U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

Modeling of the M795 155 mm Artillery Projectile Sympathetic Reaction Test

Presentation to the 2021 Insensitive Munitions & Energetic Materials (IMEM) Technology Symposium
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INTRODUCTION

- **Problem: Model M795 155 mm artillery projectile sympathetic reaction test in 3D**
  - Donor and acceptor filled with either TNT or IMX-101 explosive fills
  - Used Ignition and Growth (I&G) reactive flow model for the acceptor explosive fill
  - Calculations performed in both CTH (SNL, finite difference) and ALE3D (LLNL, finite element)
  - Performed on workstation with 56 core (total) Intel processors with 2TB of RAM

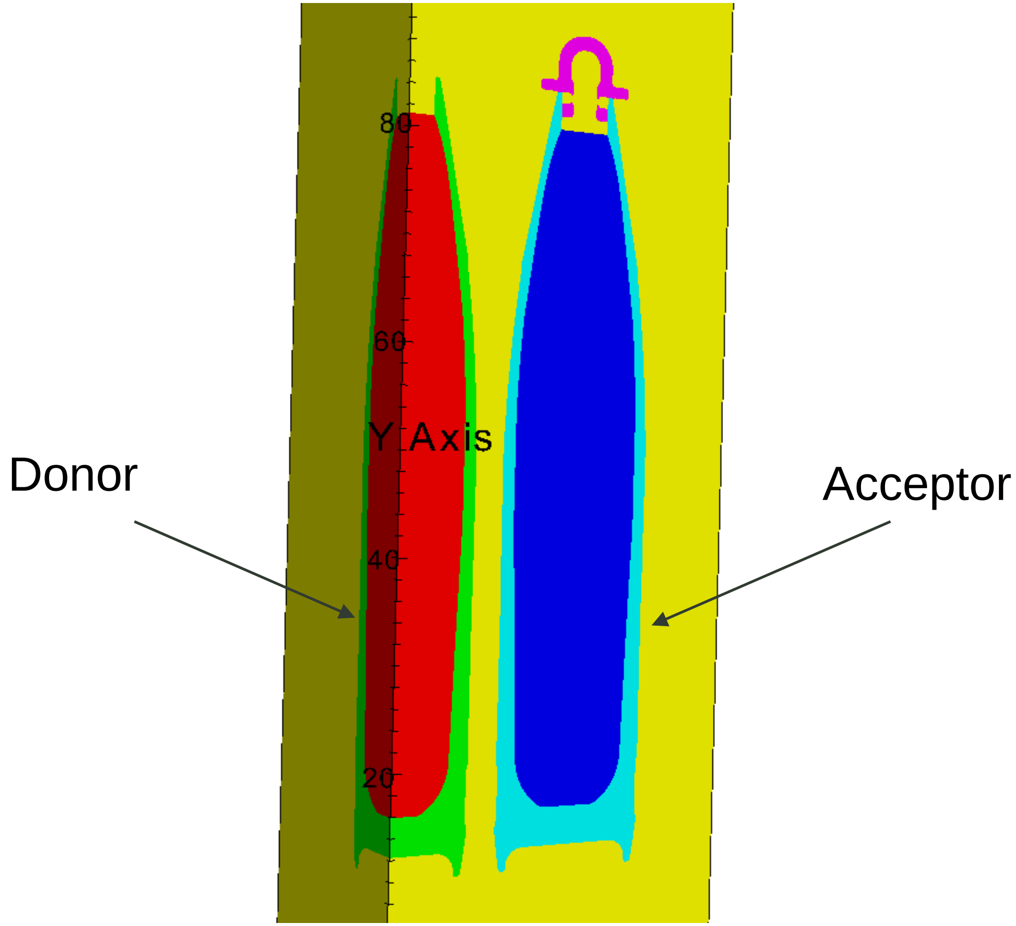
- **Challenge: Obtaining a solution in a reasonable amount of time**
  - Literature for reactive flow material models typically recommend mesh resolutions >50 elements/cm
  - For full-scale 3D problems, such a high mesh resolution is computationally expensive in terms of memory and reduced time step for explicit codes (Courant limit)
  - Typical full-scale munition models would likely require scarce supercomputer resources

- **Approach: Reduce mesh resolution to allow solution in a reasonable timeframe**
  - Allows for complete runs in a few weeks of wall-clock time on an engineering workstation computer
  - Verify reduced level of mesh resolution chosen does not result in unsatisfactory error

IGNITION AND GROWTH (I&G) REACTIVE FLOW MODEL

- **Developed in the 1970s and 80s by Lee and Tarver, includes three terms describing:**
  - Hot spot formation due to compression
  - Growth of hot spots due to formation of gas products
  - Slow final production of solid products
- **Able to capture complex reaction behavior from ignition through detonation including:**
  - 2D and 3D initiation and failure
  - Detailed propagation (corner turning)
  - Reactions from complex stimuli, including: 1) short durations shocks; 2) reflected shocks; 3) multiple shocks; and 4) ramp waves
- **Simpler models cannot capture these complex responses → I&G is relatively simple and inexpensive reactive flow model**
  - JWL equations of state for legacy, new explosives are continuously developed and updated
  - There is a large library of I&G models
- **Potential difficulty is literature recommendation for highly refined mesh**
  - Important for excellent relative agreement when developing/validating models
  - Typically varies from 50 to several 100 elements/cm, depends on material (reaction zone thickness)
  - However, solutions may asymptote to mesh-independence at lower-than-recommended resolutions

PROBLEM GEOMETRY, DOMAIN



Two unconfined projectiles

Computational domain:

(50 x 100 x 25 cm), ¼ symmetry along YZ plane, ½ symmetry along XY plane, outflow on all other boundaries

The “donor” is detonated, the “acceptor” experience a shock wave from the donor

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PROBLEM SETUP: ALE3D

- **Donor and acceptor were *both* filled with *either* TNT *or* IMX-101.**

- **Mesh is made by**
  - First hex meshing the entire computational domain.
    - Portion of acceptor that initially experiences shock is refined up to 25 elements/cm.
    - Ratioing is used to coarsen mesh away from the initial shock region of the acceptor.
  - Donor and acceptor parts are then shaped in.

- **I&G models for TNT and IMX-101 provided by LLNL.**
- **Projectile shells modeled using 4340 steel EOS and strength models from ALE3D library.**

- **Donor undergoes constant detonation velocity using programmed burn with JWL EOS at t=0.**

- **Problem run for up to 120 μs.**

PROBLEM SETUP: CTH

- **Donor and acceptor were *both* filled with *either* TNT *or* IMX-101.**

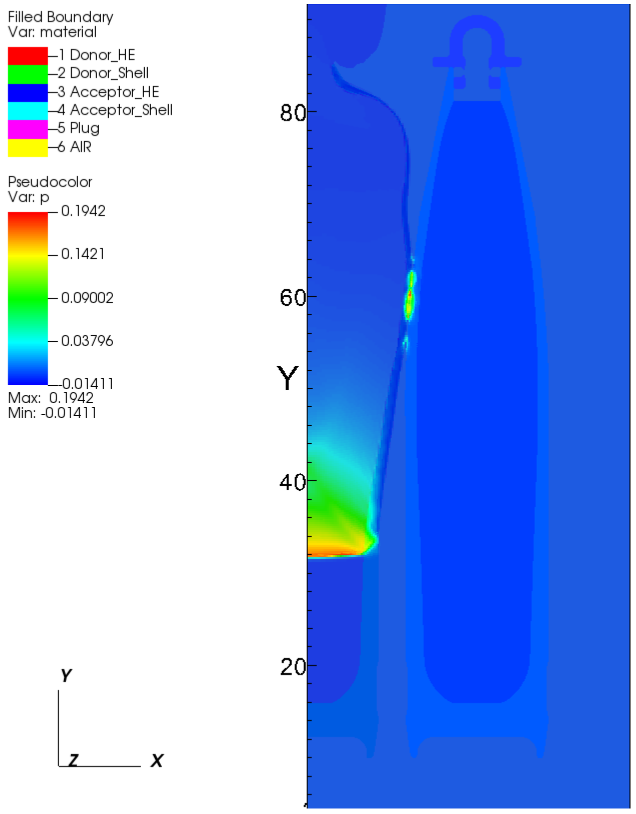
- **Model utilizes CTH's adaptive mesh refinement (AMR) algorithm to allow a mesh resolution of up to 25 elements/cm near detonation/shock waves and material interfaces.**

- **I&G models for TNT and IMX-101 provided by LLNL.**
- **Projectile shells modeled using 304 stainless steel EOS and strength models from CTH (12.2) library.**

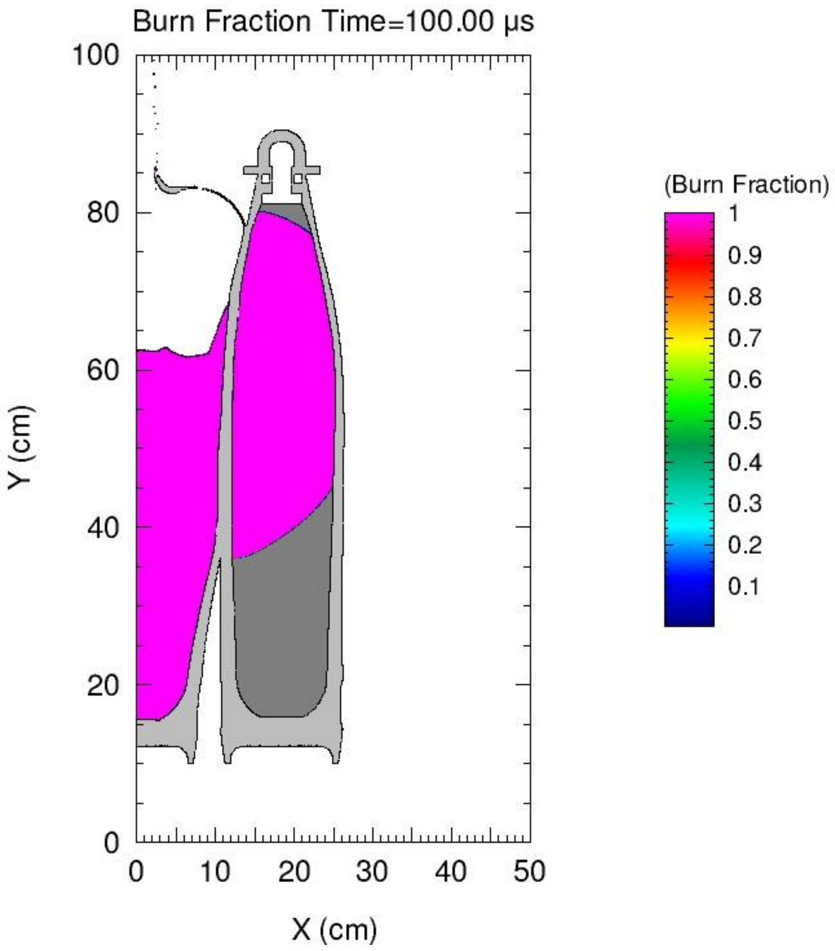
- **Donor initiated with a programmed burn in small portion (similar to a booster), then transitions to a reactive flow model for the remainder of the donor reaction.**

- **Problem run for up to 100 μs.**

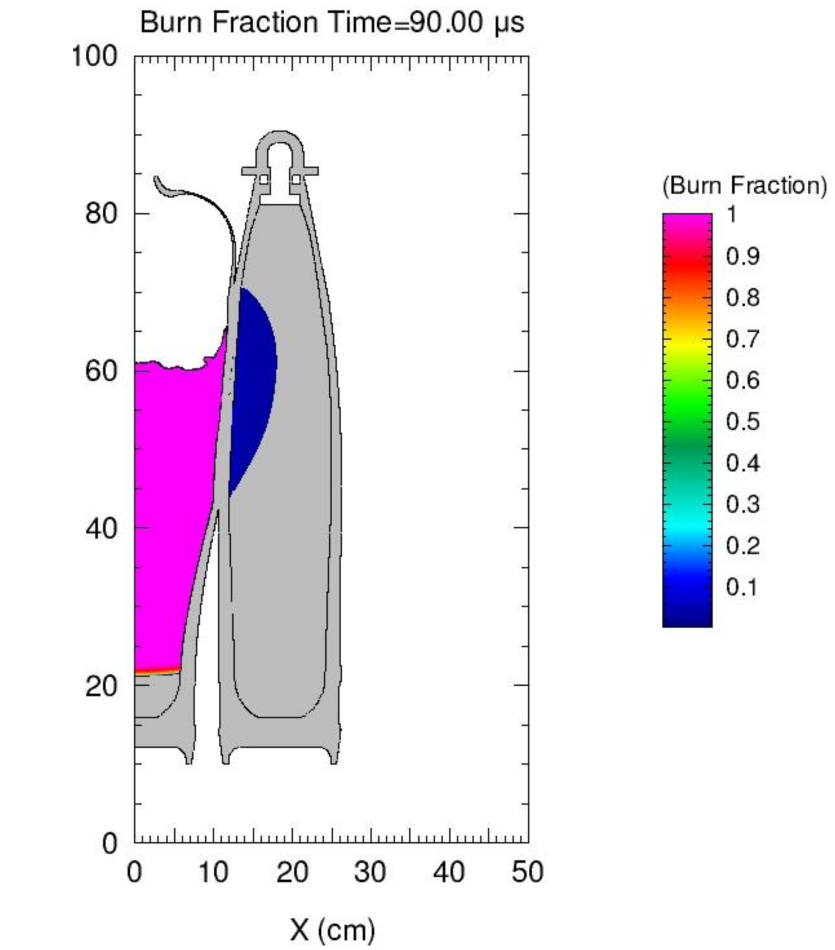
SIMULATION SNAPSHOTS OF 3D M795 PROJECTILE SYMPATHETIC REACTION



ALE3D solution at 72 μs, shortly after donor shell impacts acceptor. Plot of pressure contours (Mbar).



CTH solution for TNT filled M795s. TNT is a sensitive and the acceptor completely reacts.



CTH solution for IMX-101 fill. IMX-101 is less sensitive and the acceptor does not undergo extensive reaction.

3D SYMPATHETIC REACTION RESULTS

- **Importantly, all the simulations run showed agreement with the tests. TNT-filled M795 projectiles sympathetically detonate while IMX-101-filled M795 projectiles do not.**

Table 1. ALE3D M795 sympathetic reaction runtime summary.

HE	Max Mesh resolution (#/cm)	Elements (millions)	Generation wall-clock time (hrs)	Run wall-clock time (hrs)
TNT	12.5	14	58*	16
TNT	12.5	3.89	22*	4
TNT	5	0.92	3*	1
TNT	25	52	302*	114
IMX-101	25	52	243	132

Table 2. CTH M795 sympathetic reaction runtime summary.

HE	**Max Mesh Resolution (#/cm)**	**Simulation End Time (μsec)**	**Wall-Clock Time (hrs)**
TNT	25	100	379
IMX-101	25	90	242

- **Bottom line: we can successfully simulate sympathetic reactions that agree with tests with reasonable turnaround of ~2 weeks on an engineering workstation.**

2D EXAMINATION OF MESH RESOLUTION

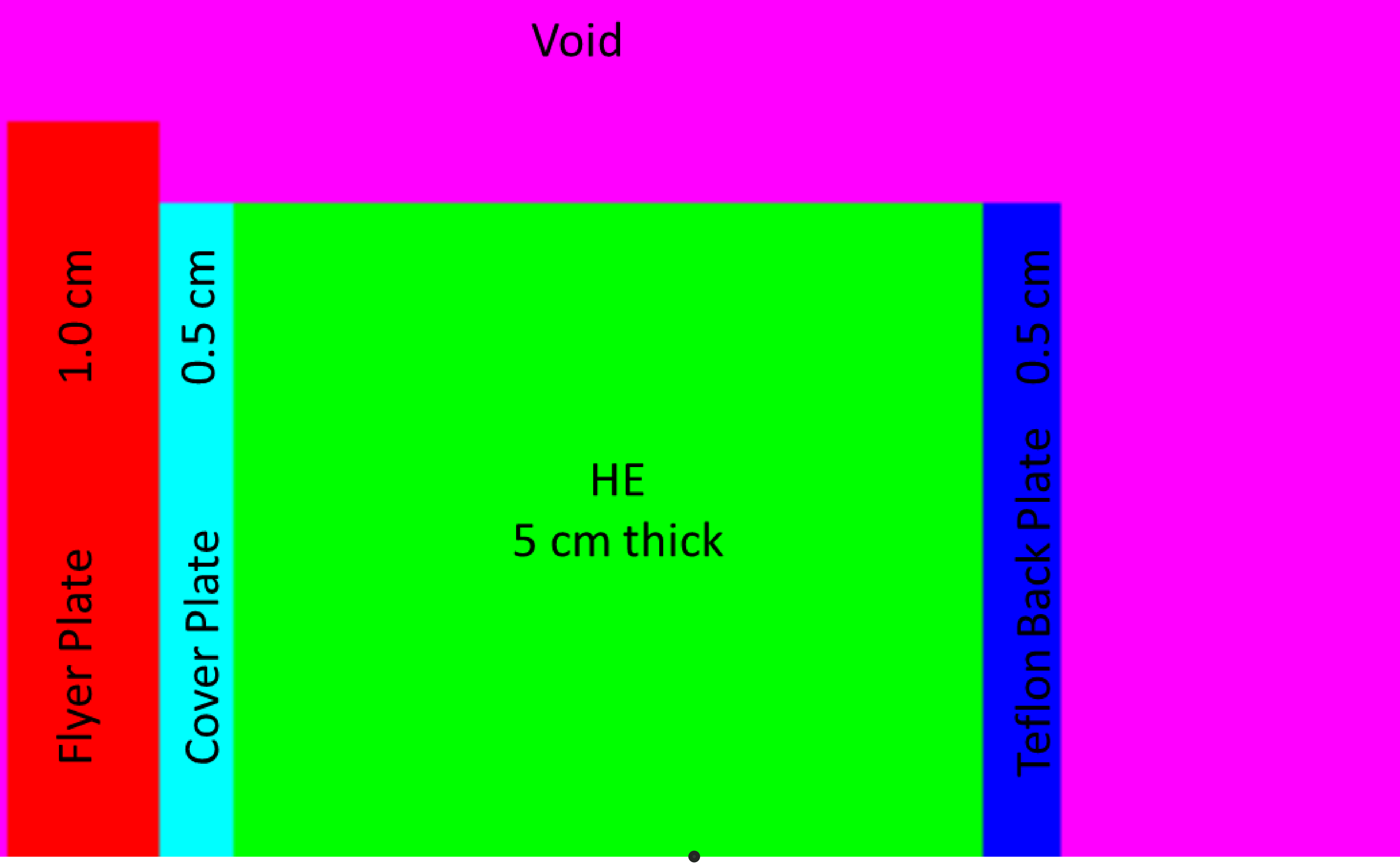
- **Reduced mesh resolution 3D models presented provide results that agree with tests, now we want to assess how the mesh resolution affects solutions using these specific I&G material models.**
- **Approach: Model 1D and 2D flyer plate impact of TNT and IMX-101 using I&G and vary mesh resolution in both ALE3D and CTH**
- **Flyer plate impact experiments are commonly used to develop/validate reactive flow models including I&G.**
- **The goal is to perform simulations with impact velocity and pressure stimuli comparable to those experienced during sympathetic reaction and flyer plate testing**

Example of a flyer plate experimental target. A sandwich consisting of a cover plate and a several layers of explosive are instrumented with pressure gauges. A plate with a diameter greater than the target strikes the experiment at a high velocity. Recorded data can be used to develop and validate reactive flow models.

Source: On the low pressure shock initiation of octahydro-1,3,5,7–tetranitro-1,3,5,7-tetrazocine based plastic bonded explosives, Vandersall, et al., J. App. Phys, 107, 094906 (2010)

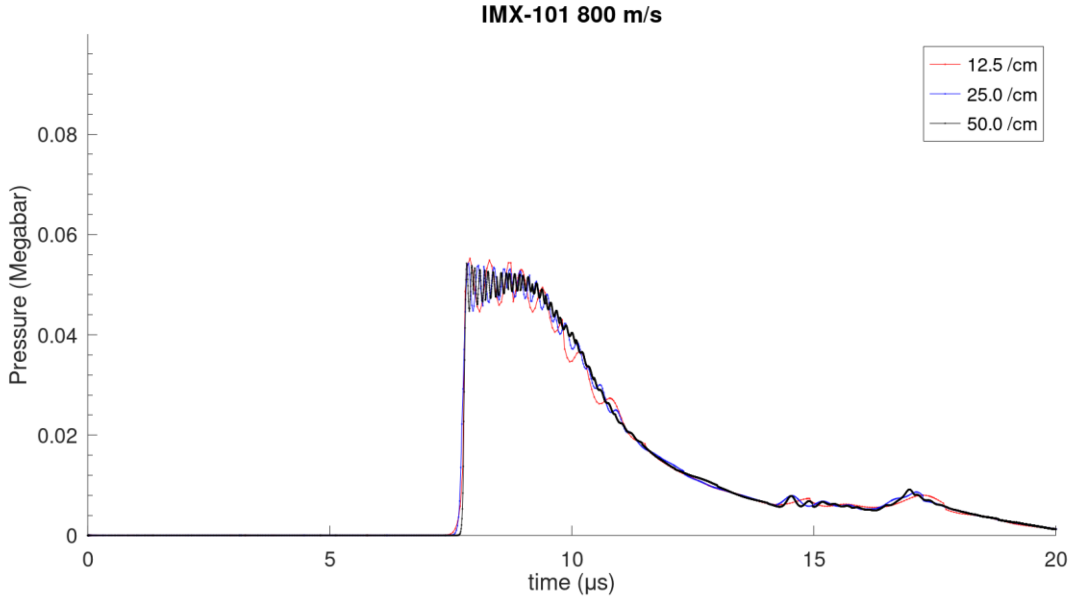
2D FLYER PLATE SETUP: ALE3D

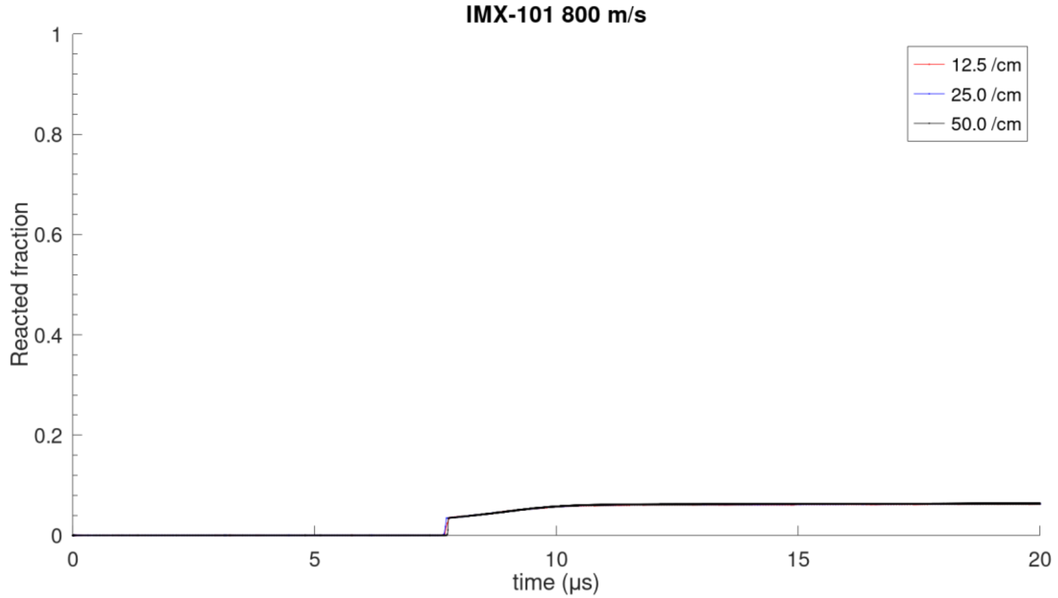
- Flyer plate, cover plate are 4340 steel
- HE is TNT or IMX-101
- Axisymmetric @ y=0 boundary
- Outflow on all other boundaries
- Flyer plate is prescribed an initial velocity [800-1800m/s]
- Pressure and reacted fraction are traced in the HE.
- Three nominal mesh resolutions: 12.5, 25, 50 elements/cm



Virtual tracer 3 cm from the records pressure, reacted fraction

ALE3D 2D RESULTS IMX-101: 800 M/S IMPACT VELOCITY



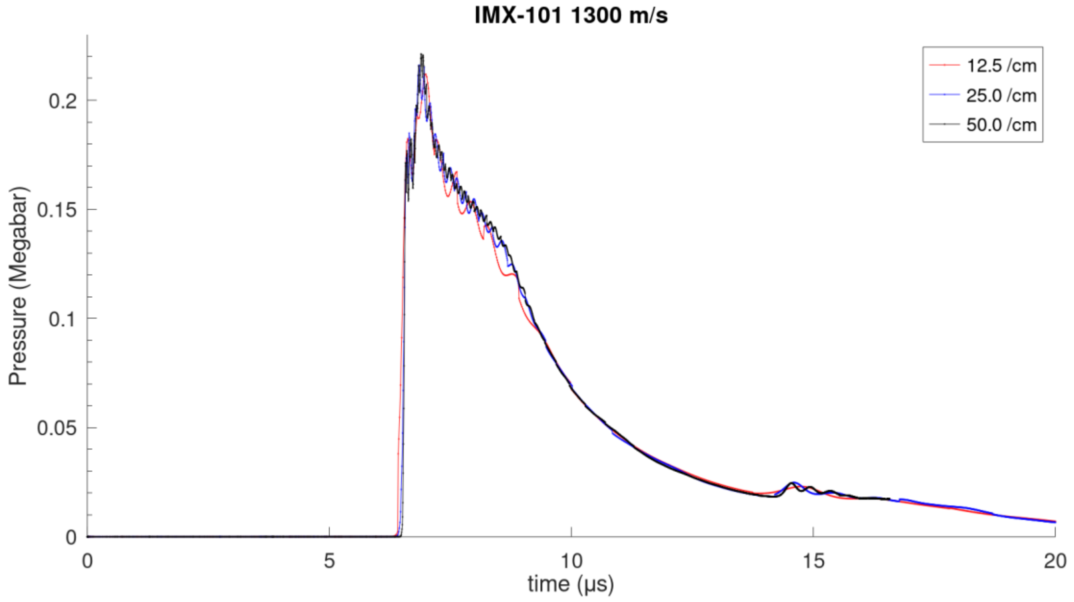


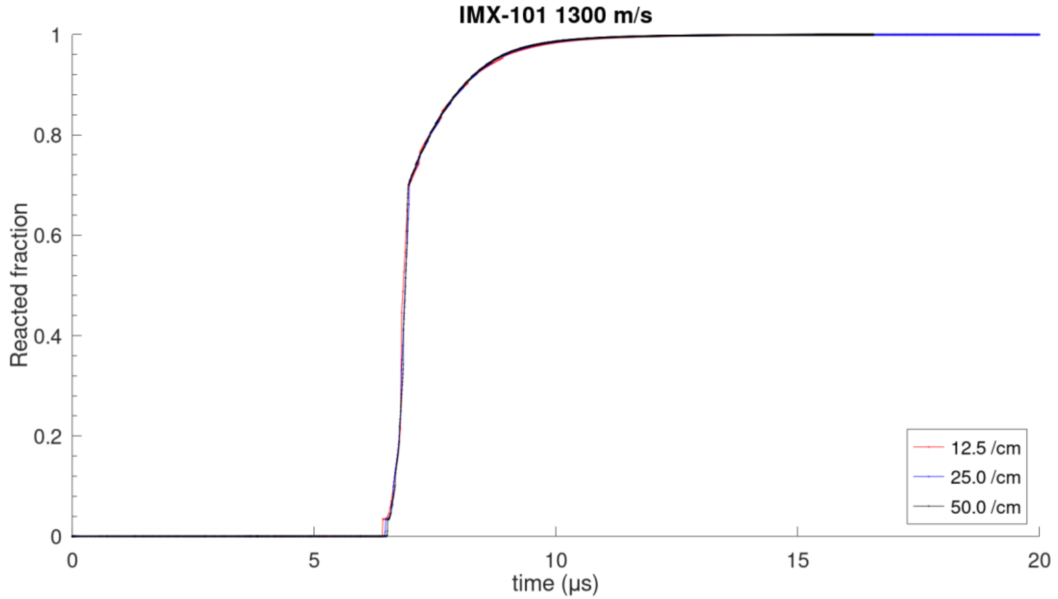
ALE3D results for IMX-101 with a flyer plate velocity of 800 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The tracer indicates that IMX-101 only reacts to limited extent.

A close examination of the results shows that the solution asymptotes towards a mesh-independent solution at a resolution ~25 elements/cm

ALE3D 2D RESULTS IMX-101: 1300 M/S IMPACT VELOCITY



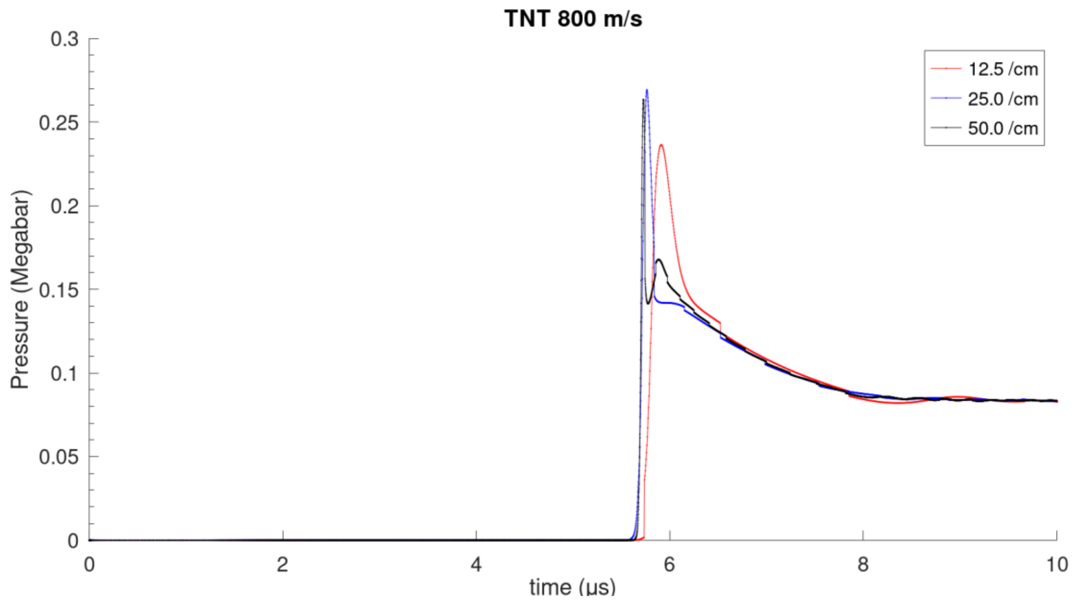


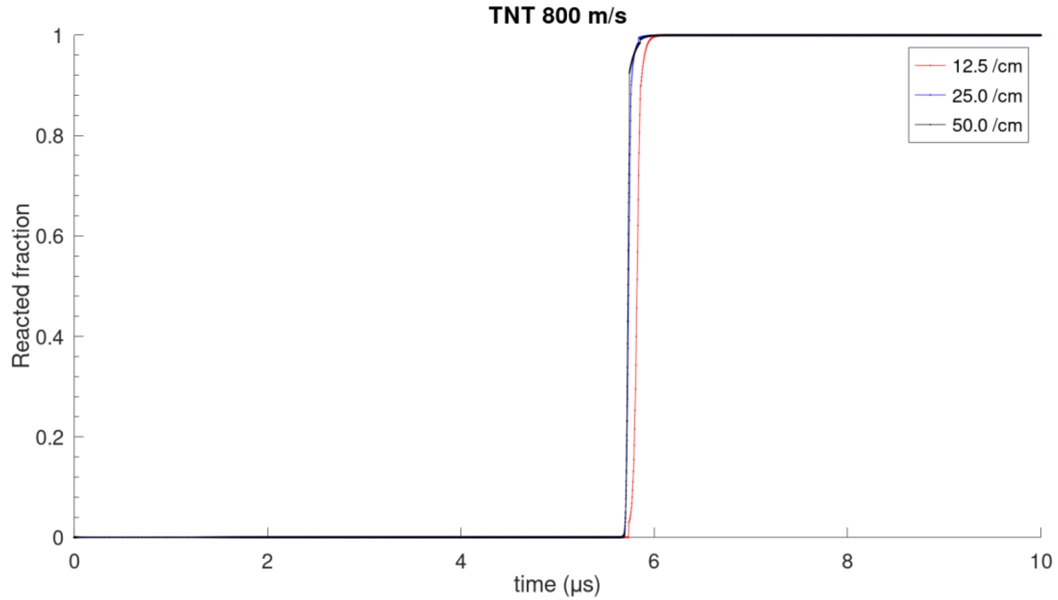
ALE3D results for IMX-101 with a flyer plate velocity of 1300 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The tracer indicates that IMX-101 is detonating at the time the reaction passes through it.

The results show very good agreement across the three levels of mesh resolution.

ALE3D 2D RESULTS TNT: 800 M/S IMPACT VELOCITY



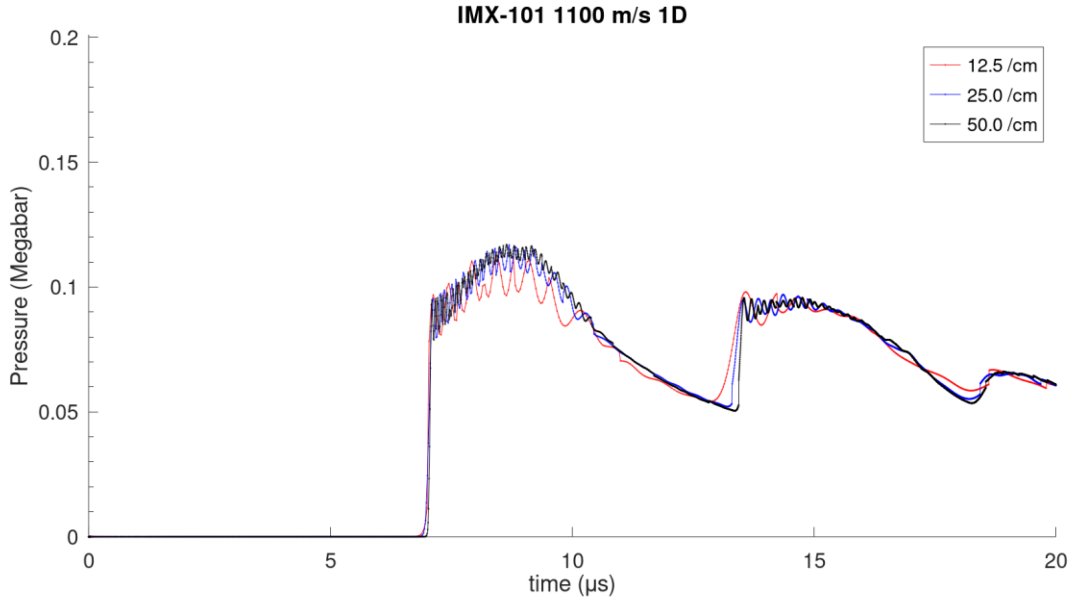


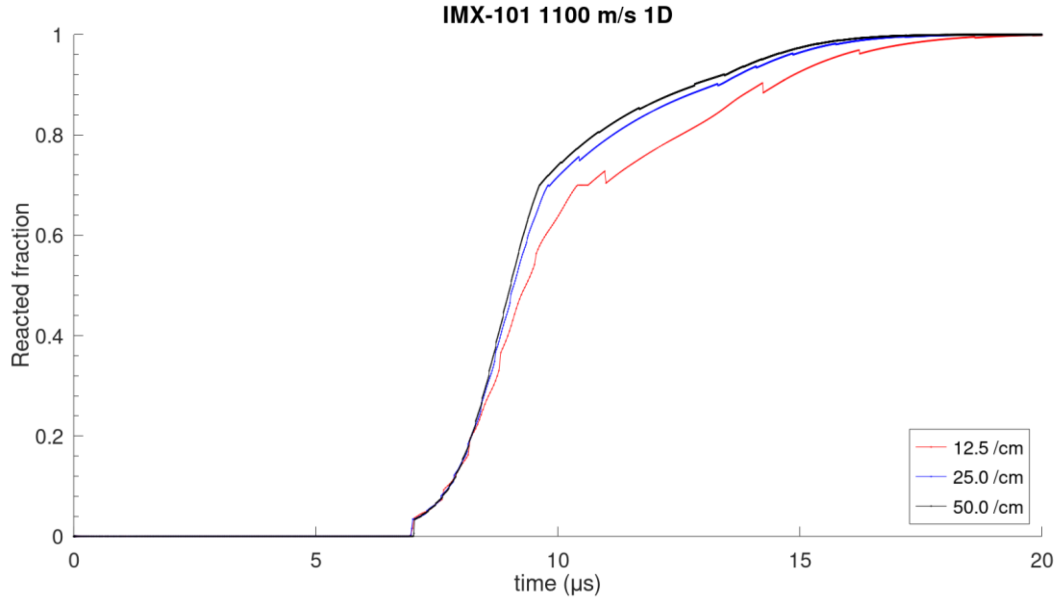
ALE3D results for TNT with a flyer plate velocity of 800 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The tracer indicates that TNT is detonating at the time the reaction passes through it.

At 12.5 elements/cm, the magnitude of the shock wave is not well captured. The time of arrival of the shock wave differs by approximately 50 nanoseconds. At a resolution of 25 elements/cm the solution is much improved.

ALE3D 1D RESULTS IMX-101: NEAR GO/NO-GO LIMIT



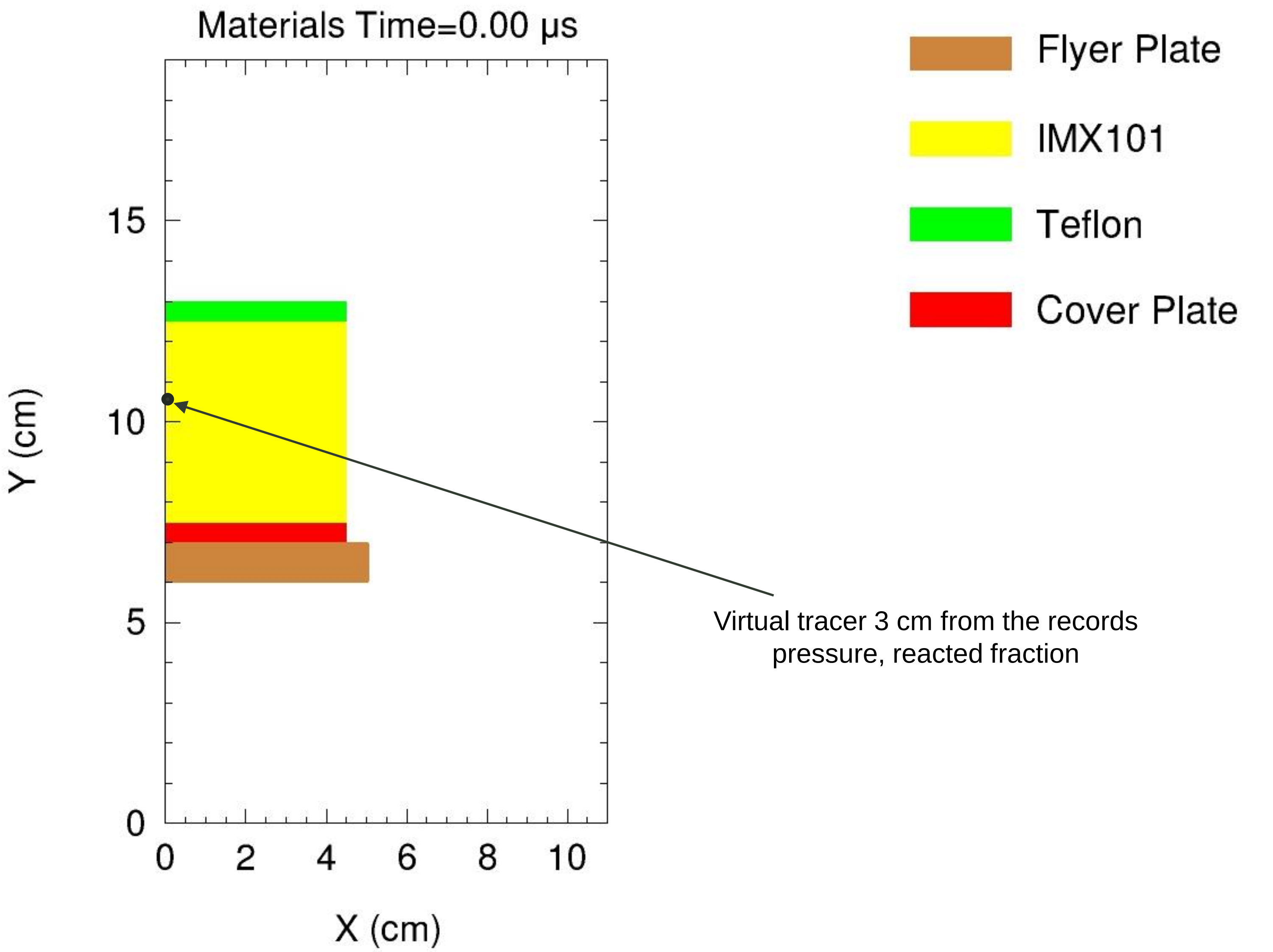


ALE3D results for IMX-101 with a flyer plate velocity of 1100 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

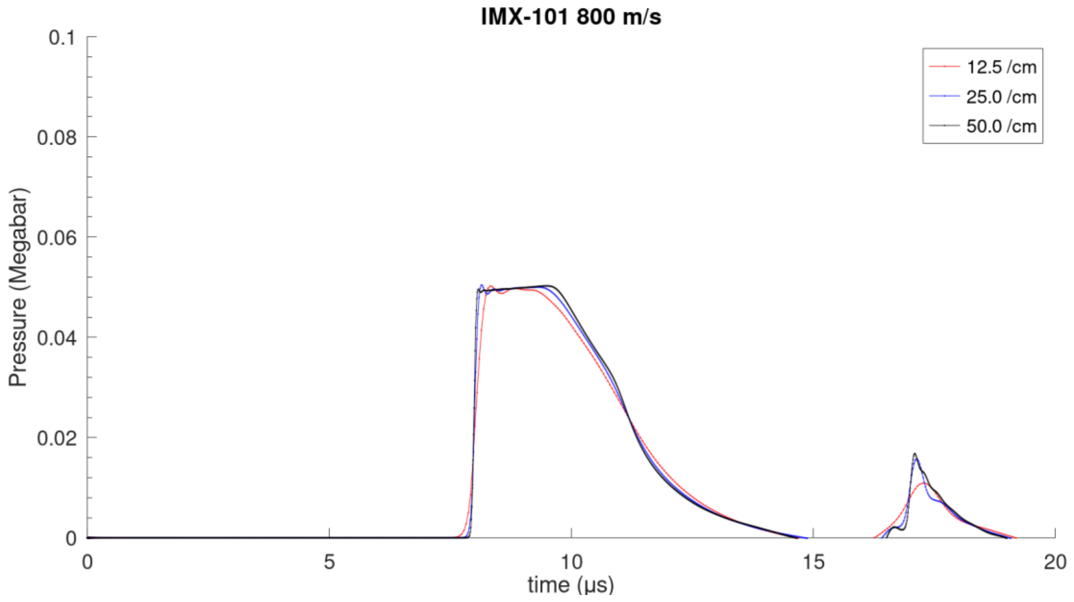
This relatively weak stimulus results in a slow but complete reaction. At 12.5 elements/cm the solution is clearly under resolved. At 25 elements/cm the solution is much improved as it approaches mesh independence.

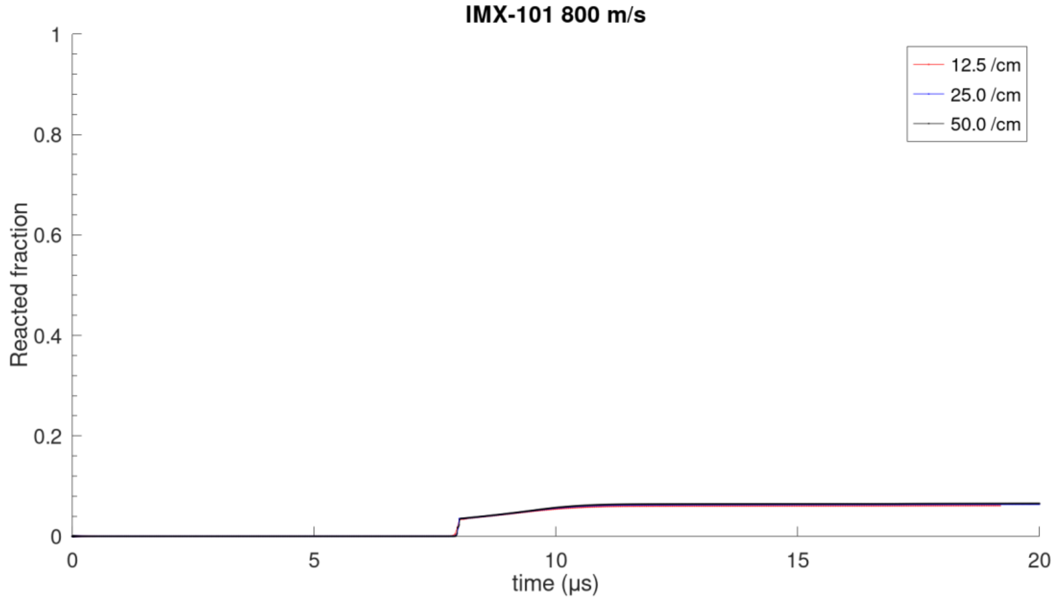
2D FLYER PLATE SETUP CTH

- Flyer plate, cover plate are 4340 steel
- HE is TNT or IMX-101
- Axisymmetric @ x=0 boundary
- Outflow on all other boundaries
- Flyer plate is prescribed an initial velocity [800-1800m/s]
- Pressure and reacted fraction are traced in the HE.
- Three mesh resolutions: 12.5, 25, 50 elements/cm



CTH 2D RESULTS IMX-101: 800 M/S IMPACT VELOCITY



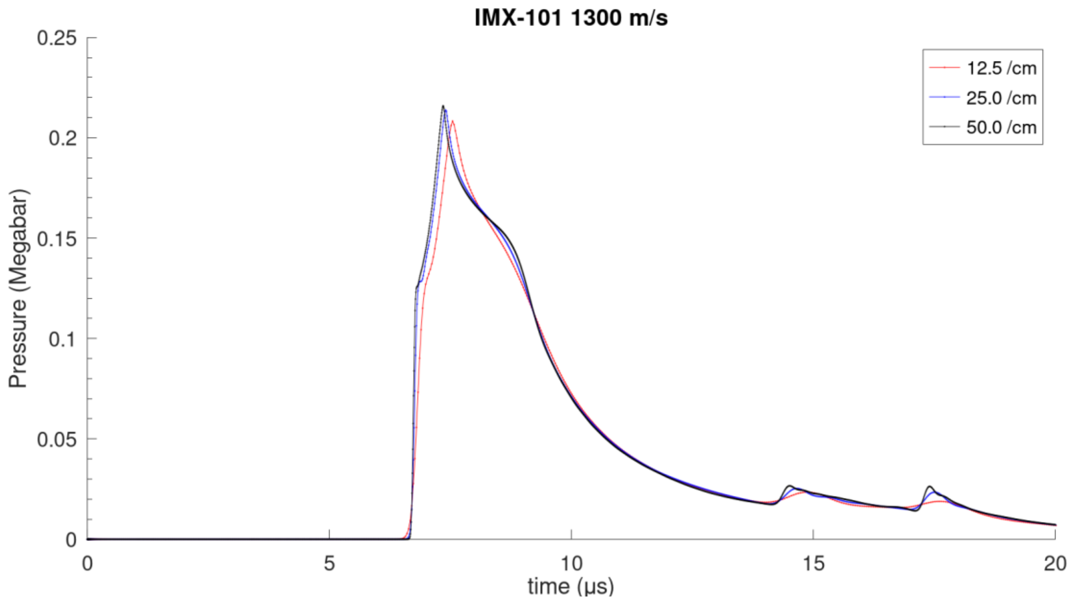


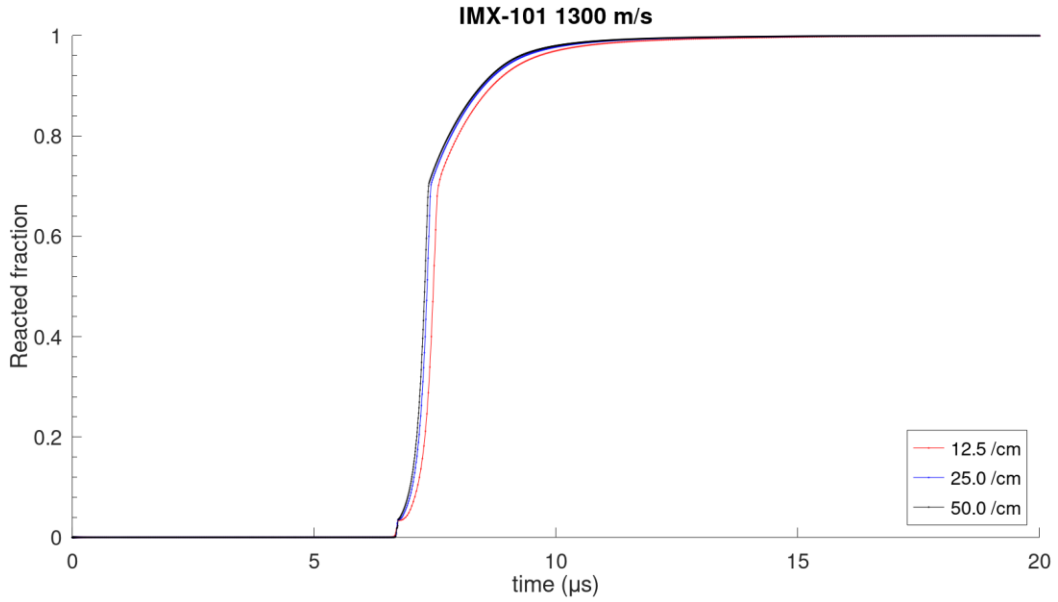
CTH results for IMX-101 with a flyer plate velocity of 800 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The extent of reaction is small with this flyer plate velocity.

The solution at 25 elements/cm is very close to the solution at 50 elements/cm.

CTH 2D RESULTS IMX-101: 1300 M/S IMPACT VELOCITY

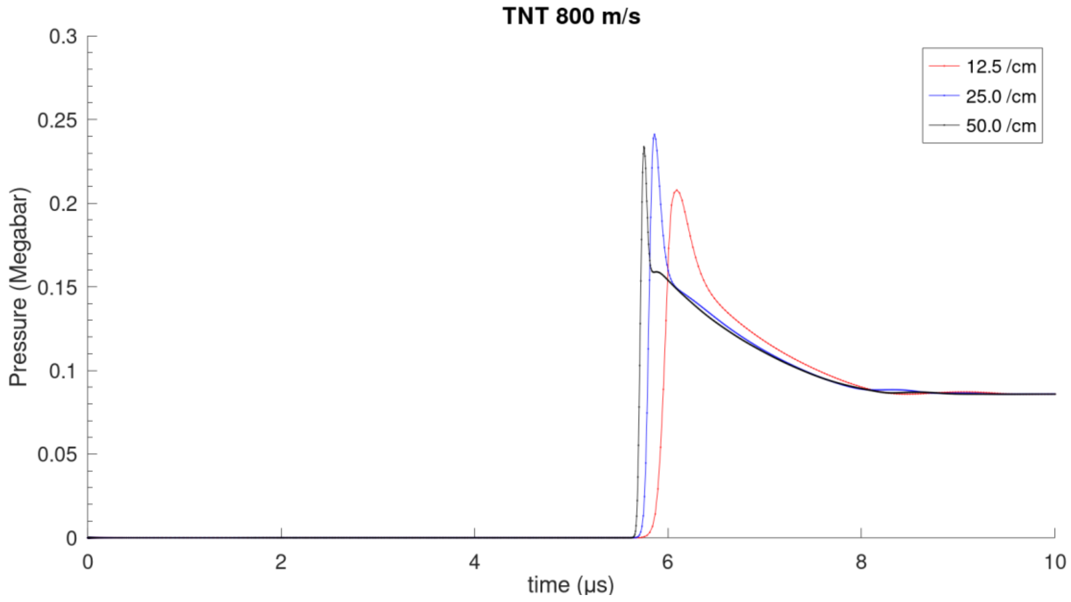


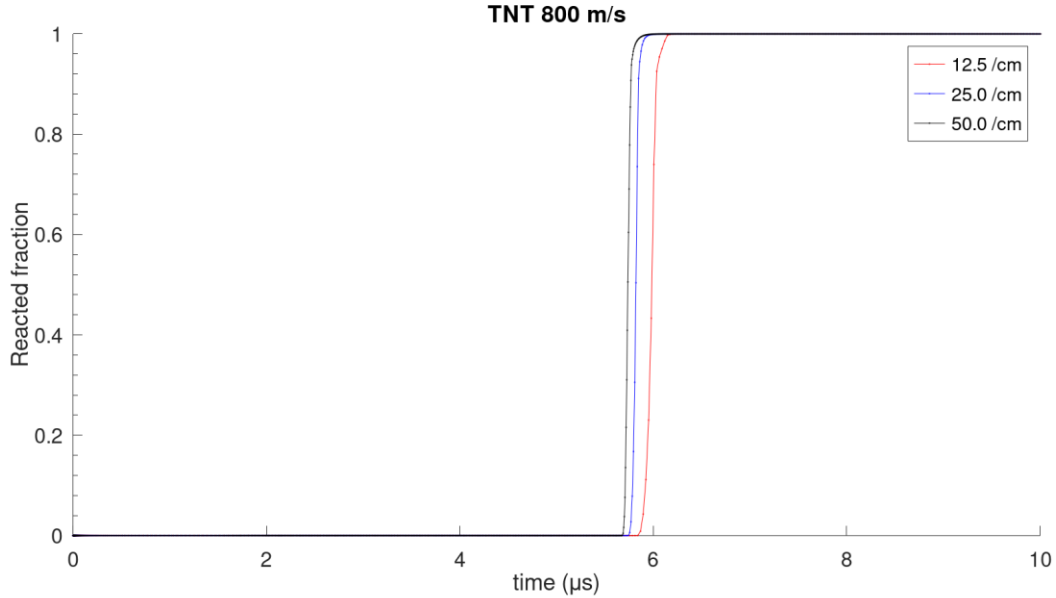


CTH results for IMX-101 with a flyer plate velocity of 1300 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The tracer indicates that IMX-101 is detonating at the time the reaction passes through it.

CTH 2D RESULTS TNT: 800 M/S IMPACT VELOCITY





CTH results for TNT with a flyer plate velocity of 800 m/s. A virtual tracer records pressure and reacted fraction at a location 3 cm from the leading edge of the initial shock.

The tracer indicates that IMX-101 is detonating at the time the reaction passes through it.

At 12.5 elements/cm, the magnitude of the shock wave is not well captured. The time of arrival of the shock wave differs by approximately 100 nanoseconds. At 25 elements/cm the solution is much closer to mesh independence.

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CONCLUSIONS

- **Reactive flow modeling literature recommends using very high mesh resolutions for I&G likely because:**
  - Model development and validation requires very low relative error.
  - Differences between hydrocodes can affect solution mesh dependence.

- **I&G can provide useful information quickly in some instances using lower-than-recommended mesh resolutions**
  - Very high resolution may not be necessary for certain applied problems.
- **A mesh resolution of approximately 25 elements/cm was determined to provide a good tradeoff between mesh economy and solution accuracy.**

- **Solutions obtained using CTH and ALE3D agreed very well with each other.**
  - CTH is probably the better approach for this problem because its 3D adaptive mesh refinement capabilities allow faster problem generation.

- **Questions?**
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  - Dr. Paritosh Dave, Senior Program Manager, Leidos

BACKUP SLIDES

I&G MODEL

Ignition | Growth Gas | Growth Solid

$$\frac{dF}{dT} = I(1-F)^b\left(\frac{\rho}{\rho_0} - 1 - a\right)^x + G_1(1-F)^c F^d p^y + G_2(1-F)^e\, F^g p^z$$

Ignition: Represents the creation of hot spots from compression of voids

Typically turns off when F reaches ~0.03-0.04

Growth Gas: Represents the growth of nascent hot spots, rapid formation of product gasses

Typically turns off when F >~0.7-0.9

Growth Solid: Represents slow formation of solid particles

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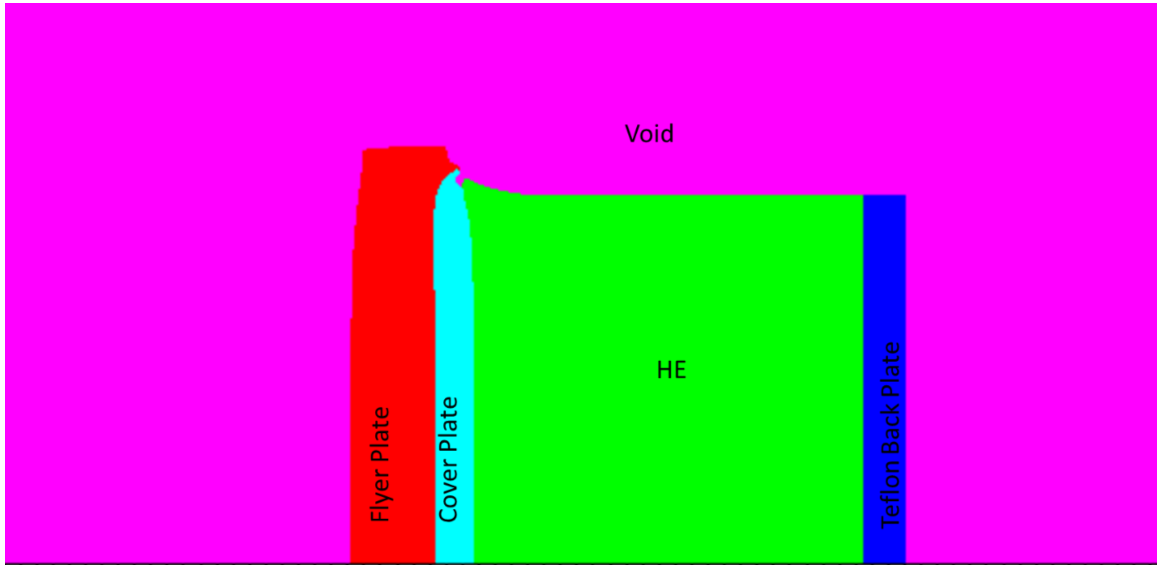
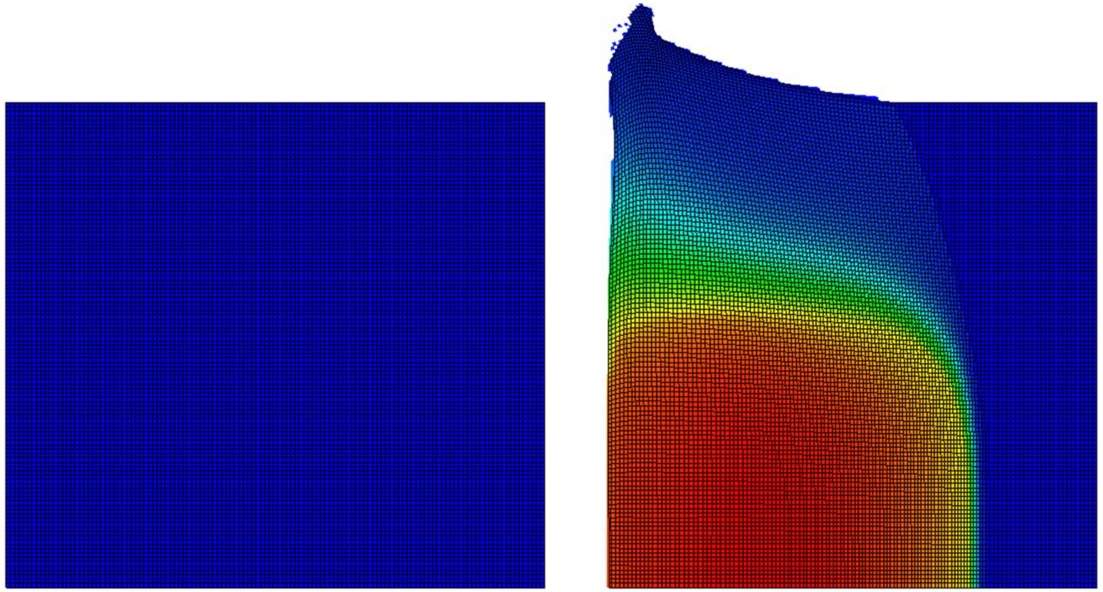
ALE3D





ALE3D solution of IMX-101, v=1300 m/s at 3.1 μs. Note the distortion of the flyer and cover plates

ALE3D solution of IMX-101, v=1300 m/s at 0 (left) and 8.1 μs (right). The Lagrangian nature of the solution causes slight mesh concentration in the x direction.

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