Malcolm Baldrige National Quality Award 2007 Award Recipient

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
PICATINNY ARSENAL, NJ

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Modeling Explosive Cladding of Metallic Liners to Gun Tubes

Jack M. Pincay, Dr. Ernest L. Baker, and David G. Pfau

26th International Symposium on Ballistics

Unlimited Release

Explosive Cladding Modeling

- Objective: Develop and demonstrate modeling for explosive barrel cladding process design and optimization.
- Approach: Physically model the process of barrel liner cladding.
  - High Explosive Behavior
  - Full scale liner cladding behavior
  - Subscale clad welding dynamics
  - Modeling development , Cladding process design, and optimization.
  - Initial Gun Modeling and Momentum Trap Modeling
- Conclusion

High Explosive Behavior

- **Original Approach (standard)**
  - Thermochemical EOS: JAGUAR
  - Thermodynamic EOS: JWLB
  - Standard method produced poor agreement to detonation velocity of TPL low density low detonation velocity formulations
- **Current Empirical Approach (BondEx-A, D2)**
  - Experimental detonation velocity
  - Empirical gurney velocity relationship
  - Empirically scaled energy output vs. volume expansion
  - Use analytic cylinder and nonlinear optimization to parameterize JWL and JWLB equations of state
- **Desired Empirical Approach**
  - New formulation (reproducible known ingredients)
  - ARDEC cylinder tests (Ta and Cu cylinders)

Cylinder Velocity

ANALYTIC CYLINDER MODEL

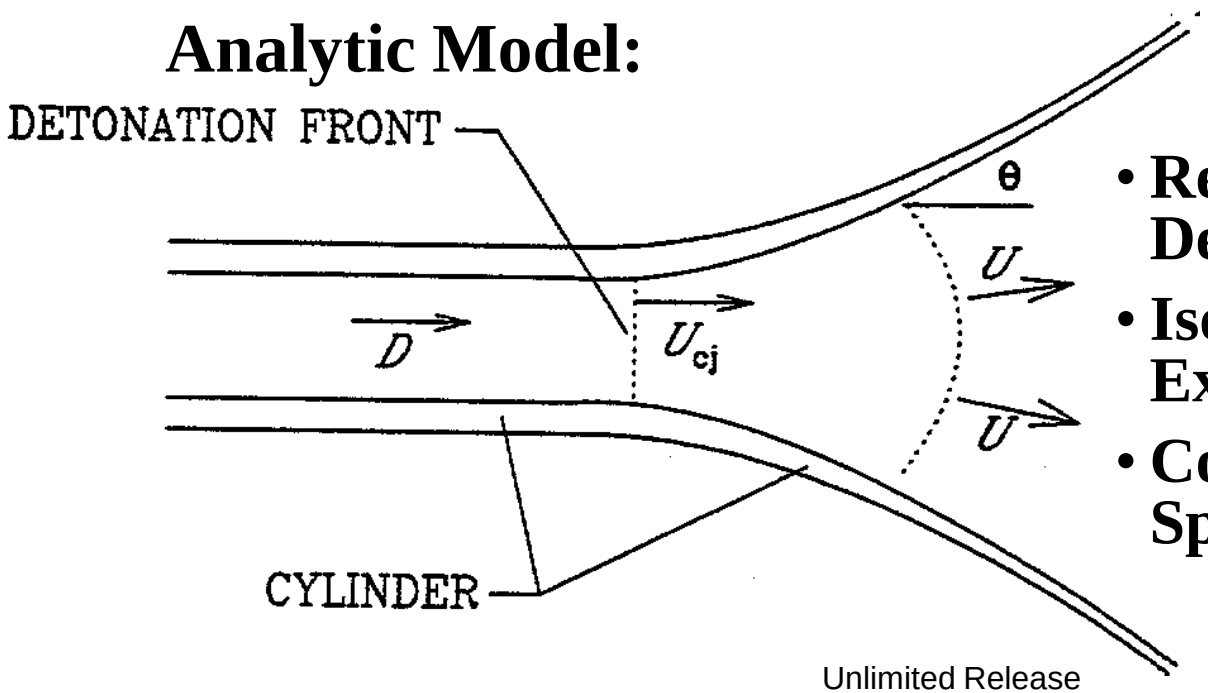
JWLB Equation of State:

$$P = \sum_i \mathrm{A}i\left(1 - \frac{\lambda}{\mathrm{R}iV^*}\right)e^{-\mathrm{R}iV^*} + \frac{\lambda E}{V^*} + \mathrm{C}\left(1 - \frac{\lambda}{\omega}\right)V^{*-(\omega+1)}$$

Gruneisen Parameter:

$$\lambda \equiv \sum\left(\mathrm{A}\lambda\mathrm{i}V^* + \mathrm{B}\lambda\mathrm{i}\right)e^{-\mathrm{R}\lambda i V^*} + \omega$$

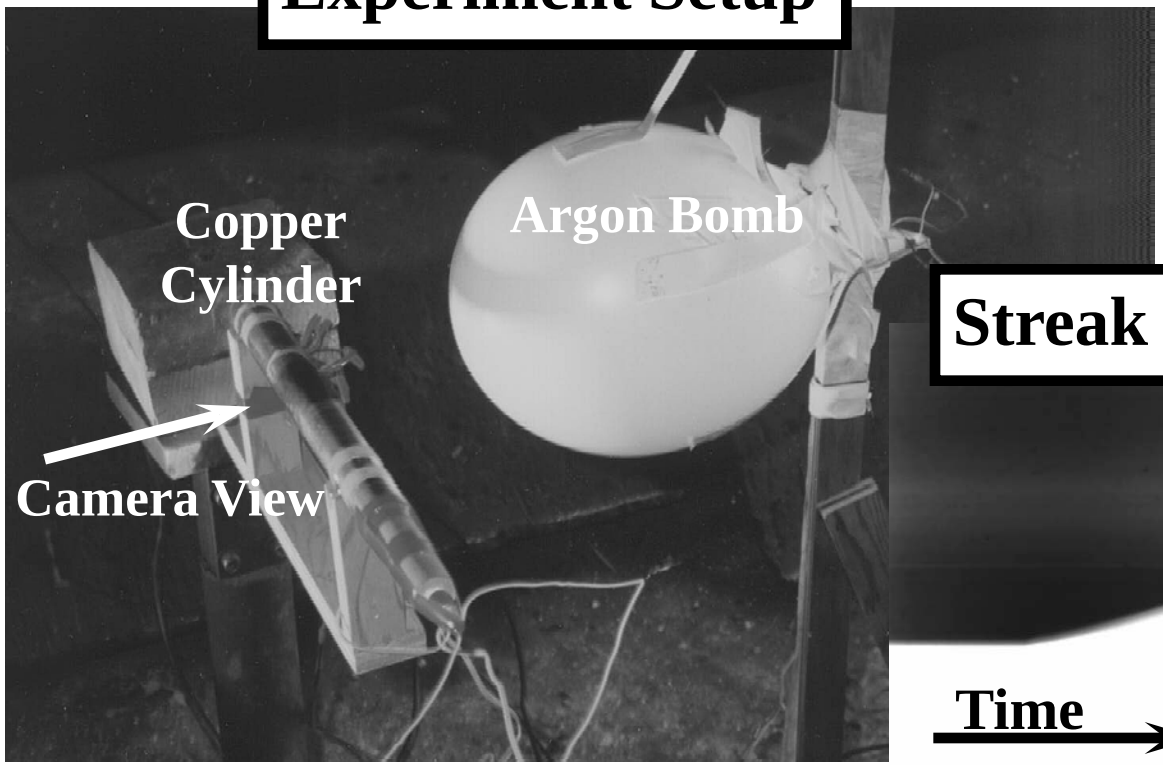
Analytic Model:



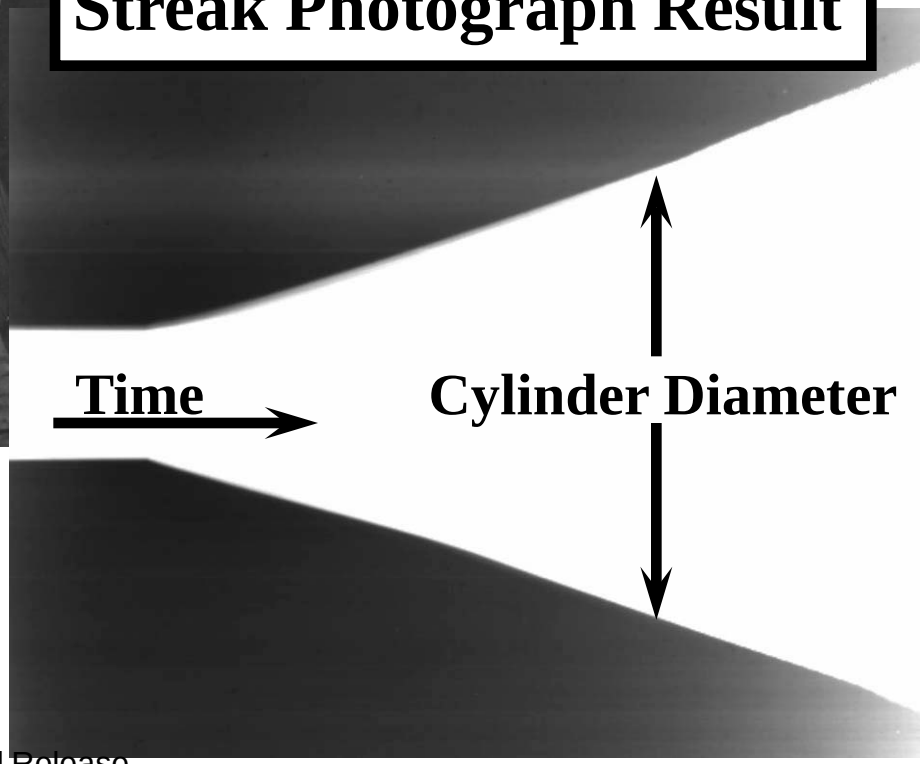
- **Reference Frame at Detonation Velocity**
- **Isentropic Products Expansion**
- **Constant Properties Along Spherical Surfaces**

ARDEC CYLINDER TEST

Experiment Setup



Streak Photograph Result



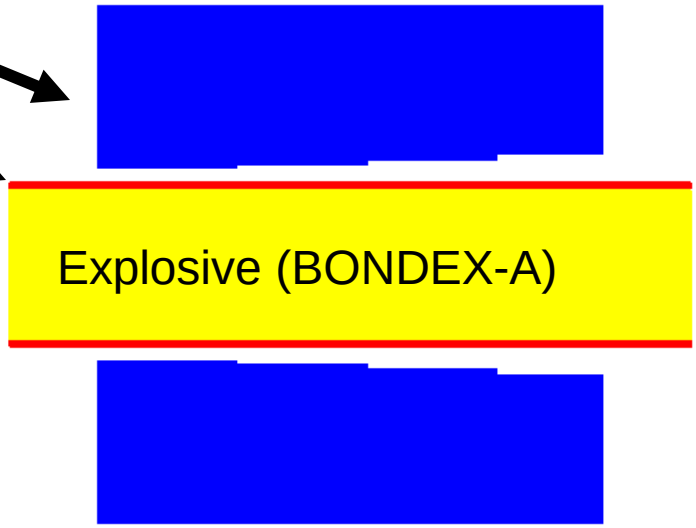
Explosive Cladding

Macro Scale Behavior

Step Test for Development (based on TPL input)

Steel Stepped Cylinder

Cladding Cylinder



CTH currently being used for modeling due to advanced ZA strength model

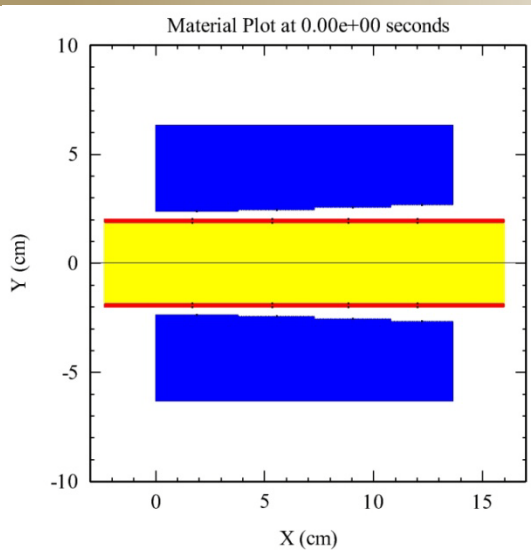
Steel Issues: 25mm Bushmaster barrel is D6AC (no current material model)
current modeling using 4340
D6AC samples sent to LANL for Hopkinson bar/material model
Modeling using Zirelli-Armstrong (ZA) strength model

Cladding Cylinder issues: No high rate strength models for Ta-5W-2Mo or Stellite 25
Downselection from step tests will determine if required

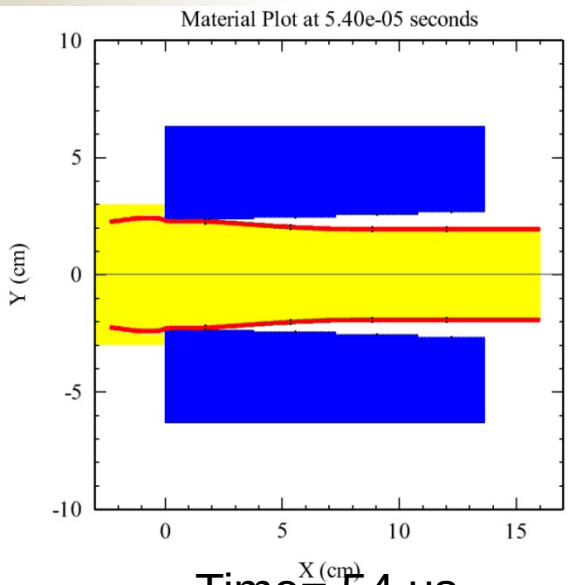
High Explosive Clad Setup

- CALE and CTH Trial runs performed
  - CTH downselected due to availability of advanced ZA strength model and parameters
- CTH Modeling
  - Tantalum as the cladding liner material.
  - Ta10W as the cladding liner material.
- Mesh Convergence Study
  - 1 mm mesh, .50 mm mesh, .25 mm mesh
- Macro-Analytic Comparison
  - Analytic Velocity Comparison
- Micro Clad welding Dynamics
  - 0.1 mm mesh

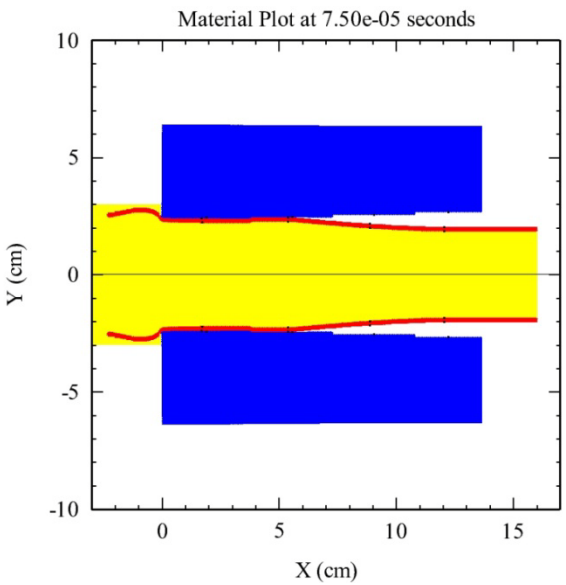
CTH Cladding Model



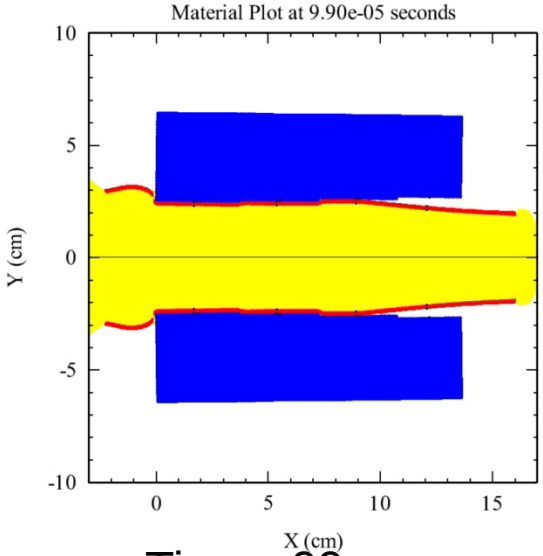
Initial State at Time=0 us



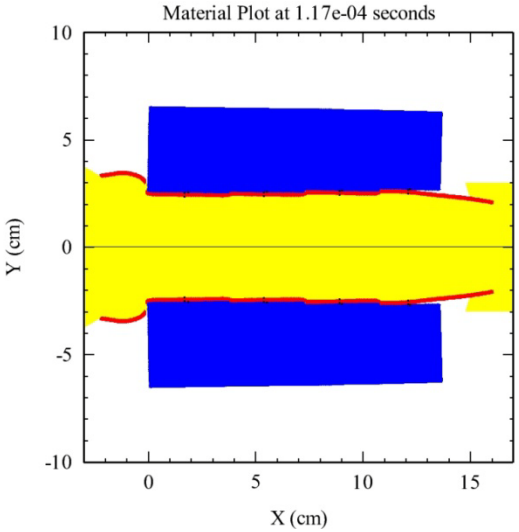
Time= 54 us



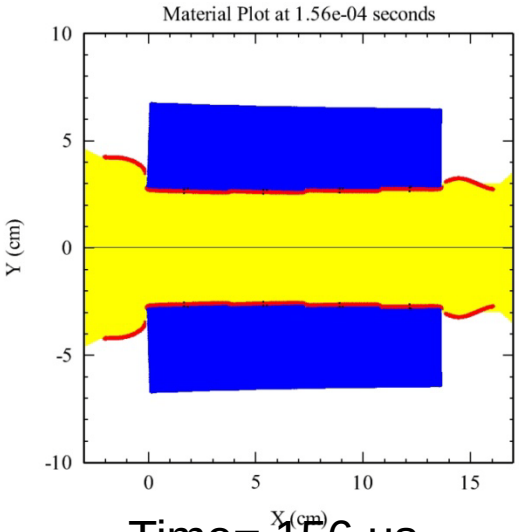
Time= 75 us



Time= 99 us

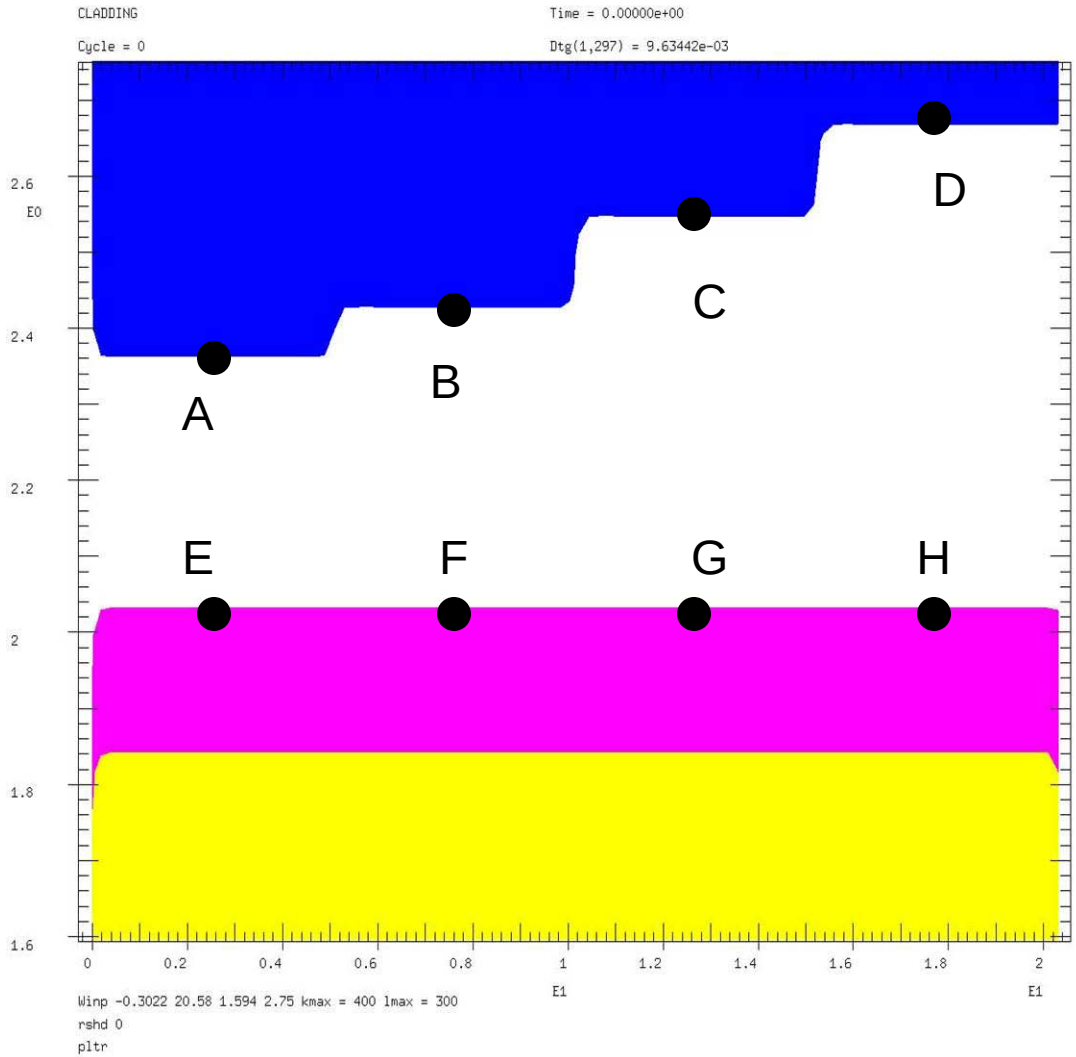


Time= 117 us



Time= 156 us

Simulation of Step Cladding

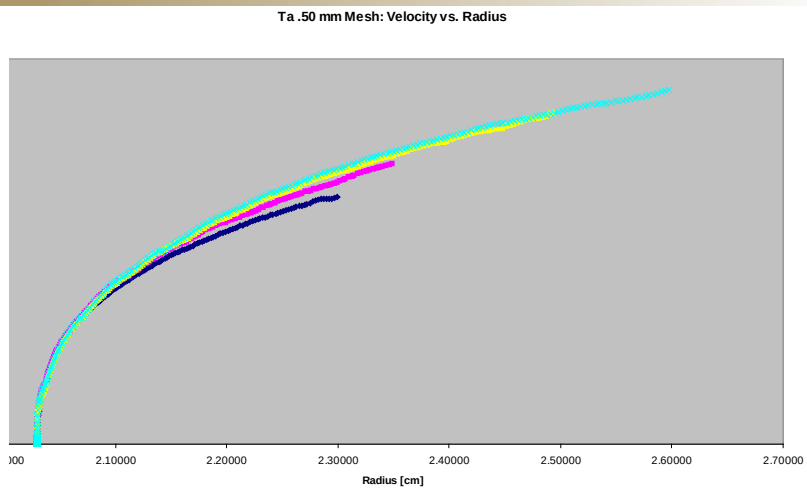


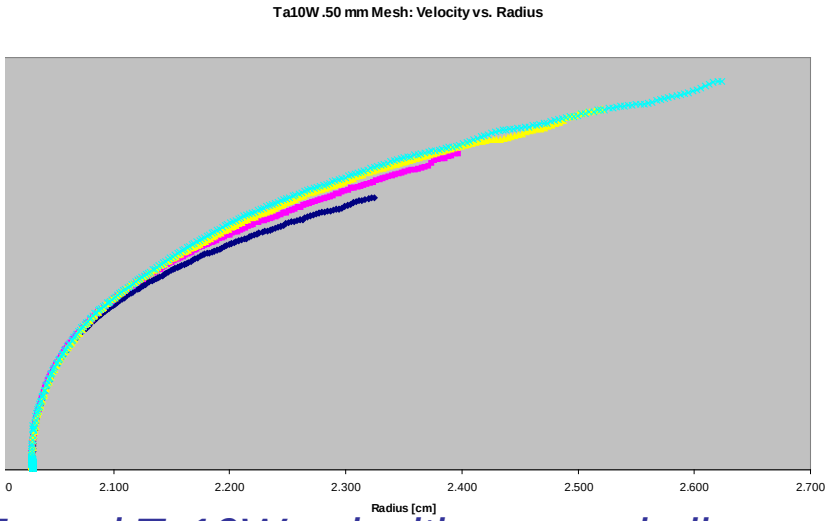
Tracer Particles were added to find velocities and pressures at the middle of each step as the tantalum is hitting the steel.

Particles A,B,C, and D are fixed on the location of the middle of each step.

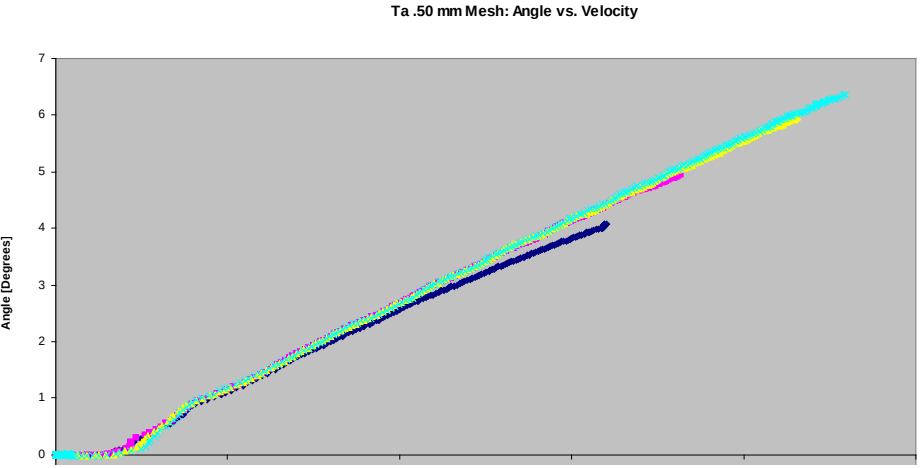
Particles E,F,G, and H are placed on the tantalum outer surface and move along with the tantalum material.

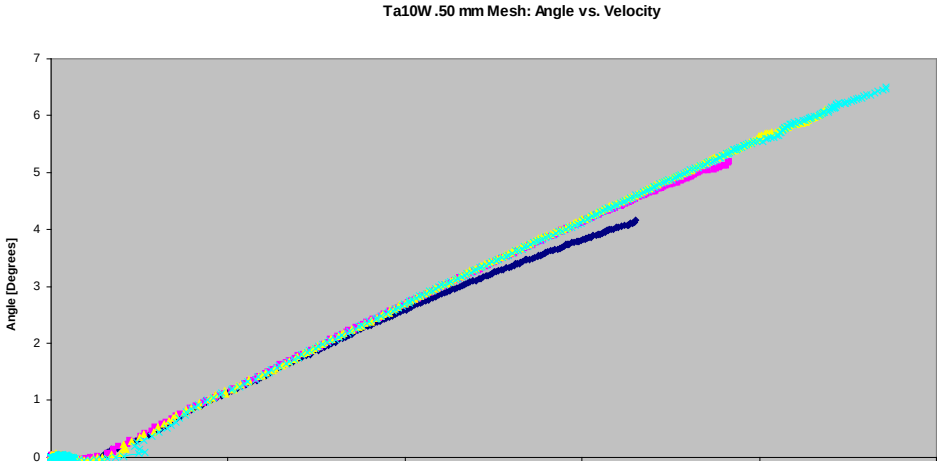
.50 mm Mesh Plot





Cladding cylinder accelerates until impact Ta and Ta10W velocities very similar



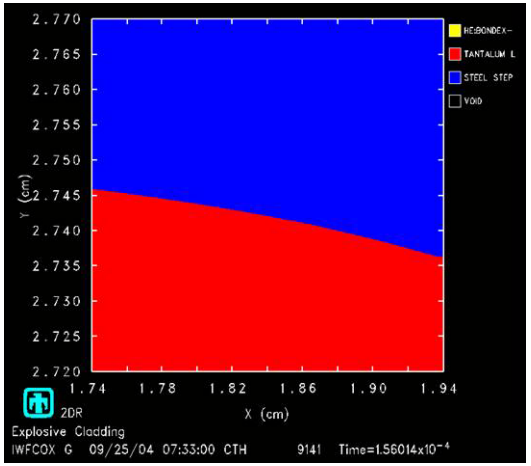


Cylinder angle increases with velocity until impact Linear angle vs. cylinder velocity (Taylor relationship)

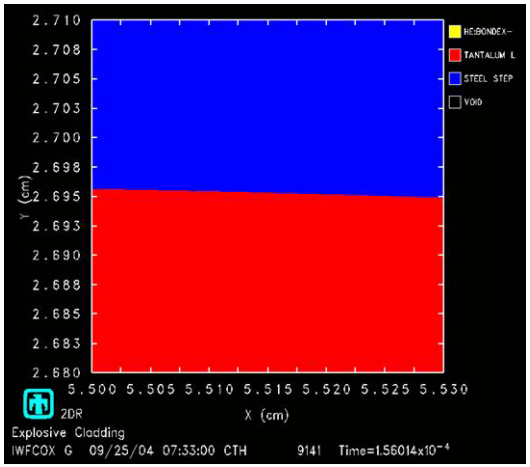
Macro Scale Cladding Interface Behavior

.25 mm Mesh Ta Plot Interface

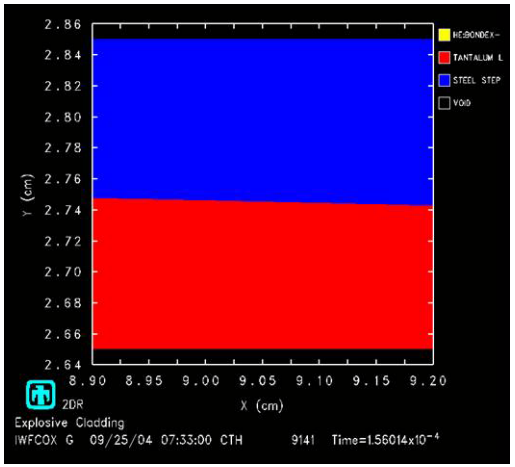
First Step Cladding is close to an arc.



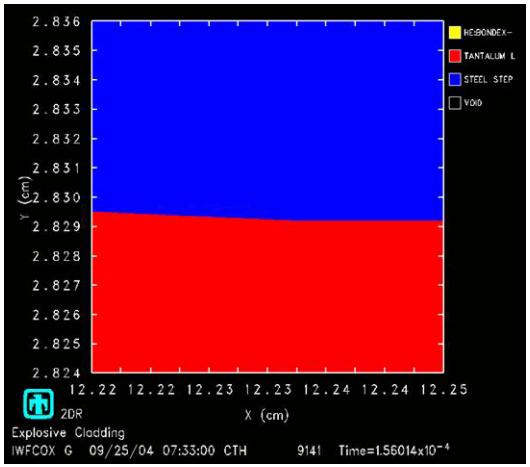
Second Step Cladding is close to a small arc.



Third Step Cladding is close to a small arc .

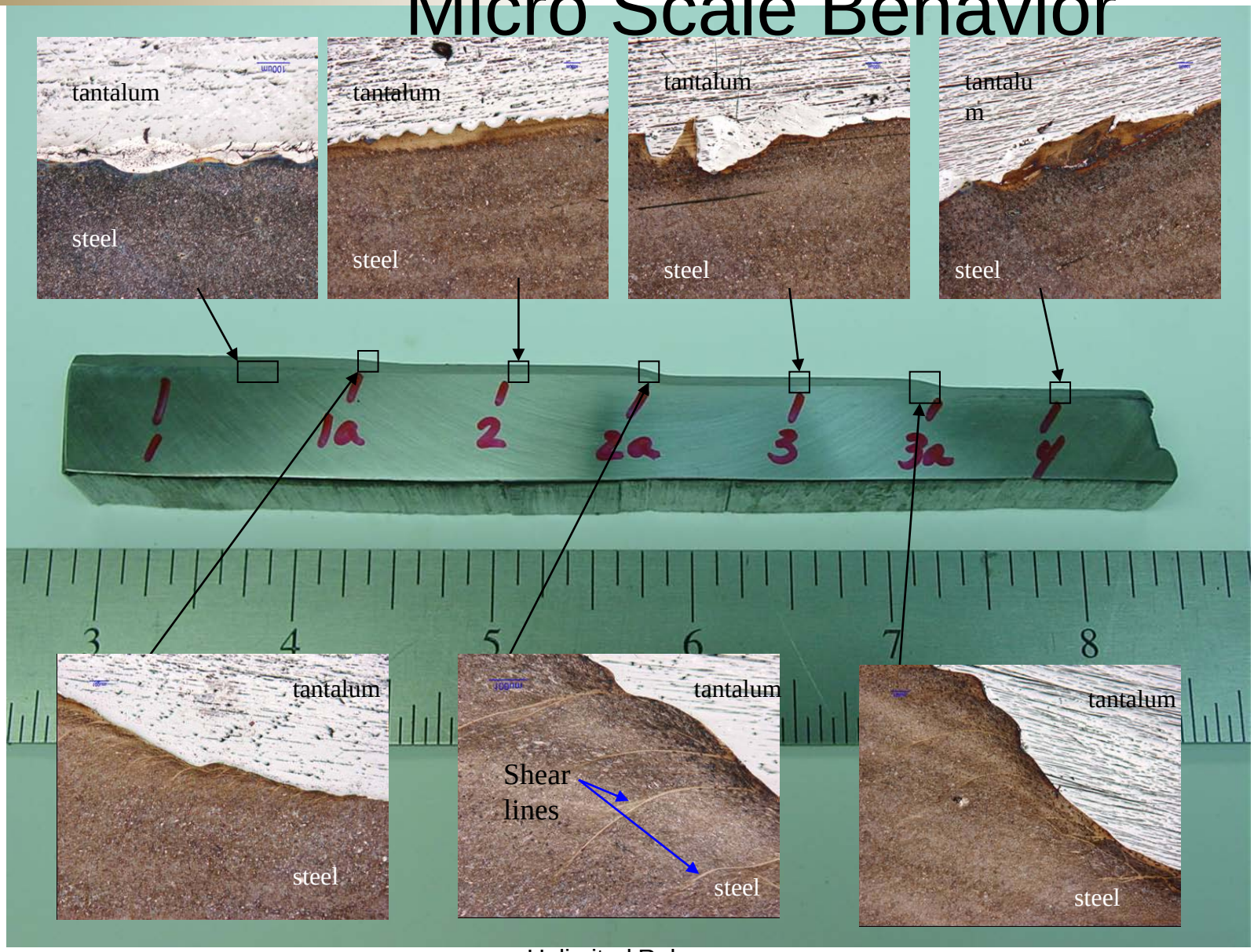


Forth Step Cladding is close to an arc.



Full macro scale dynamics are fairly well resolved using a .50mm mesh

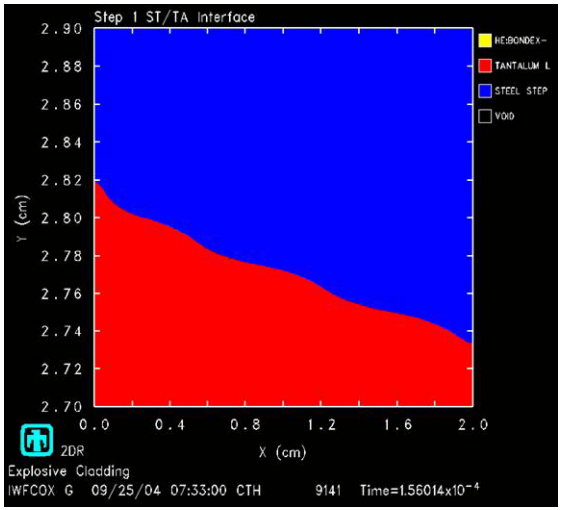
Explosive Cladding Micro Scale Behavior



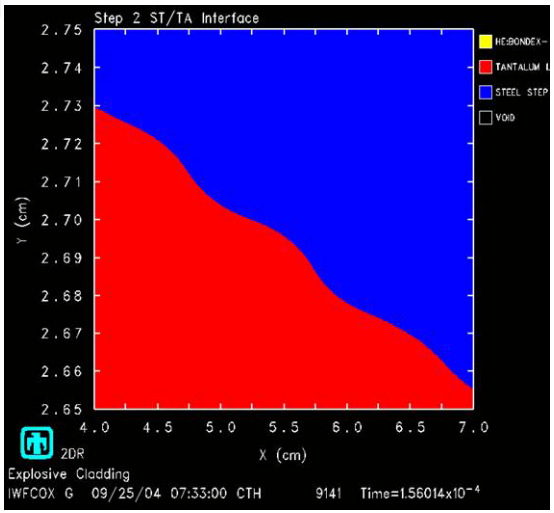
Micro Scale Cladding Interface Behavior

Ta .1 mm Mesh

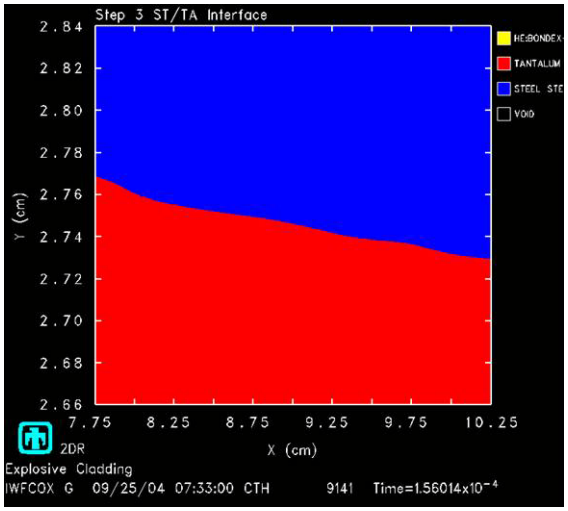
Step 1



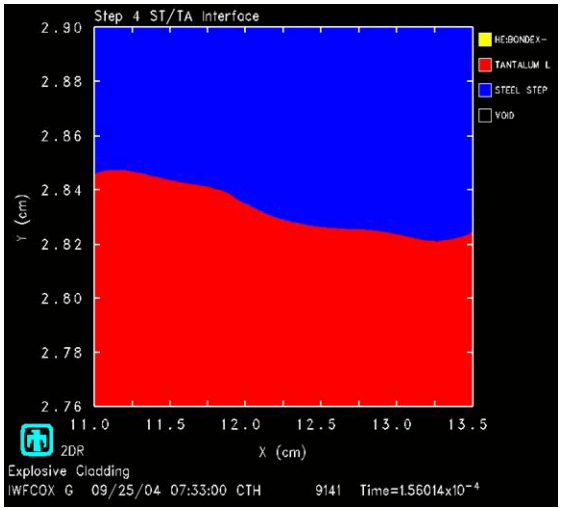
Step 2



Step 3



Step 4

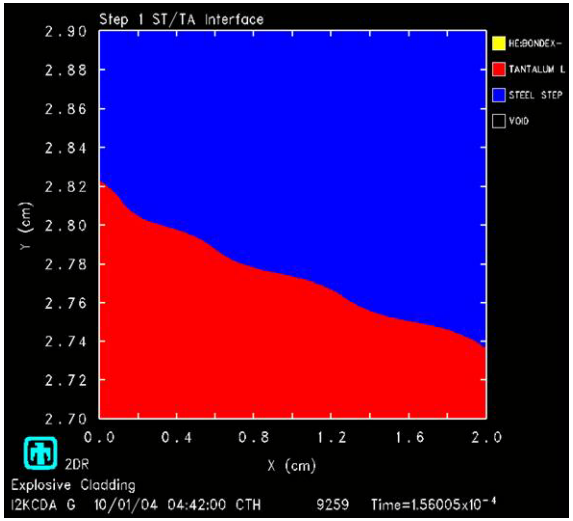


~.30mm interface wavelength identified from fine scale modeling
Hints of undesirable behavior at Step 4?

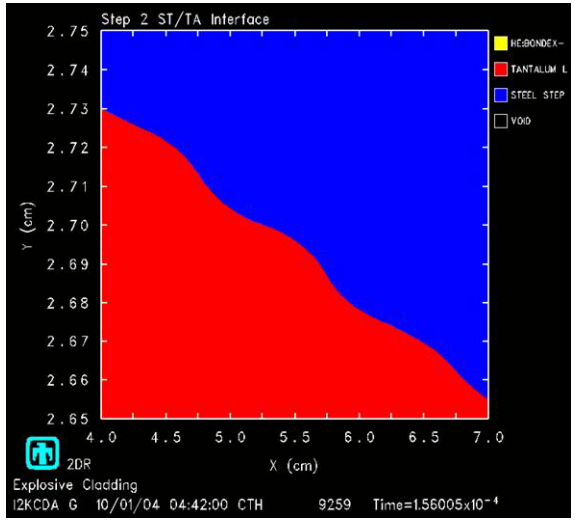
Micro Scale Cladding Interface Behavior

Ta10W .1 mm Mesh Interface

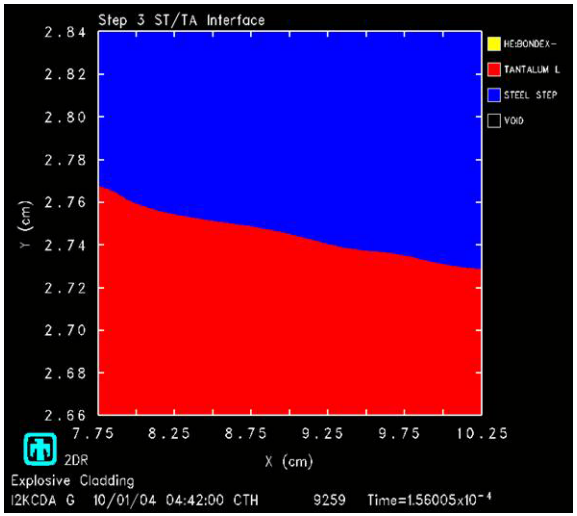
Step 1



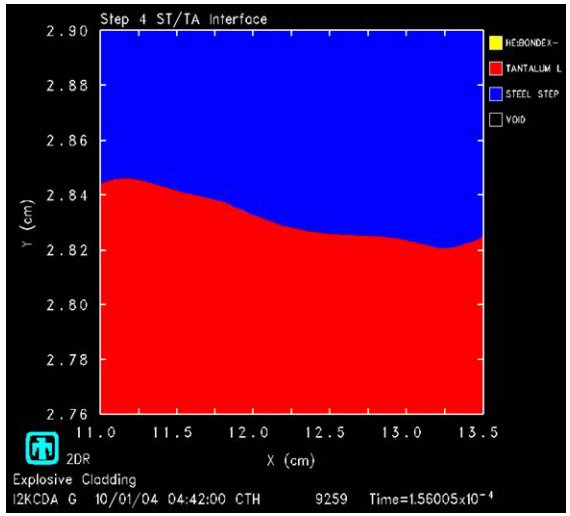
Step 2



Step 3



Step 4

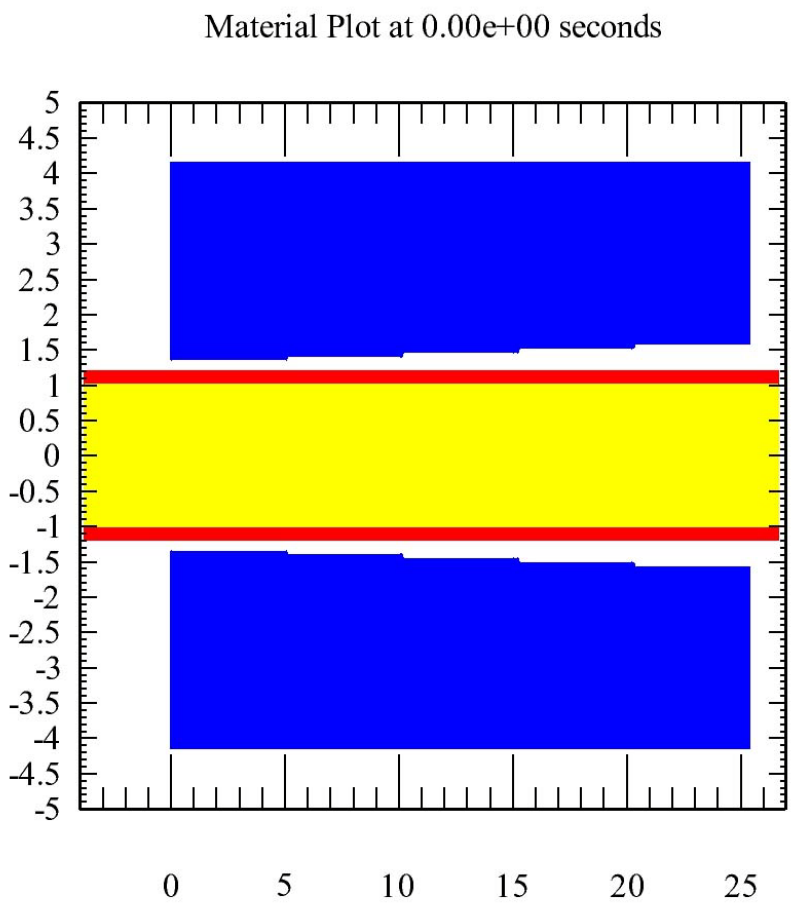


Ta and Ta10W results very similar
Further micro-scale modeling warranted

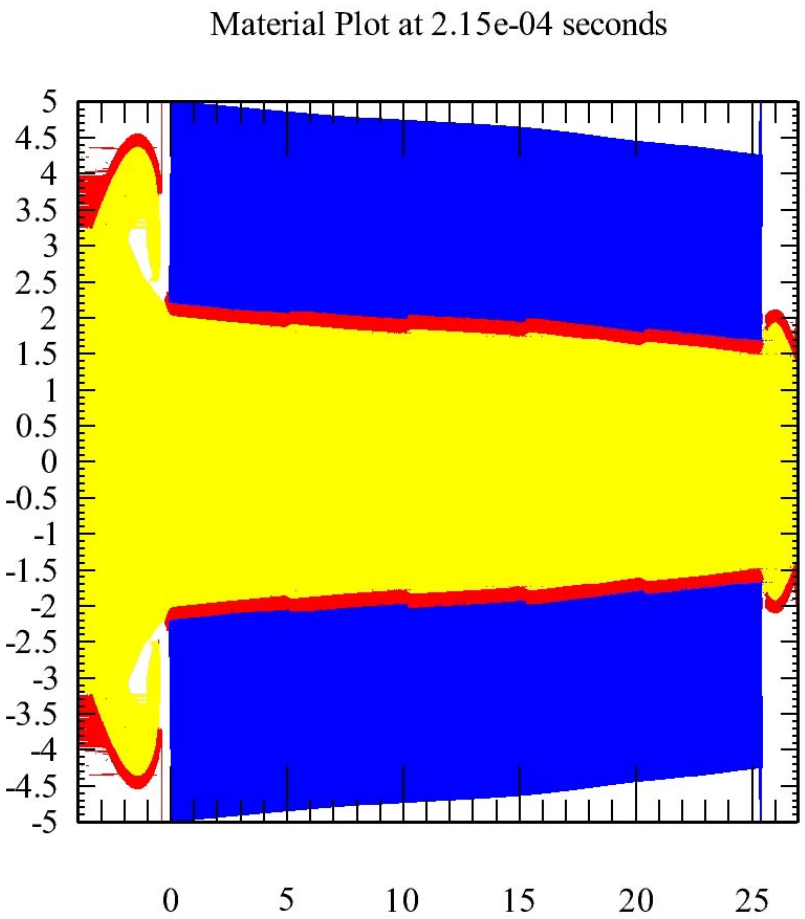
New Geometry Setup

- BondEx-D2 was used instead of BondEx-A for the explosive
- Five Steps instead of Four Steps
- .95in Geometry has a .95in tantalum outer diameter with .075in thickness
- 1in Geometry has a 1in tantalum outer diameter with .060in thickness

.95 in Tube Geometry

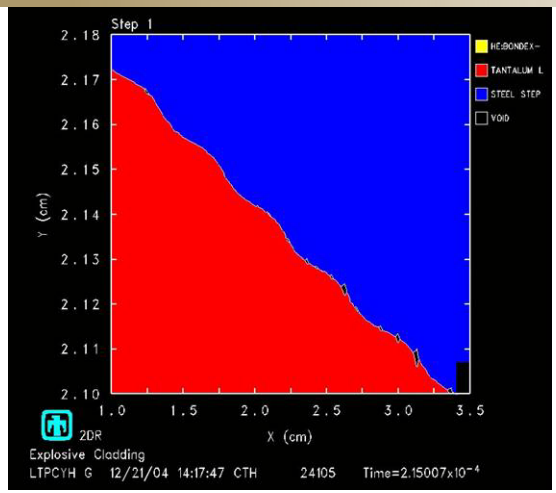


Time 0 us: Initial State

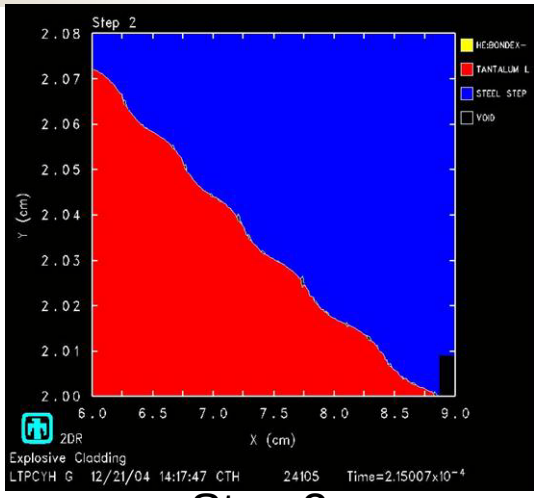


Time 215 us: Cladding Complete

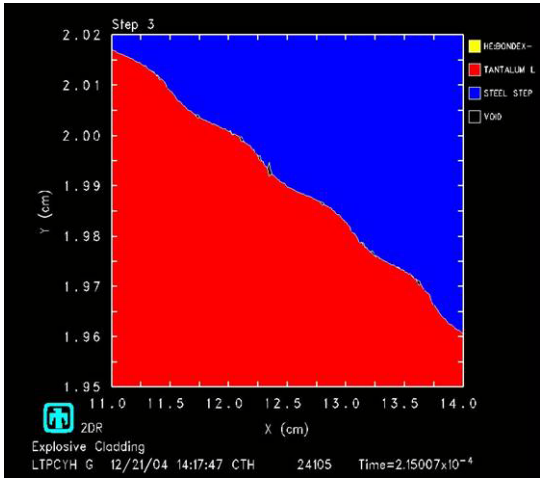
.95in Tube Ta Plot Interface



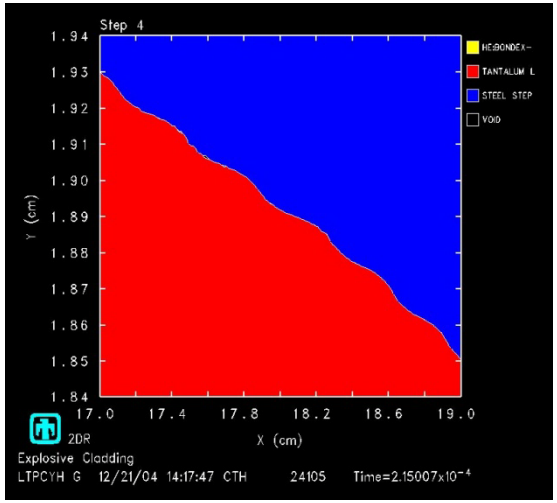
Step 1



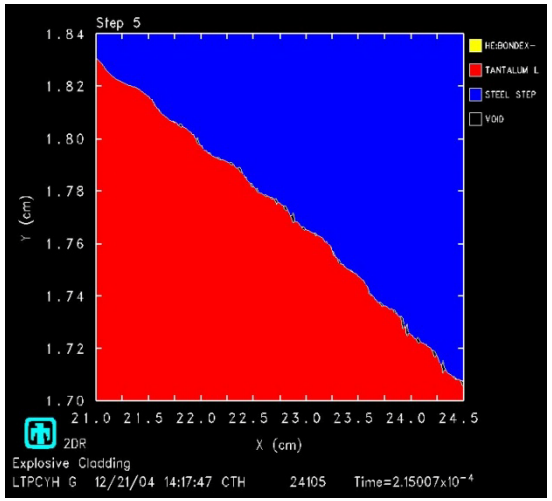
Step 2



Step 3

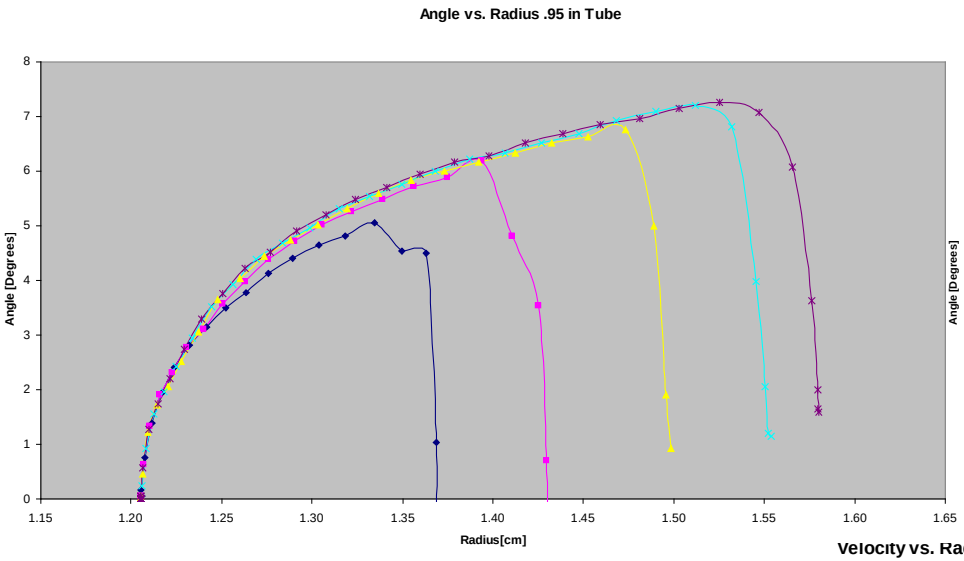


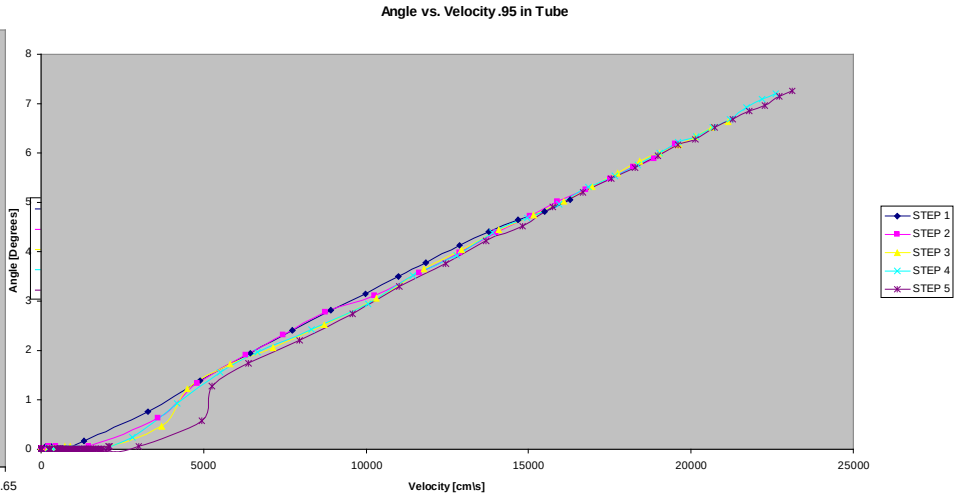
Step 4

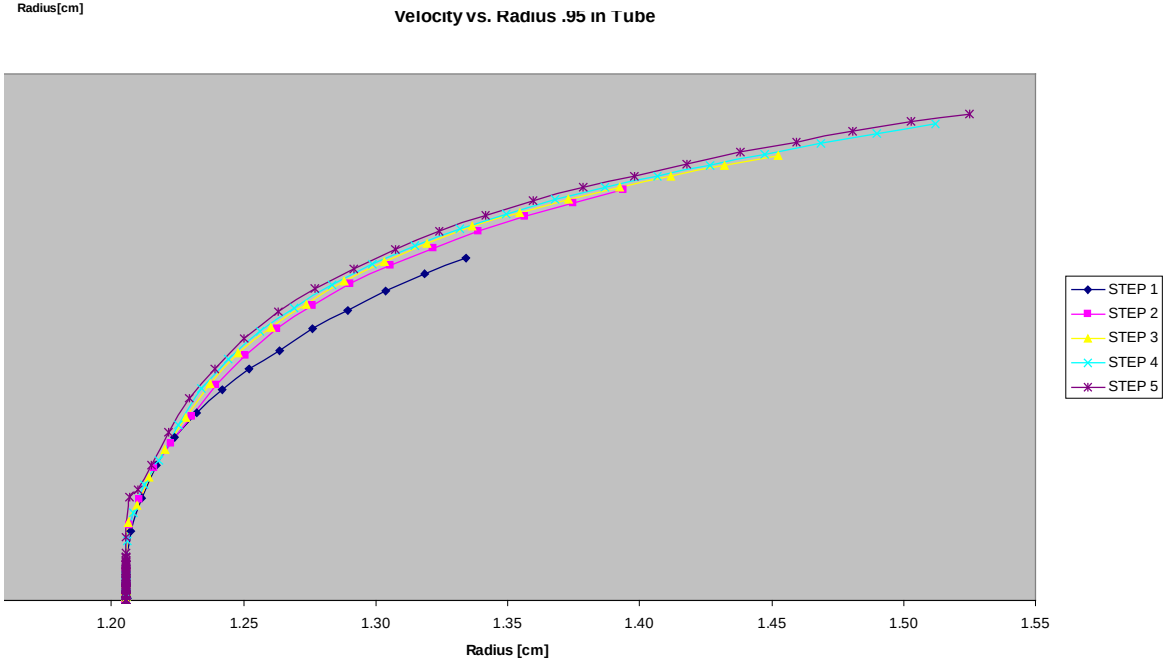


Step 5

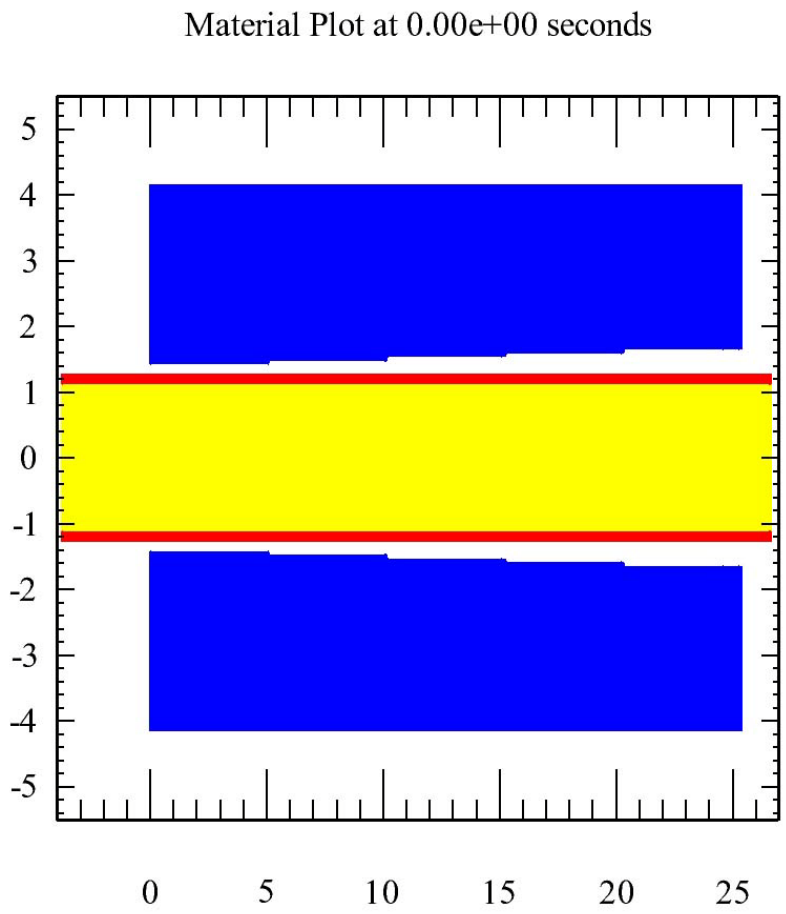
.95in Tube Plots



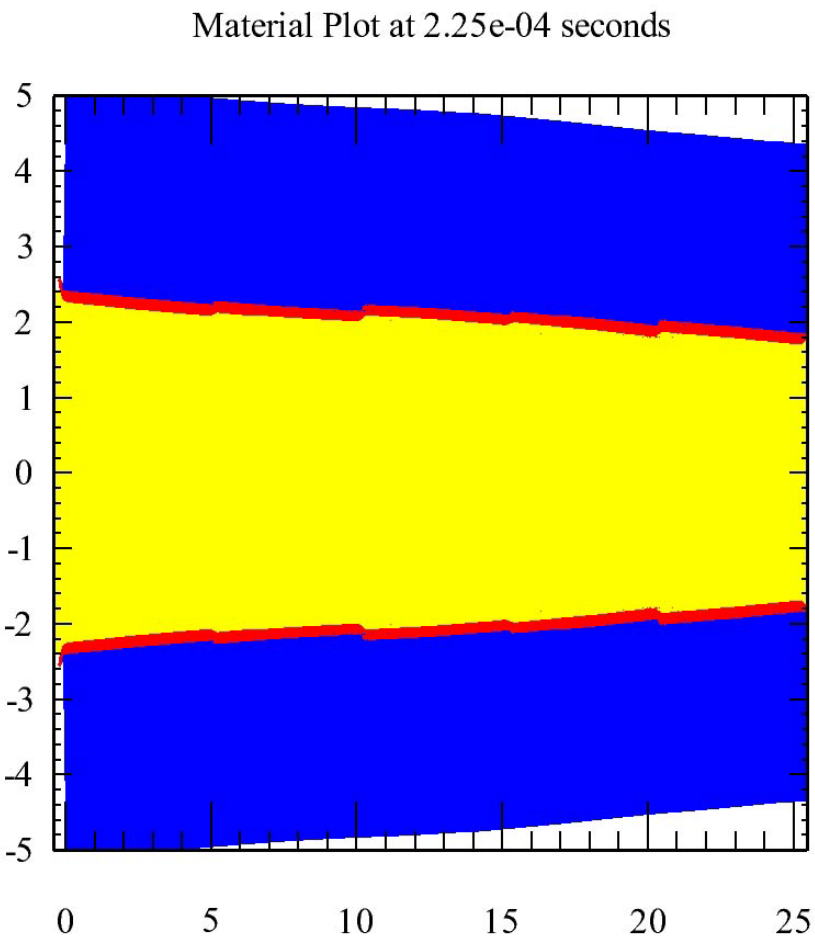




1in Tube Geometry

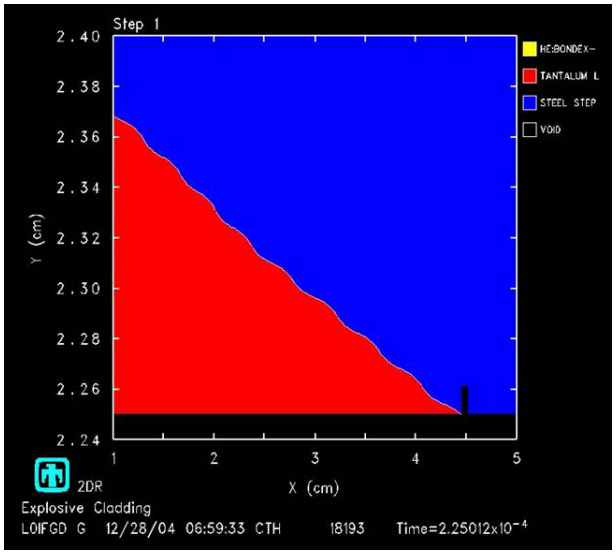


Time 0 us: Initial Setup

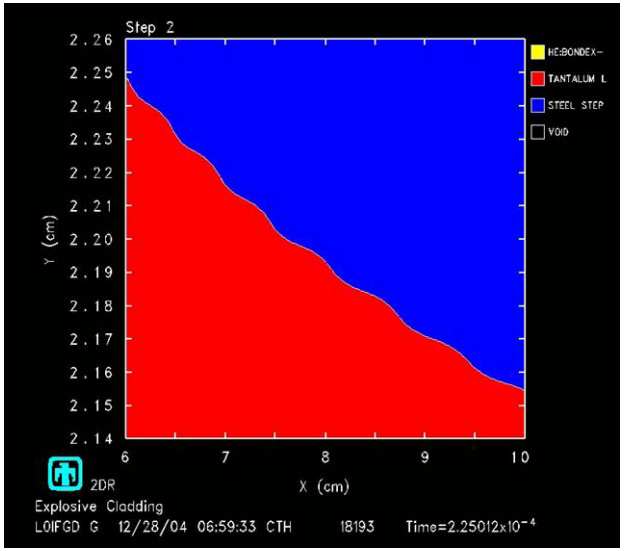


Time 225 us : Cladding Completed

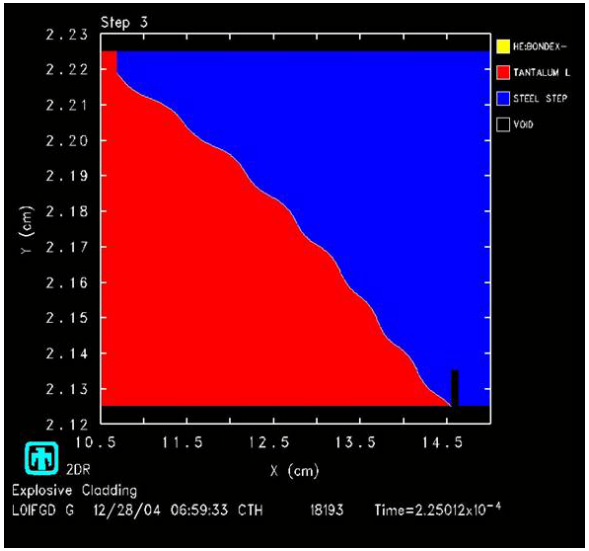
1in Ta Plot Interface



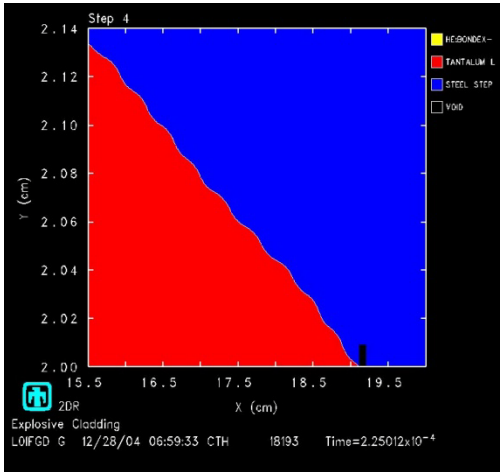
Step 1



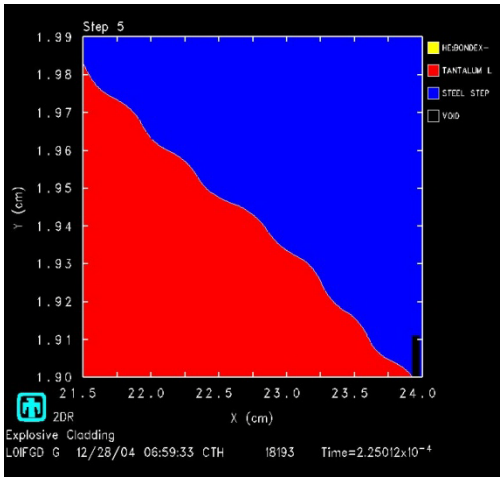
Step 2



Step 3

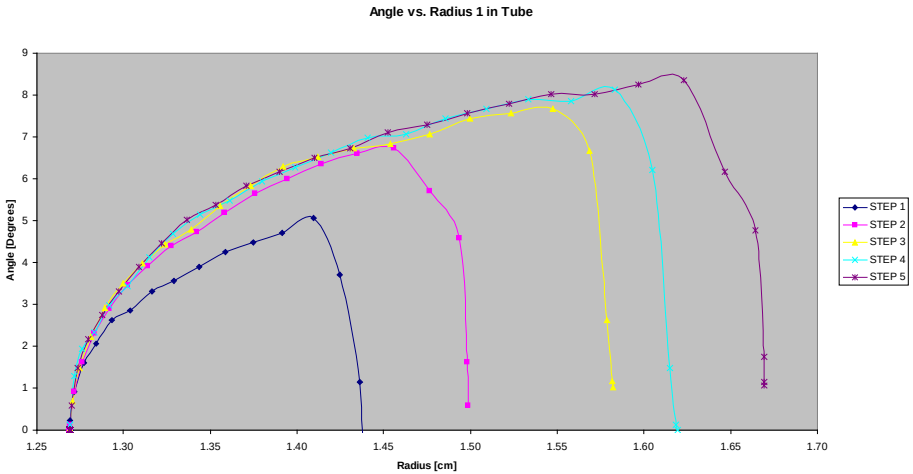


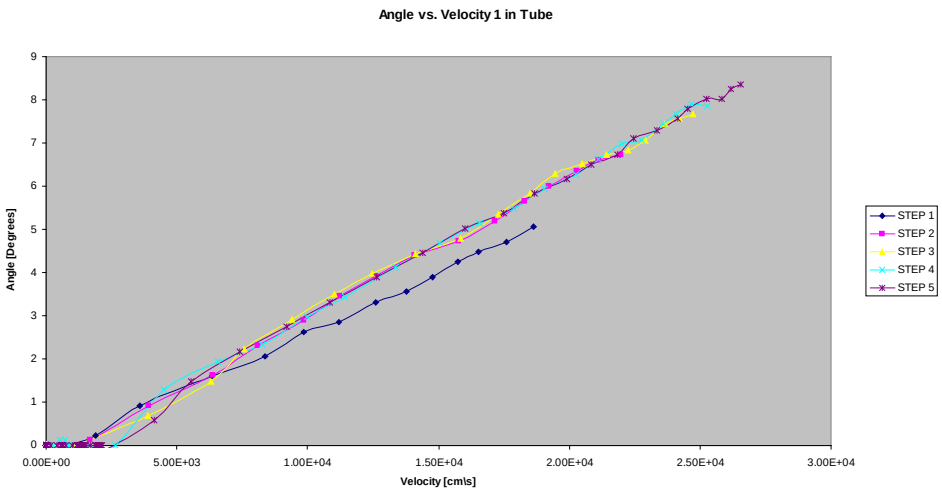
Step 4

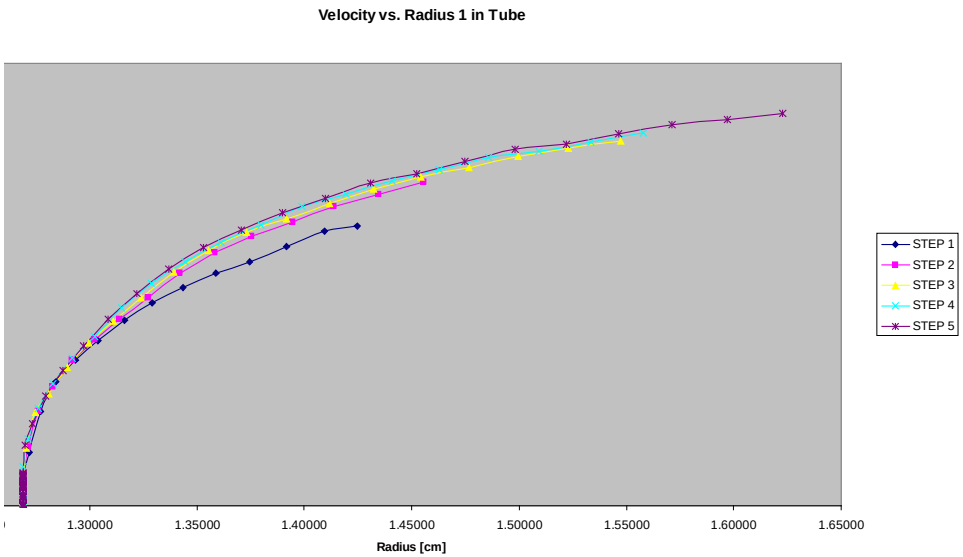


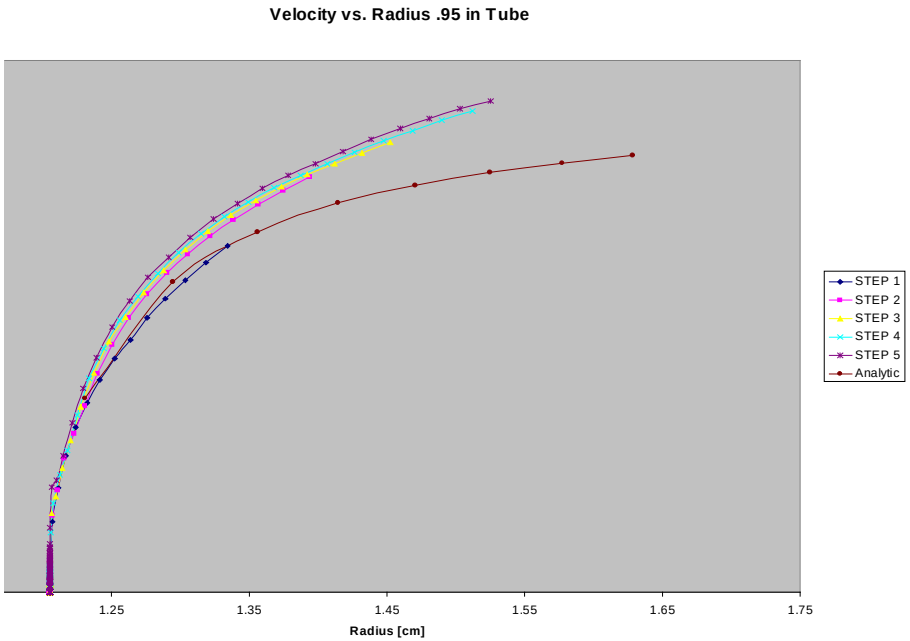
Step 5

1in Tube Plots



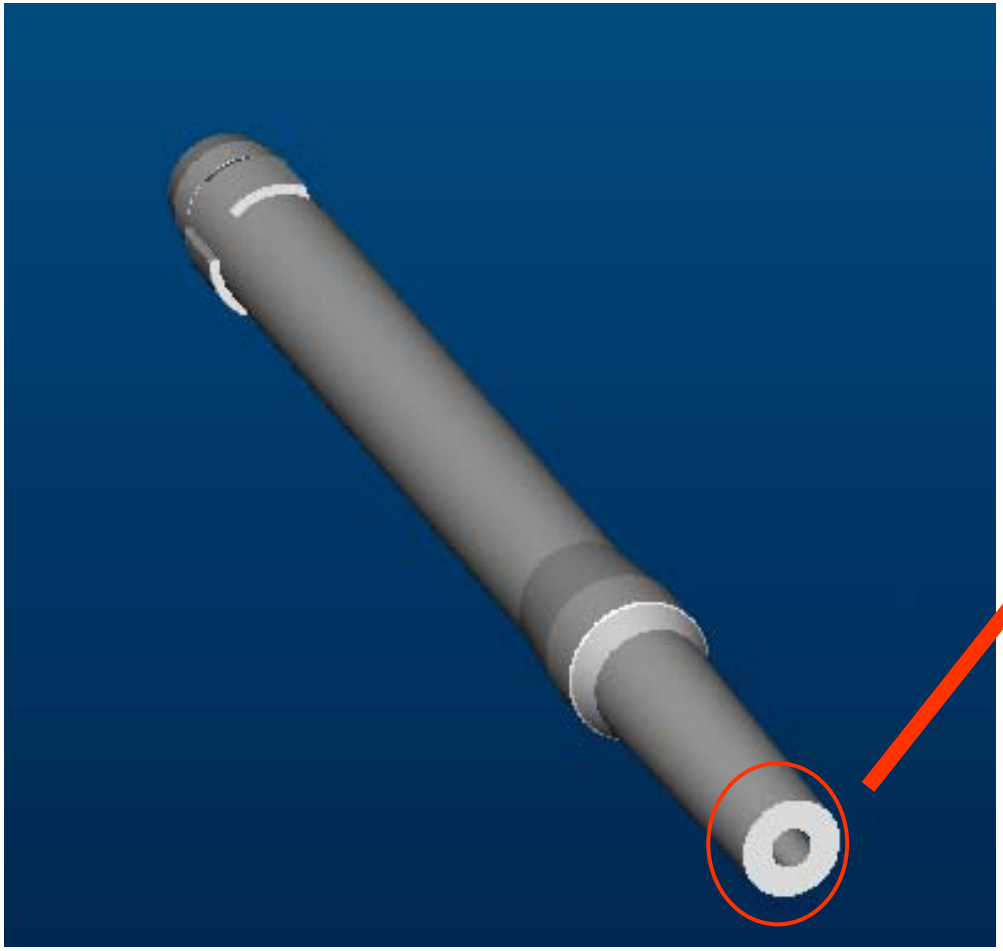






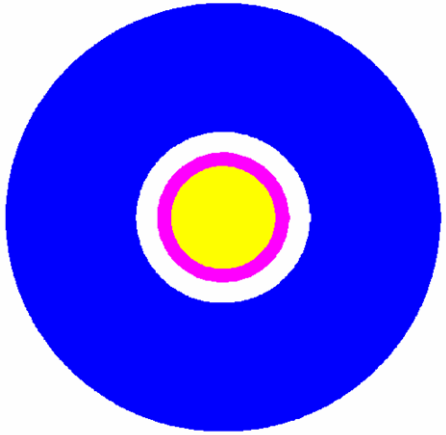
Initial Gun Modeling

Planar Model Setup



Analysis performed at 1001.5mm
(Middle of Barrel)

CALE Planar symmetry model

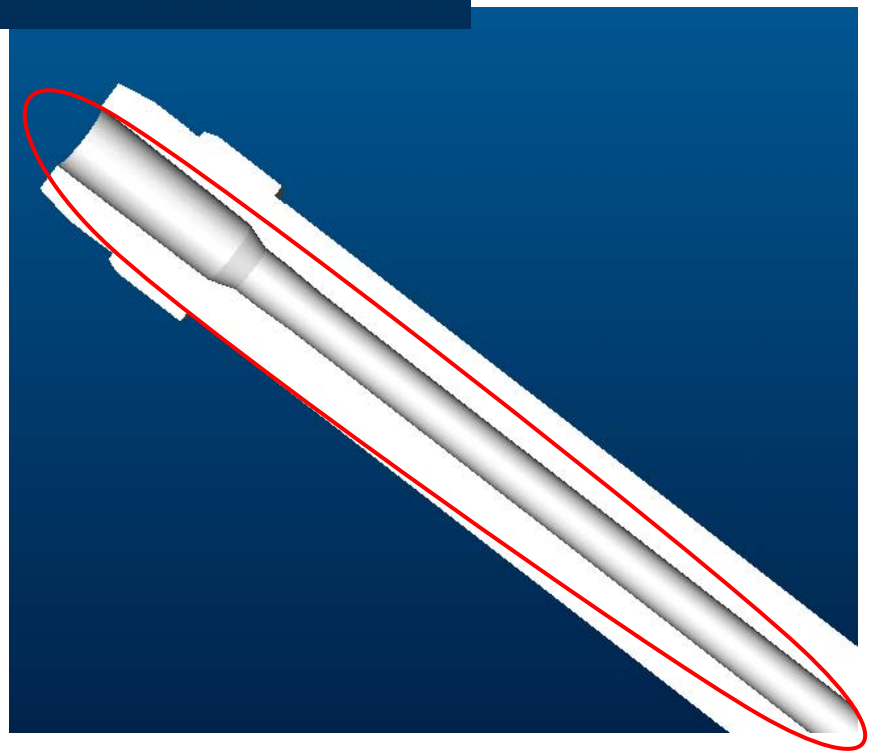


Material Legend

- Stainless Steel barrel
- Tantalum Liner
- HNS explosive
- Air

Initial Gun Modeling

Radial Symmetry Analysis

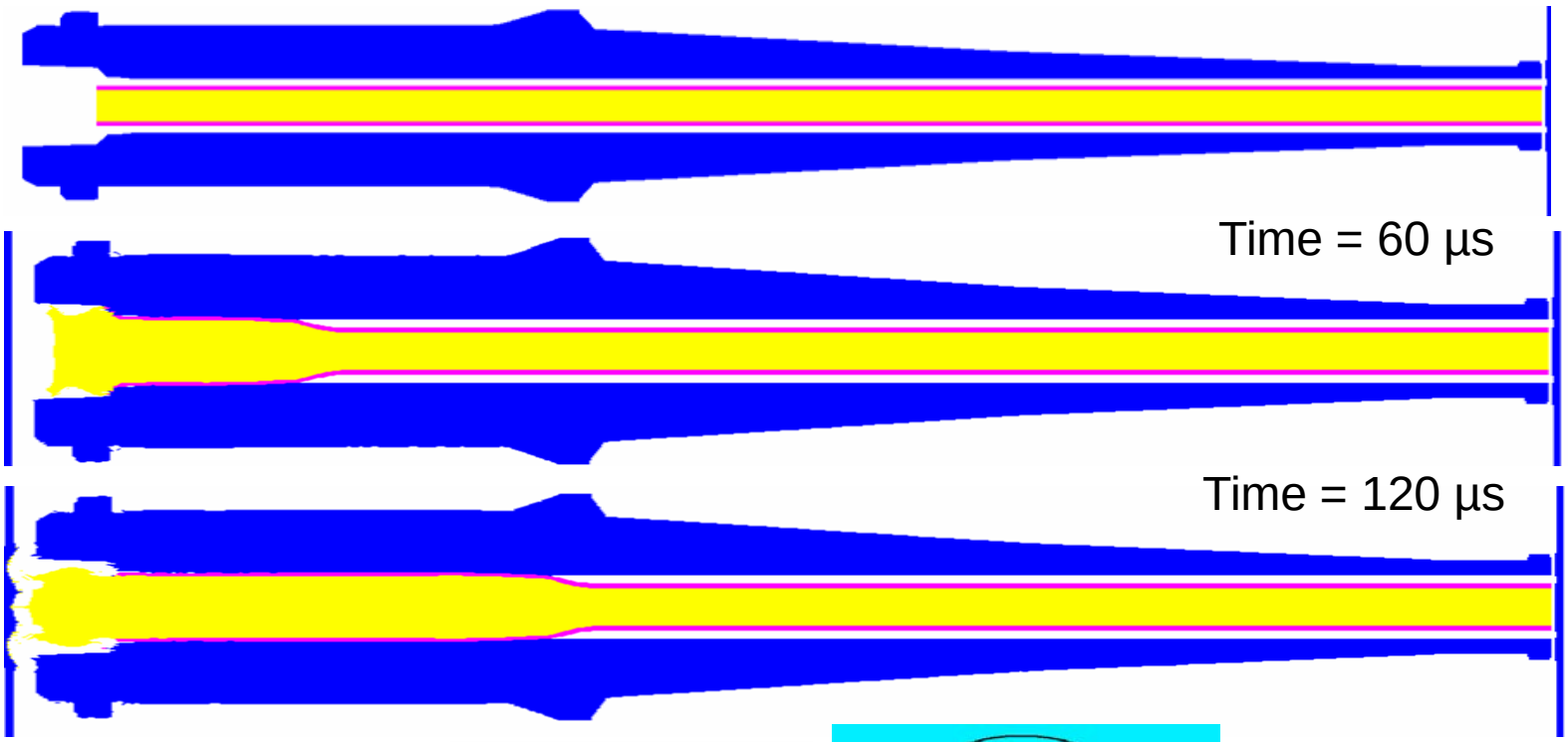


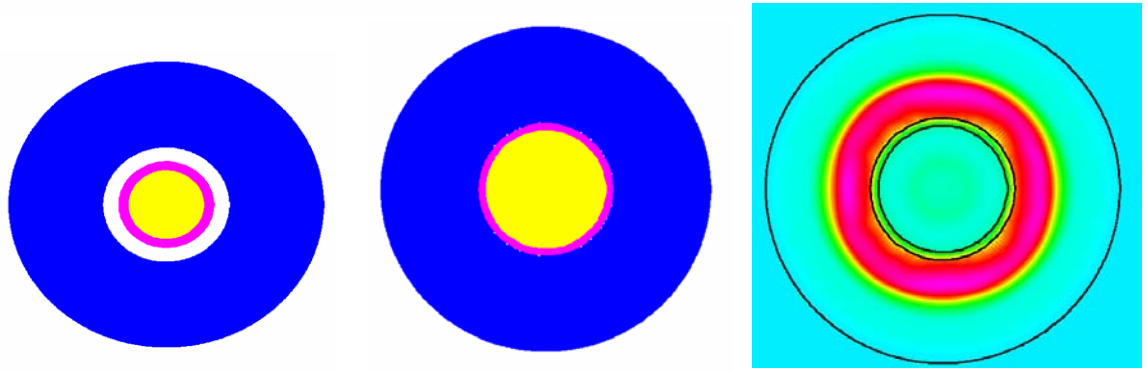
- Analysis performed on entire length of the gun barrel (2003 mm).

Initial Gun Modeling

Radial Symmetry Plots

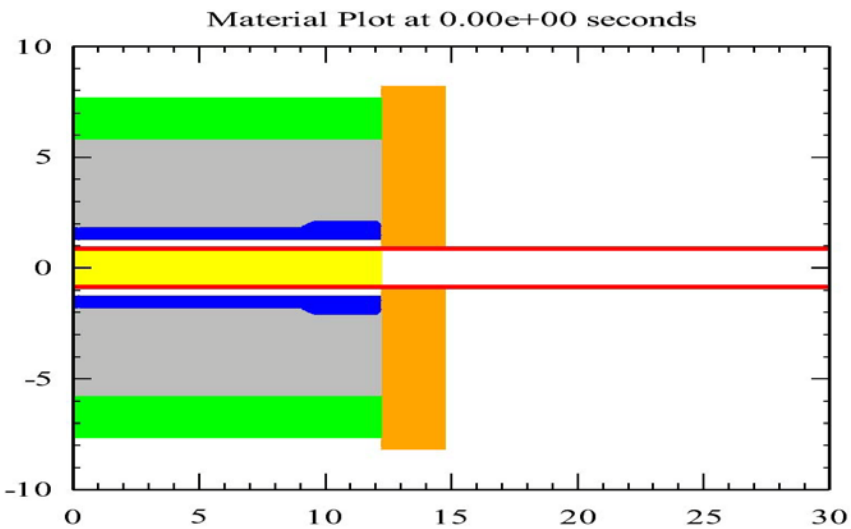
CALE Time = 0 µs



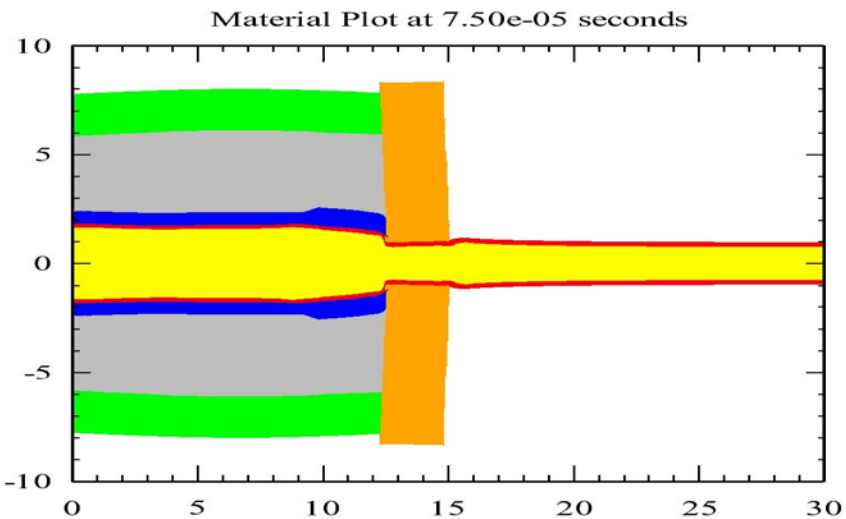


Planar Symmetry Plots

Momentum Trap Setup

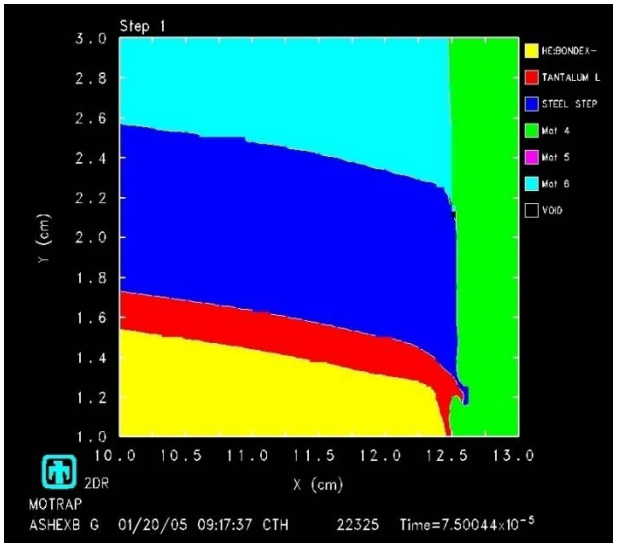


Time 0 us: Initial State



Time 75 us: After HE ignited

- 1 in Steel Plate
- .5 in Steel Plate
- Tantalum Liner
- Steel Gun Barrel
- HE:BondEx-D2
- Alloy 42



Time 75 us: Close up of Steel Barrel

Conclusions

- Explosive equation of state
  - Empirical BONDEX-A, D2 JWL/JWLB models
  - New formation BONDEX-D2: desire ARDEC cylinder tests (Ta and Cu)
- Full (macro) scale modeling
  - Physics resolved with .50mm mesh
  - Data can be used for analytic/empirical “clad quality model” input
- Sub (micro) scale modeling
  - Further .1mm modeling under investigation
  - Issue with wavelength …calculations predict longer the data …are BONDEX-D2 velocities correct? …Need to do BONDEX-D2 cylinder tests.
- Future Effort: process design and optimization
  - Two approaches: macro-analytic, micro-scale
  - Correlation using macroscale modeled characteristics and explosive experiment results
  - Correlation using further microscale modeling
  - Characterization of new explosive (ie: cylinder tests)
  - High probability for success of macro-analytic approach, micro-scale
  - Momentum trap design investigation initiated.