monolithic approach for the solve. This method is better suited for very low Reynolds flows through porous media (frequently encountered in Resin Transfer Molding (RTM) applications). See Remark 1.

VELMETH      Method for determining advection velocity:

         EQ.0: Uses FEM approximation for advection velocity

         EQ.1: Uses PFEM2 for advection velocity

**Remarks:**

1. **Anisotropic Darcy-Forcheimer Model.** When using the Anisotropic Darcy-Forcheimer model, the convective term in the Navier Stokes formulation is neglected.

**\*ICFD_CONTROL_STEADY**

Purpose: This keyword allows to specify convergence options for the steady state solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|------|------|------|------|-------|
| Variable | ITS | TOL1 | TOL2 | TOL3 | REL1 | REL2 | UREL | ORDER |
| Type | I | F | F | F | F | F | F | I |
| Default | 1e6 | 1.e-3 | 1.e-3 | 1.e-3 | 0.3 | 0.7 | 1. | 0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ITS | Maximum number of iterations to reach convergence. |
| TOL1/2/3 | Tolerance limits for the momentum pressure and temperature equations respectfully. |
| REL1/2 | Relaxation parameters for the velocity and pressure respectfully. Decreasing those values may add stability but more iterations may be needed to reach convergence. |
| UREL | Under relaxation parameter. Lowering this value may improve the final accuracy of the solution but more iterations may be needed to achieve convergence. |
| ORDER | Analysis order : |

        EQ.0: Second order. More accurate but more time consuming.

        EQ.1: First order: More stable and faster but may be less accurate.

## \*ICFD_CONTROL_SURFMESH

Purpose: Enable automatic surface remeshing. The objective of the remeshing is to improve the mesh quality on the boundaries. It should not be used on a regular basis.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RSRF | SADAPT | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0 | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|

RSRF            Indicates whether or not to perform a surface remeshing:

> EQ.0: Do not perform surface remeshing.
>
> EQ.1: Perform Laplacian smoothing surface remeshing.
>
> EQ.2: Perform curvature-preserving surface remeshing.

SADAPT       Indicates whether or not to trigger adaptive surface remeshing:

> EQ.0: Do not apply adaptive surface remeshing.
>
> EQ.1: Apply automatic surface remeshing when quality deteriorates.
>
> EQ.2: Apply automatic surface remeshing when quality deteriorates. Keep the initial element size in the case of adaptive mesh refinement using \*ICFD_CONTROL_ADAPT throughout the computation.

.

**\*ICFD_CONTROL_TAVERAGE**

Purpose: This keyword controls the restarting time for computing the time average values. By default, there is no restarting and the average quantities are given starting from $t = 0$. This keyword can be useful in turbulent problems that admit a steady state.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DT | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| DT | Over each DT time interval, the average quantities are reset. |

## \*ICFD_CONTROL_TIME

Purpose:  Change the default values related to time parameters for the fluid problem.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | TTM | DT | CFL | LCIDSF | DTMIN | DTMAX | DTINIT | TDEATH |
| Type | F | F | F | I | F | F | F | F |
| Default | $10^{28}$ | 0.0 | 1.0 | 0 | $10^{-9}$ | $10^{28}$ | ↓ | $10^{28}$ |

Optional card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DTT | | | | | | | |
| Type | F | | | | | | | |
| Default | Rem 2 | | | | | | | |

Optional card

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DTBL | DTST | DTVISC | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

Optional card

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|-------|---------|--------|--------|---------|---|
| Variable | IDR | DTDR | CFLDR | LCIDSFDR | DTMINDR | DTMAXDR | DTINITDR | |
| Type | I | F | F | I | F | F | F | |
| Default | 0 | 0.0 | 1.0 | 0 | $10^{-9}$ | $10^{28}$ | 0.0 | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TTM | Total time of simulation for the fluid problem |
| DT | Time step for the fluid problem. If nonzero, the time step will be constant and equal to this value. If set to 0.0, then the time step is automatically computed based on the fluid advection CFL condition. See Remark 1. |
| CFL | CFL number for DT = 0.0. In general, CFL specifies a scale factor that is applied to the time step. When DT = 0.0, the time step is set to the maximum value satisfying the CFL condition, in which case this scale factor is equal to the *CFL number*. |
| LCIDSF | Load curve ID specifying the CFL number when DT = 0.0 as a function of time, and more generally LCIDSF specifies the time step scale factor as a function of time. |
| DTMIN | Minimum time step. When an automatic time step is used and DTMIN is defined, the time step cannot drop below DTMIN. A negative value will refer to a time dependent load curve. |
| DTMAX | Maximum time step. When an automatic time step is used and DTMAX is defined, the time step cannot increase beyond DTMAX. A negative value will refer to a time dependent load curve. |
| DTINIT | Initial time step. If not defined, the solver will automatically determine an initial time step based on the flow velocity or dimensions of the problem in cases where there is no inflow. |
| TDEATH | Death time for the Navier Stokes solve. After TDEATH, the velocity and pressure will no longer be updated. But the temperature and other similar quantities still can. |
| DTT | Thermal time step. See Remark 2. |

| VARIABLE | DESCRIPTION |
|---|---|
| DTBL | Flag to include boundary layer elements in the automatic time step calculation. |
| | EQ.0: Exclude boundary layer elements (default). |
| | EQ.1: Include boundary layer elements. |
| DTST | Flag to include surface tension effects (when present) in the automatic time step calculation: |
| | EQ.0: Do not take it into account (default). |
| | EQ.1: Add surface tension effects. See Remark 3. |
| DTVISC | Flag to include viscous effects in the automatic time step calculation: |
| | EQ.0: Do not take it into account (default). |
| | EQ.1: Add viscous term effects. See Remark 4. |
| IDR | Temporarily overwrite time step settings during dynamic relaxation (DR) phase (see field IDR of \*ICFD_CONTROL_GENERAL) |
| | EQ.0: Off |
| | EQ.1: Overwrite timesteps settings during DR phase |
| DTDR/[..]/ DTINITDR | Time step parameters equivalent to the fields 2 through 7 on Card 1 used during DR phase. |

**Remarks:**

1.  **Courant friedrichs lewy (CFL) condition.** When an automatic time step is selected, the default behavior is to use the following Courant condition:

$$\Delta t \leq \Delta t_{\text{adv}} \leq \frac{l}{V}$$

    Here, $V$ is the fluid velocity, and $l$ is the characteristic mesh size. When using an automatic time step, it is recommended to define a minimum and maximum acceptable value. It is also recommended to give an initial value, especially in cases where no velocity boundary condition exists.

2.  **Thermal time step.** By default, the heat equation is solved using the same time step as that for the velocity/pressure system. This option allows you to assign a specific time step for the thermal solve. It can be useful in cases where the time

scales are very different between the two domains. When defined, we recommend DTT to always be greater than or equal to the regular CFD time step.

3. **Surface tension effects.** For free surface or bi-phasic cases where surface tension is present and is the dominant force, using DTST = 1 in combination with an automatic time step may be convenient. In such cases, the automatic time step is limited by the following Courant condition:

$$\Delta t \leq \Delta t_{\mathrm{st}} \leq \sqrt{\frac{\tilde{\rho} l^3}{2\pi\sigma}}$$

In this condition, $\tilde{\rho}$ is the average density between the two fluids, $l$ is the mesh size, and $\sigma$ isthe surface tension value.

4. **Diffusive effects.** In advection-driven flows, the default criteria to estimate an automatic time step is sufficient. However, in applications where the advection term is small compared to the viscous forces (usually cases that combine low Reynolds number with high viscosity value), adding the diffusion Courant condition as an additional constraint may be justified:

$$\Delta t \leq \Delta t_{\mathrm{diff}} \leq \frac{l^2}{\nu}$$

Here, $l$ is the mesh size, and $\nu$ is the kinematic viscosity.

## \*ICFD_CONTROL_TRANSIENT

Purpose: This keyword allows to specify different integration scheme options for the transient solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | TORD | FSORD | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TORD | Time integration order : |
| | EQ.0: Second order. |
| | EQ.1: First order. |
| FSORD | Fractional step integration order : |
| | EQ.0: Second order. |
| | EQ.1: First order. |

## \*ICFD_CONTROL_TURBULENCE

Purpose: Modify the default values for the turbulence model.

**Card Summary:**

**Card 1.** This card is required.

| TMOD | SUBMOD | WLAW | KS | CS | | TWLAW | TYPLUS |
|------|--------|------|----|----|--|-------|--------|

**Card 2a.** This card is read if TMOD = 1. It is optional.

| CE1 | CE2 | SIGMAEPS | SIGMAK | CMU | CCUT | | |
|-----|-----|----------|--------|-----|------|--|--|

**Card 2b.** This card is read if TMOD = 2 or 3. It is optional.

| Cs | | | | | | | |
|----|--|--|--|--|--|--|--|

**Card 2c.1.** This card is read if TMOD = 4. It is optional.

| GAMMA | BETA01 | SIGMAW1 | SIGMAK1 | BETA0ST | CCUT | | |
|-------|--------|---------|---------|---------|------|--|--|

**Card 2c.2.** This card is read if TMOD = 4. It is optional.

| A1 | BETA02 | SIGMAW2 | SIGMAK2 | CL | | | |
|----|--------|---------|---------|----|--|--|--|

**Card 2d.** This card is read if TMOD = 5. It is optional.

| CB1 | CB2 | SIGMANU | CNU1 | CW1 | CW2 | | |
|-----|-----|---------|------|-----|-----|--|--|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | TMOD | SUBMOD | WLAW | KS | CS | | TWLAW | TYPLUS |
| Type | I | I | I | F | F | | I | F |
| Default | 0 | 1 | 1 | 0. | 0. | | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TMOD | Indicates what turbulence model will be used. |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: Turbulence model based on a variational multiscale approach is used by default. |
| | EQ.1: RANS $k - \varepsilon$ approach (see Remark 1) |
| | EQ.2: LES Smagorinsky or dynamic sub-grid scale model |
| | EQ.3: LES Wall adapting local eddy-viscosity (WALE) model |
| | EQ.4: RANS $k - w$ approach (see Remark 2) |
| | EQ.5: RANS Spalart-Allmaras approach |
| SUBMOD | Turbulence sub-model. |
| | For RANS $k - \varepsilon$ approach (TMOD = 1): |
| |     EQ.1: Standard model |
| |     EQ.2: Realizable model |
| | For LES Smagorinsky or dynamic sub-grid model (TMOD = 2): |
| |     EQ.1: Smagorinsky model (see Remark 6) |
| |     EQ.2: Dynamic model (see Remark 7). |
| | For RANS $k - \omega$ approach (TMOD = 4): |
| |     EQ.1: Standard Wilcox 98 model. |
| |     EQ.2: Standard Wilcox 06 model. |
| |     EQ.3: SST Menter 2003. |
| WLAW | Law of the wall ID if a RANS turbulence model is selected (see Remark 4): |
| |     EQ.1: Standard classic law of the wall (default for TMOD = 1) with linear blending between the log and linear regions. |
| |     EQ.2: Standard Launder and Spalding law of the wall |
| |     EQ.4: Nonequilibrium Launder and Spalding law of the wall |
| |     EQ.5: Automatic classic law of the wall |
| KS | Roughness physical height, only used for RANS turbulence models. |
| CS | Roughness constant, only used for RANS turbulence models. |
| TWLAW | Thermal law of the wall flag (see Remark 8): |
| |     EQ.0: No thermal law of the wall activated. |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.1: Thermal law of the wall |
| TYPLUS | Thermal Y+ value ($Y_{+t}$). If $Y_{+t}$ is not defined, the solver will automatically estimate its value using $Y_{+tc} = Y_{+c}/\text{Pr}^{1./3.}$ with $Y_{+c} = 11.225$ the critical $Y_+$ value and Pr the Prandtl number. |

**RANS $k - \varepsilon$ Card.** **Optional card if TMOD = 1.** Optional card read if TMOD = 1. See Remark 1.

| Card 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CE1 | CE2 | SIGMAE | SIGMAK | CMU | CCUT | | |
| Type | F | F | F | F | F | F | | |
| Default | 1.44 | 1.92 | 1.3 | 1.0 | 0.09 | -1. | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CEPS1 | $k$ - $\varepsilon$ model constant, $C_{1\varepsilon}$ |
| CEPS2 | $k$ - $\varepsilon$ model constant, $C_{2\varepsilon}$ |
| SIGMAEPS | $k$ - $\varepsilon$ model constant, $\sigma_\varepsilon$ |
| SIGMAK | $k$ - $\varepsilon$ model constant, $\sigma_k$ |
| CMU | $k$ - $\varepsilon$ model constant, $C_\mu$ |
| CCUT | $k$ - $\varepsilon$ model constant, $C_{\text{cut}}$ |

**LES Card.** Optional card read if TMOD = 2 or 3.

| Card 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | Cs | | | | | | | |
| Type | F | | | | | | | |
| Default | 0.18 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| Cs | Smagorinsky constant if TMOD = 2 and SUBMOD = 1 or WALE constant if TMOD = 3 |

**RANS $k - \omega$ Card.** Optional card read if TMOD = 4. See Remark 2.

| Card 2c.1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | GAMMA | BETA01 | SIGMAW1 | SIGMAK1 | BETA0ST | CCUT | | |
| Type | F | F | F | F | F | F | | |
| Default | 1.44 | 0.072 | 2. | 2. | 0.09 | -1. | | |

**RANS $k - \omega$ Card.** Optional card read if TMOD = 4. See Remark 2.

| Card 2c.2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | A1 | BETA02 | SIGMAW2 | SIGMAK2 | CL | | | |
| Type | F | F | F | F | F | | | |
| Default | 0.31 | 0.0828 | 2 | 2 | 0.875 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| GAMMA | $k$ -$\omega$ model constant, $\gamma$ |
| BETA01 | $k$ -$\omega$ model constant, $\beta_{01}$ |
| SIGMAW1 | $k$ -$\omega$ model constant, $\sigma_{\omega 1}$ |
| SIGMAK1 | $k$ -$\omega$ model constant, $\sigma_{k1}$ |
| BETA0ST | $k$ -$\omega$ model constant, $\beta_0^*$ |
| CCUT | $k$ -$\omega$ model constant, $C_{\text{cut}}$ |
| A1 | $k$ -$\omega$ model constant, $a_1$ |
| BETA02 | $k$ -$\omega$ model constant, $\beta_{02}$ |
| SIGMAW2 | $k$ -$\omega$ model constant, $\sigma_{\omega 2}$ |

| VARIABLE | DESCRIPTION |
|---|---|
| SIGMAK2 | $k$-$\omega$ model constant, $\sigma_{k2}$ |
| CL | $k$-$\omega$ model constant, $C_l$ |

**RANS Spalart-Allmaras Card.** Optional card read if TMOD = 5.

| Card 2d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | CB1 | CB2 | SIGMANU | CNU1 | CW1 | CW2 | | |
| Type | F | F | F | F | F | F | | |
| Default | 0.1355 | 0.622 | 0.66 | 7.2 | 0.3 | 2.0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| CB1 | Spalart-Allmaras constant, $C_{b1}$ |
| CB2 | Spalart-Allmaras constant, $C_{b2}$ |
| SIGMANU | Spalart-Allmaras constant, $\sigma_\nu$ |
| CNU1 | Spalart-Allmaras constant, $C_{\nu1}$ |
| CW1 | Spalart-Allmaras constant, $C_{w1}$ |
| CW2 | Spalart-Allmaras constant, $C_{w2}$ |

**Remarks:**

1.  **$k$-$\varepsilon$ model (TMOD = 1).** For the Standard $k$-$\varepsilon$ model, the following two equations are solved for the turbulent kinetic energy ($k$) and the turbulent dissipation ($\varepsilon$):

$$\frac{\partial k}{\partial t} + \frac{\partial(ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[(\frac{\mu}{\rho} + \frac{\mu_t}{\rho\sigma_k})\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \varepsilon + S_k$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial(\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[(\frac{\mu}{\rho} + \frac{\mu_t}{\rho\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\frac{\varepsilon^2}{k} + S_e$$

Here $P_k$ is the $k$ production term (see Remark 3), $P_b$ is the production term due to buoyancy and $S_k$ and $S_e$ are the user defined source terms. $P_k$ and $P_b$ are expressed as:

$$P_k = \frac{\mu_t}{\rho} S^2$$

$$P_b = \frac{\beta \mu_t}{\rho \mathrm{Pr}_t} g_i \frac{\partial T}{\partial x_i}$$

where $S$ is the modulus of the mean rate of strain tensor ($S^2 = 2S_{ij}S_{ij}$), $\beta$ is the coefficient of thermal expansion, and $\mathrm{Pr}_t$ is the turbulent Prandtl number. The turbulent viscosity is then expressed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

For the realizable $k$ - $\varepsilon$ model, the equation for the turbulent kinetic energy does not change, but the equation for the turbulent dissipation is now expressed as:

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial(\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[(\frac{\mu}{\rho} + \frac{\mu_t}{\rho \, \sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_1 S \varepsilon - C_{2\varepsilon} \frac{\varepsilon^2}{k + \sqrt{\frac{\mu}{\rho}\varepsilon}} - \varepsilon + S_e \ .$$

Here $C_1 = \max\left[0.43, \frac{\eta}{\eta+5}\right]$ with $\eta = S\frac{k}{\varepsilon}$.

Furthermore, while the turbulent viscosity is still expressed the same way, $C_\mu$ is no longer a constant:

$$C_\mu = \frac{1}{A_0 + A_s k \frac{U^*}{\epsilon}} \ .$$

In the above,

$$U^* = \sqrt{\Omega_{ij}\Omega_{ij} + S_{ij}S_{ij}}$$
$$A_0 = 4.04$$
$$A_s = \sqrt{6}cos\left(\frac{1}{3}cos^{-1}\left(\sqrt{6}\frac{S_{ij}S_{jk}S_{ki}}{(S_{ij}S_{ij})^{3/2}}\right)\right)$$

Note that in this case, the constant value $C_\mu$ that can be input by you serves as the limiting value that $C_\mu$ can take. By default, $C_\mu = 0.09$ so:

$$0.0009 < C_\mu < 0.09$$

2.     $k$ - $\omega$ **model (TMOD = 4).** For the Standard Wilcox 06 $k$ - $\omega$ model, the following two equations are solved for the turbulent kinetic energy and the specific turbulent dissipation rate, respectively $k$ and $\omega$:

$$\frac{\partial k}{\partial t} + \frac{\partial(ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\rho} + \frac{\mu_t}{\rho \sigma_{k1}}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \beta^* k\omega + S_k$$

$$\frac{\partial \omega}{\partial t} + \frac{\partial(\omega u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\rho} + \frac{\mu_t}{\rho \sigma_{\omega1}}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \gamma\frac{\omega}{k}P_k - \beta\omega^2 + \sigma_d X_k \omega^2 + S_\omega$$

Here $P_k$ is the $k$ production term (see Remark 3) and $S_k$ and $S_\omega$ are the user defined source terms. $P_k$, $\beta^*$, $\beta$ and $\sigma_d$ are expressed as:

$$P_k = \frac{\mu_t}{\rho} S^2$$
$$\beta^* = \beta_0^* f_{\beta*}$$
$$\beta = \beta_{01} f_\beta$$
$$\sigma_d = \begin{cases} 0. & X_k \leq 0. \\ 1/8 & X_k > 0. \end{cases}$$

where

$$f_\beta = \frac{1 + 85 X_\omega}{1 + 100 X_\omega}$$
$$f_{\beta*} = 1.$$
$$X_k = \frac{1}{\omega^3} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$
$$X_\omega = \left| \frac{\Omega_{ij} \Omega_{jk} S_{ki}}{(\beta_0^* \omega)^3} \right|$$

The turbulent viscosity is then:

$$\mu_t = \rho \frac{k}{max \left[ \omega, C_l \sqrt{\dfrac{2 S_{ij} S_{ij}}{\beta_0^*}} \right]}$$

For the Standard Wilcox 98 model, the following terms are modified:

$$f_\beta = \frac{1 + 70 X_\omega}{1 + 80 X_\omega}$$
$$f_{\beta*} = \begin{cases} 1 & \text{if } X_k \leq 0. \\ \dfrac{1 + 680\,X_k{}^2}{1 + 400\,X_k{}^2} & \text{if } X_k > 0. \end{cases}$$
$$\sigma_d = 0.$$

The turbulent viscosity is then:

$$\mu_t = \rho \frac{k}{\omega}$$

For the Menter SST 2003 model, the following equations are solved:

$$\frac{\partial k}{\partial t} + \frac{\partial (k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\rho} + \frac{\mu_t}{\rho\,\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \beta_0^* k \omega + S_k$$

$$\frac{\partial \omega}{\partial t} + \frac{\partial (\omega u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\rho} + \frac{\mu_t}{\rho\,\sigma_\omega} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\gamma}{\mu_t} P_k - \beta \omega^2 + 2(1 - F_1)\,\sigma_{\omega 2} X_k \omega^2 + S_\omega$$

Each of the constants, $\gamma$, $\beta$, $\sigma_k$, and $\sigma_\omega$ are now computed by a blend of two constants with a blending function through:

$$\alpha = \alpha_1 F_1 + \alpha_2(1 - F_1)$$

The blending function $F_1$ is defined by:

$$F_1 = \tanh\left(\left[\min\left(\max\left(\frac{\sqrt{k}}{\beta_0^* \omega y}, \frac{500\nu}{y^2 \omega}\right), \frac{4\rho \sigma_{\omega 2} k}{CD \times y^2}\right)\right]^4\right)$$

With $y$ the distance to the nearest wall and:

$$CD = \max\left(2\rho \sigma_{\omega 2} X_k \omega^2, 10^{-10}\right)$$

The turbulent viscosity is then:

$$\mu_t = \rho \frac{a_1 k}{\max(a_1 \omega, S F_2)}$$

with:

$$F_2 = \tanh\left[\left(\max\left(\frac{2\sqrt{k}}{\beta_0^* \omega y}, \frac{500\nu}{y^2 \omega}\right)\right)^2\right]$$

3.  **Production term.** You can activate a limiter on the production term, $P_k$, for TMOD =1 and 4. If $C_{\text{cut}} \geq 0$ (CCUT), then:

$$P_k = \begin{cases} \min(P_k, C_{\text{cut}}\varepsilon) & \text{if } TMOD = 1 \\ \min(P_k, C_{\text{cut}}\beta_0^* k\omega) & \text{if } TMOD = 4 \end{cases}$$

This is especially common when using the Menter SST 2003 model.

4.  **Laws of the wall for RANS models.** For RANS models, the following laws of the wall are available:

    a)  *Standard Classic (WLAW = 1)* with linear blending when $5 \leq Y^+ \leq 60$.

$$U_{blend}^+(Y^+) = \left(1 - \alpha(Y^+)\right) \times Y^+ + \alpha(Y^+) \times (1/k \ln(EY^+))$$
$$\alpha(Y^+) = \frac{Y^+ - 5}{60 - 5}$$
$$Y^+ = \frac{\rho y U_\tau}{\mu}$$
$$U^+ = \frac{U}{U_\tau}$$
$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

This is the default for TMOD = 1.

    b)  *Standard Launder and Spalding (WLAW = 2)*.

$$U^* = \begin{cases} \dfrac{1}{\kappa}\ln(EY^*) & \text{if } Y^* > 11.225 \\ Y^* & \text{otherwise} \end{cases}$$

$$Y^* = \frac{\rho C_\mu^{1/4} k^{1/2} y}{\mu}$$

$$U^* = \frac{U C_\mu^{1/4} k^{1/2}}{U_\tau^2}$$

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

c) *Nonequilibrium Launder and Spalding (WLAW = 4)*. The nonequilibrium laws of the wall modify the expression of the velocity at the wall making it sensitive to the pressure gradient :

$$\tilde{U} = U - \frac{1}{2}\frac{dp}{dx}\left[\frac{y_v}{\rho\kappa\sqrt{k}}ln\left(\frac{y}{y_v}\right) + \frac{y - y_v}{\rho\kappa\sqrt{k}} + \frac{y_v^2}{\mu}\right]$$

with:

$$y_v = \frac{11.225}{y^*}y$$

This law is recommended with TMOD = 1 and in cases of complex flows involving separation, reattachment and recirculation.

d) *Automatic Classic (WLAW = 5)*. The automatic wall law attempts to blend the viscous and log layers to better account for the transition zone. In the buffer region, we have :

$$U^+ = \frac{U}{U_\tau}$$

$$U_\tau = \sqrt[4]{(\frac{U}{y^+})^4 + (\frac{U}{\frac{1}{\kappa}\ln(Ey^+)})^4}$$

This is the recommended approach for TMOD = 4.

5. **RANS turbulence model with roughness included.** When a RANS turbulence model is selected, it is possible to define extra parameters to account for roughness effects. In such cases, an extra term will be added to the logarithmic part of the different laws of the wall:

$$U^+ = \frac{1}{\kappa}\ln(E\ Y^+) - \Delta B$$

If we introduce the non-dimensional roughness height:

$$K^+ = \frac{\rho K_s C_\mu^{1/4} k^{1/2}}{\mu}\ ,$$

we have:

$$\Delta B = \begin{cases} 0 & \text{for } K^+ \le 2.25 \\ \frac{1}{\kappa} \ln \left( \frac{K^{\pm 2.25}}{87.75} + C_s K^+ \right) \times \sin \left( 0.4258(\ln K^+ - 0.811) \right) & \text{for } 2.25 < K^+ \le 90.0 \\ \frac{1}{\kappa} \ln(1 + C_s K^+) & \text{for } 90. < K^+ \end{cases}$$

6.  **LES Smagorinksy.** The LES Smagorinsky turbulence model uses the Van Driest damping function close to the wall:

$$f_v = 1 - e^{-\frac{y^+}{A^+}}$$

7.  **LES dynamic model.** The LES dynamic model is based on the model originally proposed by Germano et. al. (1991) and improved by Lilly (1992), with localization on Cs by Piomelli and Liu (1995).

8.  **Thermal law of the wall.** When the thermal law of the wall is activated, the turbulent heat flux will be calculated as an additional output variable:

$$Q_t = \rho C_p \frac{U_\tau}{T_+} (T_s - T_c)$$

$$T_+ = \begin{cases} \text{Pr}_t Y_+ & \text{if } Y_{+t} \le Y_{+tc} \\ \frac{\text{Pr}_t}{\vartheta} \log(Y_+) + \left( 3.85 \text{Pr}_t^{1.\overline{3}} - 1.3 \right)^2 + 2.12 \log(\text{Pr}_t) & \text{otherwise} \end{cases}$$

**\*ICFD_CONTROL_TURB_SYNTHESIS**

Purpose: This keyword enables the user impose a divergence-free turbulent field on inlets.

Card must be used jointly with VAD = 4 of keyword \*ICFD_BOUNDARY_PRE-SCRIBED_VEL.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | IU | IV | IW | LS | | | |
| Type | I | F | F | F | F | | | |
| Default | 0 | $10^{-3}$ | $10^{-3}$ | $10^{-3}$ | $h_{min}$ | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the surface with the turbulent velocity inlet condition. |
| IU, IV, IW | Intensity of field fluctuations over $x$, $y$, and $z$ directions, $$IU = \frac{u'}{u_{avg}}.$$ |
| LS | Integral length scale of turbulence |

**Remarks:**

1.  If this card is not defined but a turbulent field inlet has been activated. See VAD = 4 of \*ICFD_BOUNDARY_PRESCRIBED_VEL, the default parameters will be used.

## \*ICFD_DATABASE_AVERAGE

Purpose:  This keyword enables the computation of time average variables at given time intervals.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---|---|---|---|---|---|---|
| Variable | DT | | | | | | | |
| Type | F | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DT | Over each DT time interval, an average of the different fluid variables will be calculated and then reset when moving to the next DT interval. |

**Remarks:**

1.  The file name for this database is icfdavg.*.dat with the different averaged variable values copied in a ASCII format.

**\*ICFD_DATABASE_DRAG_{OPTION}**

Available options include

   VOL

Purpose: This keyword enables the computation of drag forces over given surface parts of the model. If multiple keywords are given, the forces over the PID surfaces are given in separate files and are also added and output in a separate file.

For the VOL option, drag calculation can also be applied on a volume defined by ICFD_-PART_VOL. This is mostly useful in porous media applications to output the pressure drag of the porous media domain.

**Surface Drag Cards.** Include one card for each surface on which drag is applied. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | CPID | DTOUT | PEROUT | DIVI | ELOUT | SSOUT | |
| Type | I | I | F | I | I | I | I | |
| Default | none | none | 0. | 0 | 10 | 0 | 0 | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID of the surface where the drag force will be computed. |
| CPID | Center point ID used for the calculation of the force's moment. By default the reference frame center is used is $0 = (0,0,0)$. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the ICFD timestep will be used. |
| PEROUT | Outputs the contribution of the different elements on the total drag in fractions of the total drag in the d3plots. |
| DIVI | Number of drag divisions for PEROUT. Default is 10 which means the contributions will be grouped in 10 deciles. |
| ELOUT | Outputs the drag value of each element in the d3plots. |
| SSOUT | Outputs the pressure loads caused by the fluid on each solid segment set in keyword format. FSI needs to be activated. |

**Remarks:**

1.  The file name for this database is icfdragi for instantaneous drag and icfdraga for the drag computed using average values of pressure and velocities.

2.  The output contains:

    a)  "Fpx" , "Fpy", and "Fpz" refer to the three components of the pressure drag force

    $$\mathbf{F}_p = \int P dA,$$

    where $P$ is the pressure and $A$ the surface area.

    b)  "Fvx", "Fxy", and "Fvz" refer to the three components of the viscous drag force

    $$\mathbf{F}_v = \int \mu \frac{\partial u}{\partial y} dA.$$

    where $\frac{\partial u}{\partial y}$ is the shear velocity at the wall, $\mu$ is the viscosity and $A$ is the surface area.

    c)  "Mpx", "Mpy", "Mpz", "Mvx", "Mvy", and "Mvz" refer to the three components of the pressure and viscous force moments respectively.

**\*ICFD_DATABASE_FLUX**

Purpose: This keyword enables the computation of the flow rate and average pressure over given parts of the model. If multiple keywords are given, separate files are output.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|---|---|---|---|---|
| Variable | PID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | ↓ | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the surface where the flow rates will be computed |
| DTOUT | Output frequency. Default is at every fluid timestep. |

**Remarks:**

1. **Database Name.** The file name for this database is icfd_flux.dat.

2. **Database Components.** The flux database contains the flow rate through a section, called "output flux,"

$$\Phi = \sum_i (\mathbf{V}_i \cdot \mathbf{n}_i) A_i \ ,$$

the average pressure, called "Pre-avg,"

$$P_{\text{avg}} = \frac{\sum_i P_i A_i}{\sum_i A_i} \ ,$$

and the total area, called "Areatot."

**\*ICFD_DATABASE_FLUX_SURF**

Purpose: Enable the computation of the flow rate and average pressure over a given surface (icfd part) of the model which is not necessary part of the analysis but lies in the fluid volume by mapping and interpolating volume results on the given surface.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | PID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | ↓ | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the surface where the flow rates will be computed |
| DTOUT | Output frequency. Default is at every fluid timestep. |

**Remarks:**

1. **Database Name.** The file name for this database is icfd_fluxsurf.dat.

## \*ICFD_DATABASE_FORCE_DEM

Purpose: Enable the computation of the total fluid force that is transferred to the DEM particles over time. The output is in icfd_force_dem.dat.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUT | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

|        VARIABLE        |                       DESCRIPTION                        |
|---|---|

OUT         Flag to enable computing the fluid forces and generating output:

          EQ.0: No output is generated.

          EQ.1: Output is generated.

## *ICFD_DATABASE_GOA

Purpose: Enable the computation of the geometric orifice area (GOA), a quantity of interest used to evaluate valve performance. The GOA surface connects the free edges of the leaflets. It is defined in the fluid mesh as surface mesh. If multiple keywords exist in the input deck, separate files are output. It must be used with \*MESH_SURFACE_NULL which defines parts where no physics is computed. These parts are only used for geometrical computations or post-processing.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | ↓ | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Fluid part ID of the fluid surface mesh where the GOA will be computed (see \*MESH_SURFACE_NULL) |
| DTOUT | Output frequency. The default is at every fluid time step. |

**Remarks:**

1.  **Database name.** The file name for this database is icfd_goa.dat.

2.  **GOA surface.** Define the GOA surface in the fluid mechanics problem with \*MESH_SURFACE_NULL. It is unnecessary to define \*ICFD_PART for any \*MESH_SURFACE_NULL part IDs. The surface is automatically excluded from the FSI coupling.

**\*ICFD_DATABASE_HTC**

Purpose: This keyword allows the user to trigger the calculation of the Heat transfer coefficient using different methods and to control the output options.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUT | HTC | TB | | | | | OUTDT |
| Type | I | I | F | | | | | F |
| Default | 0 | 0. | 0. | | | | | 0. |

| VARIABLE | DESCRIPTION |
|---|---|

OUT          Determines if the solver should calculate the heat transfer coefficient and how to output it :

　　　　　EQ.0: No HTC calculation

　　　　　EQ.1: HTC calculated and output in LSPP as a surface variable.

　　　　　EQ.2: The solver will also look for FSI boundaries and output the HTC value at the solid nodes in an ASCII file called icfdhtci.dat.

　　　　　EQ.3: The solver will also look for FSI boundaries that are part of SEGMENT_SETS and output the HTC for those segments in an ASCII file called icfd_convseg.****.key in a format that can directly read by LS-DYNA for a subsequent pure structural thermal analysis.

HTC          Determines how the HTC is calculated.

　　　　　EQ.0: Automatically calculated by the solver based on the average temperature flowing through the pipe section (See Remark 1).

　　　　　EQ.1: User imposed value (See Remark 2).

TB          Value of the bulk temperature if HTC = 1.

OUTDT          Output frequency of the HTC in the various ASCII files. If left to 0., the solver will output the HTC at every timestep.

**Remarks:**

1.  The heat transfer coefficient is frequently used in thermal applications to estimate the effect of the fluid cooling and it derived from a CFD calculation.

2.  The heat transfer coefficient is defined as follows:

$$h = \frac{q}{T_s - T_b}$$

with $q$ the heat flux, $T_s$ the surface temperature and $T_b$ the so called "bulk" temperature.  For external aerodynamic applications, this bulk temperature is often defined as a constant (ambient or far field conditions, HTC = 1).  However, for internal aerodynamic application, this temperature is often defined as an average temperature flowing through the pipe section with the flow velocity being used as a weighting factor (HTC = 0).

## \*ICFD_DATABASE_NODEAVG

Purpose: This keyword enables the computation of the average quantities on surface nodes defined in \*ICFD_DATABASE_NODOUT.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | 0N | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ON | If equal to 1, the average quantities will be computed. |

**Remarks:**

1. The file name for this database is icfd_nodeavg.dat.

## \*ICFD_DATABASE_NODOUT

Purpose: This keyword enables the output of ICFD data on surface nodes. For data in the fluid volume, it is advised to use points or tracers (See \*ICFD_DATABASE_-POINTOUT).

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|---|---|---|---|---|---|
| Variable | OUTLV | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | 0 | 0. | | | | | | |

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|------|------|------|------|------|------|
| Variable | NID1 | NID2 | NID3 | NID4 | NID5 | NID6 | NID7 | NID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be dumped. |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the ICFD timestep will be used. |
| NID.. | Node IDs. |

**Remarks:**

1.   The file name for this database is icfd_nodout.dat.

**\*ICFD_DATABASE_NTEMPOUT**

Purpose: Output the temperature at individual nodes in a format consistent with \*ICFD_-INITIAL_TEMPNODE to initialize a subsequent ICFD problem.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|-------|---|---|---|---|---|---|
| Variable | NID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0.0 | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Internal ICFD node ID |
| DTOUT | Output frequency |
| | EQ.0.0: The ICFD timestep will be used. |

### *ICFD_DATABASE_POINTAVG

Purpose: This keyword enables the computation of the average quantities on point sets using the parameters defined in *ICFD_DATABASE_POINTOUT.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | 0N | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ON | If equal to 1, the average quantities will be computed. |

**Remarks:**

1.  The file name for this database is icfd_psavg.dat.

## \*ICFD_DATABASE_POINTOUT

Purpose: This keyword enables the output of ICFD data on points.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|--------|-----|-----|-----|---|---|
| Variable | PSID | DTOUT | PSTYPE | VX | VY | VZ | | |
| Type | I | F | I | F | F | F | | |
| Default | 0 | 0. | 0 | 0. | 0. | 0. | | |

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|------|------|---|---|---|---|
| Variable | PID | X | Y | Z | | | | |
| Type | I | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PSID | Point Set ID. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the ICFD timestep will be used. |
| PSTYPE | Point Set type :<br>EQ.0: Fixed points.<br>EQ.1: Tracer points using prescribed velocity.<br>EQ.2: Tracer points using fluid velocity.<br>EQ.3: Tracer points using mesh velocity.. |
| VX, VY, VZ | Constant velocities to be used when PSTYPE = 1 |
| PID | Point ID |

| VARIABLE | DESCRIPTION |
| --- | --- |
| X, Y, Z | Point initial coordinates |

**Remarks:**

1. The file name for this database is icfd_pointout.dat.

## \*ICFD_DATABASE_RESIDUALS

Purpose: This keyword allows the user to output the residuals of the various systems.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | RLVL | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RLVL | Residual output level : |

    EQ.0: No output.

    EQ.1: Only outputs the number of iterations needed for solving the pressure Poisson equation.

    EQ.2: Outputs the number of iterations for the momentum, pressure, mesh movement and temperature equations.

    EQ.3: Also gives the residual for each iteration during the solve of the momentum, pressure, mesh movement and temperature equations.

**Remarks:**

1. The file names for the momentum, pressure, mesh movement and temperature equations are called icfd_residuals.moms.dat, icfd_residuals.pres.dat, icfd_residuals.mmov.dat, and icfd_residuals.temp.dat respectively.

## *ICFD_DATABASE_SSOUT

Purpose: Output the pressure load on a structure from the fluid. It can be useful for linear FSI applications, where the structure is made static, and the loads applied by the fluid are retrieved.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | OUT | OUTDT | LCIDSF | | | | | POFF |
| Type | I | I | I | | | | | F |
| Default | 0 | 0. | 0 | | | | | 0. |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUT | Determines if the solver should retrieve the pressure loads and how to output it: |

      EQ.0: Inactive

      EQ.1: The fluid solver will collect the segment sets (see \*SET_-SEGMENT) that are part of a FSI boundary and retrieve the pressure for subsequent print out in an icfd_presseg and icfd_lcsegid pair of files.

      EQ.2: Same as 1 except the results are collected in a single icfd_presseg / icfd_plcsegid pair of files and the load curves associated with each segment are made functions of time, thus taking the transient nature of the CFD analysis into account.

      EQ.3: Same as 2 except uses a more memory efficient way of handling and outputting the data.

| OUTDT | Frequency of the pressure extraction. If left as 0., the solver will extract the pressure of the fluid on the FSI boundary at every time step. This can lead to additional memory and calculation cost. |
| LCIDSF | Optional load curve ID to apply a scale factor on the fluid pressure output |
| POFF | Optional pressure offset on the fluid pressure output |

## \*ICFD_DATABASE_SSOUT_EXCLUDE

Purpose: This keyword defines which segment set IDs are excluded from the SSOUT search. No forces coming from the fluid will be transmitted on those segment sets for output (see ICFD_DATABASE_SSOUT).

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SSOUTID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SSOUTID | Segment Set ID of the solid mechanics problem which is to be excluded from the output of the fluid forces on the solid boundaries. |

**\*ICFD_DATABASE_TEMP**

Purpose: This keyword enables the computation of the average temperature and the heat flux over given parts of the model. If multiple keywords are given, separate files are output.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|---|---|---|---|---|---|
| Variable | PID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID of the surface where the average temperature and heat flux will be computed. |
| DTOUT | Output frequency. Default is at every fluid timestep. |

**Remarks:**

1. The file name for this database is icfd_thermal.dat.

2. Two average temperature are given in the icfd_thermal.dat file: "Temp-avg" and "Temp-sum". The average temperature is calculated using the local node area as weighting factor,

$$T_{\text{avg}} = \frac{\sum_i^N T_i A_i}{\sum_i^N A_i},$$

whereas, the sum is not weighted by area

$$T_{\text{sum}} = \frac{\sum_i^N T_i}{N}$$

If the mesh is regular, the two values will be of similar value. The icfd_thermal.dat output file also includes the average heat flux, the total surface area, and the average heat transfer coefficients (See \*ICFD_DATABASE_HTC).

## \*ICFD_DATABASE_TIMESTEP

Purpose: This keyword enables the output of ICFD data regarding the ICFD timestep.

**Output Options Card.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|---|---|---|---|---|---|---|
| Variable | OUTLV | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| OUTLV | Determines if the output file should be dumped. |
| | EQ.0: No output file is generated. |
| | EQ.1: The output file is generated. |

**Remarks:**

1.  The file name for this database is icfd_tsout.dat.

2.  Outputs the run's ICFD timestep versus the timestep calculated using the ICFD CFL condition as criteria (autotimestep). This can be useful in cases using a fixed timestep where big mesh deformations and/or big fluid velocity changes occur in order to track how that fixed timestep value compares to the reference auto-timestep.

## \*ICFD_DATABASE_TPD

Purpose: Enable the output of the transvalvular pressure difference (TPD) data. The TPD is computed by averaging the fluid pressure at two spheres upstream and downstream of a valve and computing the difference between them.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | X1 | Y1 | Z1 | X2 | Y2 | Z2 | |
| Type | I | F | F | F | F | F | F | |
| Default | none | 0. | 0. | 0. | 0. | 0. | 0. | |

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DTOUT | RAD1 | RAD2 | | | | | |
| Type | F | F | F | | | | | |
| Default | ↓ | 0. | 0. | | | | | |

|  VARIABLE  |  DESCRIPTION  |
|---|---|
| PID | Part ID used to plot multiple files if multiple \*ICFD_DATABASE_-TPD keywords are defined. |
| X1, X2, X3 | Coordinates of the center of the upstream sphere where the upstream average pressure is computed. |
| Y1, Y2, Y3 | Coordinates of the center of the downstream sphere where the downstream average pressure is computed. |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the ICFD time step is used. |
| R1 | Radius of the upstream sphere |
| R2 | Radius of the downstream sphere |

**Remarks:**

1. **Output filename.** The filename for this database is icfd_tpd.dat.

2. **Computing TPD.** The TPD is computed as:

$$\mathrm{TPD}(t^n) = P_{\mathrm{up}}(t^n) - P_{\mathrm{down}}(t^n)$$

## \*ICFD_DATABASE_TWINBUILDER

Purpose: Enable the output of ICFD data to be consumed by the Ansys Twin Builder static or dynamic ROM module. If this keyword is active, the solver automatically creates a directory tree compatible with the ROM module. If the model is transient, the dynamic ROM format is used. If the model is steady, the static ROM format is used. In the dynamic case, DTOUT in \*ICFD_CONTROL_OUTPUT determines the output frequency. The output scenarios are identified using the job ID for each run. The job IDs should go from 1 to the number of scenarios used to train the ROM. See Remark 1.

Include as many *cards* as desired. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUTRP | INEX1 | INEX2 | INEX3 | INEX4 | INEX5 | INEX6 | INEX7 |
| Type | A | A | A | A | A | A | A | A |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|

OUTRP        Name of the output variable or response. All the fields are nodal.

> EQ.pres:   Pressure
>
> EQ.apres:   Time average pressure
>
> EQ.vel:    Velocity
>
> EQ.avel:   Time average velocity
>
> EQ.lset:   Level set
>
> EQ.temp:   Temperature
>
> EQ.atemp:  Time average temperature

INEX1-7      Name of the input variables or excitations. Field values like pressure, velocity, and temperature are nodal arrays of boundary conditions. In the case of material properties, the values written to the excitation's files are scalars. A combination of up to seven excitations can be used for each output.

> EQ.pres:   Pressure values at imposed pressure boundary conditions.
>
> EQ.vel:   Velocity values at inflow boundary conditions.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.temp: Temperature values at imposed temperature boundary conditions. |
| | EQ.rho: Fluid density |
| | EQ.mu: Fluid viscosity |
| | EQ.hc: Heat capacity |
| | EQ.tc: Thermal conductivity |

**Remarks:**

1.  **Output structure.** This database creates a tree structure of directories that contain the different scenarios to be used to train the ROMs. The root directory name is tb_s for a static ROM and tb_d for a dynamic ROM. They are created in the location where the executable file is. The scenarios are numbered according to the job ID of the process. The user is responsible for providing numerical job IDs which are recommended to start from 1 and increase to the number of scenarios.

## \*ICFD_DATABASE_UINDEX

Purpose:  This keyword allows the user to have the solver calculate the uniformity index (See Remark 1).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUT | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| OUT | Determines if the solver should calculate the uniformity index. |
| | EQ.0: Off. |
| | EQ.1: On. |

**Remarks:**

1.  **Uniformity Index.**  The uniformity index is a post treatment quantity which measures how uniform the flow is through a given section.  It is especially useful in internal aerodynamics cases.  It is expressed as :

$$\gamma = 1 - \frac{1}{2nA} \sum_{i=1}^{n} \left[ \frac{\sqrt{(u_i - \bar{u})^2}}{\bar{u}} A_i \right]$$

with $A_i$, the local cell area, $A$ the total section area, $u_i$ the local velocity, $\bar{u}$ the average velocity through the section, and $n$ the number of cells.

Values close to 0 means that the flow is very unevenly distributed.  This can be used to identify bends, corners or turbulent effects.  Values close to 1 imply smooth or equally distributed flow through the surface.

## \*ICFD_DATABASE_WETNESS

Purpose: For free surface problems, output the wetted area as a function of time for a given surface part. It is output to an ASCII file beginning with icfd_wetness.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SPID | DTOUT | | | | | | |
| Type | I | F | | | | | | |
| Default | none | 0. | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SPID | Part ID of the surface where the wetted area will be computed |
| DTOUT | Time interval to print the output. If DTOUT is equal to 0.0, then the ICFD time step will be used. |

**Remarks:**

1. **Wetted Area.** The ICFD solver identifies a surface as wet if its level set value is positive.

## \*ICFD_DEFINE_HEATSOURCE

Purpose:  Define a volumetric heat source for evaluating the heat equation.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HSID | LCID | ISHAPE | R | PTID1 | PTID2 | | |
| Type | I | I | I | F | I | I | | |
| Default | none | none | none | none | none | none | | |

| VARIABLE | DESCRIPTION |
|---|---|
| HSID | Heat source ID |
| LCID | Load curve ID specifying the evolution of the heat source term function of time for the *X*, *Y*, and *Z* degrees-of-freedom (see \*DEFINE_CURVE,\*DEFINE_CURVE_FUNC-TION, or \*DEFINE_FUNCTION).  If using a \*DEFINE_-FUNCTION, the following arguments are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |
| ISHAPE | Shape of the volumetric heat source: |
| | EQ.1: Box shape |
| | EQ.2: Cylinder shape |
| | EQ.3: Sphere shape |
| R | Radius of the cylinder if ISHAPE = 2 or radius of the sphere if ISHAPE = 3 |
| PTID1 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on ISHAPE: |
| | ISHAPE.EQ.1: Minimum coordinates of the box |
| | ISHAPE.EQ.2: Point in the center of one base of the cylinder |
| | ISHAPE.EQ.3: Center of the sphere |
| PTID2 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on ISHAPE: |

| VARIABLE | DESCRIPTION |
|---|---|
| | ISHAPE.EQ.1: Maximum coordinates of the box |
| | ISHAPE.EQ.2: Point in the center of the other base of the cylinder |

.

## \*ICFD_DEFINE_HEMOLYSIS_INDEX

Purpose: Compute and track the hemolysis index and scalar shear stresses.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MASSDIF | C | ALPHA | BETA | PRESSTO | | | |
| Type | F | F | F | F | I | | | |
| Default | none | 3.458E-6 | 0.2777 | 2.0639 | 0 | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MASSDIFF | Mass diffusion for the hemolysis index transport problem: |
| C | Constant in the hemolysis index model, $C$ |
| ALPHA | Exponent in the hemolysis index model, $\alpha$ |
| BETA | Exponent in the hemolysis index model, $\beta$ |
| PRESSTO | Flag to impose a hemolysis index of 0 on boundaries with pressure boundary conditions: |

> EQ.0: Interpolate the hemolysis index on the boundaries from the interior of the domain
>
> EQ.1: Set the hemolysis index to 0 on boundaries with pressure boundary conditions

**\*ICFD_DEFINE_POROUS_REGION**

Purpose: Define moving isotropic porous regions. The permeability can be a constant value or defined through a time-dependent load curve or \*DEFINE_FUNCTION. Alternatively (using SENSFLG ≠ 0), this keyword optionally enables pressure sensors to specify the permeability as a function of the pressure drop across the porous domain length (see Remark 1). \*ICFD_DEFINE_POINTs determine the locations of the sensors. The first sensor is upstream of the region, and the second sensor downstream. The primary application of this feature is modeling the closing and opening of pressure-driven valves without the need for more complex moving parts (like leaflets). If points PTID1 and PTID2 (and sensors SENSID1 and SENSID2) are attached to a moving part, the points move accordingly.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PRID | ISHAPE | R | PTID1 | PTID2 | PERM | LCID | SENSFLG |
| Type | I | I | F | I | I | F | I | I |
| Default | none | none | none | none | none | none | 0 | 0 |

**Sensor Card.** Define only if SENSFLG ≠ 0 on Card 1.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SENSID1 | SENSID2 | KMIN | KMAX | DLTAPREF | SLOPE | | |
| Type | I | I | F | F | F | F | | |
| Default | none | none | none | none | 0 | 0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PRID | Porous region ID |
| ISHAPE | Shape of the volumetric porous region: |

        EQ.1: Box shape,

        EQ.2: Cylinder shape,

        EQ.3: Sphere shape,

| VARIABLE | DESCRIPTION |
|---|---|
| R | Radius of the cylinder if ISHAPE = 2. Radius of the sphere if ISHAPE = 3. |
| PTID1 | Point ID (see \*ICFD_DEFINE_POINT) with meaning depending on ISHAPE:<br><br>ISHAPE.EQ.1: Minimum coordinates of the box<br><br>ISHAPE.EQ.2: Tail point of the cylinder<br><br>ISHAPE.EQ.3: Center of the sphere |
| PTID2 | Point ID with meaning depending on ISHAPE (ignored for ISHAPE = 3):<br><br>ISHAPE.EQ.1: Maximum coordinates of the box<br><br>ISHAPE.EQ.2: Head point of the cylinder. |
| PERM | Isotropic permeability, $k$, of the region. PERM is ignored if LCID $\neq 0$ or SENSFLG = 1. |
| LCID | Load curve ID specifying the evolution of the permeability as a function of time for the $X$, $Y$, and $Z$ degrees of freedom; see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_FUNCTION. If a using a \*DEFINE_FUNCTION, the following parameters are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). Ignored if SENSFLG = 1. |
| SENSFLG | Sensor flag determining whether the permeability is a function of the pressure drop computed between the sensors:<br><br>EQ.0: Not a function of pressure drop<br><br>EQ.1: Function of a pressure drop between sensors. See Remark 1. |
| SENSID1 | Sensor (\*ICFD_DEFINE_POINT ID) upstream of the porous region |
| SENSID2 | Sensor (ICFD_DEFINE_POINT ID) downstream of the porous region |
| KMIN | Minimum permeability for the valve (closed position), $k_{min}$ |
| KMAX | Maximum permeability for the valve (open position), $k_{max}$ |
| DLTAPREF | Pressure drop that opens/closes the valve, $\Delta p_{ref}$ |

| VARIABLE | DESCRIPTION |
|---|---|
| SLOPE | Slope of the transition from $k_{max}$ to $k_{min}$, $m$. See Remark 1. |

**Remarks:**

1. **Permeability as a function of pressure drop.** When SENSFLG = 1, the pressure drop, $\Delta p$, between two sensors determines the permeability, $k$:

$$k = \frac{(k_{max} - k_{min})}{2} \times \left( 1 + \tanh \left( \frac{(\Delta p - \Delta p_{ref})}{m} \right) \right) + k_{min}$$

This feature is intended for using the porous region to model the opening and closing of a valve. At a given $\Delta p_{ref}$, the permeability switches from $k_{min}$ to $k_{max}$ as $\Delta p$ increases, modeling opening the valve. The valve closes when the opposite occurs. See Figure 7-7.
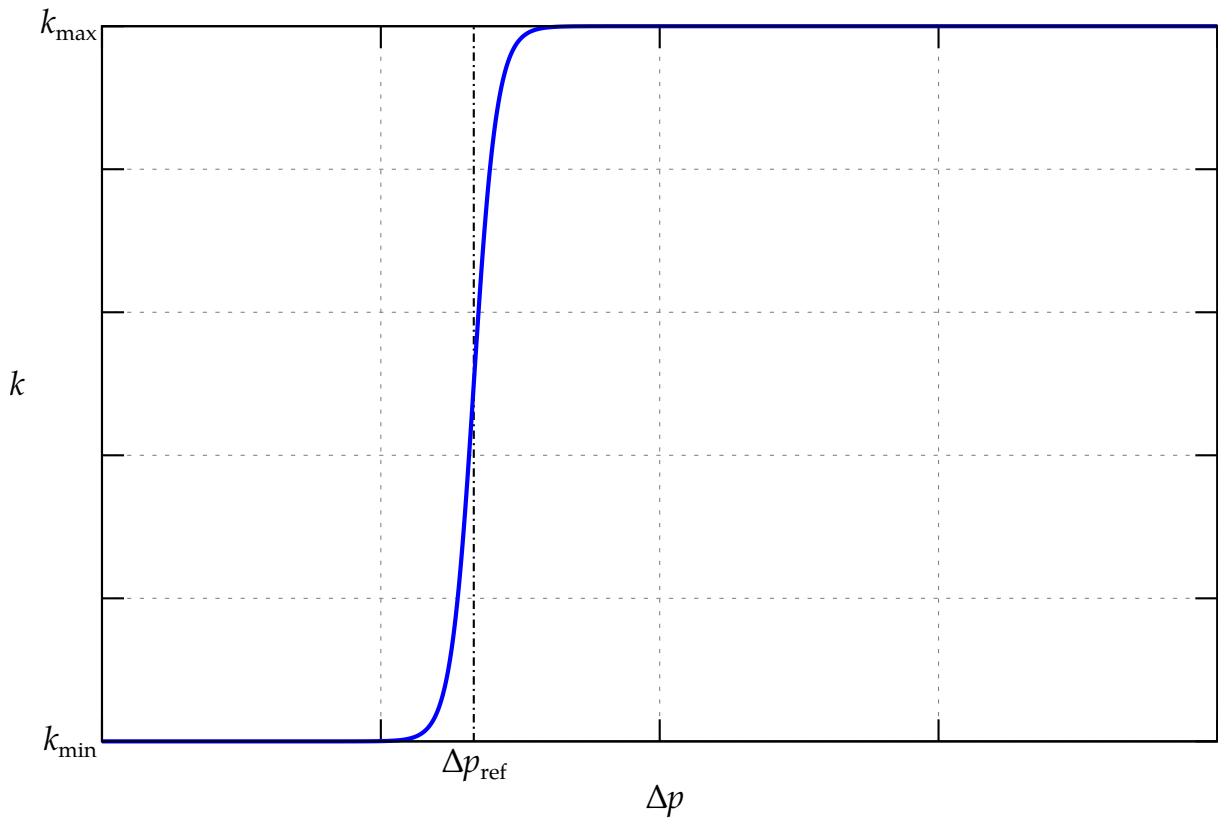


**Figure 7-7.** Pressure-driven valve law

## \*ICFD_DEFINE_RESIDENCETIMESOURCE

Purpose:  Specify a volumetric residence time (RT) source.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|------|---|-------|-------|---------|--------|---------|
| Variable | RTSID | ISHAPE | R | PTID1 | PTID2 | MASSDIFF | DEATHT | IRT0PBC |
| Type | I | I | F | I | I | F | F | I |
| Default | none | none | none | none | none | $10^{-6}$ | ↓ | 0 |

**N-Planes RT Source Card.** If ISHAPE = 4, include as many of this card as desired, one for each plane.  The next keyword ("\*") card terminates this input.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|--------|---------|---|---|---|---|---|---|
| Variable | N-PTID | N-NORID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| RTSID | RT source ID |
| ISHAPE | Shape of the volumetric RT source:<br><br>EQ.1: Box<br><br>EQ.2: Cylinder<br><br>EQ.3: Sphere<br><br>EQ.4: N-planes (see Remark 1) |
| R | Radius of the cylinder if ISHAPE = 2 or radius of the sphere if ISHAPE = 3 |
| PTID1 | ID of a point (see \*ICFD_DEFINE_POINT) giving the minimum coordinate of the box if ISHAPE = 1, the tail point for the cylinder if ISHAPE = 2, or the center of the sphere if ISHAPE = 3 |
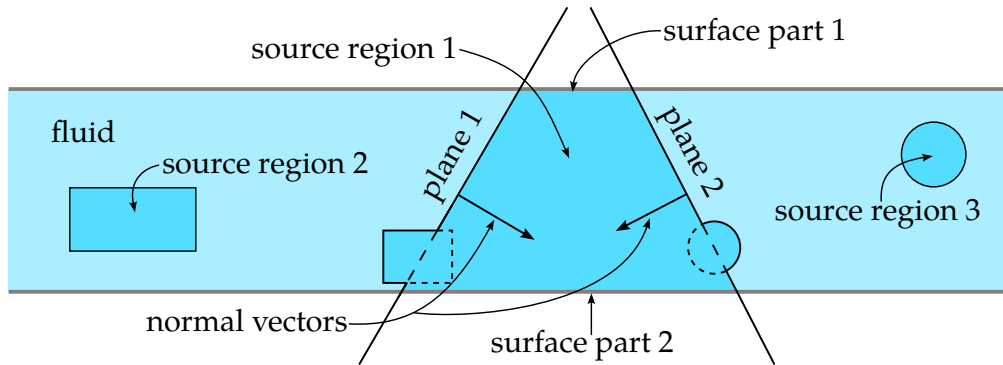
**Figure 7-8.** Illustration of different RT source regions. The combination of N-planes (two planes), two other RT sources (a box and sphere), and domain boundaries defines source region 1. Specifying source region 1 requires three instantiations of \*ICFD_DEFINE_RESIDENCETIMESOURCE: one for the two planes, one for the box, and one for the sphere. The surface parts are automatically considered; thus, planes do not need to be specified on those surfaces. Defining source region 2 and source region 3 requires an instantiation of \*ICFD_DEFINE_RESIDENCETIMESOURCE for each of those regions.

| VARIABLE | DESCRIPTION |
|---|---|
| PTID2 | ID of a point giving the maximum coordinate of the box if ISHAPE = 1 or the head point of the cylinder if ISHAPE = 2 |
| MASSDIFF | Mass diffusion for the transport equation. See Remark 2. |
| DEATHT | End time for the source<br><br>EQ.0.0: End time of the simulation. |
| IRT0PBC | Flag for which prescribed boundaries RT = 0 is imposed:<br><br>EQ.0: Imposed only on boundaries with prescribed velocity<br><br>EQ.1: Imposed on boundaries with either prescribed velocity or prescribed pressure. |
| N-PTID | ID of a point lying on the source plane for ISHAPE = 4 |
| N-NORID | ID of a point whose coordinate components specify the normal vector of the plane for ISHAPE = 4 |

**Remarks:**

1.  **N-planes RT source shape.** If ISHAPE = 4, the residence time source (seed) region is defined through a set of one or more infinite planes (N-planes). The

resulting region must be a concave region inside the fluid domain. The N-plane shape can be combined with other source shapes, and it works in the sense of nesting them and/or combining them through set union operations (set intersection operations are not supported). The domain boundary parts are natural surfaces defining these injection regions, and they do not need to be added to the list of planes. The source shapes can have different birth and end times, so the combined region can change in time. See Figure 7-8 for an illustration.

Each instantiation of Card 2 defines a plane using two point IDs (see \*ICFD_DEFINE_POINT). The first point is a point lying on the $i^{th}$ plane. The coordinate components of the second point are treated as a vector giving the normal vector of the plane. The normal vector must point to the interior of the region.

Figure 7-8 illustrates using N-planes with other sources and domain boundaries. This situation requires five instantiations of \*ICFD_DEFINE_RESIDENCETIME-SOURCE. Three of the instantiations are for source region 1 (for the planes, box, and sphere), one for source region 2, and one for source region 3. The surface parts making up source region 1 are automatically considered; thus, planes do not need to be specified on those surfaces. Keyword input for this scenario could look as follows:

```
*ICFD_DEFINE_RESIDENCETIMESOURCE
$ These are planes 1 and 2 in source region 1
$    RTSID    ISHAPE         R     PTID1     PTID2  MASSDIFF     DEATHT     IRT0BC
         1         4
$ plane 1
$   N-PTID   N-NORID
        10        11
$ plane 2
$   N-PTID   N-NORID
        20        21
*ICFD_DEFINE_RESIDENCETIMESOURCE
$ This is the box in source region 1
$    RTSID    ISHAPE         R     PTID1     PTID2  MASSDIFF     DEATHT     IRT0BC
         2         1                  30        31
*ICFD_DEFINE_RESIDENCETIMESOURCE
$ This is the sphere in source region 1
$    RTSID    ISHAPE         R     PTID1     PTID2  MASSDIFF     DEATHT     IRT0BC
         3         3       5.0        20
*ICFD_DEFINE_RESIDENCETIMESOURCE
$ This is the box specifying source region 2
$    RTSID    ISHAPE         R     PTID1     PTID2  MASSDIFF     DEATHT     IRT0BC
         4         1                  40        41
*ICFD_DEFINE_RESIDENCETIMESOURCE
$ This is the cylinder specifying source region 3
$    RTSID    ISHAPE         R     PTID1     PTID2  MASSDIFF     DEATHT     IRT0BC
         5         2       7.0        50        51
```

2.  **Mass diffusion.** The same MASSDIFF parameter must be used when defining multiple \*ICFD_DEFINE_RESIDENCETIMESOURCE instantiations in an input deck.

## \*ICFD_DEFINE_SOURCE

Purpose: Define a volumetric external force for the momentum equation solve.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-------|-------|-------|-------|------|-------|-------|
| Variable | SID | LCIDX | LCIDY | LCIDZ | SHAPE | R | PTID1 | PTID2 |
| Type | I | I | I | I | I | F | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SID | Source ID |
| LCIDX/Y/Z | Load curve IDs specifying the evolution of the volumetric force as a function of time for the three global components |
| SHAPE | Shape to which the volumetric force is applied: |
| |     EQ.1: Box |
| |     EQ.2: Cylinder |
| |     EQ.3: Sphere |
| R | Radius of the cylinder or sphere if SHAPE = 2 or 3 |
| PTID1 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on SHAPE: |
| |     SHAPE.EQ.1: Minimum coordinates of the box |
| |     SHAPE.EQ.2: Tail point of the cylinder |
| |     SHAPE.EQ.3: Origin of the sphere |
| PTID2 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on SHAPE: |
| |     SHAPE.EQ.1: Maximum coordinates of the box |
| |     SHAPE.EQ.2: Head point of the cylinder |

## \*ICFD_DEFINE_SPTRANSPSOURCE

Purpose: Specify a volumetric species source for the species transport solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | SPTRSID | LCID | ISHAPE | R | PTID1 | PTID2 | | SPIND |
| Type | I | I | I | F | I | I | | I |
| Default | none | none | none | none | none | none | | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SPTRSID | Species transport source ID |
| LCID | Load curve ID specifying the evolution of the species source term as a function of time for the $X$, $Y$, and $Z$ degrees of freedom (see \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, and \*DEFINE_FUNCTION). If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f(x, y,z, vx, vy, vz, temp, pres, time). |
| ISHAPE | Shape of the volumetric species source: |
| | EQ.1: Box |
| | EQ.2: Cylinder |
| | EQ.3: Sphere. |
| R | Radius of the cylinder if ISHAPE = 2 or radius of the sphere if ISHAPE = 3. |
| PTID1 | ID of a point (see \*ICFD_DEFINE_POINT) giving the minimum coordinate of the box if ISHAPE = 1, the tail point for the cylinder if ISHAPE = 2, or the origin of the sphere if ISHAPE = 3. |
| PTID2 | ID of a point giving the maximum coordinate of the box if ISHAPE = 1 or the head point of the cylinder if ISHAPE = 2. |
| SPIND | Index of the species for which the source term applies. For instance, if the source term is for the second species in a multi-species transport problem, this index is 2. |

## \*ICFD_DEFINE_TRANSFORM

Purpose: Enable applying translations, rotations, and scaling on the initial surface mesh before generating the volume mesh. This feature makes possible quick changes (such as when switching between unit systems) on the geometry without having to manually edit the case.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|---|---|---|
| Variable | PID | TRX | TRY | TRZ | SF | | | |
| Type | I | F | F | F | F | | | |
| Default | none | 0.0 | 0.0 | 0.0 | 1.0 | | | |

Optional card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-----|-----|-----|-----|-------|---|
| Variable | ORX | ORY | ORZ | NX | NY | NZ | ANGLE | |
| Type | F | F | F | F | F | F | F | |
| Default | 0. | 0. | 0. | 0. | 0. | 0. | 0. | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Surface PID on which to apply the transformation. |
| | EQ.0: Apply the transformation to the entire model. |
| TRX/TRY/TRZ | Translation offset in the global $X$, $Y$, and $Z$-directions |
| SF | Scale factor to be applied on the $X$, $Y$, and $Z$ coordinates |
| ORX/ORY/ORZ | Origin point of the rotation |
| NX/NY/NZ | Normal for the rotation |
| ANGLE | Angle of rotation (in degrees) |

## \*ICFD_DEFINE_TURBSOURCE

Purpose: Define an external source for the RANS turbulence equations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|--------|--------|--------|------|-------|-------|
| Variable | TSID | LCIDK | LCIDEP | LCIDNU | ISHAPE | R | PTID1 | PTID2 |
| Type | I | I | I | I | I | F | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| TSID | Turbulent external source ID |
| LCIDK | Load curve ID specifying the evolution of the external source term function of time for the turbulent kinetic energy, $k$, equation (see \*DEFINE_CURVE,\*DEFINE_-CURVE_FUNCTION, or \*DEFINE_FUNCTION). If using a \*DEFINE_FUNCTION, the following arguments are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |
| LCIDEP | Load curve ID specifying the evolution of the external source term function of time for the turbulent diffusion, $\varepsilon$, or specific rate of dissipation, $w$, equation (see \*DEFINE_-CURVE,\*DEFINE_CURVE_FUNCTION, or \*DEFINE_-FUNCTION). If using a \*DEFINE_FUNCTION, the following arguments are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |
| LCIDNU | Load curve ID specifying the evolution of the external source term function of time for the kinematic eddy turbulent viscosity equation used in the Spalart-Allmaras model (see \*DEFINE_CURVE,\*DEFINE_CURVE_FUNCTION, or \*DEFINE_FUNCTION). If using a \*DEFINE_FUNCTION, the following arguments are allowed: f(x, y, z, vx, vy, vz, temp, pres, time). |
| ISHAPE | Shape of the external source:<br><br>EQ.1: Box shape<br><br>EQ.2: Cylinder shape |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.3: Sphere shape |
| R | Radius of the cylinder if ISHAPE = 2 or radius of the sphere if ISHAPE = 3 |
| PTID1 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on ISHAPE: |
| | ISHAPE.EQ.1: Minimum coordinates of the box |
| | ISHAPE.EQ.2: Point in the center of one base of the cylinder |
| | ISHAPE.EQ.3: Center of the sphere |
| PTID2 | Point ID (see \*ICFD_DEFINE_POINT) whose meaning depends on ISHAPE: |
| | ISHAPE.EQ.1: Maximum coordinates of the box |
| | ISHAPE.EQ.2: Point in the center of the other base of the cylinder |

.

## *ICFD_DEFINE_POINT

Purpose: This keyword defines a point in space that could be used for multiple purposes.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | POID | X | Y | Z | CONSTPID | | | |
| Type | I | F | F | F | I | | | |
| Default | none | none | none | none | none | | | |

**Optional Card 2.** Load curve IDS specifying velocity components of translating point

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LCIDX | LCIDY | LCIDZ | | | | | |
| Type | I | I | I | | | | | |
| Default | 0 | 0 | 0 | | | | | |

**Optional Card 3.** Load curve IDS and rotation axis of rotating point

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | LCIDW | XT | YT | ZT | XH | YH | ZH | |
| Type | I | F | F | F | F | F | F | |
| Default | 0 | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| POID | Point ID. |
| X/Y/Z | x, y ,z coordinates for the point. |

| VARIABLE | DESCRIPTION |
|---|---|
| CONSTPID | Surface Part ID to which the point is constrained. This means that if the selected surface moves, then the localization of the point will update as well. |
| LCIDX/LCIDY/LCIDZ | The point can be made to translate. Those are the three load curve IDs for the three translation components. |
| LCIDW | The point can also be made to rotate. This load curve specifies the angular velocity. |
| XT/YT/ZT | Rotation axis tail point coordinates. |
| XH/YH/ZH | Rotation axis head point coordinates. |

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## \*ICFD_DEFINE_NONINERTIAL

Purpose: Define a non-inertial reference frame to avoid heavy mesh distortions and remeshing associated with large-scale rotations. This frame helps when modeling spinning cylinders, wind turbines, and turbomachinery.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | W1 | W2 | W3 | R | PTID | L | LCID | RELV |
| Type | F | F | F | F | I | F | I | I |
| Default | none | none | none | none | none | none | none | 0 |

| VARIABLE | DESCRIPTION |
|---|---|
| W1, W2, W3 | Rotational velocity, $\omega$, along the $X$, $Y$, and $Z$-axes |
| R | Radius of the rotating reference frame. |

   GT.0.0: Constant value

   LT.0.0: $|R|$ refers to a \*DEFINE_FUNCTION ID. The function supports the following arguments: f(x, y, z, vx, vy, vz, temp, pres, time).
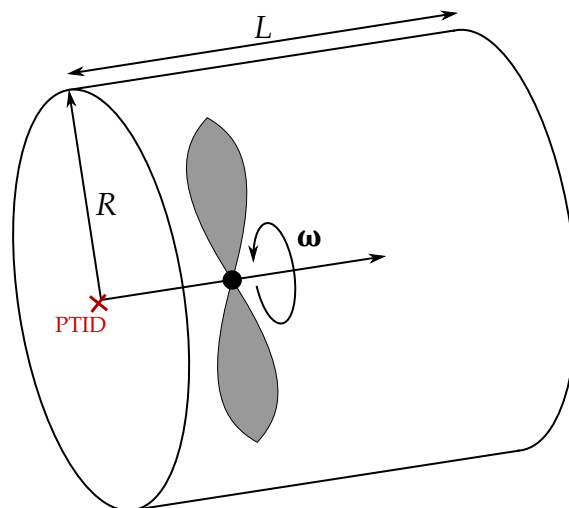


**Figure 7-9.** Example of using a non-inertial reference frame

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PTID | Starting point ID for the reference frame (See \*ICFD_DEFINE_-POINT) |
| L | Length of the rotating reference frame |
| LCID | Load curve for scaling factor of $\omega$. |
| | GT.0: Load curve ID (see \*DEFINE_CURVE) for the curve giving the scale factor as a function of time |
| | LT.0: \|LCID\| refers to a \*DEFINE_FUNCTION ID. The function supports the following arguments: f(x, y, z, vx, vy, vz, temp, pres, time). |
| RELV | Velocities computed and displayed: |
| | EQ.0: Relative velocity, only the non-rotating components of the velocity are used and displayed. |
| | EQ.1: Absolute velocity. All the components of the velocity are used. Useful in cases where several or at least one non-inertial reference frame is combined with an inertial "classical" reference frame. |

## \*ICFD_DEFINE_WAVE_DAMPING

Purpose:  This keyword defines a damping zone for free surface waves.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | NID | L | F1 | F2 | N | LCID | |
| Type | I | I | F | F | F | I | I | |
| Default | none | none | | 10 | 10 | 1 | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Point ID defining the start of the damping layer. |
| NID | Normal ID defined using ICFD_DEFINE_POINT and pointing to the outgoing direction of the damping layer. |
| L | Length of damping layer.  If no is value specified, the damping layer will have a length corresponding to five element lengths. |
| F1/F2 | Linear and quadratic damping factor terms. |
| N | Damping term factor. |
| LCID | Load curve ID acting as temporal scale factor on damping term. |

**Remarks:**

1.  The damping is achieved by adding a source term to the momentum equations :

$$s^d = w \, (f_1 + f_2 |u|) \, u$$

with $w$ the weight function :

$$w = \frac{e^\gamma - 1}{e - 1}$$

and $\gamma$ the blending function which allows a smooth insertion of the source term in the damping layer :

$$\gamma = \left( \frac{x - x_{sd}}{x_{ed} - x_{sd}} \right)^n$$

$x_{sd}$ and $x_{ed}$ representing the start and end coordinates of the damping zone.

**\*ICFD_INITIAL**

Purpose: Simple initialization of velocity and temperature within a volume.

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | PID | Vx | Vy | Vz | T | P | | DFUNC |
| Type | I | F | F | F | F | F | | I |
| Default | none | none | none | none | none | none | | 0 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part ID for the volume elements or the surface elements where the values are initialized (see \*ICFD_PART_VOL and \*ICFD_PART). PID = 0 to assign the initial condition to all nodes at once. |
| Vx | x coordinate for the velocity. |
| Vy | y coordinate for the velocity. |
| Vz | z coordinate for the velocity. |
| T | Initial temperature. |
| P | Initial Pressure. |
| DFUNC | Option to define initial conditions using \*DEFINE_FUNCTION |

      EQ.0: Turned off.

      EQ.1: Turned on. All previous flags for initial velocity, pressure and temperature now refer to \*DEFINE_FUNCTION IDs. The following parameters are allowed : $f(x, y, z)$, allowing to define initial profiles function of coordinates.

**\*ICFD_INITIAL_LEVELSET**

Purpose: Define an initial level set surface instead of a multi-fluid domain (replaces the need for *MESH_INTERF).

Include as many cards as needed. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | STYPE | NX | NY | NZ | X | Y | Z | INVERT |
| Type | I | F | F | F | F | F | F | I |
| Default | none | none | none | none | none | none | none | 0 |

| VARIABLE | DESCRIPTION |
|---|---|
| STYPE | Initial surface type: |
| | EQ.0/1: Generated by a section plane. |
| | EQ.2: Generated by a box. See Remark 1. |
| | EQ.3: Generated by a sphere. |
| | EQ.4: Generated by a cylinder. |
| NX, NY, NZ | $X$, $Y$ and $Z$ components of the section plane normal if STYPE = 1. Minimum coordinates of the box, $P_{min}$, if STYPE = 2. NX is the sphere/cylinder radius if STYPE = 3 and STYPE = 4. NY is the cylinder length if STYPE = 4. NZ is the global axis if STYPE = 4 (NZ = 1, 2, or 3 means $X$-axis, $Y$-axis, or $Z$-axis, respectively). |
| X, Y, Z | $X$, $Y$ and $Z$ components of the section plane origin point if STYPE = 1 and 4. Maximum coordinates of the box, $P_{max}$, if STYPE = 2. Coordinates of the sphere origin point if STYPE = 3. |
| INVERT | Inversion of initial level set: |
| | EQ.0: No inversion. Positive level set values are assigned to nodes contained within the volume defined by STYPE. |
| | EQ.1: The sign of the initial level set values is reversed. |

**Remarks:**

1.  **Box Adjacent to Fluid Boundaries.** When STYPE = 2 is used and the box is adjacent to the fluid boundaries such as during a dam break simulation, the distance from any point in the fluid to the fluid boundary must remain smaller than the distance to the defined box. Therefore, the $P_{min}$ coordinates need to be defined far outside the initial fluid domain.

2.  **Multiple Keyword Definitions.** Multiple definitions of this keyword are possible, but the different shapes generated must not intersect for a correct initialization.
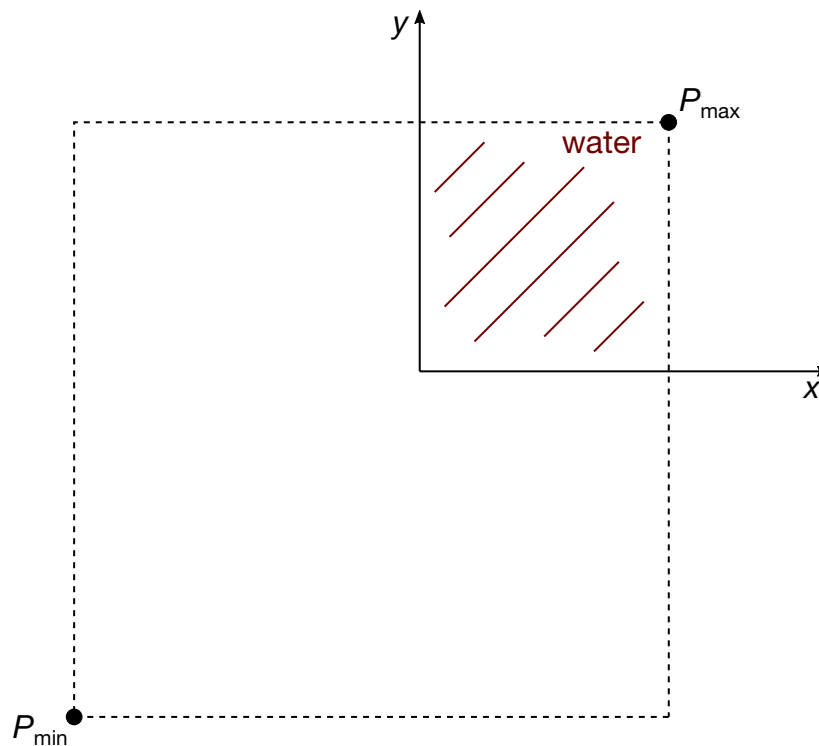


**Figure 7-10.** 2D Dam breaking example with initial levelset surface defined using STYPE = 2. $P_{min}$ is defined sufficiently far away from the fluid surface boundaries.

**\*ICFD_INITIAL_SPTRANSP**

Purpose:  Initialize the concentration of the species being transported within a volume.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | | | | | | | |
| Type | I | | | | | | | |
| Default | 0 | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DFID-1 | DFID-2 | DFID-3 | DFID-4 | DFID-5 | DFID-6 | DFID-7 | DFID-8 |
| Type | I | I | I | I | I | I | I | I |
| Default | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID for the volume elements or surface elements where the values are initialized. |
| | EQ.0:  Assign the initial condition to all nodes at once |
| DFID-*i* | \*DEFINE_FUNCTION ID defining the initialization for the concentration of the $i^{th}$ species at $t = 0$. The following parameters are allowed: f(x, y, z). |

**\*ICFD_INITIAL_TEMPNODE**

Purpose:  Allow the solver to initialize the temperature at individual nodes.

Include as many cards as needed.  This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NID | TEMP | | | | | | |
| Type | I | F | | | | | | |
| Default | none | none | | | | | | |

|          VARIABLE          |                DESCRIPTION                |
|---|---|
| NID | Internal ICFD node ID |
| TEMP | Initial temperature value |

## \*ICFD_INITIAL_TURBULENCE

Purpose: Modify the default initial values of the turbulence quantities for a RANS turbulence model.

Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | I | R | K | EW | | | |
| Type | I | F | F | F | F | | | |
| Default | none | none | none | optional | optional | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part ID for the volume elements or the surface elements where the values are initialized (see \*ICFD_PART_VOL and \*ICFD_PART). Set PID to 0 to assign the initial condition to all nodes at once. |
| I | Initial turbulence intensity, $I$ |
| R | Initial turbulence viscosity to laminar viscosity ratio ($r = \mu_{\text{turb}}/\mu$). |
| K | Initial kinetic energy. When defined, it replaces the choice of I.<br><br>LT.0.0: $|K|$ refers to a \*DEFINE_FUNCTION ID. The following parameters are allowed: $f(x, y, z)$, allowing you to define initial profiles as a function of coordinates. |
| EW | Initial turbulence specific dissipation rate or dissipation rate depending on the choice of turbulence model. When defined, it replaces the choice of R.<br><br>LT.0.0: $|EW|$ refers to a \*DEFINE_FUNCTION ID. The following parameters are allowed: $f(x, y, z)$, allowing you to define initial profiles as a function of coordinates. |

**Remarks:**

1. **Default Initial Conditions.** If no initial conditions have been assigned to a specific PID, the solver will automatically pick I = 0.05 (5%) and R = 10000.

## *ICFD_MAT_*{OPTION}*

Available options include

      TITLE

Purpose: Specify physical properties for the fluid material.

### Fluid Material Card Sets:

The Material Fluid Parameters Card is required. If a second card is given, it must be a Thermal Fluid Parameters Card. If the fluid thermal properties are not needed, the second card can be a blank card. With the third card, you can associate the fluid material to a non-Newtonian model, to a porous media model, to a species transport model, and/or to a viscoelastic model (see *ICFD_MODEL_NONNEWT, *ICFD_MODEL_POROUS, *ICFD_MODEL_SPECIES_TRANSPORT, and *ICFD_MODEL_VISCOELASTIC).

### Material Fluid Parameters Card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | FLG | RO | VIS | ST | STSFLCID | CA | |
| Type | I | I | F | F | F | I | F | |
| Default | none | none | 0. | 0. | 0. | none | 0. | |

**Thermal Fluid Parameters Card.** Only to be defined if the thermal problem is solved. Otherwise include a blank card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HC | TC | BETA | PRT | HCSFLCID | TCSFLCID | | |
| Type | F | F | F | F | I | I | | |
| Default | 0. | 0. | 0. | 0.85 | none | none | | |

**Additional fluid models.** Only to be defined if the fluid is non-Newtonian, there is a porous media, and/or a species is being transported.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NNMOID | PMMOID | | SPTRID | | VID | | |
| Type | I | I | | I | | I | | |
| Default | optional | optional | | optional | | optional | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material ID |
| FLG | Flag to choose between fully incompressible, slightly compressible, or barotropic flows: |
| | **EQ.0:** Vacuum (free surface problems only) |
| | **EQ.1:** Fully incompressible fluid. |
| RO | Flow density |
| VIS | Dynamic viscosity |
| ST | Surface tension coefficient |
| STSFLCID | Load curve ID for scale factor applied on ST as a function of time. See \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DE-FINE_FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f( x, y, z, vx, vy, vz, temp, pres, time). |
| CA | Contact angle |
| HC | Heat capacity |
| TC | Thermal conductivity |
| BETA | Thermal expansion coefficient used in the Boussinesq approximation for buoyancy |
| PRT | Turbulent Prandlt number. Only used if K-Epsilon turbulence model selected. |

| VARIABLE | DESCRIPTION |
|---|---|
| HCSFLCID | Load curve ID for scale factor applied on HC function of time. See \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_-FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f( x, y, z, vx, vy, vz, temp, pres, time). |
| TCSFLCID | Load curve ID for scale factor applied on TC function of time. See \*DEFINE_CURVE, \*DEFINE_CURVE_FUNCTION, or \*DEFINE_-FUNCTION. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f( x, y, z, vx, vy, vz, temp, pres, time). |
| NNMOID | Non-Newtonian model ID. This refers to a non-Newtonian fluid model defined using \*ICFD_MODEL_NONNEWT. |
| PMMOID | Porous media model ID. This refers to a porous media model defined using \*ICFD_MODEL_POROUS. |
| SPTRID | Species transport model ID. This refers to a species transport model defined using \*ICFD_MODEL_SPECIES_TRANSPORT. |
| VID | Viscoelastic model ID. This refers to a viscoelastic model defined using \*ICFD_MODEL_VISCOELASTIC. |

### \*ICFD_MODEL_NONNEWT

Purpose: Specify a non-newtonian model or a viscosity law that can associated to a fluid material.

**Non-Newtonian Model ID and type.**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|---|---|---|---|---|---|
| Variable | NNMOID | NNID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

**Non-Newtonian Fluid Parameters Card.**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|-------|--------|-------|--------|---|---|
| Variable | K | N | MUMIN | LAMBDA | ALPHA | TALPHA | | |
| Type | F | F | F | F | F | F | | |
| Default | 0.0 | 0.0 | 0.0 | 1.e30 | 0.0 | 0.0 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NNMOID | Non-Newtonian Model ID. |
| NNID | Non-Newtonian fluid model type : |

        EQ.1 : Power-Law model

        EQ.2 : Carreau model

        EQ.3 : Cross model

        EQ.4 : Herschel-Bulkley model

        EQ.5 : Cross II model

        EQ.6 : Sutherland formula for temperature dependent viscosity

        EQ.7 : Power-Law for temperature dependent viscosity

        EQ.8 : Viscosity defined by Load Curve ID or Function ID

| VARIABLE | DESCRIPTION |
|---|---|
| K | Consistency index if NNID = 1 and 4. Zero shear Viscosity if NNID = 2,3 and 5.Reference viscosity if NNID = 6 and NNID = 7. Load curve ID or function ID if NNID = 8. |
| N | Measure of the deviation of the fluid from Newtonian (Power Law index) for NNID = 1,2,3,4,5,7. Not used for NNID = 6 and 8. |
| MUMIN | Minimum acceptable viscosity value if NNID = 1. Infinite Shear Viscosity if NNID = 2,5.Yielding viscosity if NNID = 4.Not used if NNID = 3,6,7,8. |
| LAMBDA | Maximum acceptable viscosity value if NNID = 1. Time constant if NNID = 2, 3, 5. Yield Stress Threshold if NNID = 4.Sutherland constant if NNID = 6. Not used if NNID = 7,8. |
| ALPHA | Activation energy if NNID = 1, 2. Not used if NNID = 3,4,5,6,7,8. |
| TALPHA | Reference temperature if NNID = 2. Not used if NNID = 1,3,4,5,6,7,8 |

**Remarks:**

1. For the Non-Newtonian models, the viscosity is expressed as :

   a) POWER-LAW :

$$\mu = k\dot{\gamma}^{n-1}e^{\alpha T_0/T}$$

$$\mu_{min} < \mu < \mu_{max}$$

With $k$ the consistency index, $n$ the power law index, $\alpha$ the activation energy, $T_0$ the initial temperature, $T$ the temperature at any given time $t$, $\mu_{min}$ the minimum acceptable viscosity and $\mu_{max}$ the maximum acceptable viscosity.

   b) CARREAU :

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\left[1 + (H(T)\dot{\gamma}\lambda)^2\right]^{(n-1)/2}$$

$$H(T) = exp\left[\alpha(\frac{1}{T - T_0} - \frac{1}{T_\alpha - T_0})\right]$$

With $\mu_\infty$ the infinite shear viscosity, $\mu_0$ the zero shear viscosity, $n$ the power law index, $\lambda$ a time constant, $\alpha$ the activation energy, $T_0$ the initial temperature, $T$

the temperature at any given time $t$ and $T_\alpha$ the reference temperature at which $H(T) = 1$.

c) CROSS :

$$\mu = \frac{\mu_0}{1 + (\lambda\dot{\gamma})^{1-n}}$$

With $\mu_0$ the zero shear viscosity, $n$ the power law index and $\lambda$ a time constant.

d) HERSCHEL-BULKLEY :

$$\mu = \mu_0 \text{ if } (\dot{\gamma} < \tau_0/\mu_0)$$

$$\mu = \frac{\tau_0 + k[\dot{\gamma}^n - (\tau_0/\mu_0)^n]}{\dot{\gamma}}$$

With $k$ the consistency index, $\tau_0$ the Yield stress threshold, $\mu_0$ the yielding viscosity and $n$ the power law index.

e) CROSS II :

$$\mu = \mu_\infty + \frac{\mu_0 - \mu_\infty}{1 + (\lambda\dot{\gamma})^n}$$

With $\mu_0$ the zero shear viscosity, $\mu_\infty$ the infinite shear viscosity, $n$ the power law index and $\lambda$ a time constant.

2. For the temperature dependent viscosity models, the viscosity is expressed as :

a) SUTHERLAND's LAW :

$$\mu = \mu_0 (\frac{T}{T_0})^{3/2} \frac{T_0 + S}{T + S}$$

With $\mu_0$ a reference viscosity, $T_0$ the initial temperature (which therefore must not be 0.), $T$ the temperature at any given time $t$ and $S$ Sutherland's constant.

b) POWER LAW :

$$\mu = \mu_0 (\frac{T}{T_0})^n$$

With $\mu_0$ a reference viscosity, $T_0$ the initial temperature (which therefore must not be 0.), $T$ the temperature at any given time $t$ and $n$ the power law index.

3. For NNID = 8, a load curve function of time, a curve function or a function can be used. If it references a DEFINE_FUNCTION, the following arguments are allowed $f(x, y, z, vx, vy, vz, temp, pres, shear, time)$.

### *ICFD_MODEL_POROUS

Purpose:  Specify a porous media model.

**Card Summary:**

**Card 1.**  This card is required.

| PMMOID | PMMTYPE | FORM | RHOCP | KAPPA | | | |
|--------|---------|------|-------|-------|--|--|--|

**Card 2a.**  This card is included if PMMTYPE = 1, 2, or 8.

| POR | PER | FF | | PSFLCID | | | |
|-----|-----|----|--|---------|--|--|--|

**Card 2b.**  This card is included if PMMTYPE = 3 or 10.

| POR | TH | | FABTH | PVLCID | | | |
|-----|----|--|-------|--------|--|--|--|

**Card 2c.**  This card is included if PMMTYPE = 4, 6, or 7.

| POR | | | | | | | |
|-----|--|--|--|--|--|--|--|

**Card 2d.**  This card is included if PMMTYPE = 5.

| POR | THX | THY | THZ | PVLCIDX | PVLCIDY | PVLCIDZ | |
|-----|-----|-----|-----|---------|---------|---------|--|

**Card 2e.**  This card is included if PMMTYPE = 11.

| POR | ALPHA | BETA | | | | | |
|-----|-------|------|--|--|--|--|--|

**Card 3.**  This card is included if PMMTYPE = 4, 5, 6, or 7

| KXP | KYP | KZP | | | | | |
|-----|-----|-----|--|--|--|--|--|

**Card 4a.**  This card is included if PMMTYPE = 4 or 6.

| PROJXPX | PROJXPY | PROJXPZ | PROJYPX | PROJYPY | PROJYPZ | | |
|---------|---------|---------|---------|---------|---------|--|--|

**Card 4b.**  This card is included if PMMTYPE = 5 or 7.

| PID1REF | PID2REF | | | | | | |
|---------|---------|--|--|--|--|--|--|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|---------|------|-------|-------|---|---|---|
| Variable | PMMOID | PMMTYPE | FORM | RHOCP | KAPPA | | | |
| Type | I | I | I | F | F | | | |
| Default | none | none | 0 | 0.0 | 0.0 | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PMMOID | Porous media model ID |
| PMMTYPE | Porous media model type: |

EQ.1: Isotropic porous media - Ergun correlation

EQ.2: Isotropic porous media - Darcy-Forchheimer model

EQ.3: Isotropic porous media - permeability defined through pressure-velocity data

EQ.4: Anisotropic porous media. Fixed local reference frame (see Figure 7-11).

EQ.5: Anisotropic porous media model - moving local reference frame and permeability vector in local reference frame $(x', y', z')$ defined by three pressure-velocity curves.

EQ.6: Anisotropic porous media model - moving local reference frame and permeability vector constant.

EQ.7: Anisotropic porous media model - moving local reference frame and permeability vector constant. This model differs from PMMTYPE = 6 in the way the local reference frame is moved.

EQ.8: Main parachute model to be used jointly with \*MESH_-EMBEDSHELL for the parachute surface. Similar to PMMTYPE = 2.

EQ.10: Parachute model to be used jointly with \*MESH_EM-BEDSHELL where the fabric permeability and Forchheimer factor are computed from the pressure-velocity curves of experimental data given by a \*LOAD_CURVE. Similar to PMMTYPE = 3.

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.11: Parachute model similar to PMMTYPE = 8, but pressure gradient is directly defined by coefficients $\alpha$ and $\beta$ as: $$\frac{\Delta P(u_x)}{\Delta x} = \alpha u_x + \beta u_x{}^2 \ .$$ |
| FORM | Porous media formulation: |
| | EQ.0: Classical (default) |
| | EQ.2: Interstitial velocity |
| RHOCP | Density of the structure multiplied by the specific heat of the structure |
| KAPPA | Thermal conductivity of the structure |

**Porous Media Parameters Card (PMMTYPE = 1, 2, and 8).** This card is included PMM-TYPE = 1, 2, or 8.

| Card 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | POR | PER | FF | | PSFLCID | | | |
| Type | F | F | F | | I | | | |
| Default | 0. | 0. | 0. | | optional | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| POR | Porosity, $\varepsilon$ |
| PER | Permeability, $\kappa$ |
| FF | Forchheimer factor to be defined if PMMTYPE = 2 or 8. |
| PSFLCID | Optional permeability scale factor load curve ID, \*DEFINE_CURVE_FUNCTION ID or \*DEFINE_FUNCTION ID. If a \*DEFINE_FUNCTION is used, the following parameters are allowed: f( x, y, z, vx, vy, vz, temp, pres, time). |

**Porous Media Parameters Card (PMMTYPE = 3 and 10).** This card is included if PMMTYPE = 3 or 10.

| Card 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|------|---|-------|--------|---|---|---|
| Variable | POR | TH | | FABTH | PVLCID | | | |
| Type | F | F | | F | I | | | |
| Default | 0. | 0. | | 0. | none | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| POR | Porosity, $\varepsilon$ |
| TH | Probe thickness if PMMTYPE = 3 |
| FABTH | Fabric thickness if PMMTYPE = 10 |
| PVLCID | Pressure as a function of velocity load curve ID |

**Porous Media Parameters Card (PMMTYPE = 4, 6, and 7).** This card is included if PMMTYPE = 4, 6, or 7.

| Card 2c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|------|---|---|---|---|---|---|---|
| Variable | POR | | | | | | | |
| Type | F | | | | | | | |
| Default | 0. | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| POR | Porosity, $\varepsilon$ |

**Porous Media Parameters Card (PMMTYPE = 5).** This card is included if PMM-TYPE = 5.

| Card 2d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|-----|-----|-----|---------|---------|---------|---|
| Variable | POR | THX | THY | THZ | PVLCIDX | PVLCIDY | PVLCIDZ | |
| Type | F | F | F | F | I | I | I | |
| Default | 0. | 0. | 0. | 0. | none | none | none | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| POR | Porosity, $\varepsilon$ |
| THX | Probe thickness, $\Delta x$ |
| THY | Probe thickness, $\Delta y$ |
| THZ | Probe thickness, $\Delta z$ |
| PVLCIDX | Load curve ID for pressure as a function of velocity in the global $X$-direction |
| PVLCIDY | Load curve ID for pressure as a function of velocity in the global $Y$-direction |
| PVLCIDZ | Load curve ID for pressure as a function of velocity in the global $Z$-direction |

**Porous Media Parameters Card (PMMTYPE = 11).** This card is included if PMM-TYPE = 11.

| Card 2e | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|-----|-------|------|---|---|---|---|---|
| Variable | POR | ALPHA | BETA | | | | | |
| Type | F | F | F | | | | | |
| Default | 0. | 0. | 0. | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| POR | Porosity, $\varepsilon$ |
| ALPHA | Coefficient, $\alpha$ |
| BETA | Coefficient, $\beta$ |

**Permeability Vector Card in local reference frame.** Only to be defined if the porous media is anisotropic (PMMTYPE = 4, 5, 6, 7).

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | KXP | KYP | KZP | | | | | |
| Type | F | F | F | | | | | |
| Default | 0. | 0. | 0. | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| KXP, KYP, KZP | Permeability vector in local reference frame $(x', y', z')$. Those values become scale factors if PMMTYPE = 5. |

**Projection of Local Vectors in Global Reference Frame.** This card is defined if PMM-TYPE = 4 or 6.

| Card 4a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PROJXPX | PROJXPY | PROJXPZ | PROJYPX | PROJYPY | PROJYPZ | | |
| Type | F/I | F/I | F/I | F/I | F/I | F/I | | |
| Default | 0./0 | 0./0 | 0./0 | 0./0 | 0./0 | 0./0 | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PROJXPX, PROJXPY, PROJXPZ | Projection of the local permeability vector, $\mathbf{x}'$, in the global reference frame, $(x, y, z)$. If PMMTYPE = 6, PROJXPX, PROJXPY, and PRPJXPZ become load curve IDs, so the coordinates of the local $\mathbf{x}'$ vector can change in time. |

| VARIABLE | DESCRIPTION |
|---|---|
| PROJYPX, PROJYPY, PROJYPZ | Projection of the local permeability vector, $\mathbf{y}'$, in the global reference frame, $(x, y, z)$. If PMMTYPE = 6, PROJYPX, PROJYPY, and PRPJYPZ become load curve IDs, so the coordinates of the local $\mathbf{y}'$ vector can change in time. |

**Local Reference Frame Vectors.** This card is defined if PMMTYPE = 5 or 7.

| Card 4b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1REF | PID2REF | | | | | | |
| Type | I | I | | | | | | |
| Default | 0 | 0. | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID1REF, PID2REF | Two local reference frame vectors are defined by the coordinates of the two-point IDs defined by PID1REF and PID2REF. (See \*ICFD_DEFINE_POINT). Since those points can be made to move, it is therefore possible to define a moving reference frame for the anisotropic porous media domain. |

**Remarks:**

1.  **Generalized Flow Equations in a Porous Media.** Let $\varepsilon$ be the porosity and $\kappa$ be the permeability of the porous media. Then,

$$\varepsilon = \frac{\text{void volume}}{\text{total volume}} \ .$$

$u_i$, the volume averaged velocity field, can then be defined in terms of the fluid velocity field, $u_{if}$, as:

$$u_i = \varepsilon u_{if} \ .$$

The generalized flow equations of momentum and mass conservation can be expressed as:

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\rho}{\varepsilon}\left[\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\frac{u_i u_j}{\varepsilon}\right)\right] = -\frac{1}{\varepsilon}\frac{\partial(P\varepsilon)}{\partial x_i} + \frac{\mu}{\varepsilon}\left(\frac{\partial^2 u_i}{\partial x_j \partial x_j}\right) + \rho g_i - D_i$$
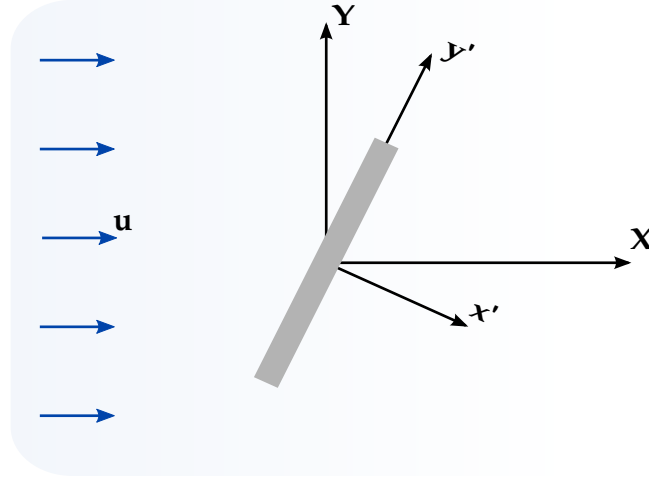
**Figure 7-11.** Anisotropic porous media vectors definition (PMMTYPE = 4, 5, 6, and 7). The vectors **X** and **Y** are the global axes; $x'$ and $y'$ define the system for the primed coordinate $(x', y', z')$.

where $D_i$ are the forces exerted on the fluid by the porous matrix (see Remarks 2 and 3).

2. **Porous Forces for Isotropic Models.** For the isotropic model, the porous forces are a function of the matrix porosity and its permeability. For the isotropic case, three models are available:

   a) *Model 1 (Ergun correlation).*

   $$D_i = \frac{\mu u_i}{\kappa} + \frac{1.75\rho|U|}{\sqrt{150}\sqrt{\kappa}\varepsilon^{3/2}} u_i$$

   b) *Model 2 (Darcy-Forcheimer).*

   $$D_i = \frac{\mu u_i}{\kappa} + \frac{F\varepsilon\rho|U|}{\sqrt{\kappa}} u_i$$

   c) *Model 3.* Using the $\Delta P - V$ experimental data. In this case, it is assumed that the pressure-velocity curve was obtained by applying a pressure difference or pressure drop on both ends of a porous slab of thickness $\Delta x$ with porous properties $\kappa$ and $\varepsilon$. It then becomes possible for the solver to fit that experimental curve with a quadratic polynomial of the form $\Delta P(u_x) = \alpha u_x^2 + \beta u_x$. Once $\alpha$ and $\beta$ are known, it is possible to estimate $D_i$.

3. **Anisotropic Darcy-Forcheimer Term.** The anisotropic (see Figure 7-11) version of the Darcy-Forcheimer term can be written as:

   $$D_i = \mu B_{ij} u_j + F\varepsilon|U|C_{ij}u_j$$
   $$B_{ij} = \left(K_{ij}\right)^{-1}$$
   $$C_{ij} = \left(K_{ij}\right)^{-1/2}$$

Here $K_{ij}$ is the anisotropic permeability tensor.

## \*ICFD_MODEL_SPECIES_TRANSPORT

Purpose: Specify a passive or reactive multi-species transport model that can be associated with a fluid material.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | SPTRID | SPNMBR | DENSRCT | DENSFID | | | | |
| Type | I | I | I | I | | | | |
| Default | none | none | 0 | none | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | MASSDIF1 | MASSDIF2 | MASSDIF3 | MASSDIF4 | MASSDIF5 | MASSDIF6 | MASSDIF7 | MASSDIF8 |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

**Reaction Rate Card.** Include this card if DENSRCT = 2.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | FID1 | FID2 | FID3 | FID4 | FID5 | FID6 | FID7 | FID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SPTRID | Species transport model ID |
| SPNMBR | Number of species:<br>EQ.1: One (passive) species<br>EQ.2: Two species |

| VARIABLE | DESCRIPTION |
|---|---|
| | $\vdots$ |
| | EQ.8: Eight species |
| DENSRCT | Flag for kind of species transport: |
| | EQ.0: Passive species transport |
| | EQ.1: Passive species transport where the fluid density depends on the concentrations of the species. DENSFID gives the fluid density as a function of species concentrations. |
| | EQ.2: Reactive species transport. Card 3 gives the reaction rates for each species. |
| DENSFID | Function ID for DENSRCT = 1 giving the fluid density as a function of species concentrations. The following parameters are allowed: f(x,y,z,vx,vy,vz,temp,pres,time,conc1,conc2,…,conc8). Here, x, y, and z are the coordinates, vx, vy, and vz are the components of the velocity, time is the time, pres is the pressure, conc$i$ is the concentration of the $i$th species. |
| MASSDIF$i$ | Mass diffusion for the $i$th species |
| FID$i$ | Function ID giving the reaction rate for the $i$th species. The following parameters are allowed: f(x,y,z,time,temp,pres,conc1,conc2,…,conc8). Here, x, y, and z are the coordinates, time is the time, pres is the pressure, conc$i$ is the concentration of the $i$th species. |

## *ICFD_MODEL_VISCOELASTIC

Purpose: Specify a viscoelastic model that can be associated with a fluid material.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VID | VTYPE | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RTIME | PVISC | MOBF | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| VID | Viscoelastic model ID |
| VTYPE | Viscoelastic model type:<br>    EQ.1: Oldroyd-B model<br>    EQ.2: Giesekus model |
| RTIME | Relaxation time |
| PVISC | Polymeric viscosity |
| MOBF | Mobility factor (for VTYPE = 2 only) |

**\*ICFD_PART_***{OPTION}*

Available options include

TITLE

Purpose: Define parts for this incompressible flow solver.

The TITLE option allows the user to define an additional optional line with a HEADING in order to associate a name to the part.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HEADING | | | | | | | |
| Type | A | | | | | | | |
| Default | none | | | | | | | |

**Part Material Card.** Include as many cards as needed. This input ends at the next keyword ("\*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | SECID | MID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part identifier for fluid surfaces. |
| SECID | Section identifier defined with the \*ICFD_SECTION card. |
| MID | Material identifier defined with the \*ICFD_MAT card. |

## *ICFD_PART_VOL_*{OPTION}*

Available options include

      TITLE

Purpose: This keyword assigns material properties to the nodes enclosed by surface ICFD parts.

The TITLE option allows the user to define an additional optional line with a HEADING in order to associate a name to the part.

| Title | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | HEADING | | | | | | | |
| Type | A | | | | | | | |
| Default | none | | | | | | | |

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | SECID | MID | | | | | |
| Type | I | I | I | | | | | |
| Default | none | none | none | | | | | |

Provide as many cards as necessary. This input ends at the next keyword ("*") card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SPID1 | SPID2 | SPID3 | SPID4 | SPID5 | SPID6 | SPID7 | SPID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PID | Part identifier for fluid volumes. |
| SECID | Section identifier defined by the \*ICFD_SECTION card. |
| MID | Material identifier. |
| SPID1, … | Part IDs for the surface elements that define the volume mesh. |
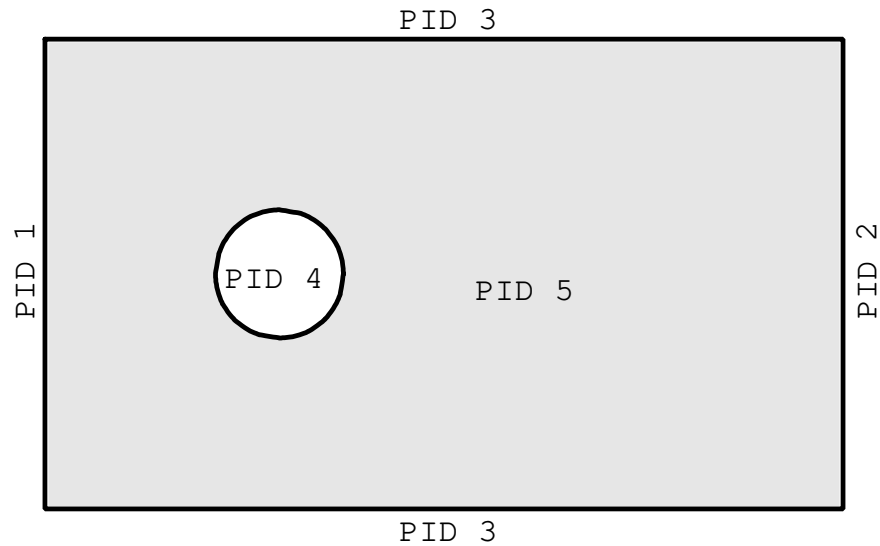


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$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$   *ICFD_PART_VOL
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ PART ID 5 is defined by the surfaces that enclose it.
$
*ICFD_PART_VOL
$
$...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....8
$     pid      secid      mid
       5          1          1
$...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....8
$     pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
       1          2          3          4
```

**\*ICFD_SECTION**

Purpose: Define a section for the incompressible flow solver.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SID | Section identifier. |

## \*ICFD_SET_NODE_LIST

Purpose: Only used in cases where the mesh is specified by the user (See \*MESH_VOLUME_ELEMENT). Defines a set of nodes associated with a part ID on which boundary conditions can be applied.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SID | PID | | | | | | |
| Type | I | I | | | | | | |
| Default | none | none | | | | | | |

**Node List Card.** Provide as many cards as necessary. This input ends at the next keyword ("*") card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NID1 | NID2 | NID3 | NID4 | NID5 | NID6 | NID7 | NID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| SID | Set ID |
| PID | Associated Part ID. |
| NID1, … | Node IDs |

**Remarks:**

1.  The convention is the similar to the one used by the keyword \*SET_NODE_LIST and serves a similar purpose.

## \*ICFD_SOLVER_SPLIT

Purpose: This keyword provides an option to trigger an iterative procedure on the fluid system. This procedure aims to bring more precision to the final pressure and velocity values but is often very time consuming. It must therefore be used with caution. It is intended only for special cases. For stability purposes, this method is automatically used for the first ICFD time step.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | NIT | TOL | | | | | | |
| Type | I | F | | | | | | |
| Default | 1 | $10^{-3}$ | | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| NIT | Maximum Number of iterations of the system for each fluid time step. If TOL criteria is not reached after NIT iterations, the run will proceed. |
| TOL | Tolerance Criteria for the pressure residual during the fluid system solve. |

**\*ICFD_SOLVER_TOL_FSI**

Purpose: This keyword allows the user to change the default tolerance values for the Newton Raphson loop in the strong FSI analysis. *Care should be taken when deviating from the default values.*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | | | |
| Type | F | F | | I | | | | |
| Default | $10^{-5}$ | $10^{-5}$ | | 1000 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq RTOL$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |

## \*ICFD_SOLVER_TOL_LSET

Purpose: This keyword allows the user to change the default tolerance values for the advection equation for levelset. *Care should be taken when deviating from the default values.*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|---|-------|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | | | |
| Type | F | F | | I | | | | |
| Default | $10^{-8}$ | $10^{-8}$ | | 1000 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq RTOL$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |

## \*ICFD_SOLVER_TOL_MMOV

Purpose: This keyword allows the user to change the default tolerance values for the mesh movement algorithm. *Care should be taken when deviating from the default values*.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | DISPTOL | | |
| Type | F | F | | I | | F | | |
| Default | 1e-8 | 1e-8 | | 1000 | | 0. | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq \text{RTOL}$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |
| DISPTOL | Element deformation tolerance before a matrix reassembly is triggered. Default is 0. which means any element deformation detected will automatically trigger a matrix reassembly. Higher values will potentially save calculation times at the expense of accuracy. |

## \*ICFD_SOLVER_TOL_MOM

Purpose: This keyword allows the user to change the default tolerance values for the momentum equation solve. *Care should be taken when deviating from the default values.*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | | | |
| Type | F | F | | I | | | | |
| Default | $10^{-8}$ | $10^{-8}$ | | 1000 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq \text{RTOL}$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |

## \*ICFD_SOLVER_TOL_MONOLITHIC

Purpose: This keyword allows the user to change the default tolerance values for the monolithic solver. *Care should be taken when deviating from the default values*.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | | | |
| Type | F | F | | I | | | | |
| Default | $10^{-8}$ | $10^{-8}$ | | 1000 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq \text{RTOL}$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |

## \*ICFD_SOLVER_TOL_PRE

Purpose: Change the default tolerance values for the Poisson equation for pressure. *Care should be taken when deviating from the default values.*

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|---|-------|-------|------|---|---|
| Variable | ATOL | RTOL | | MAXIT | PREID | PTOL | | |
| Type | F | F | | I | I | F | | |
| Default | $10^{-8}$ | $10^{-8}$ | | 1000 | 2 | $10^{-3}$ | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ATOL | Absolute convergence criteria. Convergence is achieved when $\text{Residual}_{i+1} - \text{Residual}_i \leq \text{ATOL}$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(\text{Residual}_{i+1} - \text{Residual}_i)/\text{Residual}_{\text{initial}} \leq \text{RTOL}$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |
| PREID | Choice of Preconditioner for the Conjugate Gradient Solve: |
| | EQ.1: Diagonal Preconditioner |
| | EQ.2: Incomplete LU factorization |
| | EQ.5: Global MUMPS factorization |
| PTOL | Preconditioner tolerance (a.k.a Drop Tolerance if PREID = 2) |

**\*ICFD_SOLVER_TOL_TEMP**

Purpose: This keyword allows the user to change the default tolerance values for the heat equation. To be handled with great care.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|------|---|-------|---|---|---|---|
| Variable | ATOL | RTOL | | MAXIT | | | | |
| Type | F | F | | I | | | | |
| Default | 1e-8 | 1e-8 | | 1000 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| ATOL | Absolute convergence criteria. Convergence is achieved when $Residual_{i+1} - Residual_i \leq ATOL$. If a negative integer is entered, then that value will be used as a load curve ID for ATOL. |
| RTOL | Relative convergence criteria. Convergence is achieved when $(Residual_{i+1} - Residual_i)/Residual_{initial} \leq RTOL$. If a negative integer is entered, then that value will be used as a load curve ID for RTOL. |
| MAXIT | Maximum number of iterations allowed to achieve convergence. If a negative integer is entered, then that value will be used as a load curve ID for MAXIT. |

# \*MESH

The keyword *MESH is used to create a mesh that will be used in the analysis. So far only tetrahedral (or triangular in 2D) elements can be generated. The keyword cards in this section are defined in alphabetical order:

*MESH_BL

*MESH_BL_SYM

*MESH_EMBEDSHELL

*MESH_INTERF

*MESH_NODE

*MESH_SIZE

*MESH_SIZE_SHAPE

*MESH_SURFACE_ELEMENT

*MESH_SURFACE_NODE

*MESH_SURFACE_NULL

*MESH_VOLUME

*MESH_VOLUME_ELEMENT

*MESH_VOLUME_NODE

*MESH_VOLUME_PART

## *MESH_BL

Purpose: Define a boundary-layer mesh as a refinement on the volume-mesh. The boundary layer mesh is constructed by subdividing elements near the surface.

**Boundary Layer Cards.** Define as many cards as are necessary. The next keyword ("*") card terminates this input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|------|-------|------|------|------|------|---|---|
| Variable | PID | NELTH | BLTH | BLFE | BLST | BLDR | | |
| Type | I | I | F | F | I | I | | |
| Default | none | none | 0. | 0. | 0 | 0 | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| PID | Part identifier for the surface element |
| NELTH | Number of elements normal to the surface (in the boundary layer) is NELTH + 1. See Remark 5. |
| BLTH | Boundary layer mesh thickness if BLST = 1 or 2. Growth scale factor if BLST = 3. Ignored if BLST = 0. See Remark 5. |
| BLFE | Distance between the wall and the first volume mesh node if BLST = 3. Scaling coefficient if BLST = 1 or 2. Ignored if BLST =0. See Remark 5. |
| BLST | Boundary layer mesh generation strategy: |
| | EQ.0: $2^{\text{NELTH}+1}$ subdivisions based on surface mesh size (default). See Remark 1. |
| | EQ.1: Power law using BLTH and NELTH with BLFE as a scale factor. See Remark 2 and Figure 8-1. |
| | EQ.2: Geometric series based on BLTH and BLFE. See Remark 3 and Figure 8-2. |
| | EQ.3: Repartition following a growth scale factor (BLTH). See Remark 4 and Figure 8-3. |
| BLDR | Boundary layer mesh generation during the dynamic relaxation phase when present (see *ICFD_CONTROL_GENERAL): |

| VARIABLE | DESCRIPTION |
|---|---|
| | EQ.0: On. No distinction for boundary layer mesh generation between the dynamic relaxation and transient phases. |
| | EQ.1: Off. Boundary layer mesh is not generated during the dynamic relaxation phase. |

**Remarks:**

1.  **BLST = 0.** For BLST = 0, for every additional NELTH, the automatic volume mesher will divide the elements closest to the surface by two so that the smallest element in the boundary layer mesh will have an aspect ratio of $2^{\text{NELTH}+1}$. A default boundary layer mesh thickness based on the surface mesh size will be chosen.

2.  **BLST = 1.** For a constant repartition of the nodes in the boundary layer, use BLST = 1 with BLFE = 1. For BLST = 1, starting from the wall, the position of node $n$ in the normal direction is given by:

$$X_n = \left(\frac{n}{\text{NELTH} + 1}\right)^{[5\times(1-\text{BLFE})]} \frac{\text{BLTH}}{\sum_{i=1}^{\text{NELTH}+1}\left[\frac{i}{(\text{NELTH} + 1)}\right]^{[5\times(1-\text{BLFE})]}}$$

3.  **BLST = 2.** Setting BLFE = 1 makes BLST = 2 equivalent to BLST = 0 except that BLST = 2 allows you to specify the boundary layer thickness instead of automatically using the local surface mesh size. For BLST = 2, starting from BLTH from the wall, each newly inserted node will have its location closer to the wall, following this law:

$$X_n = (0.5 \times \text{BLFE})^n \times \text{BLTH}(1 - 0.5 \times \text{BLFE})$$

4.  **BLST = 3.** For BLST = 3, starting from the wall, the position of node $n$ in the normal direction is given by:

$$X_n = \sum_{i=0}^{n} \text{BLFE} \times \text{BLTH}^i \text{ with } 0 \leq n \leq \text{NELTH}$$

5.  **Dynamically changing boundary layer.** For NELTH, BLTH, and BLFE, setting a negative value will point to a time-dependent load curve which enables dynamically changing the boundary layer settings in cases involving remeshing (including returning a 0 value for the number of elements which effectively disables the boundary layer). NELTH and BLTH also accept a \*DEFINE_FUNCTION as input with time and the x, y, and z coordinates accepted as arguments.
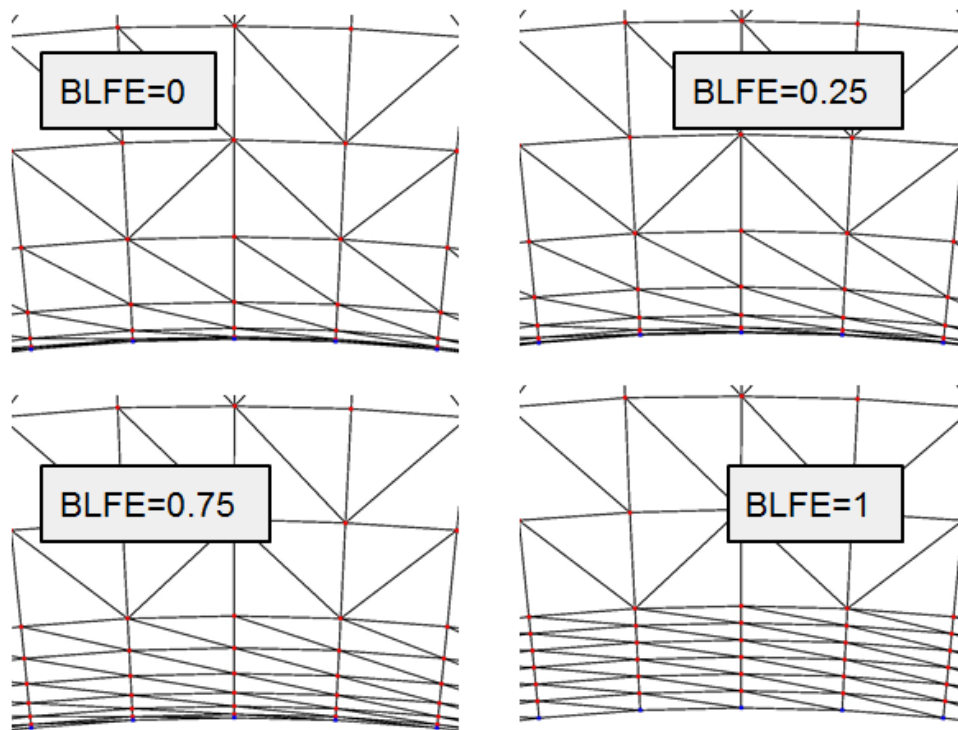
**Figure 8-1.** BLST = 1 example
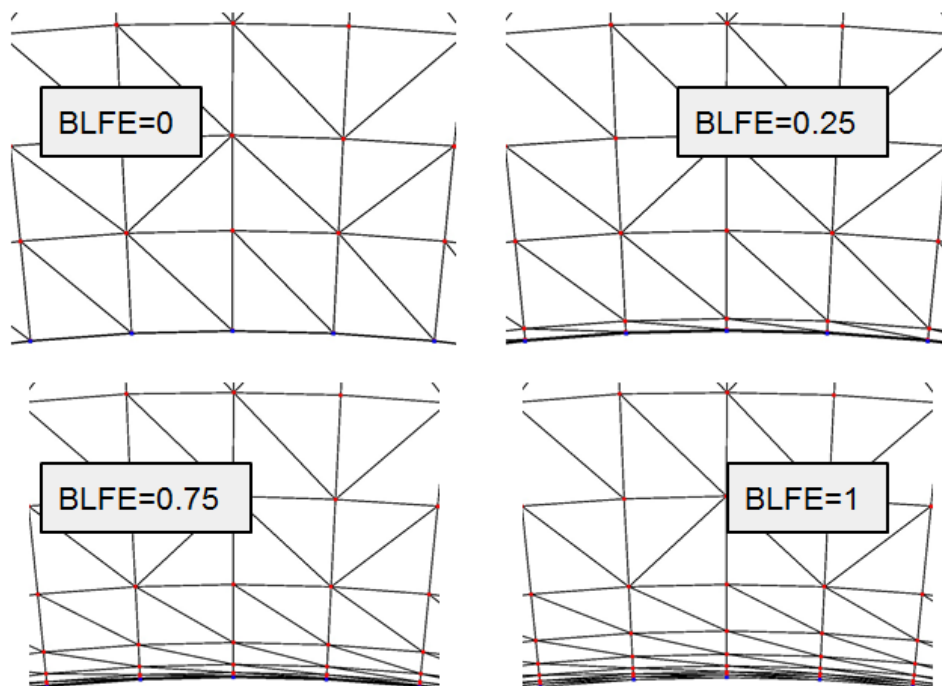


**Figure 8-2.** BLST = 2 example
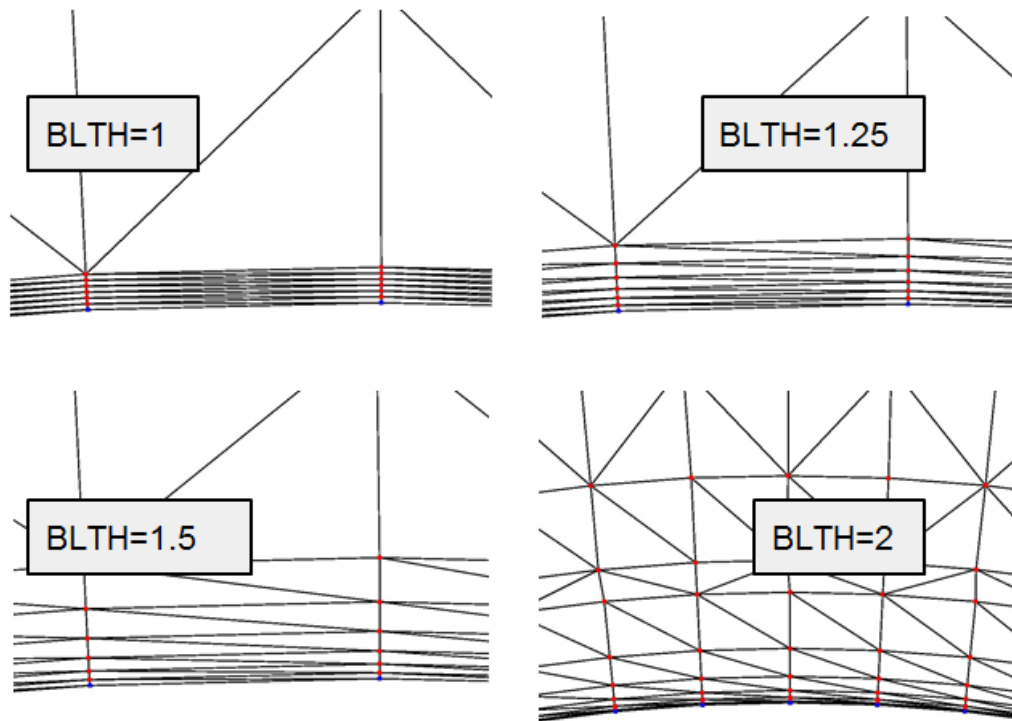
**Figure 8-3.** BLST = 3 example

## *MESH_BL_SYM

Purpose: Specify the part IDs that will have symmetry conditions for the boundary layer. On these surfaces, the boundary layer mesh follows the surface tangent.

**Boundary Layer with Symmetry Condition Cards.** Define as many cards as necessary. The next "*" card terminates the input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| PID1, … | Part identifiers for the surface element. This is the surface with symmetry. |

**\*MESH_EMBEDSHELL**

Purpose: Define surfaces that the mesher will embed inside the volume mesh. These surfaces will have no thickness and will conform to the rest of the volume mesh having matching nodes on the interface.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VOLID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

Define as many cards as are necessary based on the number of PIDs (the next "\*" card terminates the input.)

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| VOLID | ID assigned to the new volume in the keyword \*MESH_VOLUME. The surface mesh size will be applied to this volume. |
| PID*n* | Part IDs for the surface elements that will be embedded in the volume mesh. |

## *MESH_INTERF

Purpose: Define the surfaces that will be used by the mesher to specify fluid interfaces in multi-fluid simulations.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VOLID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

Define as many cards as are necessary based on the number of PIDs. This input ends at the next keyword ("*") card.

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| VOLID | ID assigned to the new volume in the keyword *MESH_VOLUME. The interface meshes will be applied to this volume. |
| PID*n* | Part IDs for the surface elements. |

**\*MESH_NODE**

Purpose: Define a fluid node and its coordinates. These nodes are used in the mesh generation process by the \*MESH_SURFACE_ELEMENT keyword, or as user defined volume nodes by the \*MESH_VOLUME_ELEMENT keyword.

**Node Cards.** Include one additional card for each node. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|---|---|---|---|---|---|---|---|---|----|
| Variable | NID | X | | Y | | Z | | | | |
| Type | I | F | | F | | F | | | | |
| Default | none | 0 | | 0 | | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Node ID. A unique number with respect to the other surface nodes. |
| X | *x* coordinate. |
| Y | *y* coordinate. |
| Z | *z* coordinate. |

**Remarks:**

1.  The data card format for the \*MESH_NODE keyword is identical to \*NODE.

2.  The \*MESH_NODE keyword supersedes \*MESH_SURFACE_NODE, which was for surfaces nodes as well as \*MESH_VOLUME_NODE for, which was for volume nodes in user defined.

## *MESH_SIZE

Purpose: Define the surfaces that will be used by the mesher to specify a local mesh size inside the volume. If no internal mesh is used to specify the size, the mesher will use a linear interpolation of the surface sizes that define the volume enclosure.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VOLID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

Define as many cards as are necessary based on the number of PIDs (the next "*" card terminates the input.).

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| VOLID | ID assigned to the new volume in the keyword *MESH_VOLUME. The mesh sizing will be applied to this volume. |
| PID*n* | Part IDs for the surface elements that are used to define the mesh size next to the surface mesh. |

## \*MESH_SIZE_SHAPE

Purpose: Defines a local mesh size in specific zones corresponding to given geometrical shapes (box, sphere, cylinder, and polynomial). The solver automatically applies the conditions specified during the generation of the volume mesh. This zone does not need to be entirely defined in the volume mesh. In the polynomial case, we recommend defining several zones for better mesh size control.

**Card Summary:**

**Card Sets.** Add as many sets of these cards as needed. This input ends with the next keyword ("*") card.

**Card 1.** This card is required.

| SNAME | FORCE | METHOD | BT | DT | | | |
|-------|-------|--------|-----|-----|--|--|--|

**Card 2a.** Include this card if SNAME = box and METHOD = 0.

| MSIZE | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ | |
|-------|-------|-------|-------|-------|-------|-------|--|

**Card 2b.** Include this card if SNAME = sphere and METHOD = 0.

| MSIZE | RADIUS | CENTERX | CENTERY | CENTERZ | | | |
|-------|--------|---------|---------|---------|--|--|--|

**Card 2c.** Include this card if SNAME = cylinder and METHOD = 0.

| MSIZE | RADIUS | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ |
|-------|--------|-------|-------|-------|-------|-------|-------|

**Card 2d.** Include this card if SNAME = pol and METHOD = 0.

| MSIZE | X | Y | Z | NX | NY | NZ | |
|-------|---|---|---|----|----|----|--|

**Card 2e.** Include this card if METHOD = 1.

| MSIZE | RADIUS | PTID1 | PTID2 | | RMIN | | |
|-------|--------|-------|-------|--|------|--|--|

**Card 2f.** Include this card if METHOD = 2.

| MSIZE | RADIUS | NID1 | NID2 | | | | |
|-------|--------|------|------|--|--|--|--|

**Data Card Definitions:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-------|-------|--------|-----|-------|---|---|---|
| Variable | SNAME | FORCE | METHOD | BT | DT | | | |
| Type | A | I | I | F | F | | | |
| Default | none | 0 | 0 | 0. | $10^{12}$ | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SNAME | Shape name. Possibilities include box, cylinder, pol, and sphere. |
| FORCE | Flag to keep the mesh size criteria even after performing remeshing: |
| | EQ.0: Exclude boundary layer elements (default). |
| | EQ.1: Include boundary layer elements. |
| METHOD | Specifies which method to use when defining the second card: |
| | EQ.0: Default, directly input the coordinates. |
| | EQ.1: Define the coordinates with *ICFD_DEFINE_POINT IDs. See Remark 1. |
| | EQ.2: Define the coordinates by using user node IDs from solid mechanics. This method is only available when a solid mechanics problem is present. See Remark 1. |
| BT/DT | Birth and death time of the mesh size area in cases where remeshing occurs. |

**Box Case.** Card 2 for SNAME = box and METHOD = 0

| Cards 2a | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|-------|-------|-------|-------|-------|-------|-------|---|
| Variable | MSIZE | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSIZE | Mesh size that needs to be applied in the zone of the shape. A negative value points to a \*DEFINE_FUNCTION. If using a \*DEFINE_FUNCTION, the following parameters are allowed: f(x, y, z, time). |
| PMIN*i* | *x*, *y*, or *z* value for the point of minimum coordinates |
| PMAX*i* | *x*, *y*, or *z* value for the point of maximum coordinates |

**Sphere Case.** Card 2 for SNAME = sphere and METHOD = 0

| Cards 2b | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|---|---|---|---|---|---|---|---|
| Variable | MSIZE | RADIUS | CENTERX | CENTERY | CENTERZ | | | |
| Type | F | F | F | F | F | | | |
| Default | none | none | none | none | none | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| MSIZE | Mesh size that needs to be applied in the zone of the shape |
| RADIUS | Radius of the sphere |
| CENTER*i* | *x*, *y*, and *z* coordinates of the sphere's center |

**Cylinder Case.** Card 2 for SNAME = cylinder and METHOD = 0

| Cards 2c | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|---|---|---|---|---|---|---|---|
| Variable | MSIZE | RADIUS | PMINX | PMINY | PMINZ | PMAXX | PMAXY | PMAXZ |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| MSIZE | Mesh size that needs to be applied in the zone of the shape |
| RADIUS | Radius of the cylinder |
| PMIN*i* | *x*, *y*, or *z* value for the point of minimum coordinates |
| PMAX*i* | *x*, *y*, or *z* value for the point of maximum coordinates |

**Polynomial Case.** Card 2 for SNAME = pol and METHOD = 0

| Cards 2d | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSIZE | X | Y | Z | NX | NY | NZ | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | none | none | none | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSIZE | Mesh size that needs to be applied in the zone of the shape |
| X/Y/Z | Coordinates of starting point |
| NX/NY/NZ | Direction in which the mesh size will be applied |

**METHOD = 1 Case.** Card 2 for METHOD = 1.

| Cards 2e | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSIZE | RADIUS | PTID1 | PTID2 | | RMIN | | |
| Type | F | F | I | I | | F | | |
| Default | none | none | none | none | | 0. | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSIZE | Mesh size that needs to be applied in the zone of the shape defined by SNAME |

| VARIABLE | DESCRIPTION |
|---|---|
| RADIUS | Radius of the sphere if SNAME is sphere or radius of the cylinder if SNAME is cylinder. Ignored otherwise. |
| PTID1 | Point ID 1, referring to a *ICFD_DEFINE_POINT. It replaces PMIN*i* for box and cylinder, X/Y/Z for pol, and CENTER for sphere. |
| PTID2 | Point ID 2. It is ignored if SNAME is sphere. It replaces PMAX*i* for box and cylinder and NX/NY/NZ for pol. |
| RMIN | Optional radius available if SNAME is sphere or cylinder to define an internal sphere/cylinder where the *MESH_SIZE_SHAPE does not apply. When defined, RMIN should be smaller than RADIUS. |

**METHOD = 2 Case.** Card 2 for METHOD=2

| Cards 2f | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MSIZE | RADIUS | NID1 | NID2 | | | | |
| Type | F | F | I | I | | | | |
| Default | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MSIZE | Mesh size that needs to be applied in the zone of the shape defined by SNAME |
| RADIUS | Radius of the sphere if SNAME is sphere or radius of the cylinder if SNAME is cylinder. Ignored otherwise. |
| NID1/NID2 | User node IDs that come from the solid mechanics problem. Equivalent usage to PTID1 and PTID2. NID1 replaces PMIN*i* for box and cylinder, X/Y/Z for pol, and CENTER for sphere. NID2 is ignored if SNAME is sphere. It replaces PMAX*i* for box and cylinder and NX/NY/NZ for pol. |

**Remarks:**

1.  **Moving coordinates.** METHOD = 2 and 3 have the advantage of allowing the region to move since the regions move with *ICFD_DEFINE_POINTs and nodes

from the solid mechanics' problem, respectively.  Thus, these methods provide control over how the mesh size area evolves as a function of time (in cases where remeshing occurs).

**\*MESH_SURFACE_ELEMENT**

Purpose: Specify a set of surface elements (quadrilateral or triangular in 3D and linear segments in 2D) that will be used by the mesher to construct a volume mesh. These surface elements may define the enclosed volume to be meshed, or alternatively they can be used to specify different mesh sizes inside the volume (see card \*MESH_SIZE**).**

Each solver that supports the \*MESH volume mesher for building its volume mesh uses the PID given for each surface element specified with this keyword differently.

1.   For the \*ICFD solver, the \*ICFD_PART keyword references the surface mesh PIDs.

2.   For the \*DUALCESE solver, the MSPIDs in \*DUALCESE_BOUNDARY_... keywords cards reference the surface element PIDs. Note that when the dual CESE solver uses \*MESH_SURFACE_ELEMENT, this card defines which boundary faces belong to each mesh surface PID. In this case, no other mechanism exists for defining these PIDs. Also, when the dual CESE solver is defined with \*MESH cards, there should not be any \*DUALCESE_SEGMENTSET cards related to the dual CESE mesh.

**Surface Element Card.** Define as many cards as necessary. The next keyword ("\*") card terminates this input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|------|------|------|------|------|------|---|---|---|----|
| Variable | EID | PID | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | I | I | | | | |
| Default | none | none | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| EID | Element ID. A unique number with respect to all \*MESH_SUR-FACE_ELEMENTS cards. |
| PID | Mesh surface part ID. A unique identifier for the surface to which this mesh surface element belongs. |
| N1 | Nodal point 1 |
| N2 | Nodal point 2 |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| N3 | Nodal point 3 |
| N4 | Nodal point 4 |

**Remarks:**

1.  **Defining Surface Elements.** The convention for defining surface elements is the same as for \*ELEMENT_SHELL. In the case of a triangular face, N3 = N4. In 2D N2 = N3 = N4. Note that the accepted card format is 6i8 (not 6i10).

**\*MESH_SURFACE_NODE**

Purpose: Define a node and its coordinates. These nodes will be used in the mesh generation process by the \*MESH_SURFACE_ELEMENT keyword.

\*MESH_NODE supersedes this card; so please use \*MESH_NODE instead of this card.

**Surface Node Cards.** Include one card for each node. Include as many cards a necessary. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|---|---|---|---|---|---|---|---|---|----|
| Variable | NID | X | | Y | | Z | | | | |
| Type | I | F | | F | | F | | | | |
| Default | none | 0 | | 0 | | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Node ID. This NID must be unique within the set of surface nodes. |
| X | *x* coordinate. |
| Y | *y* coordinate. |
| Z | *z* coordinate. |

**\*MESH_SURFACE_NULL**

Purpose: Specify a set of surface part IDs to be used during post-processing. The part IDs are defined with the \*MESH_SURFACE_ELEMENT keyword. Elements from \*MESH_SURFACE_ELEMENT that belong to a \*MESH_SURFACE_NULL part are not used by the mesher to construct a volume mesh. These surface elements are not involved in any physics computation.

For the \*ICFD solver, the \*ICFD_PART keyword referencing the null surface mesh PIDs is not necessary.

**Null Surface Element Card.** Define as many cards as necessary. The next keyword ("*") card terminates this input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | | | | |
| Type | I | I | I | I | I | I | | | | |
| Default | none | none | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| PID*i* | Mesh surface part ID *i* |

**\*MESH_VOLUME**

Purpose: This keyword defines the volume space that will be meshed. The boundaries of the volume are the surfaces defined by *MESH_SURFACE_ELEMENT. The surfaces listed have to be non-overlapping, and should not leave any gaps or open spaces between the surface boundaries. On the boundary between two neighbor surfaces, nodes have to be in common (no duplicate nodes) and should match exactly on the interface. They are defined by the keyword *MESH_SURFACE_NODE. This card will be ignored if the volume mesh is specified by the user and not generated automatically.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | VOLID | | | | | | | |
| Type | I | | | | | | | |
| Default | none | | | | | | | |

Define as many cards as are necessary based on the number of PIDs (the next "*" card terminates the input.)

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID1 | PID2 | PID3 | PID4 | PID5 | PID6 | PID7 | PID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| VOLID | ID assigned to the new volume. |
| PID*n* | Part IDs for the surface elements that are used to define the volume. |

## *MESH_VOLUME_ELEMENT

Purpose: Specify a set of volume elements for the fluid volume mesh in cases where the volume mesh is specified by the user and not generated automatically. The nodal point are specified in the *MESH_VOLUME_NODE keyword. Only tetrahedral elements are supported (triangles in 2D).

**Volume Element Card.** Define as many cards as necessary. The next "*" card terminates the input.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Variable | EID | PID | N1 | N2 | N3 | N4 | | | | |
| Type | I | I | I | I | I | I | | | | |
| Default | none | none | none | none | none | none | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| EID | Element ID. A unique number with respect to all *MESH_VOLUME_ELEMENTS cards. |
| PID | Part ID. A unique part identification number. |
| N1 | Nodal point 1. |
| N2 | Nodal point 2. |
| N3 | Nodal point 3. |
| N4 | Nodal point 4. |

**Remarks:**

1.  The convention is the same used by the keyword *ELEMENT_SOLID.

## \*MESH_VOLUME_NODE

Purpose: Define a node and its coordinates. This keyword is only used in cases where the fluid volume mesh is provided by the user and is not automatically generated. It serves the same purpose as the \*NODE keyword for solid mechanics. Only tetrahedral elements are supported.

\*MESH_NODE supersedes this card; so please use \*MESH_NODE instead of this card.

**Volume Node Cards.** Include as many cards in the following format as desired. This input ends at the next keyword ("\*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Variable | NID | X | | Y | | Z | | | | |
| Type | I | F | | F | | F | | | | |
| Default | none | 0 | | 0 | | 0 | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| NID | Node ID. A unique number with respect to the other volume nodes. |
| X | *x* coordinate. |
| Y | *y* coordinate. |
| Z | *z* coordinate. |

## *MESH_VOLUME_PART

Purpose: Associate a volume part number created by a *MESH_VOLUME card with the part number of a part card from a selected solver (designated by the SOLVER field).

**Mesh Volume Part Card.** Include as many cards in the following format as desired. This input ends at the next keyword ("*") card.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | VOLPRT | SOLPRT | SOLVER | | | | | |
| Type | I | I | A | | | | | |
| Default | | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| VOLPRT | Part ID of a volume part created by a *MESH_VOLUME card. |
| SOLPRT | Part ID of a part created using SOLVER's part card. |
| SOLVER | Name of a solver using a mesh created with *MESH cards. |

# *STOCHASTIC

The keyword *STOCHASTIC is used to describe the particles and numerical details for solving a set of stochastic PDEs. Currently, there are two types of stochastic PDE models in the code: a spray model and a model of embedded particles in TBX explosives. The keyword cards for using these models are:

*STOCHASTIC_SPRAY_PARTICLES

*STOCHASTIC_TBX_PARTICLES

An additional option "_TITLE" may be appended to all *STOCHASTIC keywords. If this option is used, then an 80 character string is read as a title from the first card of that keyword's input. At present, LS-DYNA does not make use of the title. Inclusion of titles gives greater clarity to input decks.

## *STOCHASTIC_SPRAY_PARTICLES

Purpose: Specify particle and other model details for spray modeling using stochastic PDEs that approximate such processes. A pair of cards is required to specify the characteristics of each nozzle (cards 3 and 4 describe the first nozzle).

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | INJDIST | IBRKUP | ICOLLDE | IEVAP | IPULSE | LIMPR | IDFUEL | |
| Type | I | I | I | I | I | I | I | |
| Default | 1 | none | none | 0 | none | none | 1 | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | RHOP | TIP | PMASS | PRTRTE | STRINJ | DURINJ | | |
| Type | F | F | F | F | F | F | | |

**Nozzle card 1:** Provide as many pairs of nozzle cards 1 and 2 as necessary. This input ends at the next keyword ("*") card (following a nozzle card 2).

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | XORIG | YORIG | ZORIG | SMR | VELINJ | DRNOZ | DTHNOZ | |
| Type | F | F | F | F | F | F | F | |

**Nozzle card 2:** Provide as many pairs of nozzle cards 1 and 2 as necessary.  This input ends at the next keyword ("*") card.

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|-----|-----|------|-------|------|------|---|---|
| Variable | TILTXY | TILTXZ | CONE | DCONE | ANOZ | AMP0 | | |
| Type | F | F | F | F | F | F | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| INJDIST | Spray particle size distribution: |

        EQ.1:      uniform

        EQ.2:      Rosin-Rammler (default)

        EQ.3:      Chi-squared degree of 2

        EQ.4:      Chi-squared degree of 6

| VARIABLE | DESCRIPTION |
|----------|-------------|
| IBRKUP | Type of particle breakup model: |

        EQ.0:      off (no breakup)

        EQ.1:      TAB

        EQ.2:      KHRT

**ICOLLDE**      Turn collision modeling on or off

**IEVAP**      Evaporation flag:

        EQ.0:      off (no evaporation)

        EQ.1:      Turn evaporation on (see Remark 1)

**IPULSE**      Type of injection:

        EQ.0:      continuous injection

        EQ.1:      sine wave

        EQ.2:      square wave

**LIMPRT**      Upper limit on the number of parent particles modeled in this spray.  This is not used with the continuous injection case (IPULSE = 0).

| VARIABLE | DESCRIPTION |
|---|---|
| IDFUEL | Selected spray liquid fuels: |

| | | |
|---|---|---|
| | EQ.1: | (Default), $H_2O$ |
| | EQ.2: | Benzene, $C_6H_6$ |
| | EQ.3: | Diesel # 2, $C_{12}H_{26}$ |
| | EQ.4: | Diesel # 2, $C_{13}H_{13}$ |
| | EQ.5: | Ethanol, $C_2H_5OH$ |
| | EQ.6: | Gasoline, $C_8H_{18}$ |
| | EQ.7: | Jet-A, $C_{12}H_{23}$ |
| | EQ.8: | Kerosene, $C_{12}H_{23}$ |
| | EQ.9: | Methanol, $CH_3OH$ |
| | EQ.10: | N-dodecane, $C_{12}H_{26}$ |

| VARIABLE | DESCRIPTION |
|---|---|
| RHOP | Particle density |
| TIP | Initial particle temperature. |
| PMASS | Total particle mass |
| PRTRTE | Number of particles injected per second for continuous injection. |
| STRINJ | Start of injection(s) |
| DURINJ | Duration of injection(s) |
| XORIG | X-coordinate of center of a nozzle's exit plane |
| YORIG | Y-coordinate of center of a nozzle's exit plane |
| ZORIG | Z-coordinate of center of a nozzle's exit plane |
| SMR | Sauter mean radius |
| VELINJ | Injection velocity |
| DRNOZ | Nozzle radius |
| DTHNOZ | Azimuthal angle (in degrees measured counterclockwise) of the injector nozzle from the j = 1 plane. |

| VARIABLE | DESCRIPTION |
|---|---|
| TILTXY | Rotation angle (in degrees) of the injector in the x-y plane, where 0.0 points towards the 3 o'clock position (j = 1 line), and the angle increases counterclockwise from there. |
| TILTXZ | Inclination angle (in degrees) of the injection in the x-z plane, where 0.0 points straight down, x > 0.0 points in the positive x direction, and x < 0.0 points in the negative x direction. |
| CONE | Spray mean cone angle (in degrees) for hollow cone spray; spray cone angle (in degrees) for solid cone spray. |
| DCONE | Injection liquid jet thickness in degrees. |
| ANOZ | Area of injector |
| AMP0 | Initial amplitude of droplet oscillation at injector |

**Remarks:**

1.   When IEVAP = 1, the keyword input file must be modified in a fashion similar to a chemistry problem.  This is illustrated in a portion of an example keyword file below.  That is, the following keywords need to be used, along with the inclusion of other chemistry-related files (i.e. evap.inp and the corresponding thermodynamics data file):

     \*CHEMISTRY_MODEL

     \*CHEMISTRY_COMPOSITION

     \*CHEMISTRY_CONTROL_FULL

     \*CESE_INITIAL_CHEMISTRY

```
$ Setup stochastic particles
$
*STOCHASTIC_SPRAY_PARTICLES
$  injdist   ibrkup  icollide     ievap    ipulse    limprt     fuelid
        3        1         0         1         0    100000          1
$    rhop       tip pmass[Kg]    prtrte   str_inj   dur_inj
   1000.0      300.      0.01      1.0e7       0.0      10.0
$  the next card is needed for fireball position and max.  particle velocity:
$    XORIG     YORIG     ZORIG       SMR   Velinj      Drnoz    Dthnoz
    0.005     0.005     1.0e-5    5.0e-6    200.0     9.0e-5
$   TILTXY    TILTXZ      CONE     DCONE      ANOZ       AMP0
      0.0       0.0      15.0      15.0    2.5e-8        0.0
$
*CHEMISTRY_MODEL
$ model_id    jacsel     errlim
```

```
      10          1         0.0
   evap.inp
  therm.dat
   tran.dat
$
*CHEMISTRY_COMPOSITION
$  comp_id  model_id
        11        10
$  molefra   Species
      1.0        O2
      3.76       N2
$
*CHEMISTRY_CONTROL_FULL
$   sol_id   errlim
        5
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ Set global initial conditions for fluid
$
*CESE_INITIAL_CHEMISTRY
$   sol_id   comp_id
        5        11
$INITIAL CONDITIONS
$     uic       vic       wic       ric       pic       tic       hic
      0.0       0.0       0.0       1.2   101325.    300.0       0.0
```

**\*STOCHASTIC_TBX_PARTICLES**

Purpose: Specify particle and other model details for stochastic PDEs that model embedded particles in TBX explosives. Note that the components listed on the corresponding *CHEMISTRY_COMPOSITION card are in terms of molar concentrations of the species (in units of moles/[length]$^3$, where [length] is the user's length unit).

For further information on the theory of the TBX model that has been implemented, a document on this topic can be found at this URL:

https://lsdyna.ansys.com/cese-cfd-documentation/

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PCOMB | NPRTCL | MXCNT | PMASS | SMR | RHOP | TICP | T_IGNIT |
| Type | I | I | I | F | F | F | F | F |
| Default | 0 | none | none | none | none | none | none | none |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | INITDST | AZIMTH | ALTITD | CPS/CVS | HVAP | EMISS | BOLTZ | |
| Type | I | F | F | F | F | F | F | |
| Default | 1 | none | none | none | none | optional | optional | |
| Remarks | | | | | | 1 | 1 | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | XORIG | YORIG | ZORIG | XVEL | YVEL | ZVEL | FRADIUS | |
| Type | F | F | F | F | F | F | F | |
| Default | none | none | none | 0.0 | 0.0 | 0.0 | none | |

| VARIABLE | DESCRIPTION |
|---|---|
| PCOMB | Particle combustion model:<br><br>    EQ.0: No burning<br><br>    EQ.1: K-model |
| NPRTCL | Initial total number of parent particles (discrete particles for calculation) |
| MXCNT | Maximum allowed number of parent particles (during the simulation) |
| PMASS | Total particle mass |
| SMR | Sort mean particle radius |
| RHOP | Particle density |
| TICP | Initial particle temperature |
| T_IGNIT | Particle ignition temperature |
| INITDST | Initial particle distribution:<br><br>    EQ.1: Spatially uniform<br><br>    EQ.2: Rosin-Rammler<br><br>    EQ.3: Chi-squared |
| AZIMTH | Angle in degrees from the $x$-axis in the $xy$-plane of the reference frame of the TBX explosive (0 < AZMITH < 360) |
| ALTITD | Angle in degrees from the $z$-axis of the reference frame of the TBX explosive (0 < ALTITD < 180) |
| CPS/CVS | Heat coefficient |
| HVAP | Latent heat of vaporization |
| EMISS | Particle emissivity |
| BOLTZ | Boltzmann coefficient |
| XORIG | $x$-coordinate of the origin of the initial reference frame of the TBX explosive |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| YORIG | $y$-coordinate of the origin of the initial reference frame of the TBX explosive |
| ZORIG | $z$-coordinate of the origin of the initial reference frame of the TBX explosive |
| XVEL | $x$-component of the initial particle velocity of the TBX explosive |
| YVEL | $y$-component of the initial particle velocity of the TBX explosive |
| ZVEL | $z$-component of the initial particle velocity of the TBX explosive |
| FRADIUS | Radius of the explosive area |

**Remarks:**

1. **Radiation heat transfer.** If radiation heat transfer is being modeled, then EMISS and BOLTZ are required.

# \*LSO

These cards provide a general data output mechanism, causing the creation of a sequence of LSDA files.  This facility is intended to allow several different time sequences of data to be output in the same simulation.  In addition, any number of domains (and any number of variables on those domains) may be specified within each time sequence.  The keyword cards in this section are defined in alphabetical order:

    \*LSO_DOMAIN

    \*LSO_ID_SET (*not available in the single-precision version of LS-DYNA*)

    \*LSO_POINT_SET

    \*LSO_TIME_SEQUENCE

    \*LSO_VARIABLE_GROUP

Note that only the mechanics solver is available in the single-precision version of LS-DYNA, and therefore, only LSO mechanics variables are available for output from single precision LS-DYNA.   These mechanics variables are listed by domain type in a separate document.  This document (LSO_VARIABLES.TXT) is created by running the command: LS-DYNA print_lso_doc.  Contrary to LSO_VARIABLES.TXT,   element quantities such as stress are not available for output from the mechanics solver to the "lso" database.

An additional option "_TITLE**"** may be appended to all \*LSO keywords.  If this option is used, then an 80 character string is read as a title from the first card of that keyword's input.  At present, LS-DYNA does not make use of the title.  Inclusion of titles gives greater clarity to input decks.

## \*LSO_DOMAIN

Purpose: This command provides a way to specify variables on a subset of the domain for a given solver.  This domain can be a subset of the mesh used by that solver, a set of output points created with \*LSO_POINT_SET, or a set of objects created with \*LSO_ID_-SET. The frequency and duration of the output for any given domain is determined by each \*LSO_TIME_SEQUENCE card that references this \*LSO_DOMAIN card. Note that for the single-precision version of LS-DYNA, the only allowed value of SOLVER_-NAME = MECH.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | DOMAIN_TYPE | | | | | | | |
| Type | A | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SOLVER_NAME | | | | | | | |
| Type | A | | | | | | | |

**Special Domains Card.** Card 3 when DOMAIN_TYPE is one of ROGO, CIRCUIT, THIST_POINT or TRACER_POINT.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | OUTID | REFID | | REDUCT | | | | |
| Type | I | I | | I | | | | |
| Default | none | none | | none | | | | |

**Miscellaneous Domain Card.** Card 3 when DOMAIN_TYPE is one of NODE, PART, SEGMENT, SURFACE_NODE, SURFACE_ELEMENT, VOLUME_ELEMENT, SUR-FACE_PART, VOLUME_PART.

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | OUTID | REFID | OVERRIDE | REDUCT | | | | |
| Type | I | I | I | I | | | | |
| Default | none | 0 | 0 | none | | | | |

**Variable Name Card.** Provide as many cards as necessary. This input ends at the next keyword ("*") card

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | VARIABLE_NAME | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| DOMAIN_TYPE | The type of domain for which LSO output may be generated. |
| SOLVER_NAME | Selects the solver from which data is output on this domain. Accepted entries so far are "MECH", "EM", "CESE", and "ICFD". |
| OUTID | LSO domain ID associated with this domain, and used by *LSO_TIME_SEQUENCE cards. |
| REFID | Support set ID. This can be a set defined by a *SET card, a *LSO_ID_SET, card, or a *LSO_POINT_SET card. Unless OVERRIDE is specified, this set must be of the same type as DOMAIN_TYPE. |
| OVERRIDE | If non-zero, then REFID is interpreted as: |

       EQ.1: a PART set for SOLVER_NAME

       EQ.2: a PART set of volume parts created with a *LSO_ID_-SET card (volume parts are defined with *MESH_-VOLUME cards).

| VARIABLE | DESCRIPTION |
|---|---|

EQ.3: a PART set of surface parts created with a \*LSO_ID_-SET card (surface parts are defined with \*MESH_SUR-FACE_ELEMENT cards).

EQ.4: a set of segment sets created with a \*LSO_ID_SET card.

| | | |
|---|---|---|
| **VECTORS** | **EN** magneticF electricFie vecpotFie currentDen | A function that operates on the entire domain and returns a single value for scalar variables, three values for vector variables, or 6 values for symmetric tensor variables. For RE-DUCT="range", the number of returned values doubles. The following are the supported functions: |
| **SCALARS** | ScalarPote | |

EQ.BLANK:    no reduction (default)

EQ."none":    Same as above

EQ."avg":    the average by component

EQ."average":    Same as above

EQ."min":    the minimum by component

EQ."minimum":    Same as above

EQ."max":    the maximum by component

EQ."maximum":    Same as above

REDUCT

EQ."sum":    the sum by component

EQ."range":    the minimum by component followed by the maximum by component

VARIA-BLE_NAME      Either the name of a single output variable or a variable group. See remarks.

**Remarks:**

1.  Supported choices for VARIABLE_NAME are listed by DOMAIN_TYPE for each SOLVER_NAME in a separate document. This document (LSO_VARIA-BLES.TXT) is created by running the command: LS-DYNA print_lso_doc. The following table shows a sample of the point output variables available when DOMAIN_TYPE = THIST_POINT:

**\*LSO_ID_SET**

Purpose:  Provides a way to create a set of existing sets (segment sets), or to define a set that is not available with other set-related keyword cards.  These are then used in other \*LSO cards to specify LSO output.  This card is not available in the single precision version of LS-DYNA.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SETID | TYPE | SOLVER | | | | | |
| Type | I | A | A | | | | | |
| Default | none | none | MECH | | | | | |

**Referenced IDs.**  Provide as many cards as necessary.  This input ends at the next keyword ("*") card

| Card | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | ID1 | ID2 | ID3 | ID4 | ID5 | ID6 | ID7 | ID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| SETID | Identifier for this ID set. |

| VARIABLE | DESCRIPTION |
|---|---|
| TYPE | The kind of IDs in this set: |

<div>

TYPE      The kind of IDs in this set:

       EQ.'SEG_SETS':     Each ID is a segment set connected with SOLVER.

       EQ.'CIRCUIT':     Each ID is a circuit ID (from \*EM cards)

       EQ.'SURF_PARTS':     Each ID is a surface part number (See \*MESH_SURFACE_ELEMENT)

       EQ.'VOL_PARTS':     Each ID is a volume part number (See \*MESH_VOLUME)

       EQ.'SURF_ELES':     Each ID is a surface element number (See \*MESH_SURFACE_ELEMENT)

SOLVER      Name of the solver (MECH, ICFD, CESE, EM, …)

ID1, …      IDs of the TYPE kind.

</div>

**\*LSO_POINT_SET**

Purpose: Define a list of points used to sample variables in time. Of the different sampling methods, the most common one is to specify points for time history output.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | SETID | USE | | | | | | |
| Type | I | I | | | | | | |
| Default | none | 1 | | | | | | |
| Remarks | | 1 | | | | | | |

**Point Cards.** Provide as many cards as necessary. This input ends at the next keyword ("*") card

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | X | Y | Z | | | | | |
| Type | F | F | F | | | | | |
| Default | none | none | none | | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| SETID | Identifier for this point set which is used by \*LSO_DOMAIN |
| USE | Points in this set are used as:<br><br>EQ.1: fixed time history points (default)<br><br>EQ.2: positions of tracer particles |
| X, Y, Z | Coordinates of a point. As many points as desired can be specified. |

**Remarks:**

1. **USE.** For USE = 1, with the ICFD and CESE solvers, the fixed points must remain inside the fluid mesh or a zero result is returned, while for the EM solver, the points can be defined inside the conductors or in the air. In the latter case, the fields will be computed using a Biot-Savart type integration. For USE = 2, a massless tracer particle is tracked for the ICFD and CESE solvers using their local velocity field to integrate the position of each particle in time.

**\*LSO_TIME_SEQUENCE**

Purpose: This command provides users with maximum flexibility in specifying exactly what they want to have appear in the output LSO binary database. Each instance of the \*LSO_TIME_SEQUENCE command creates a new time sequence with an independent output frequency and duration. Furthermore, while the default domain for each output variable will be the entire mesh on which that variable is defined, at all selected snapshot times, the \*LSO_DOMAIN keyword commands can be used to specify that output will only occur on a portion of SOLVER_NAME's mesh, and for a limited time interval, or that it will occur at a set of points (see \*LSO_POINT_SET), or over a set of object IDs (see \*LSO_ID_SET). Note that for the single-precision version of LS-DYNA, the only allowed value of SOLVER_NAME = MECH.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | SOLVER_NAME | | | | | | | |
| Type | A | | | | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | DT | LCDT | LCOPT | NPLTC | TBEG | TEND | | |
| Type | F | I | I | I | F | F | | |
| Default | 0.0 | 0 | 1 | 0 | 0.0 | 0.0 | | |
| Remarks | 1 | 1 | 1 | 1 | | | | |

**Domain IDs.** Provide as many cards as necessary. This input ends at the next keyword ("*") card, or when a global variable name card appears

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | DOMID1 | DOMID2 | DOMID3 | DOMID4 | DOMID5 | DOMID6 | DOMID7 | DOMID8 |
| Type | I | I | I | I | I | I | I | I |
| Default | none | none | none | none | none | none | none | none |

**Global variable names.** Provide as many cards as necessary. This input ends at the next keyword ("*") card

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | GLOBAL_VAR | | | | | | | |
| Type | A | | | | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SOLVER_NAME | Selects the solver from which data is output in this time sequence. Accepted entries so far are 'MECH', 'EM', 'CESE' and 'ICFD' |
| DT | Time interval between outputs. |
| LCDT | Optional load curve ID specifying the time interval between dumps. |
| LCOPT | Flag to govern behavior of plot frequency load curve: |

      **EQ.1:** At the time each plot is generated, the load curve value is added to the current time to determine the next plot time (this is the default behavior).

      **EQ.2:** At the time each plot is generated, the next plot time T is computed so that T = the current time plus the load curve value at the time T.

      **EQ.3:** A plot is generated for each ordinate point in the load curve definition. The actual value of the load curve is ignored.

| VARIABLE | DESCRIPTION |
|---|---|
| NPLTC | DT = ENDTIM/NPLTC overrides DT specified in the first field. |
| TBEG | The problem time at which to begin writing output to this time sequence |
| TEND | The problem time at which to terminate writing output to this time sequence |
| DOMID1, … | Output set ID defining the domain over which variable output is to be performed in this time sequence. Each DOMID refers to the domain identifier in an \*LSO_DOMAIN keyword card. |
| GLOBAL_VAR | The name of a global output variable computed by SOLVER_-NAME. This variable must have a single value (scalar, vector, or tensor), and therefore does not depend upon any DOMID. Any number of such variables may be specified with a given time sequence. These variables are listed as having "global" domain for SOLVER_NAME in a separate document. This document (LSO_VARIABLES.TXT) is created by running the command: LS-DYNA print_lso_doc. |

**Remarks:**

1.  If LCDT is nonzero, then it is used and DT and NPLTC are ignored. If LCDT is zero and NPLTC is non-zero, then NPLTC determines the snapshot time increment. If LCDT and NPLTC are both zero, then the minimum non-zero time increment specified by DT is used to determine the snapshot times.

## \*LSO_VARIABLE_GROUP

Purpose: To provide a means of defining a shorthand name for a group of variables. That is, wherever the given group name is used, it is replaced by the list of variables given in this command. Note that for the single-precision version of LS-DYNA, the only allowed value of SOLVER_NAME = MECH.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | SOLVER_NAME | | | | |
| Type | | | | A | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | DOMAIN_TYPE | | | | |
| Type | | | | A | | | | |

| Card 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | GROUP_NAME | | | | |
| Type | | | | A | | | | |

**List Of Variables In Group**. Provide as many cards as necessary. This input ends at the next keyword ("\*") card

| Card 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Variable | | | | VAR_NAME | | | | |
| Type | | | | A | | | | |

| VARIABLE | DESCRIPTION |
|----------|-------------|
| SOLVER_NAME | Selects the solver for which data is output in a time sequence. |

| VARIABLE | DESCRIPTION |
| --- | --- |
| DOMAIN_TYPE | Name of the type of domain on which each VAR_NAME is defined. |
| GROUP_NAME | Name of (or alias for) the group of names given by the listed VAR_NAMEs |
| VAR_NAME | The name of an output variable computed by SOLVER_NAME |

**Remarks:**

1.  Valid VAR_NAMEs depend both upon the SOLVER_NAME and the DOMAIN_TYPE. These variables are listed by DOMAIN_TYPE for each SOLVER_NAME in a separate document. This document (LSO_VARIABLES.TXT) is created by running the command: LS-DYNA print_lso_doc.