OVERVIEW OF ALE METHOD IN LS-DYNA

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ELEMENT FORMULATIONS REVIEW

A physical process involving fluids or fluid-like behavior may often be modeled in more than one way, using more than one solid element formulation. In LS-DYNA, the *SECTION_SOLID command is used to specify the element formulation ELFORM:

ELFORM:

1 = Constant stress solid (pure Lagrangian formulation).

5 = 1-point ALE element (single material domain).

6 = 1-point Eulerian element (single material domain).

7 = 1-point Eulerian Ambient element (single material domain).

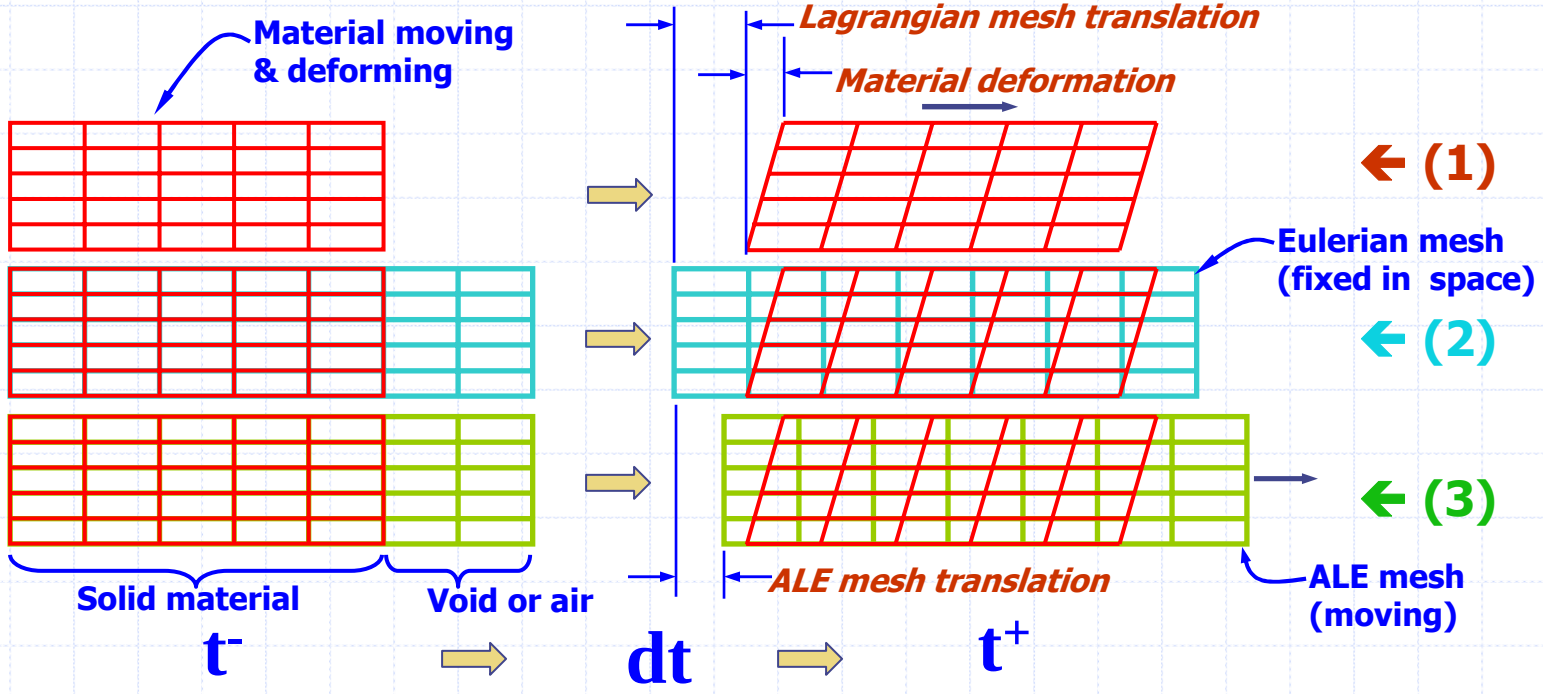
12 = 1-point ALE single-material-and-void (two-material domain).

11 = 1-point ALE multi-material element ← *most versatile and widely used ALE formulation*

ELEMENT FORMULATIONS REVIEW

Element Formulations and Applications:

Let us consider a 2D example, a solid material is moved and then deformed as shown below. Three formulations may be used: (1) Lagrangian, (2) Eulerian, (3) ALE (Arbitrary-Lagrangian-Eulerian).

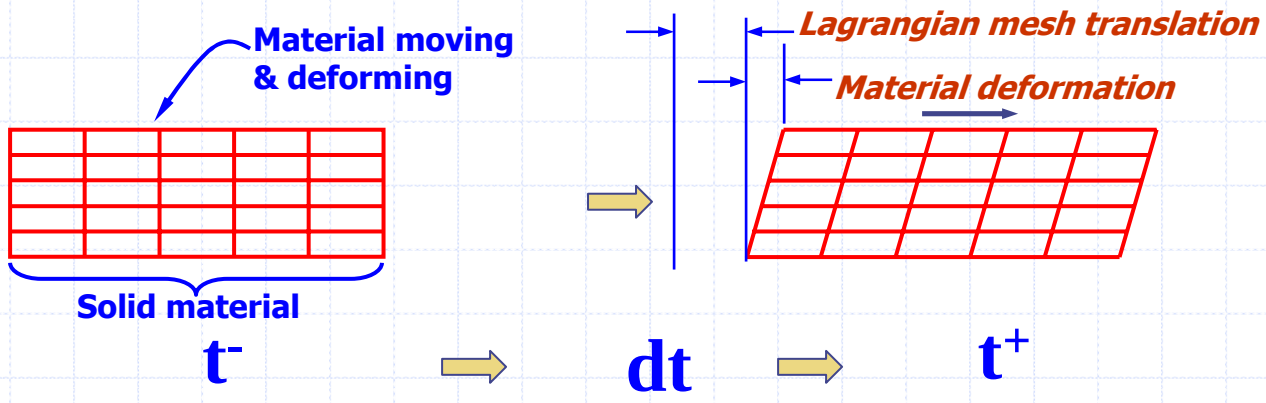


LAGRANGIAN

(1) Lagrangian:

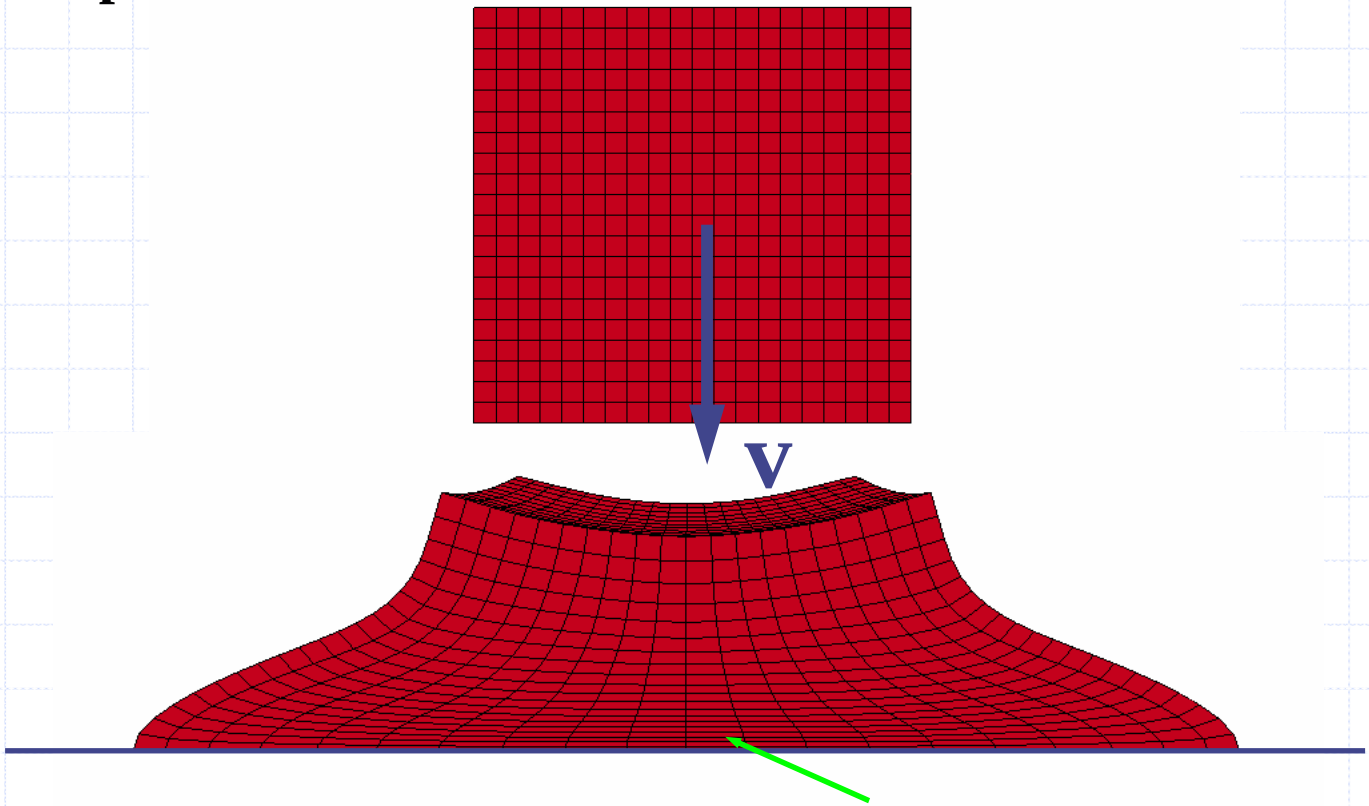
The nodes of the mesh are attached to the imaginary material "points". These nodes move and deform with the material. This is shown in (1) above.

The Lagrangian elements contains the same material throughout the calculation.



PURE LAGRANGIAN (ELFORM=1)

- **Mesh deforms with the material.**
- **PROBLEM:**
  - **Lagrangian formulation can lose accuracy at very large distortion of the elements.**
  - **Time step can approach zero.**



Pure Lagrangian Taylor Bar Impact

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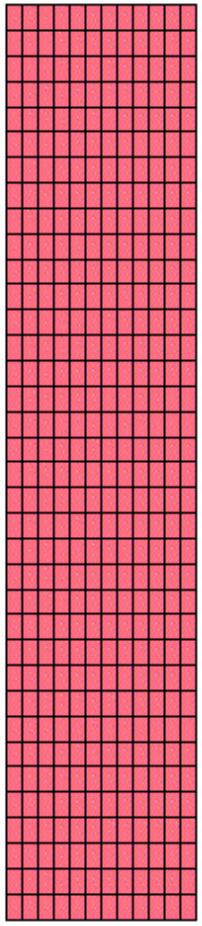


Severely distorted elements near impact surface.

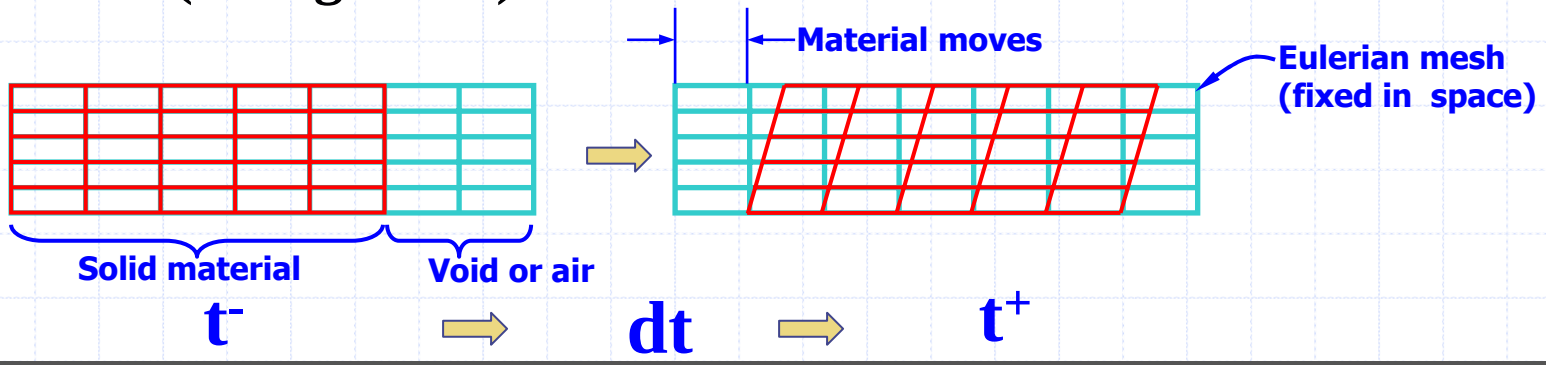
EULERIAN

(2) Eulerian:

Hypothetically consider 2 overlapping meshes, one is a background reference mesh which is fixed in space, and the other is a virtual mesh attached to the material which "flows" through the reference mesh. This may be visualized in 2 steps:

First, the material is deformed in a Lagrangian step just like the Lagrangian formulation.

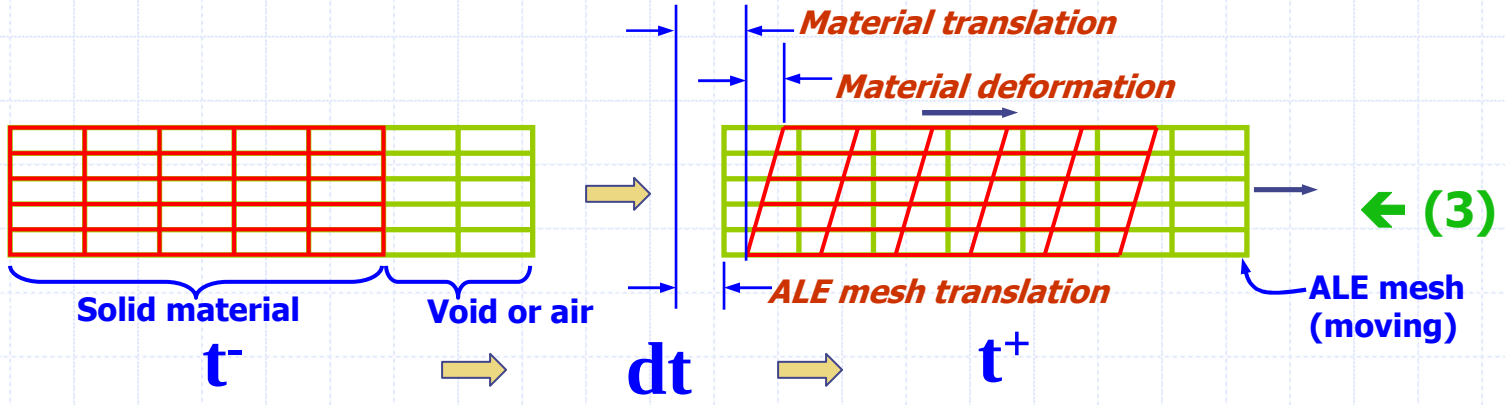
Then, the element state variables in the virtual "Lagrangian elements" (red) are *remapped* or *advected* or *transported* back onto the fixed (background) reference Eulerian mesh.



ALE

(3) ALE:

Consider 2 overlapping meshes, one is a background mesh which can move arbitrarily in space, and the other is a virtual mesh attached to the material which "flows" through the former moving mesh. This may be visualized in 2 steps. First, the material is deformed in a Lagrangian step just like the Lagrangian formulation. Then, the element state variables in the virtual "Lagrangian elements" (red) are *remapped* or *advected* or *transported* back onto the moving (background) reference ALE mesh (green).



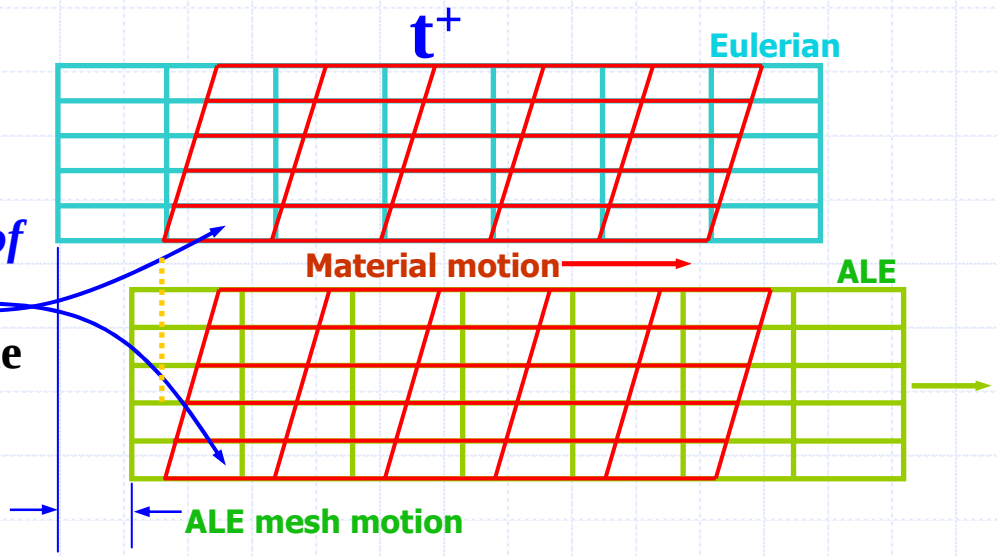
ALE

(3) ALE:

Hence Eulerian method is a subset of the ALE method where the reference mesh stays fixed in space.

Subsequently we will refer only to the ALE method for generality.

The main difference between pure Eulerian vs. ALE method is *different amounts of material being advected* through the meshes due to the reference mesh positions.

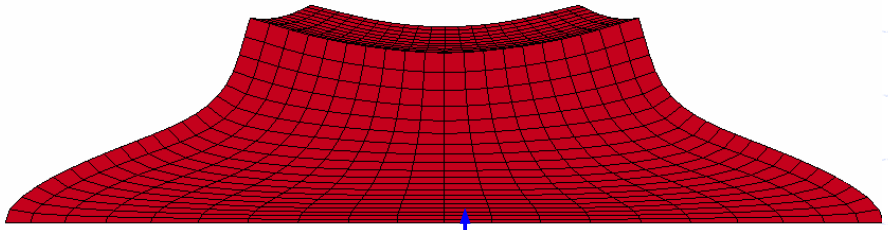


ALE SINGLE MATERIAL (ELFORM=5)

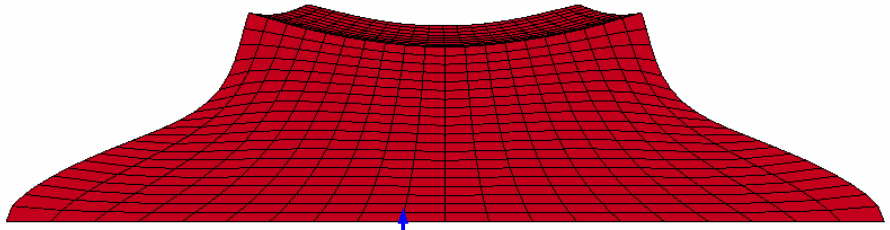
- One material – one mesh. Lagrangian-like! The overall mesh follows the overall material domain.
- Nodes within the mesh may be rearranged, i.e., smoothed, to avoid badly distorted elements.
- ALE = motion allowed for the overall mesh and the nodes within.

(ALE :=Material(s) can *flow* through a mesh which itself can *move*)

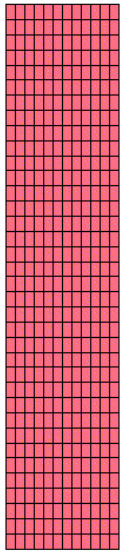
PURE Lagrangian



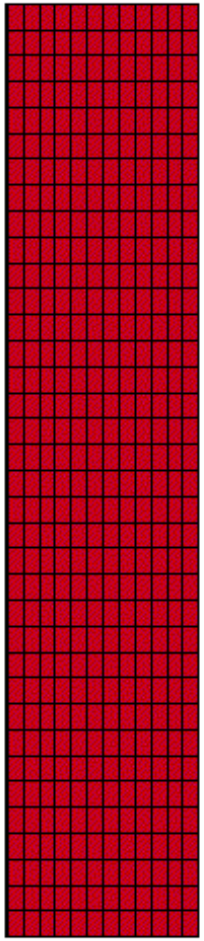
ALE Single Material



Single Material ALE Formulation with Smoothing



ELFORM 1 (Lagrangian)



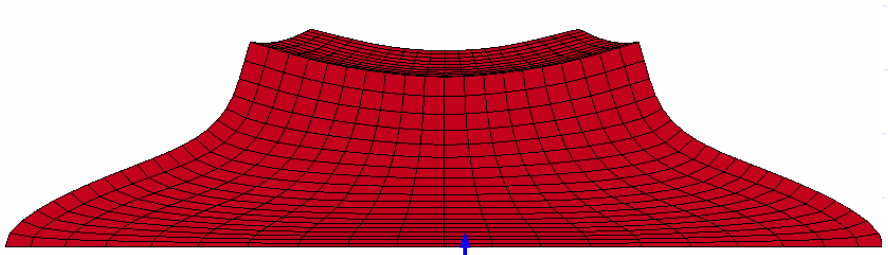
ELFORM 5 (Single material ALE)

ALE SINGLE MATERIAL (ELFORM=5)

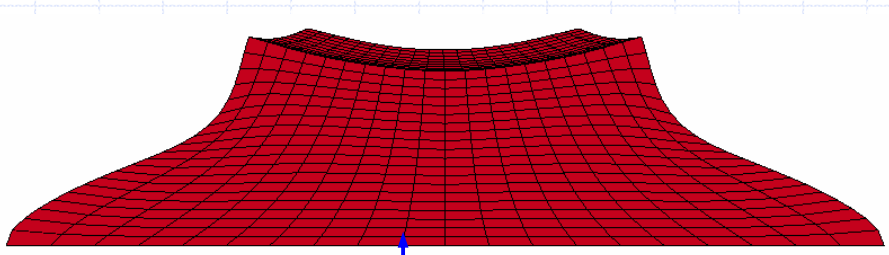
- **Relative motion between material and internal, smoothed mesh results in relative flow of material between element boundaries ➔ requires extra terms in the conservation equations. These are the ADVECTION (or flow) terms.**

- **Only one material is allowed in this formulation and mesh smoothing is effective for only moderate deformation. Thus application of this formulation is limited to mostly academic problems.**

PURE Lagrangian

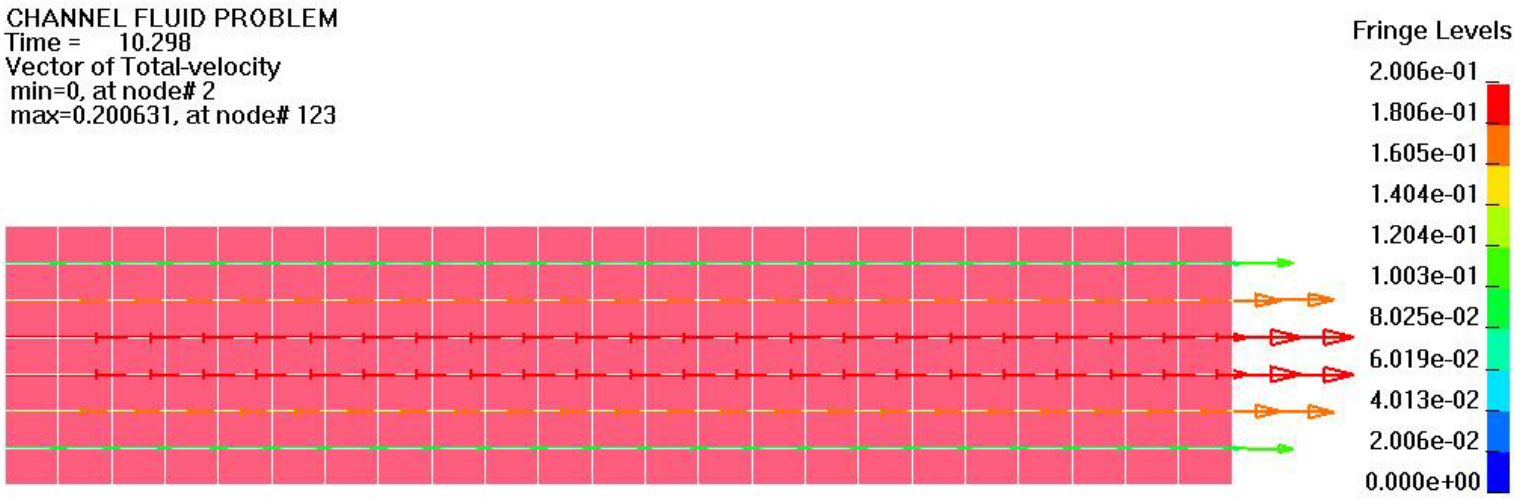


ALE Single Material



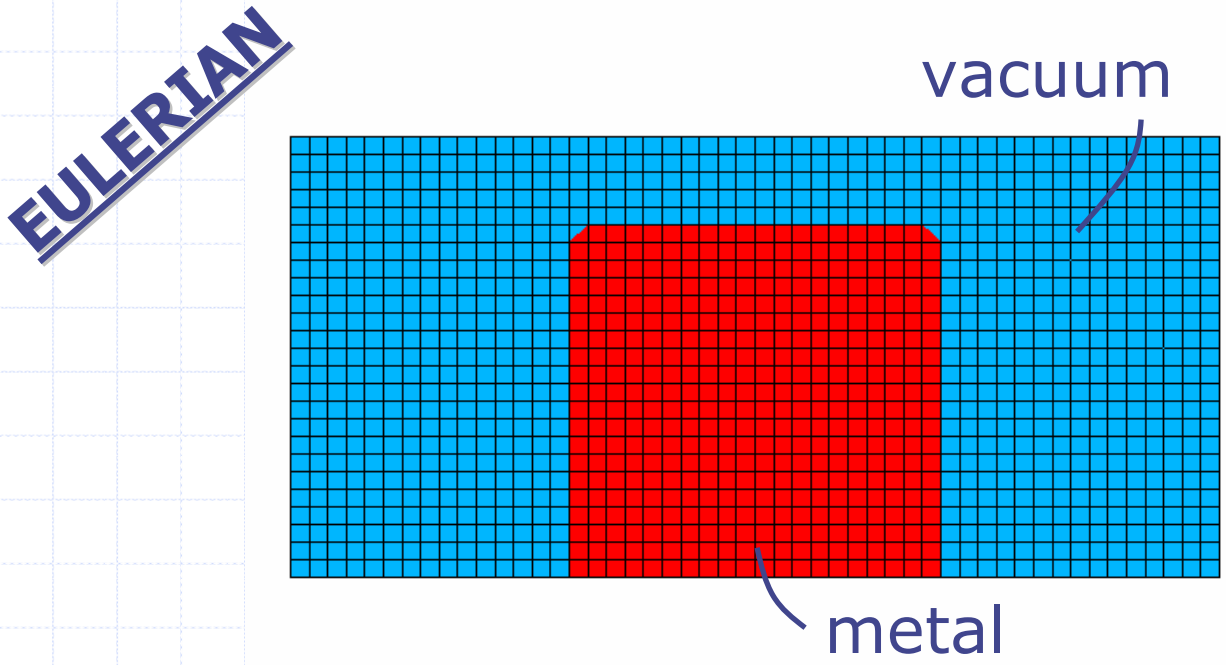
SINGLE MATERIAL EULERIAN (ELFORM=6&7)

- **Eulerian = Eulerian mesh is fixed in space.**
- **ONE material flows through this fixed mesh. There is no mixing of materials.**
- **PROBLEM: Only a single material is modeled. There is no fluid interface for fluid/structure penalty coupling (cannot visualize leakage). Thus this formulation is, again, limited to mostly academic problems.**



MULTI-MATERIAL EULERIAN or ALE (ELFORM=11&12)

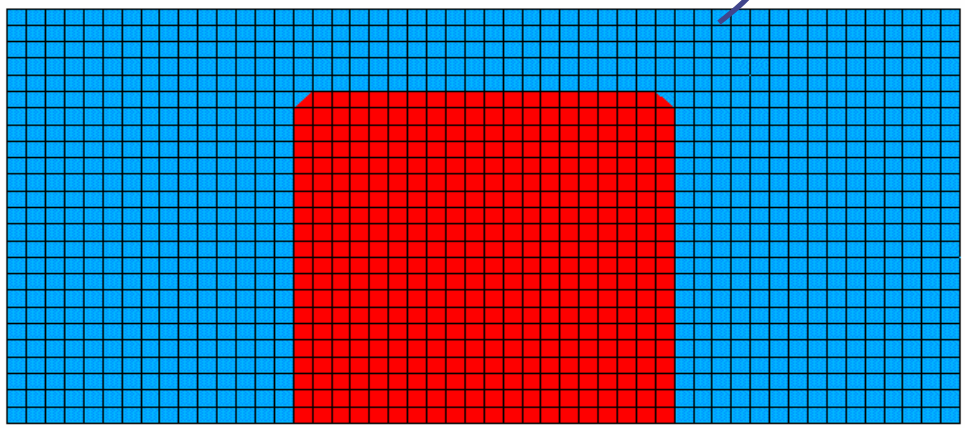
The only difference between Multi-Material Eulerian and Multi-Material ALE methods is that the Eulerian mesh is fixed in space while ALE is allowed to move.



MULTI-MATERIAL EULERIAN or ALE (ELFORM=11&12)

By introducing ALE in the multi-material formulation, the model can be made smaller and the numerical errors can be kept on a lower level (less material is advected).

ALE mesh is allowed to translate, rotate, expand, or contract (see *ale_reference_system)



ALE

(ALE :=Material(s) can *flow* through the mesh which itself can *move*)

VERY BRIEF SUMMARY OF ALE COMPUTATION

Computational cycle:

ALE method uses the Operator Split technique to perform a 2-step computational cycle:

1. **First a Lagrangian step is taken**
2. **Second, the state variables of the deformed material configuration are mapped back onto the reference mesh – this is called an advection step.**

Conservation Laws:

Conservations of mass, momentum and energy together with material constitutive equations are used to solve for the state variables.

FLUID-STRUCTURE INTERACTION - FSI (ALE/Lagrangian Coupling)

MATERIAL INTERACTIONS - FSI

Lagrangian material hits Lagrangian material ➔ *CONTACT

ALE material hits ALE material ➔ Merged Nodes (Advection)

Lagrangian material hits ALE material ➔ *CONSTRAINED_LAGRANGE_IN_SOLID

Material Interactions via *CONSTRAINED_LAGRANGE_IN_SOLID

Fluid-Structure Interactions (FSI) Between ALE ("Fluid") and Lagrangian ("Structure") Materials, each modeled with separate meshes:

LS-DYNA searches for the *INTERSECTIONS* between the Lagrangian parts & ALE parts.

If a coupled Lagrangian surface is detected inside an ALE element, LS-DYNA marks the Lagrangian-Eulerian coupling points (NQUAD) at t^-.

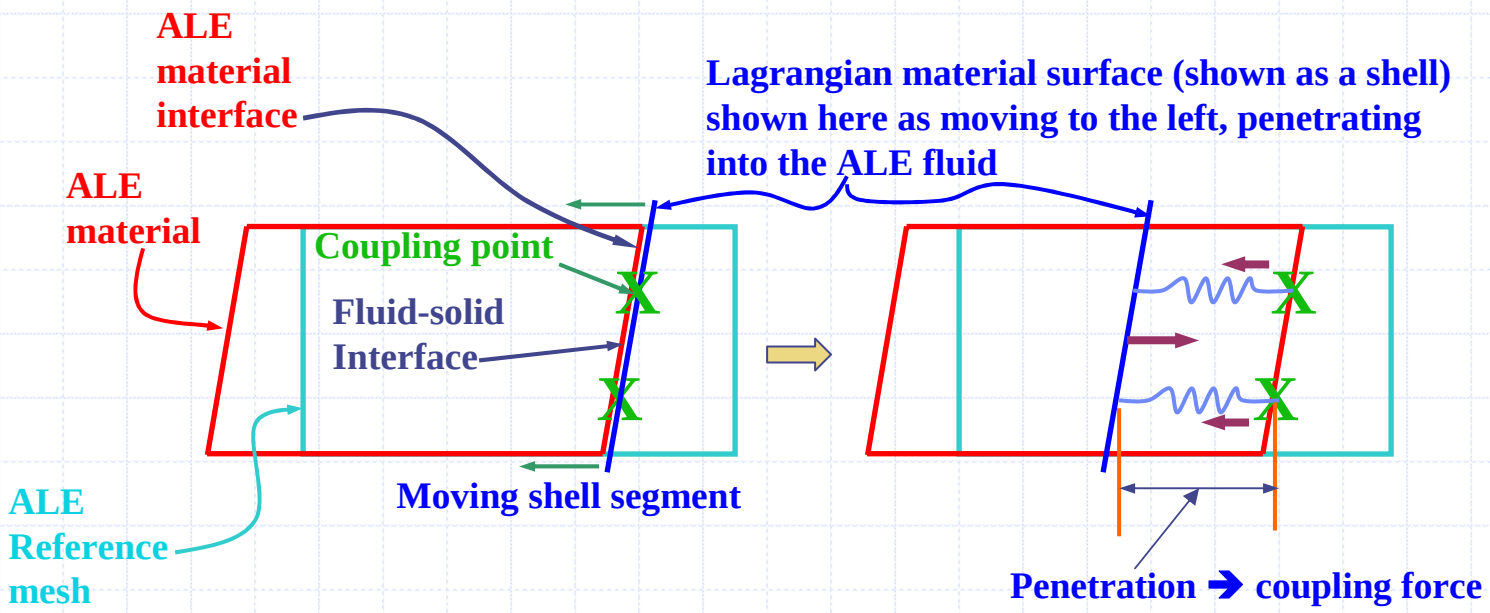
It then tracks the independent motion of the 2 materials over dt (ALE material interface is tracked based on its volume fraction in the element).

Then it computes the penetration distance of the ALE material across the Lagrangian surface.

Coupling forces are calculated based on this penetration and re-distributed back onto both materials.

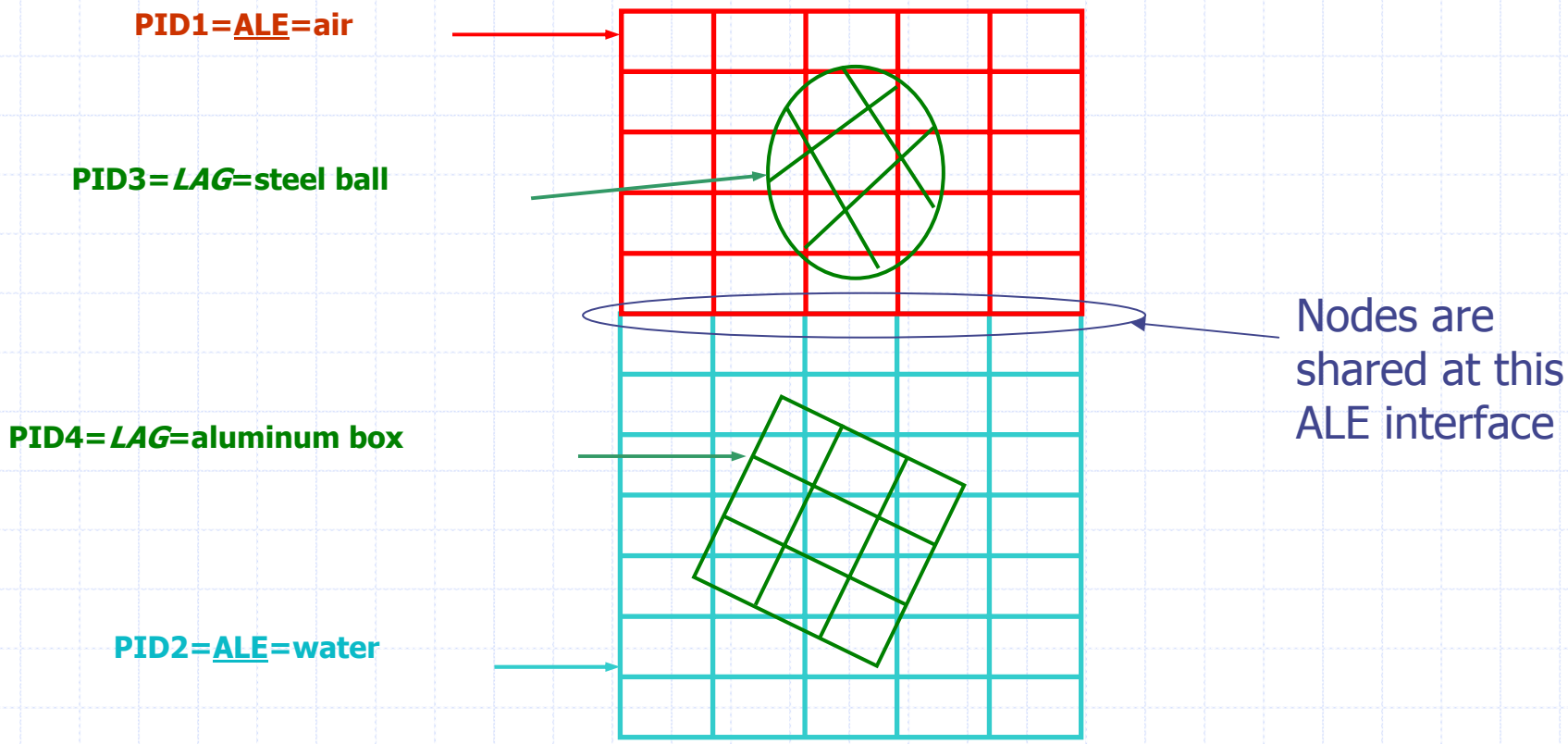
Material Interactions via *CONSTRAINED_LAGRANGE_IN_SOLID

The coupling forces are usually computed based on a Penalty Method (similar to that used for standard Lagrangian contact).

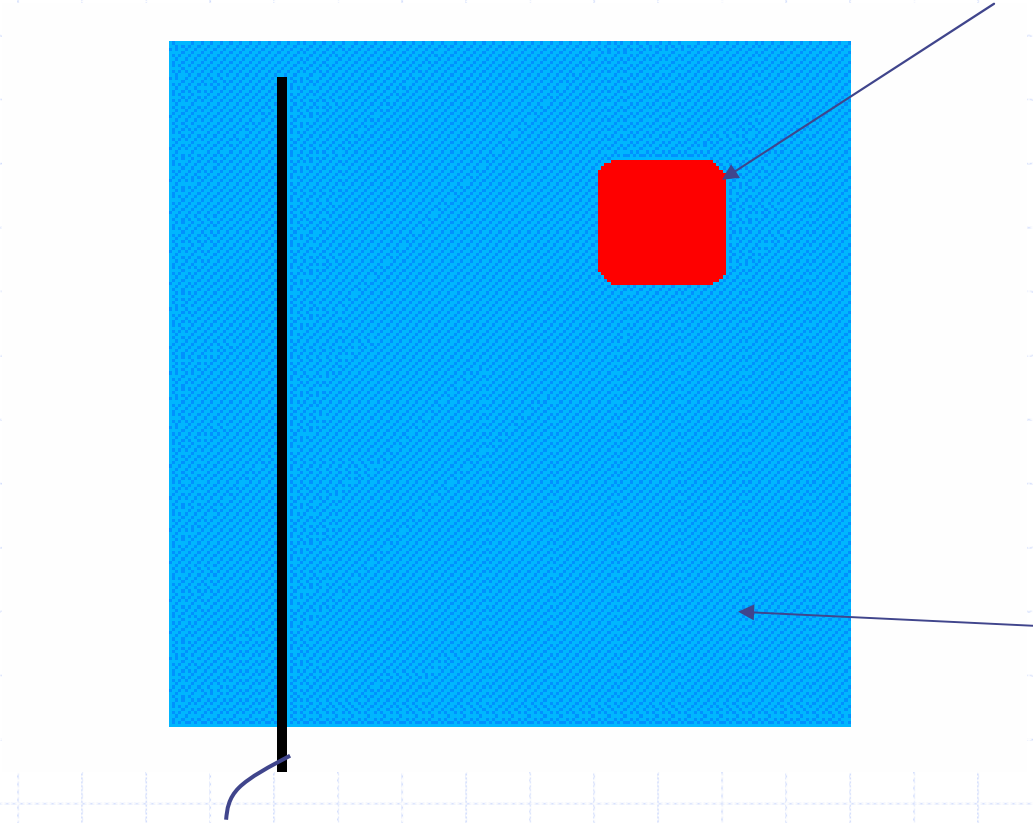


Meshing for ALE/Lagrange Coupling

Lagrangian mesh intersects ALE mesh but nodes are not shared between ALE and Lagrangian parts.

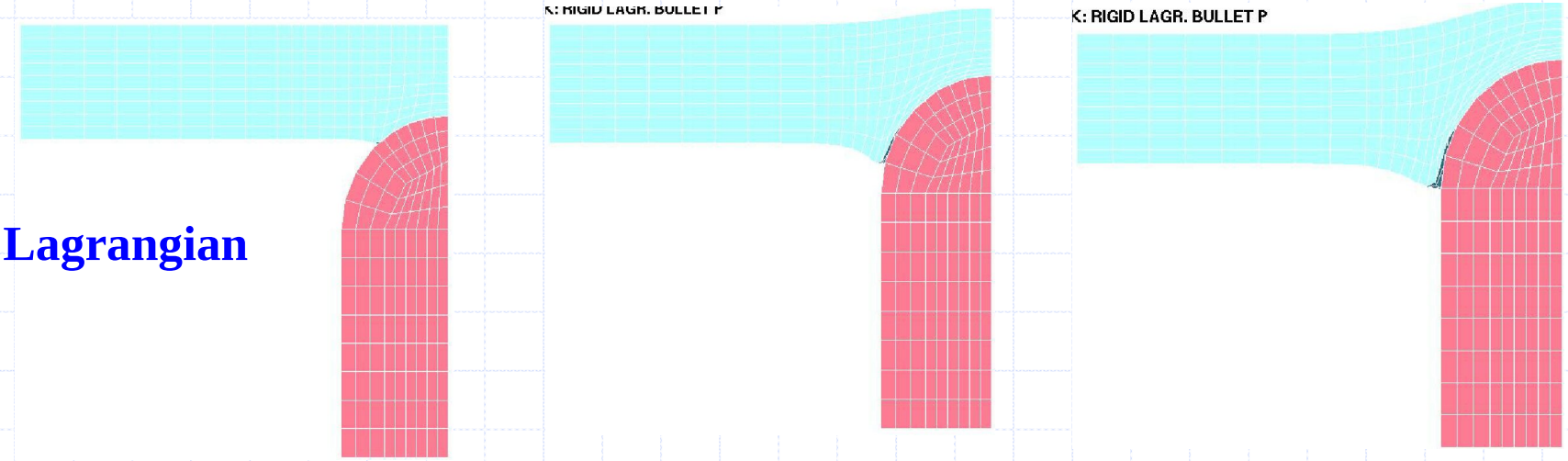


Simple Example of Euler/Lagrange Coupling:



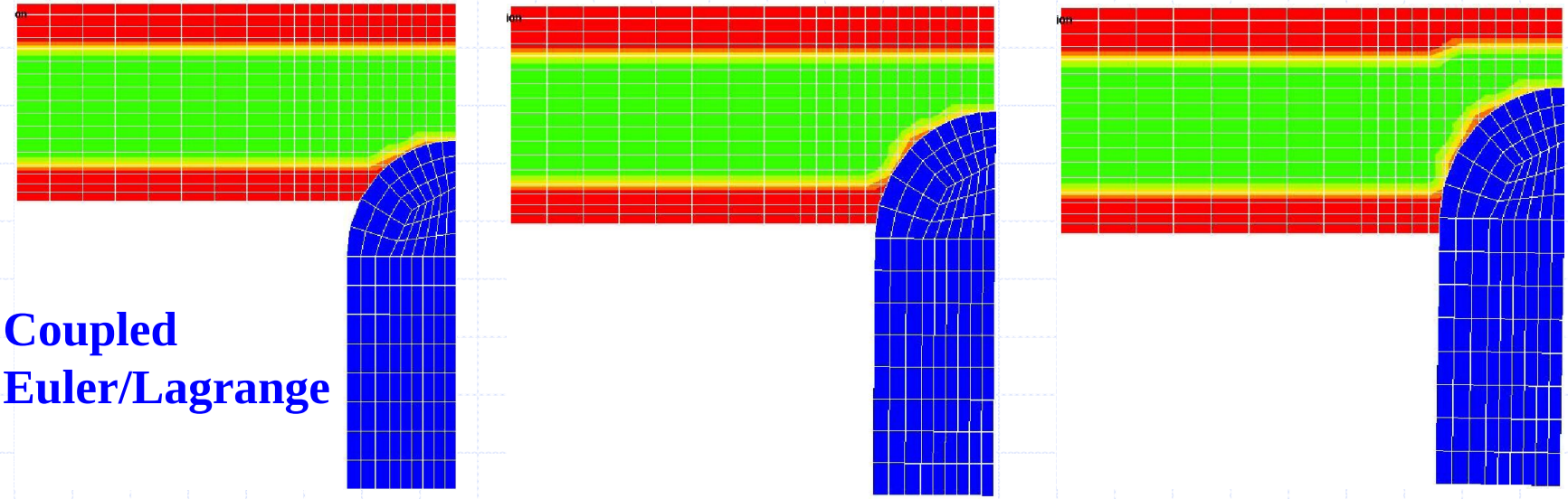
Penetration Simulation (2 approaches)

Lagrangian

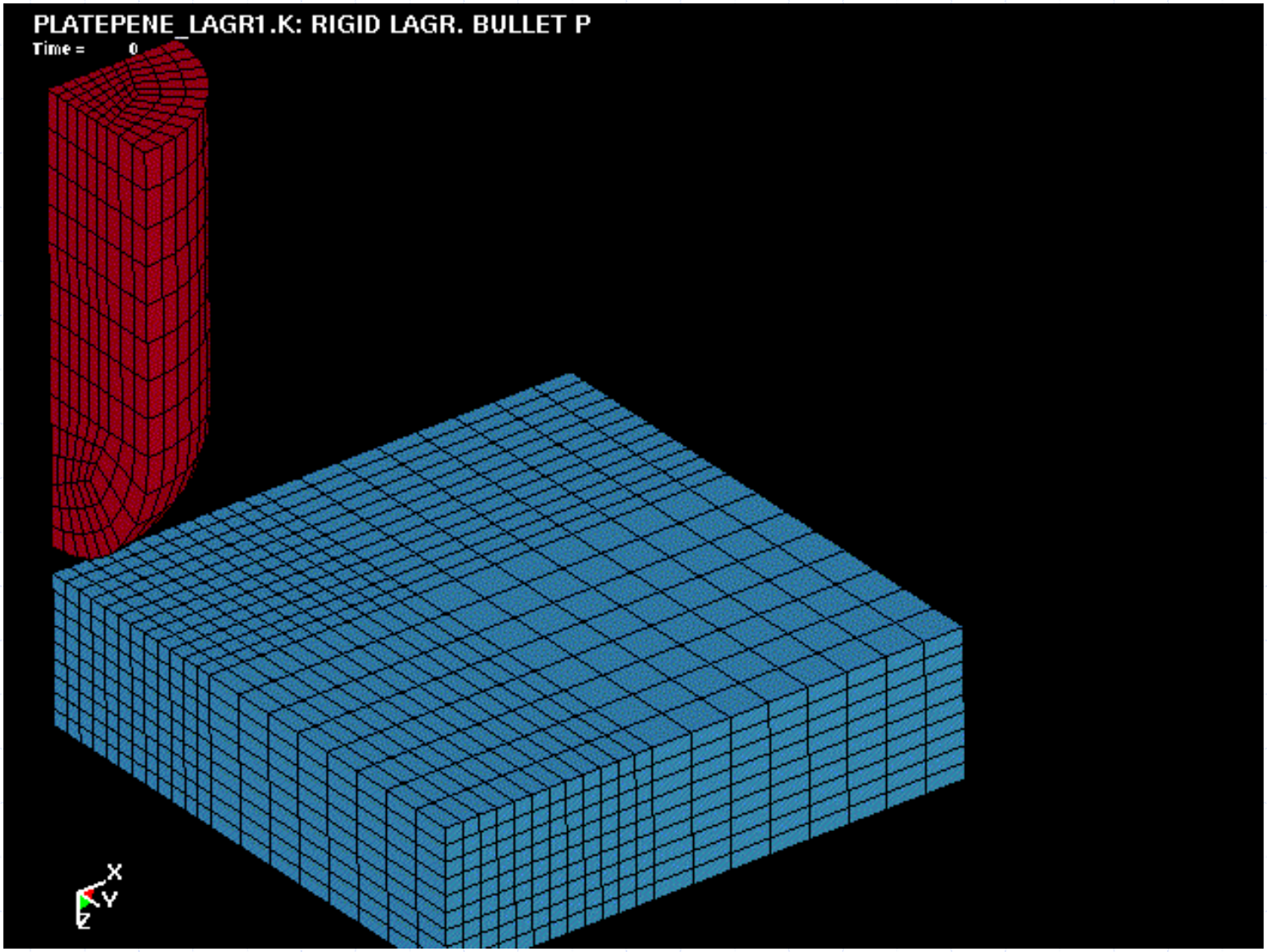


Note below the extra air or void domain for target material to flow into

Coupled Euler/Lagrange

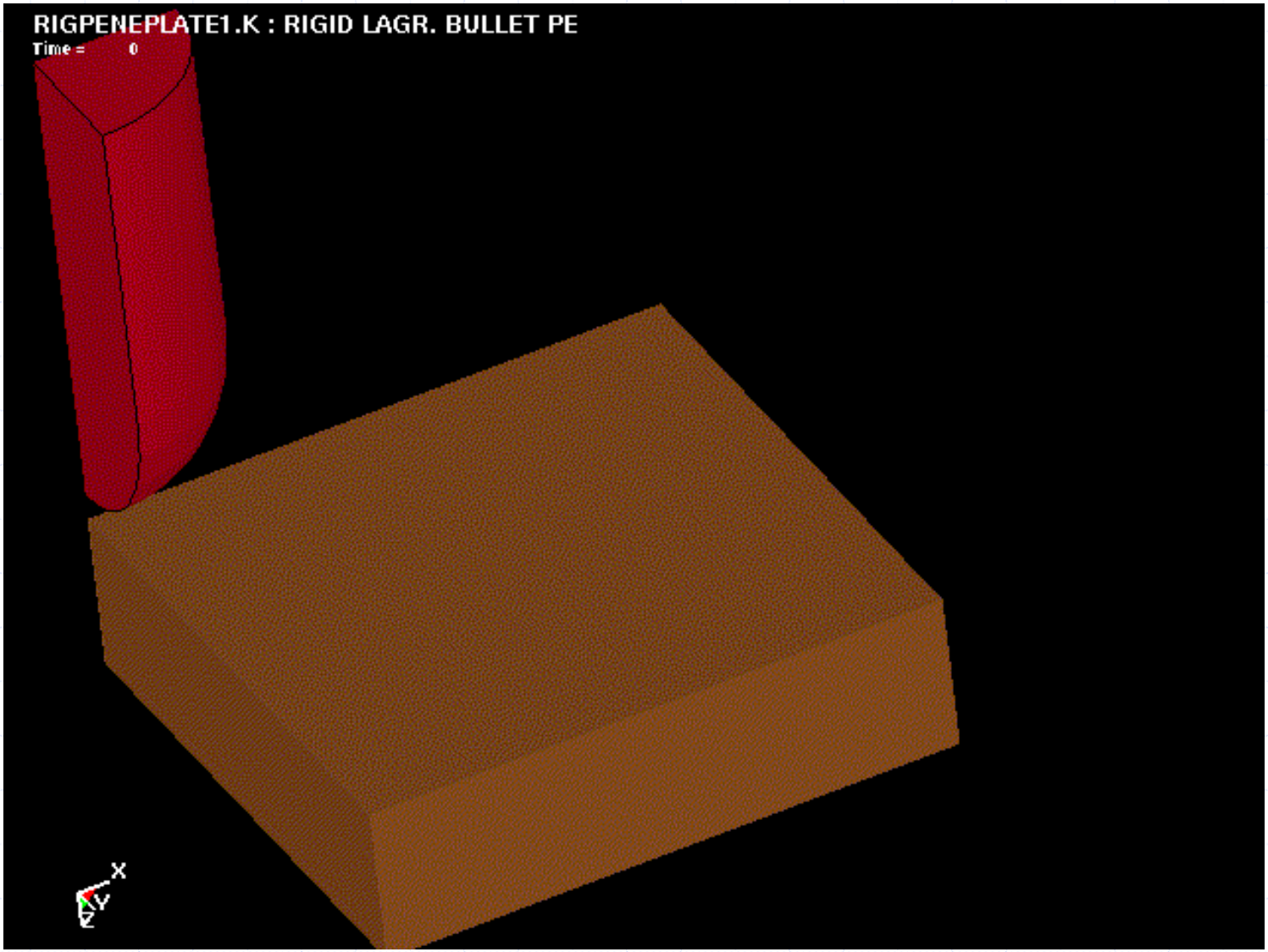


Lagrangian only

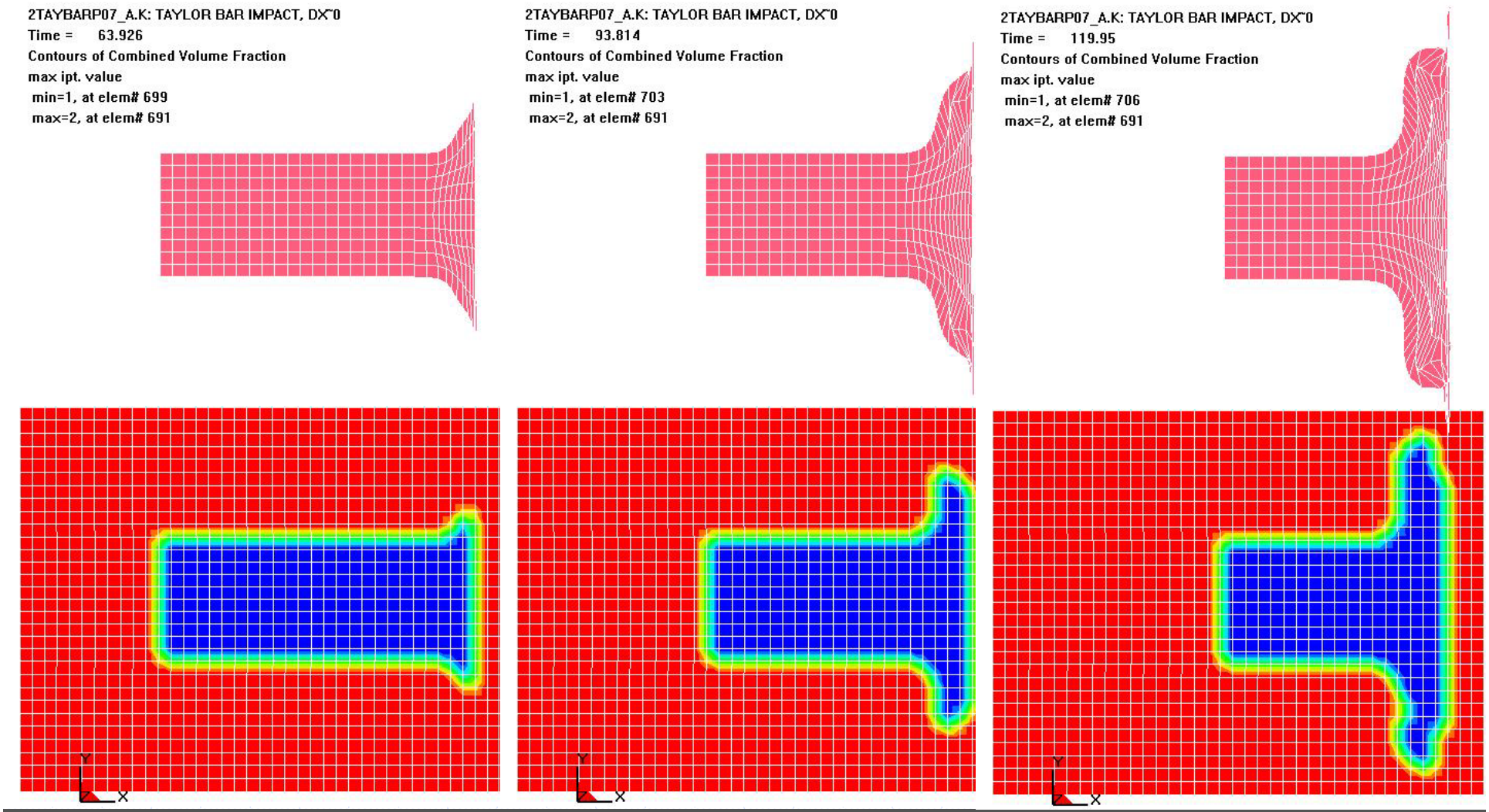


Coupled Euler/Lagrange

(Air or void domain is not shown for clarity)



Taylor Bar Impact
Lagrangian vs. Euler/Lagrange Coupling



MATERIAL INTERFACES FOR MULTI-MATERIAL ALE

MATERIAL INTERFACES

Multi-Material ALE: Distinctions among PART|MESH|MATERIAL:

In ALE terminology, the user should distinguish between a "*PART ID" and an "ALE-Multi-Material-Group ID" (AMMG ID):

A PART ID refers to a group of elements, i.e., some portion of the mesh which will usually contain one material(1) at time zero. As the ALE materials subsequently move across mesh lines, each element in the PART may contain more than one material, hence the term "multi-material".

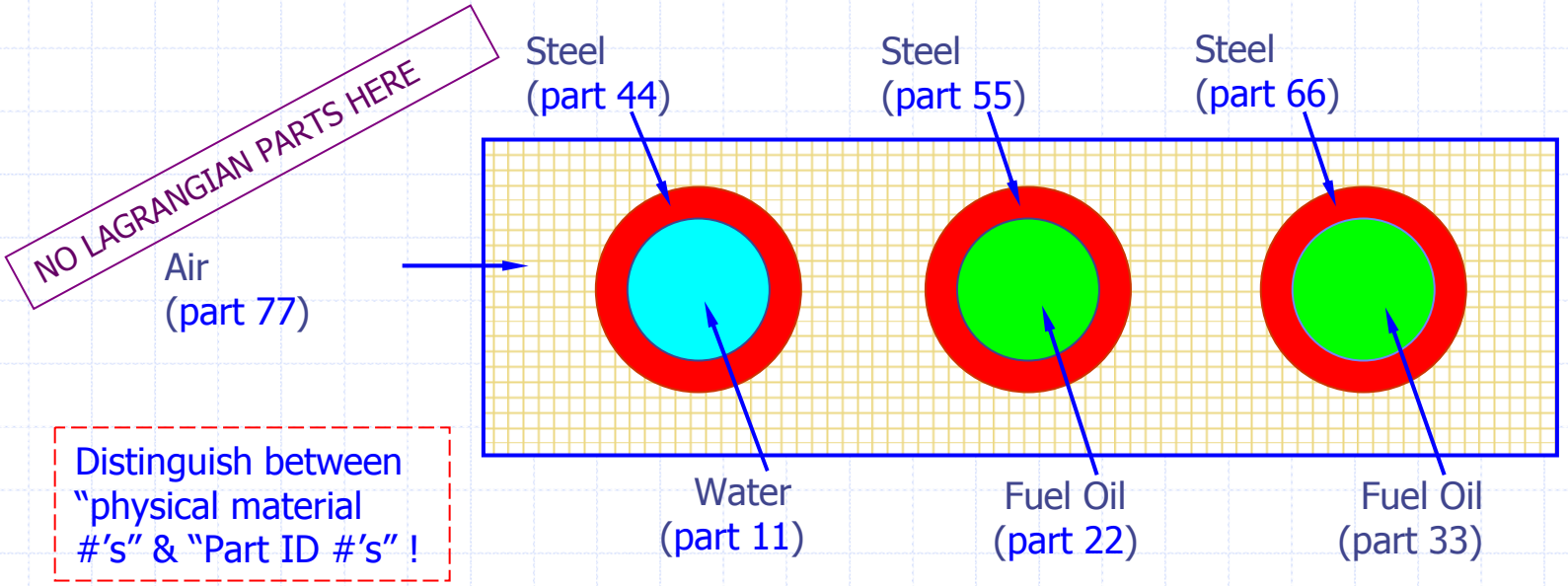
An AMMG refers to a region containing one physical material. For multi-material ALE, the card *ALE_MULTI-MATERIAL_GROUP sets up the ALE material groups. Internally throughout the simulation, the material interface of each AMMG is tracked.

(1) ***INITIAL_VOLUME_FRACTION_GEOMETRY** can be used to initially fill a PART with multiple materials.*

MATERIAL INTERFACES

Example :

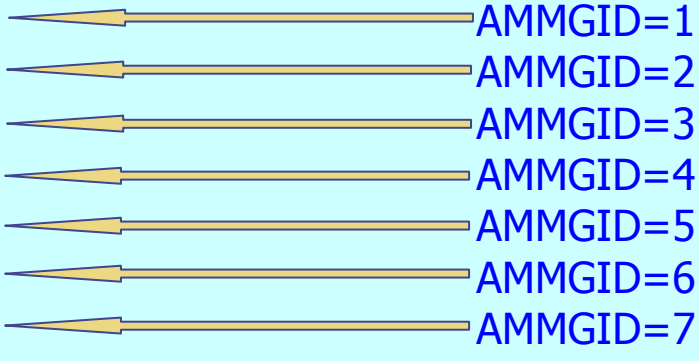
Consider a model having 3 containers filled with 2 different physical materials (water, fuel oil). The containers are made of the same material, say, steel. Assume that these containers break apart, spilling the fluids. *ALE_MULTI-MATERIAL_GROUP (AMMGID) defines the material grouping for treating multi-material elements & interface tracking.



MATERIAL INTERFACES

APPROACH #1: Maintaining the interfaces for each part ID.

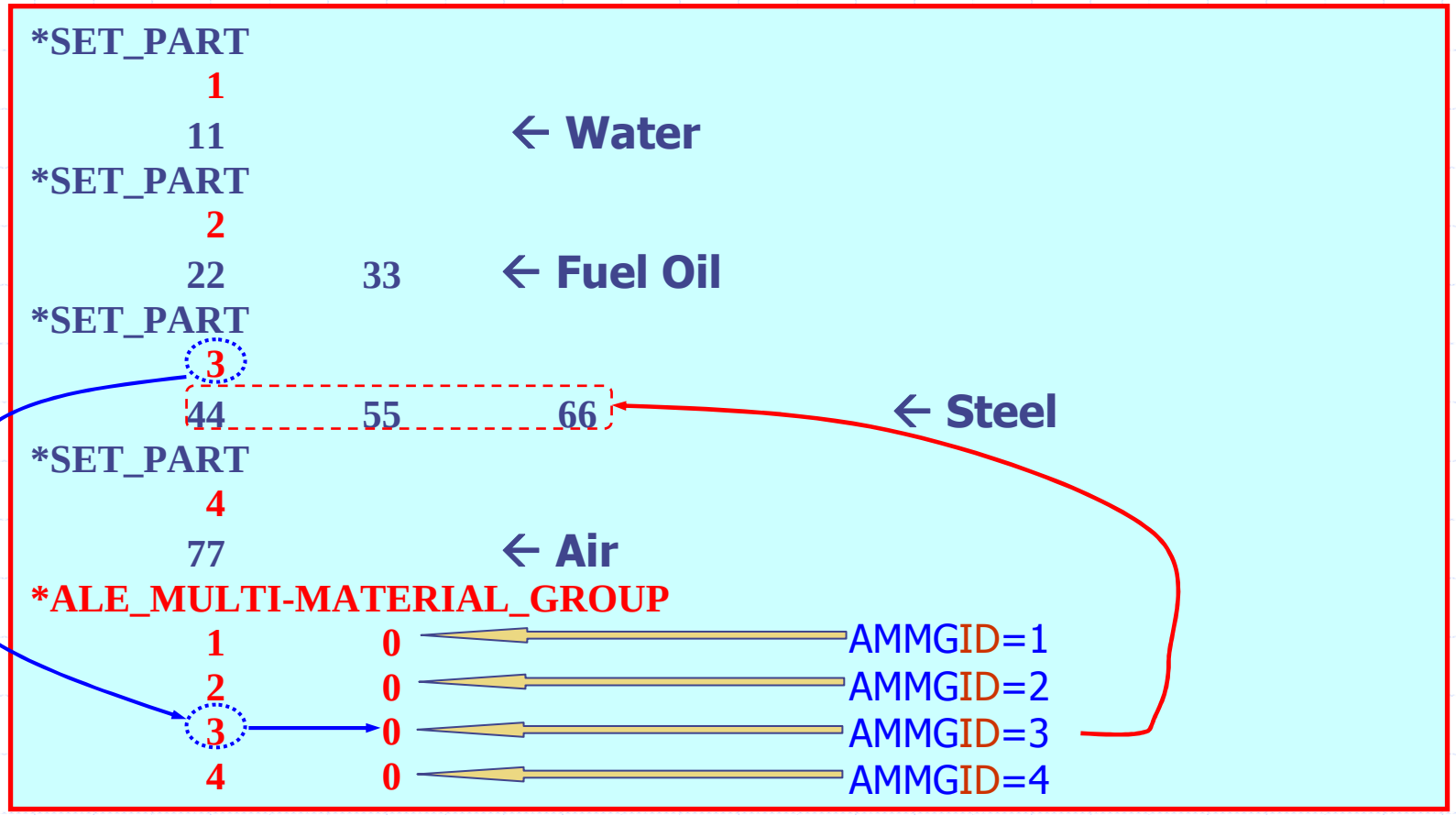
```
*ALE_MULTI-MATERIAL_GROUP
        11        1
        22        1
        33        1
        44        1
        55        1
        66        1
        77        1
```



Then, the interface of each part (11-77) will be tracked. This is, however, expensive due to the additional interface tracking computations, and not necessarily more accurate. As the same physical material, e.g., fuel oil from parts 2 and 3, flow into the same element, they behave realistically as a single material. Thus tracking their interfaces separately may not be necessary.

Sidebar: whenever more than 3 materials are present in 1 element, it may be advisable to refine the mesh.

APPROACH #2: If we group the physical materials together, fewer AMMGs are required.



Then, only the interfaces of the 4 physical materials will be tracked instead of all 7 "logical" interfaces (less expensive).

MULTI-MATERIAL or "MIXED" ELEMENT

The composite stress in a multi-material ALE element is the volume-fraction-weighted average stress of the individual material stresses,

.

$$\sigma^* = \sum_{k=1}^{\text{nmat}} \eta_k \sigma_k \qquad \sum_{k=1}^{\text{nmat}} \eta_k = 1 \qquad \eta_i = \text{Material Volume Fractions}$$

Example:

If a cell is 20% water, 30% steel, and 50% air,

stress in that cell is $0.2(\sigma_{water}) + 0.3(\sigma_{steel}) + 0.5(\sigma_{air})$

MATERIAL INTERFACES

Displaying AMMGs, i.e., ALE materials, in LS-Prepost:

We can display the material interface contours by…

FComp ➔ Misc ➔ History variable ➔ [Fringe|Isos] ➔ Apply
Where the History variable may be:

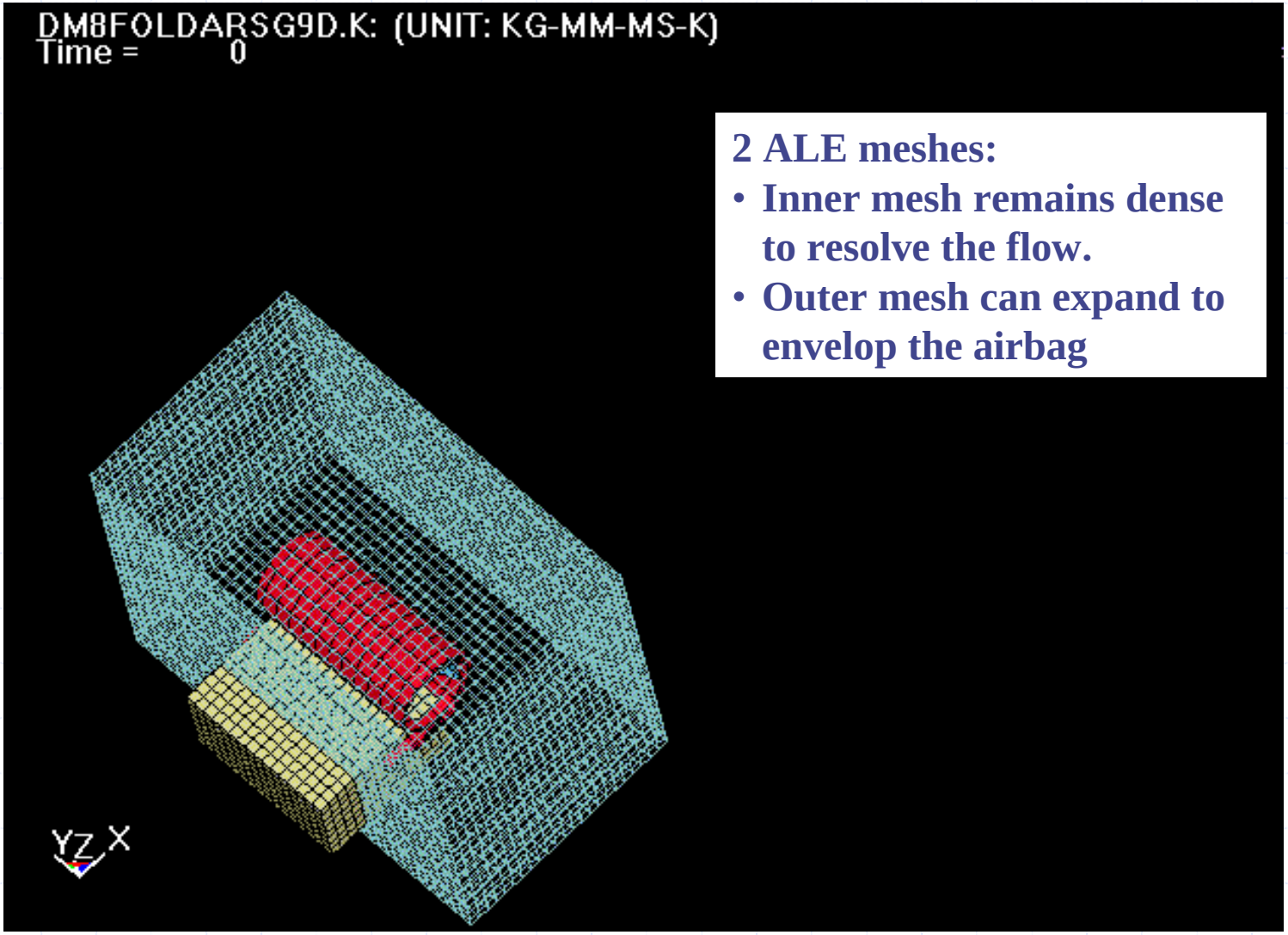
- **Fluid density**
- **Volume fraction of AMMG1 of the model**
- **…**
- **Volume fraction of AMMGn of the model**
- **Combined Volume fractions of the model**

Or

Selpar > Fluid

ALE EXAMPLE APPLICATIONS

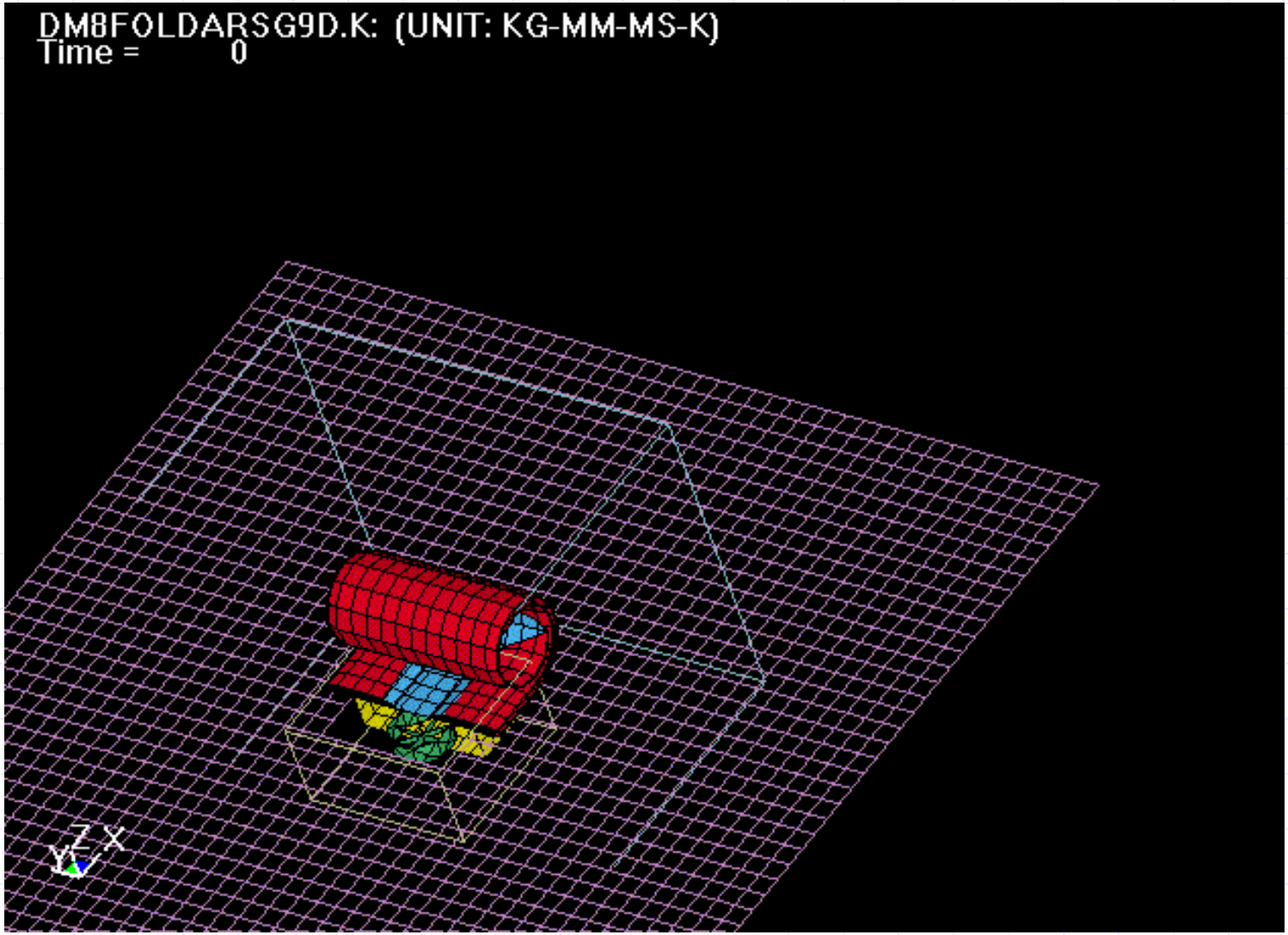
Airbag Example illustrating automatic ALE mesh translation and expansion via the command *ALE_REFERENCE_SYSTEM



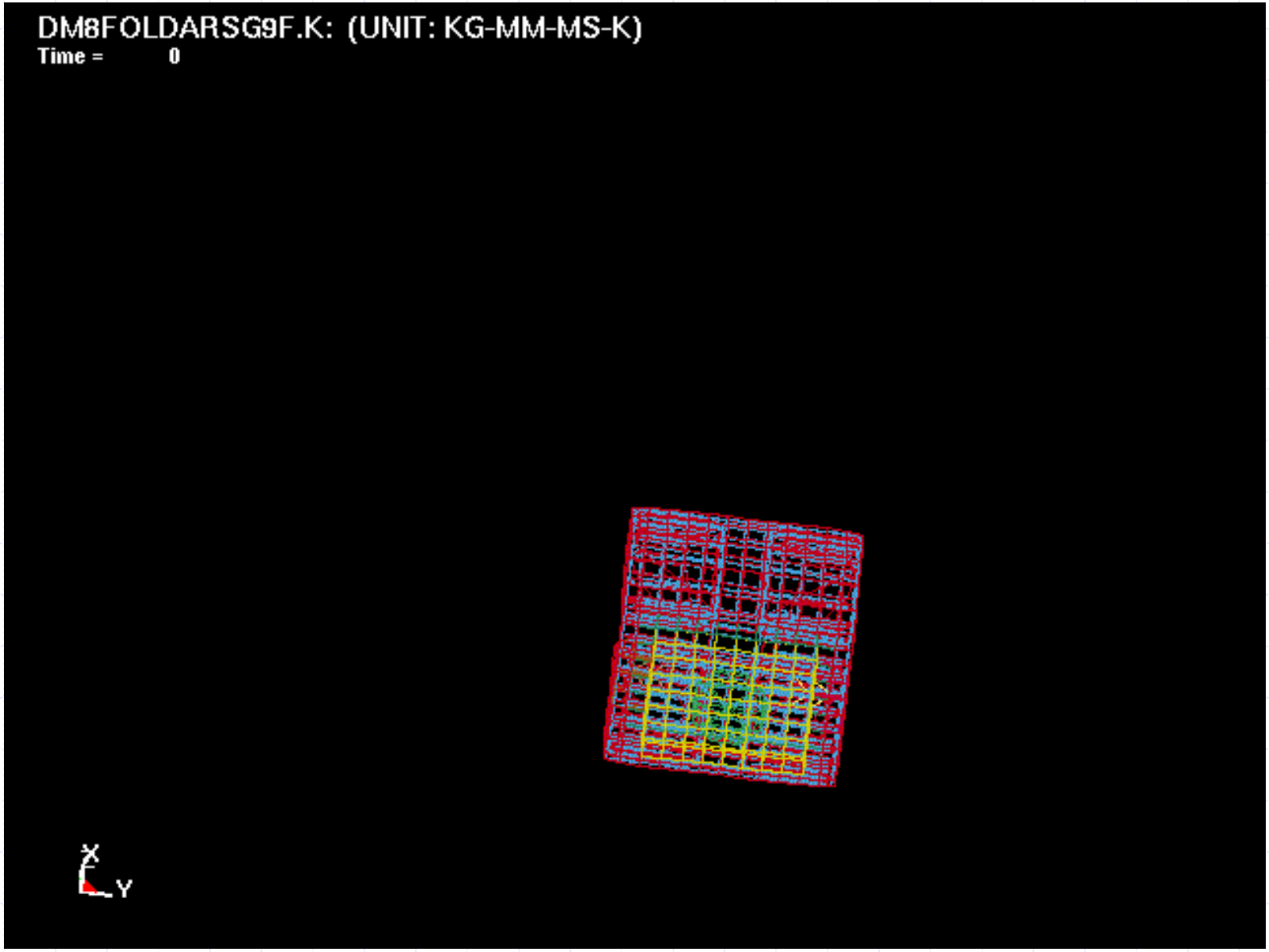
2 ALE meshes:

- Inner mesh remains dense to resolve the flow.
- Outer mesh can expand to envelop the airbag

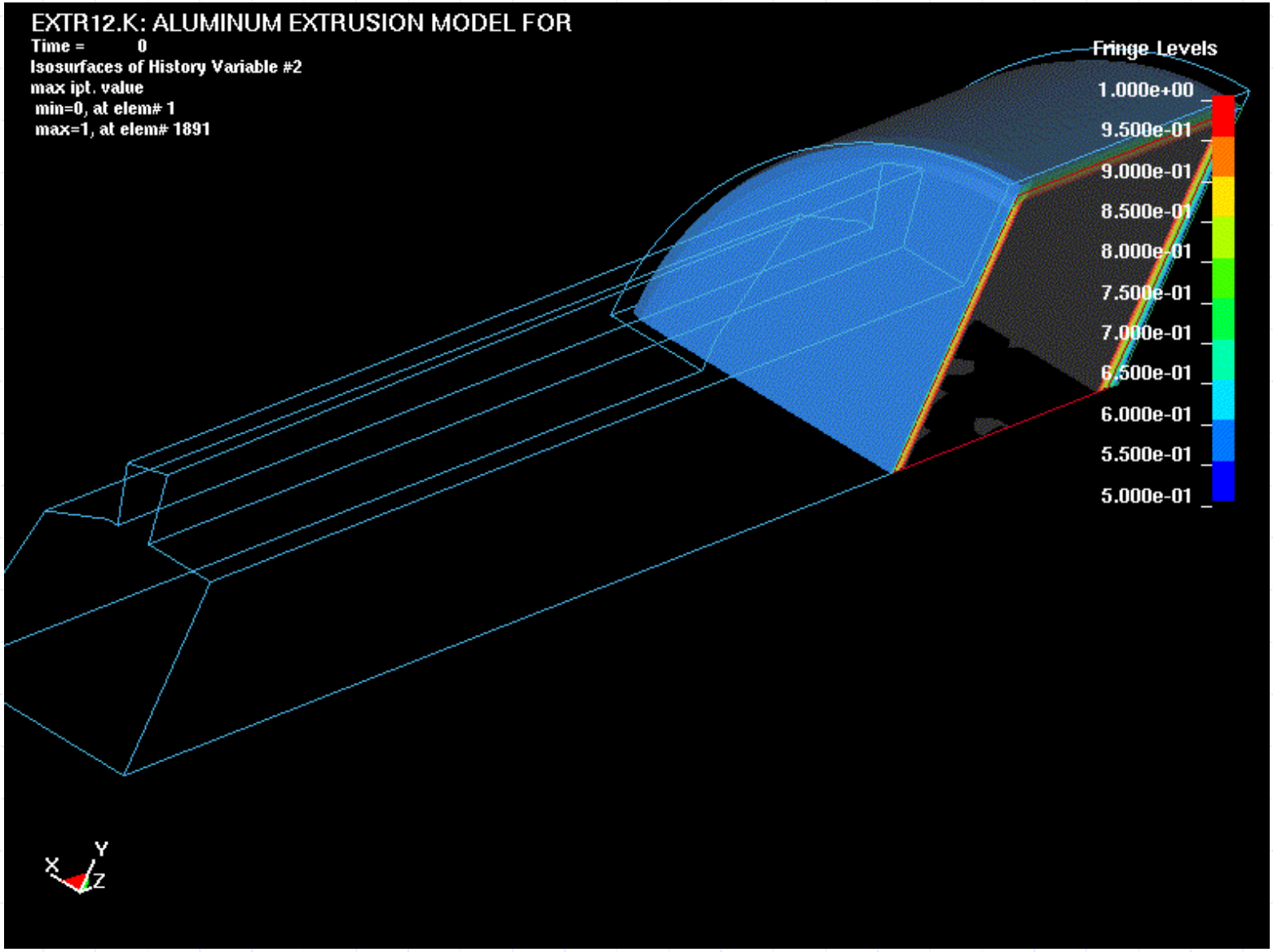
AIRBAG WITH PHYSICAL VENTING FLOW



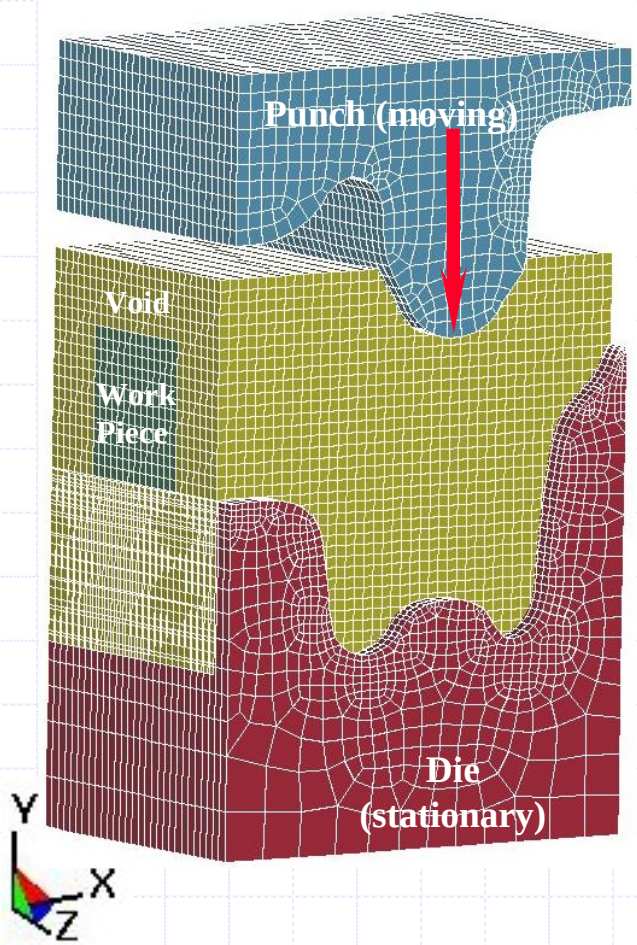
Switching AMMG ID across vent hole



METAL EXTRUSION using Euler/Lagrange Coupling



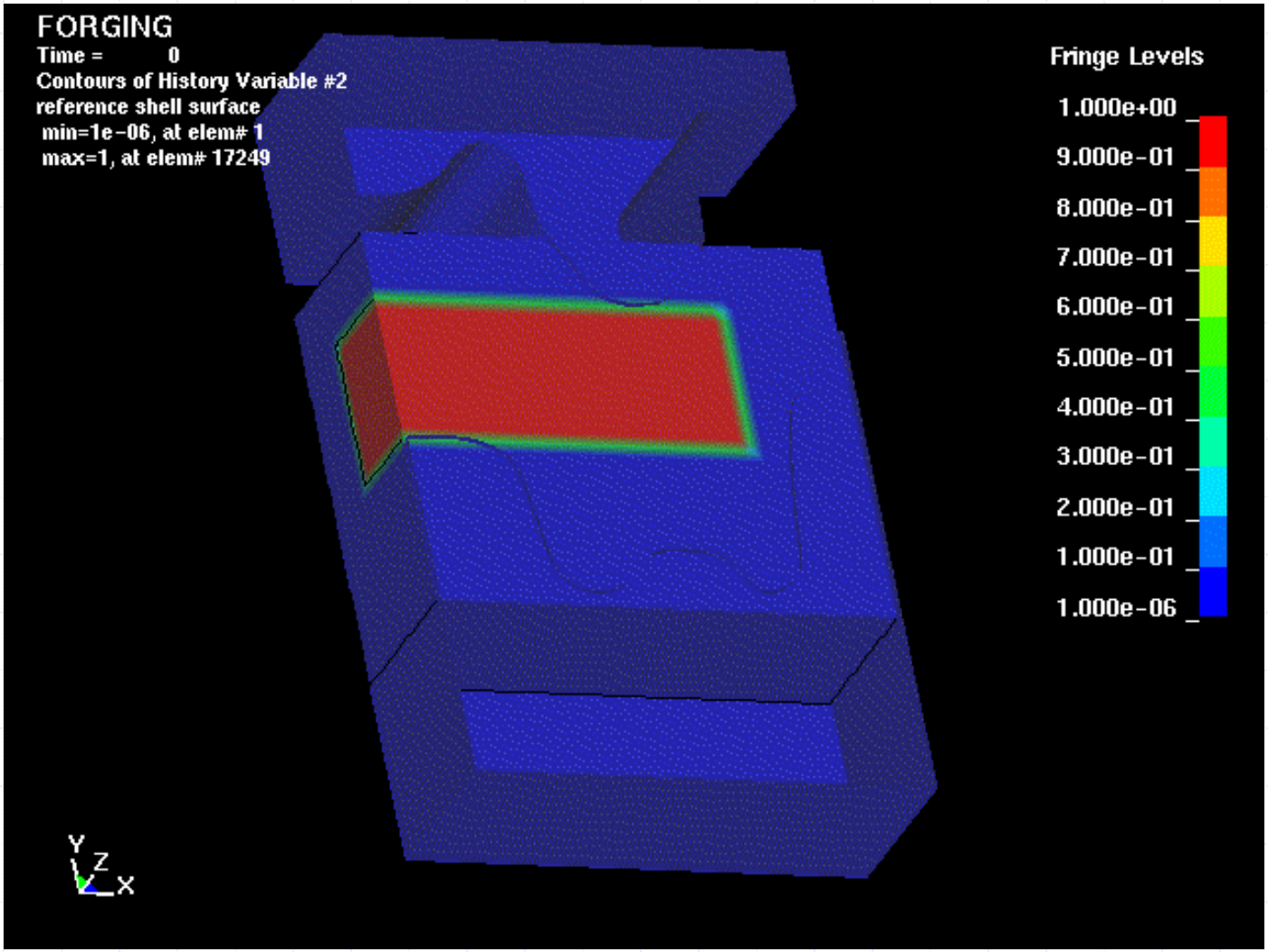
FORGING



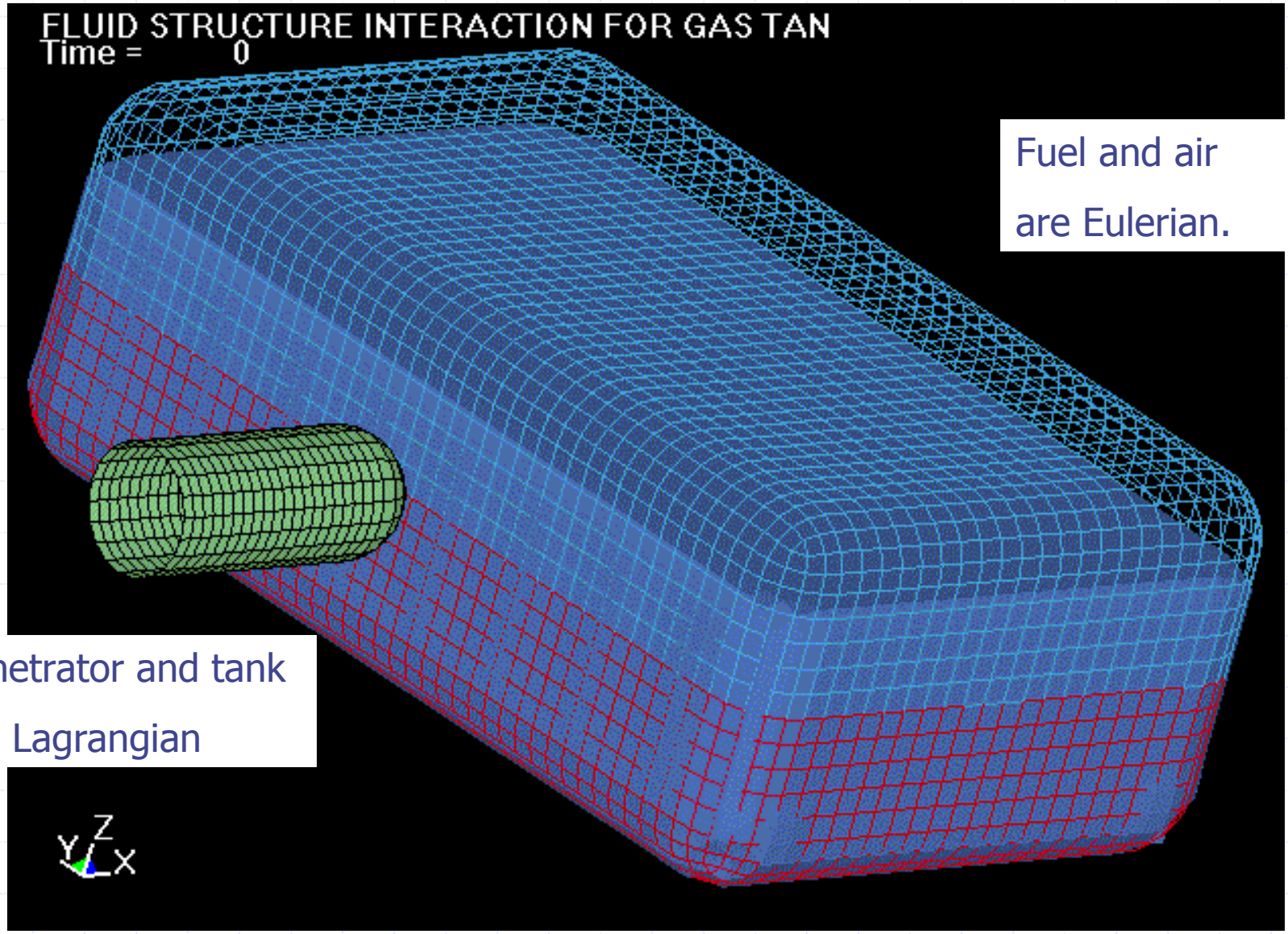
- Both tool pieces, punch and die, are modeled as Lagrangian *rigid shell* structures .
- The workpiece is modeled as *solid* ALE material which is allowed to deform|flow into surrounding void space.
- The void mesh can overlap with the rigid tool structures.

FORGING

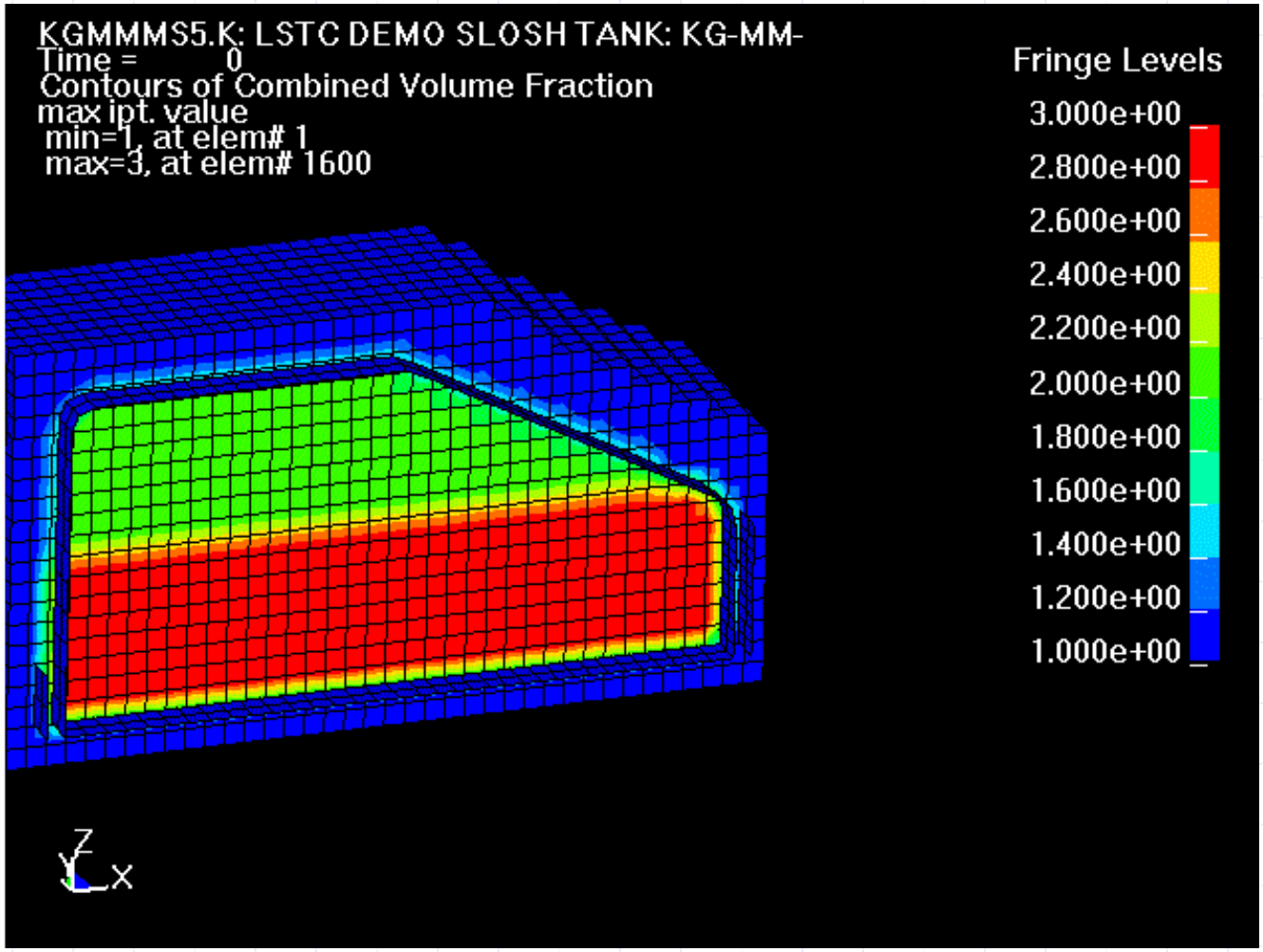
Result viewed in cross-section



FUEL TANK IMPACT



FUEL TANK SLOSHING
Coupled ALE/Lagrange



Reference mesh for fuel and air moves, hence ALE (not Eulerian)

PLATE-WATER IMPACT

OVERVIEW:

A Lagrangian plate moves with initial downward velocity through air, then hits water.

- **The Air and Water are defined as ALE Multi-Materials (tracking the interface of the two material within each element).**
- **The Steel Plate is defined as Lagrangian.**
- **The Lagrangian body/mesh can overlap the ALE/fluid meshes.**
- **The ALE-Multi-Material meshes have merged nodes on their shared boundaries.**

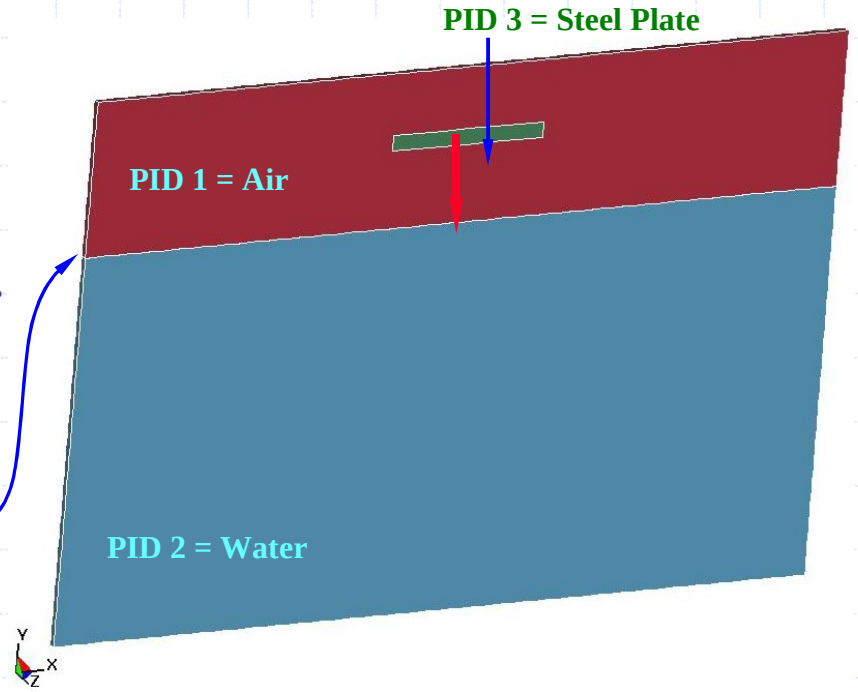
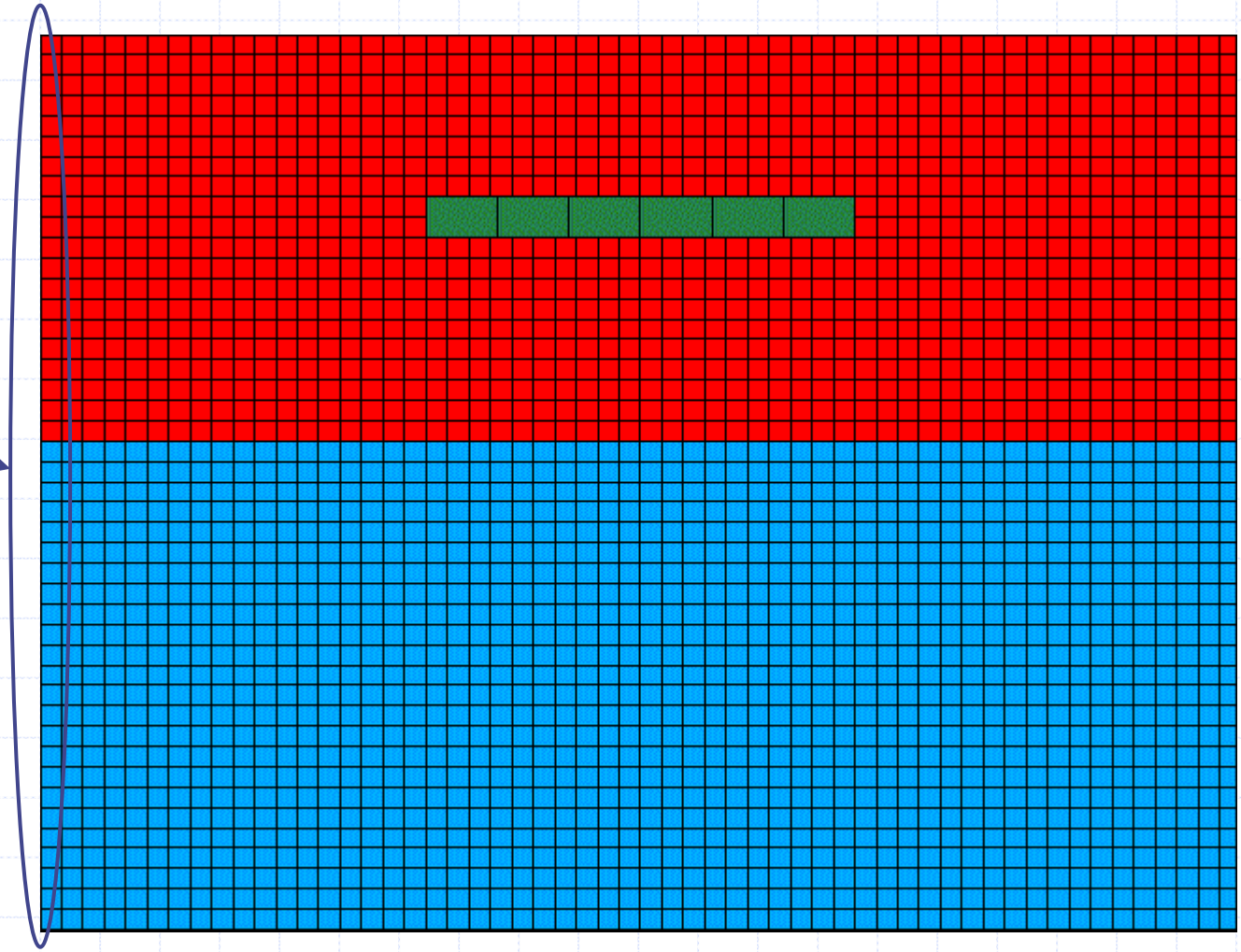
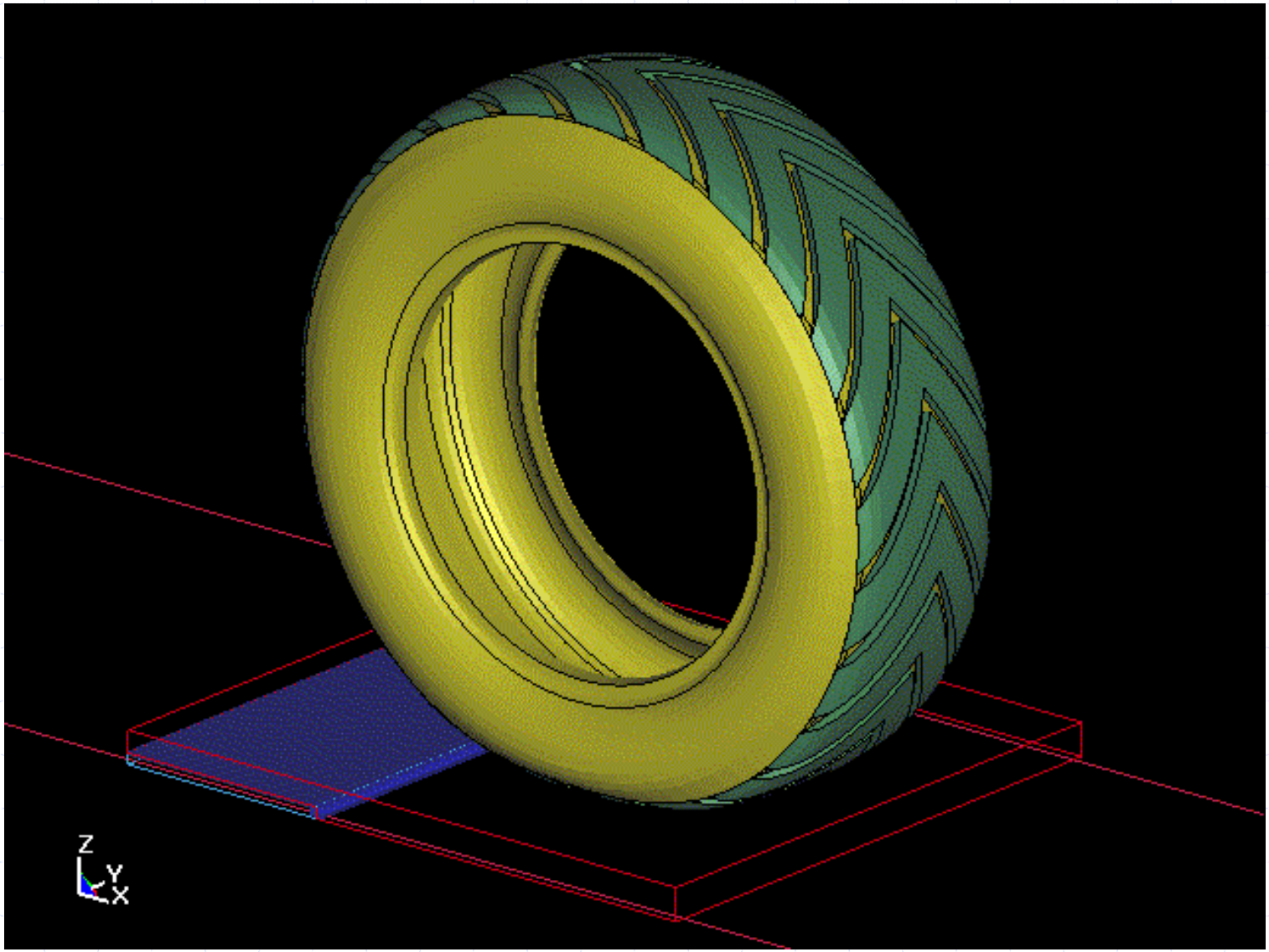


PLATE-WATER IMPACT
Coupled Euler/Lagrange

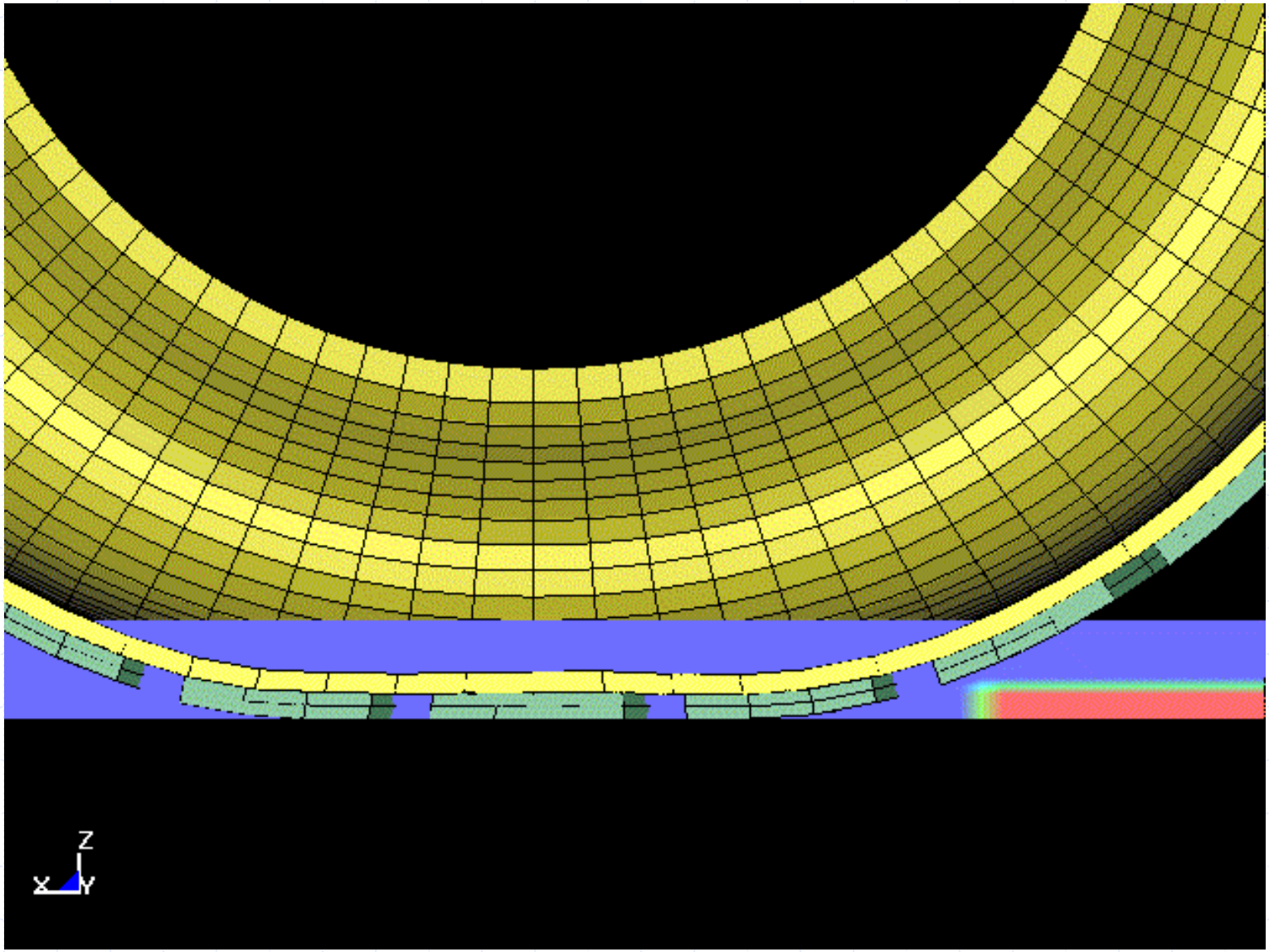
In this example, nodes are constrained perpendicular to boundary (typical)



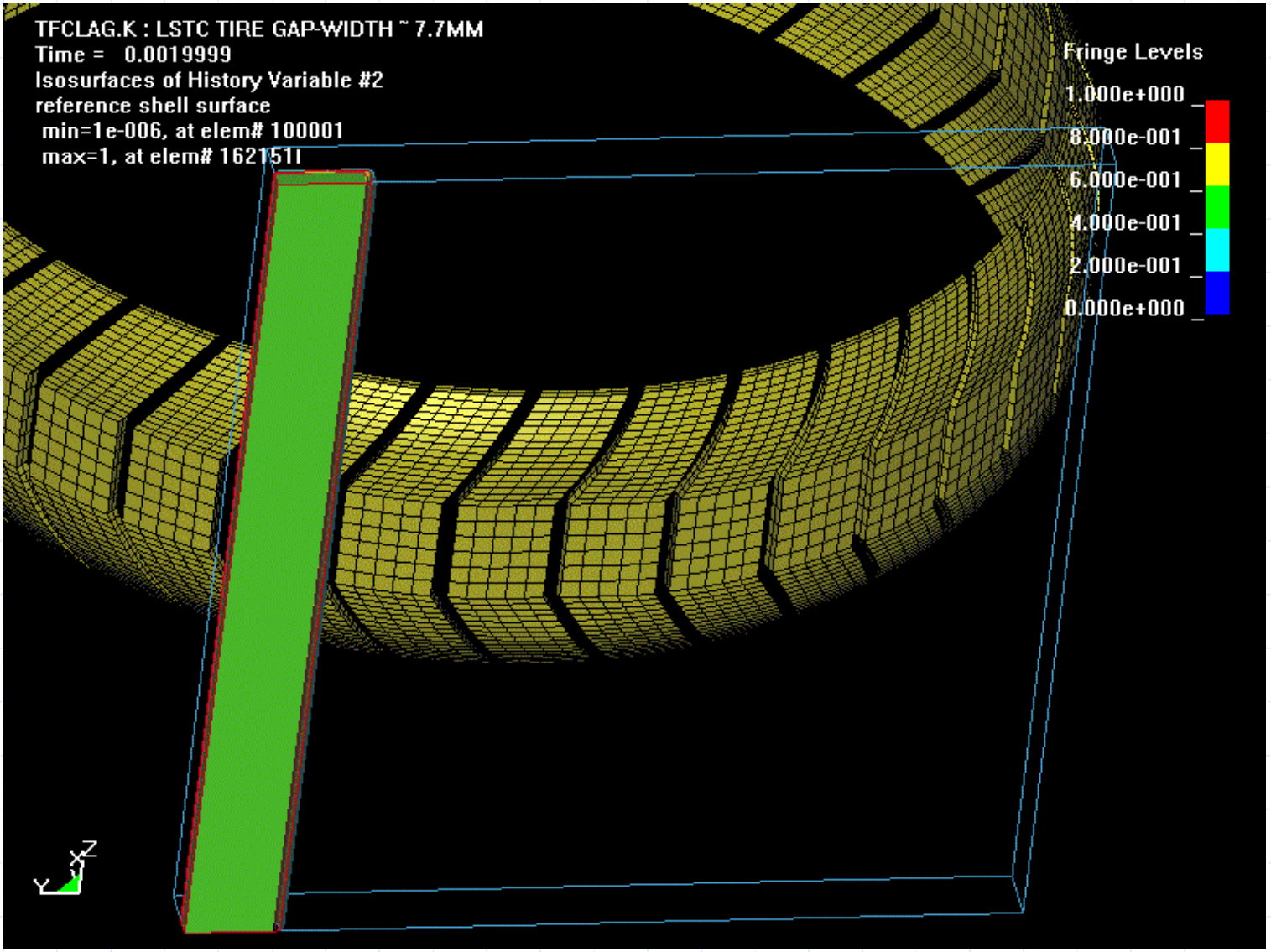
TIRE HYDROPLANING



TIRE HYDROPLANING



TIRE HYDROPLANING



FREQUENTLY USED COMMANDS IN ALE MODELS

*KEYWORD	*CONSTRAINED_LAGRANGE_IN_SOLID	
*TITLE	*SET_MULTI-MATERIAL_GROUP_LIST	*AIRBAG_ALE
*CONTROL_TERMINATION		*AIRBAG_ADVANCED_ALE
*CONTROL_TIMESTEP	*PART	
*CONTROL_ENERGY	*SECTION_SOLID	*AIRBAG_HYBRID
*DATABASE_BINARY_D3PLOT	*MAT_NULL	
*DATABASE_GLSTAT	*MAT_FABRIC	
*DATABASE_MATSUM	*EOS_LINEAR_POLYNOMIAL	
	*EOS_IDEAL_GAS	*BOUNDARY_AMBIENT_EOS
*DATABASE_FSI	*EOS_GRUNEISEN	*BOUNDARY_PRESCRIBED_MOTION_
*CONTROL_ALE	*HOURGLASS	*BOUNDARY_NON_REFLECTING
*ALE_MULTI-MATERIAL_GROUP		*INITIAL_VOID
*ALE_REFERENCE_SYSTEM_GROUP	*SECTION_POINT_SOURCE_MIXTURE	*INITIAL_VELOCITY_
*ALE_REFERENCE_SYSTEM_NODE	*MAT_GAS_MIXTURE	*LOAD_BODY_
*ALE_REFERENCE_SYSTEM_CURVE	*INITAL_GAS_MIXTURE	*LOAD_SEGMENT_SET
*ALE_REFERENCE_SYSTEM_SWITCH	*INITIAL_VOLUME_FRACTION_GEOMETRY	*RIGIDWALL_PLANAR