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Shrapnel Generation from Recyclable Transmission Lines

Presented at the 18th Technology of Fusion Energy

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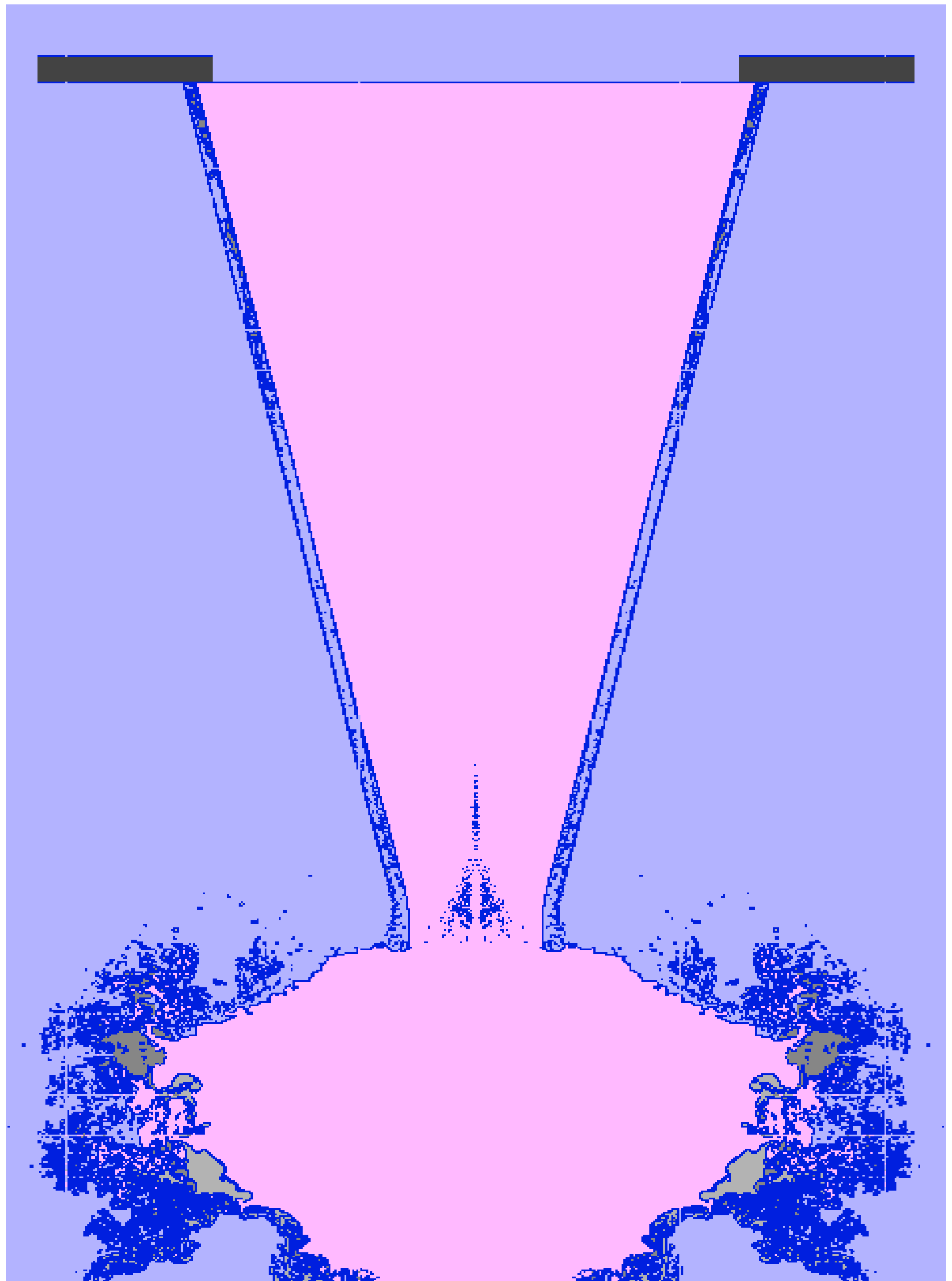
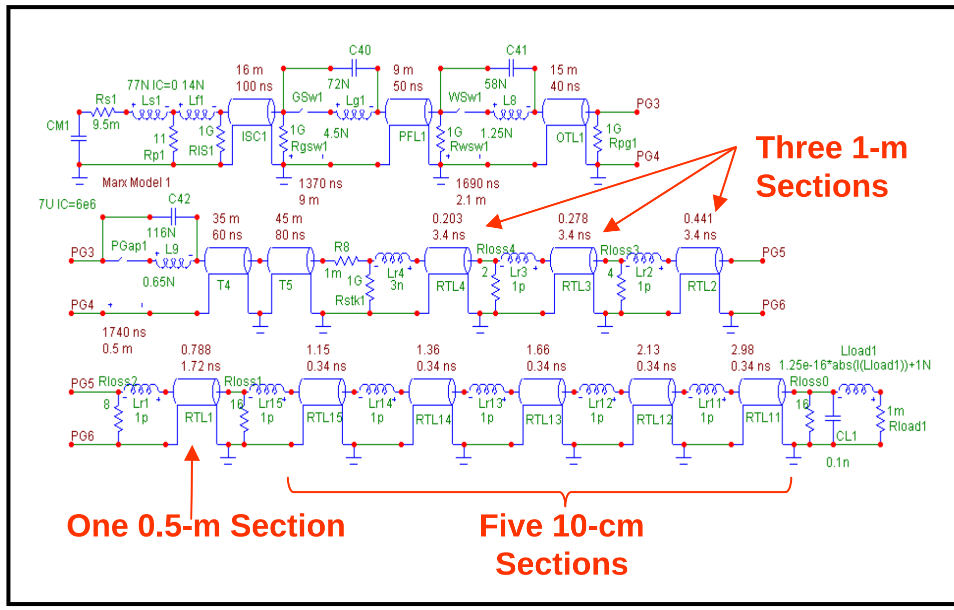
Objectives



- Characterize the shrapnel from target and transmission lines
  - Size and velocity
- Better understand threat to in-vessel components
  - First wall, diagnostics, etc.

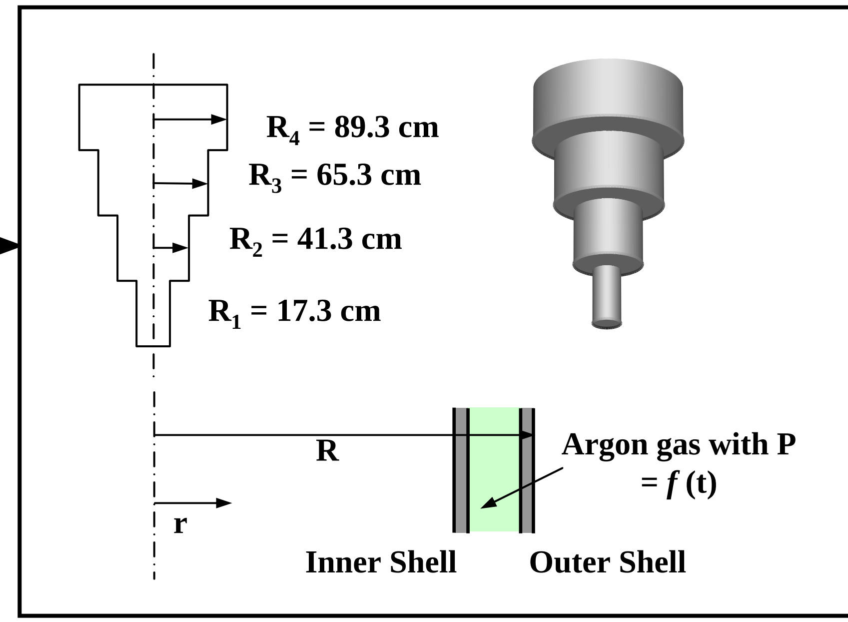
Shrapnel Modeling Methodology

Magnetic Pressure from Electrical Loading



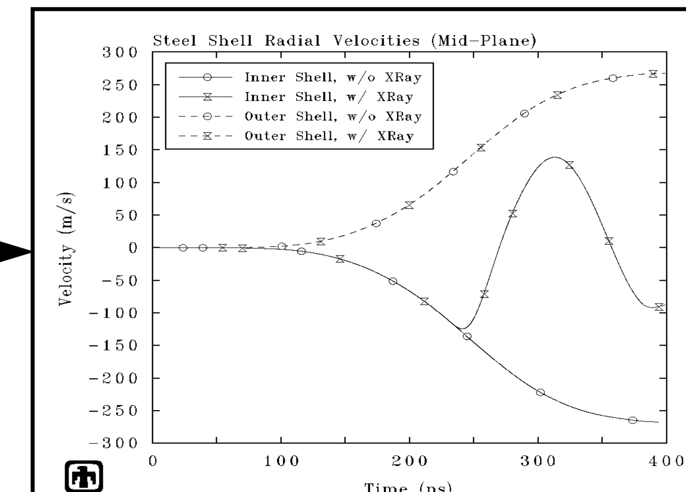
Circuit Modeling – Smith

RTL Response to Equivalent Mechanical Loading

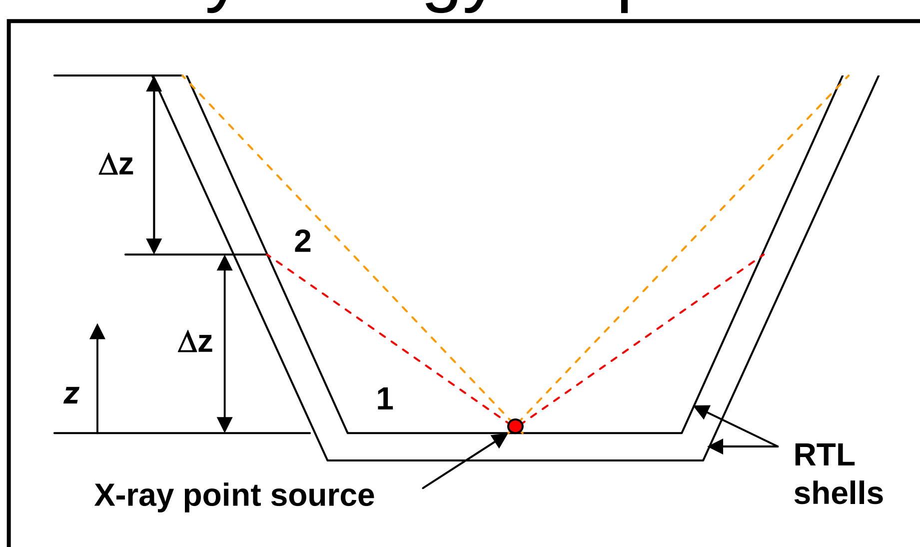


CTH – Kipp

Superposition of Mechanical and E_{dep} in 1-D CTH Model

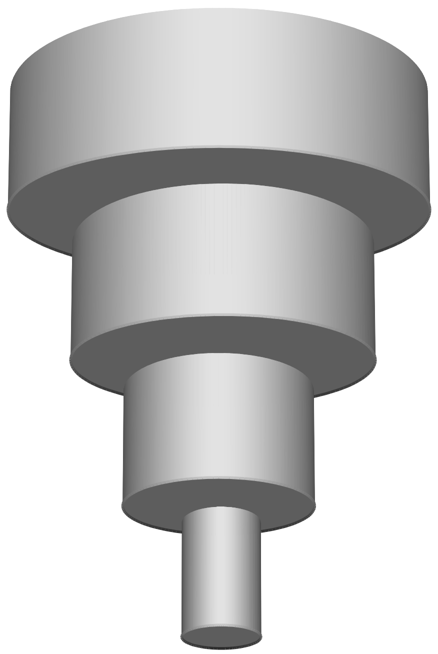


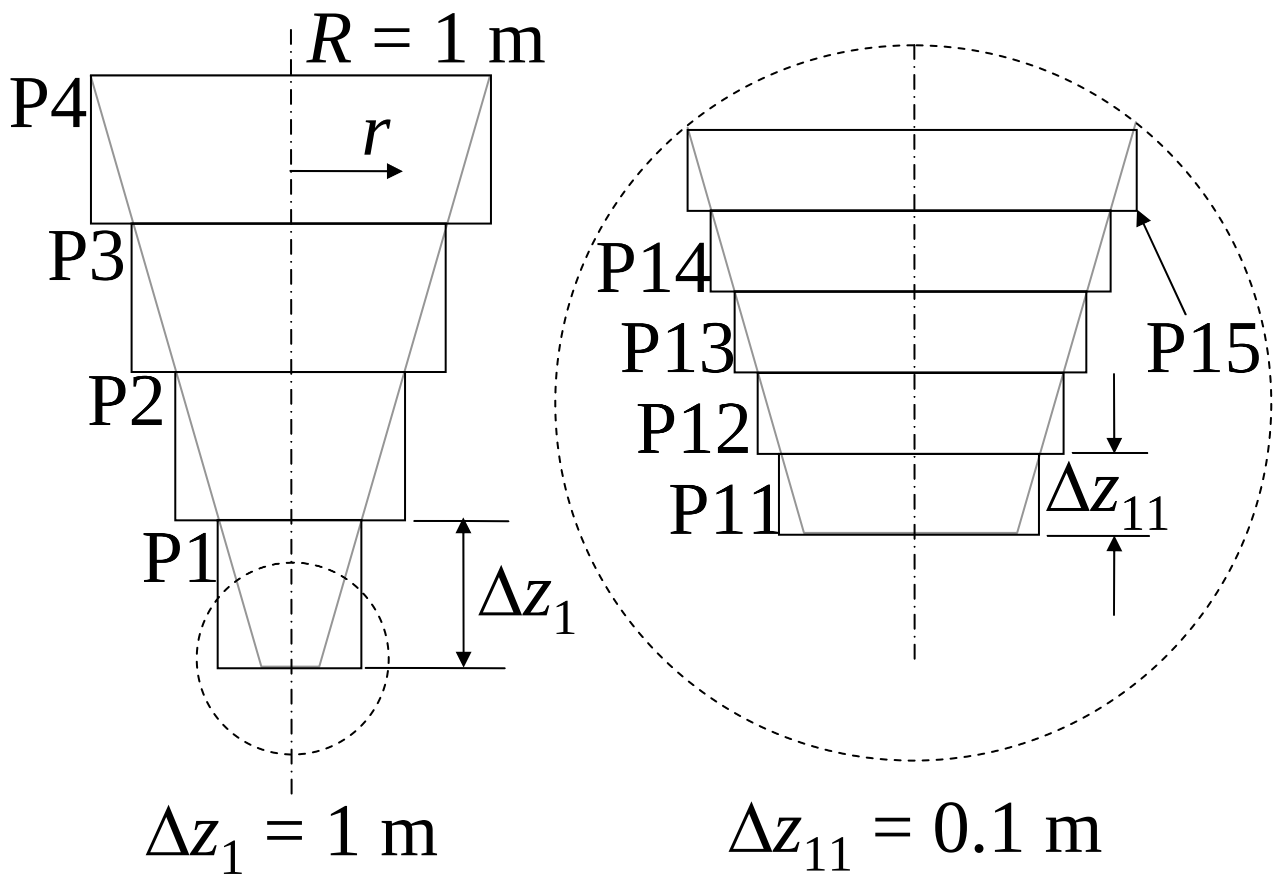
X-ray Energy Deposition

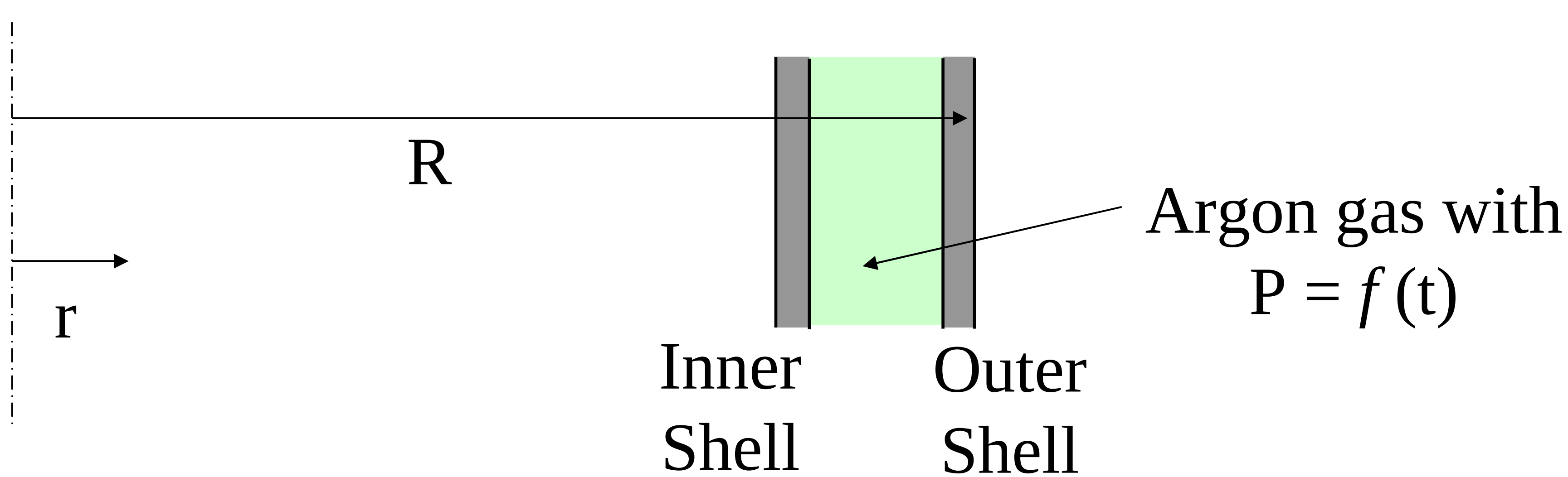


Estimation of Shrapnel Size Distribution and Energy

CTH Modeling







- **RTL modeled as discrete cylinders**
  - **Each simulation independent**
    - **Uncoupled solutions**
  - **Under equivalent mechanical loading**
    - **Argon gas modeled in between RTL shells**

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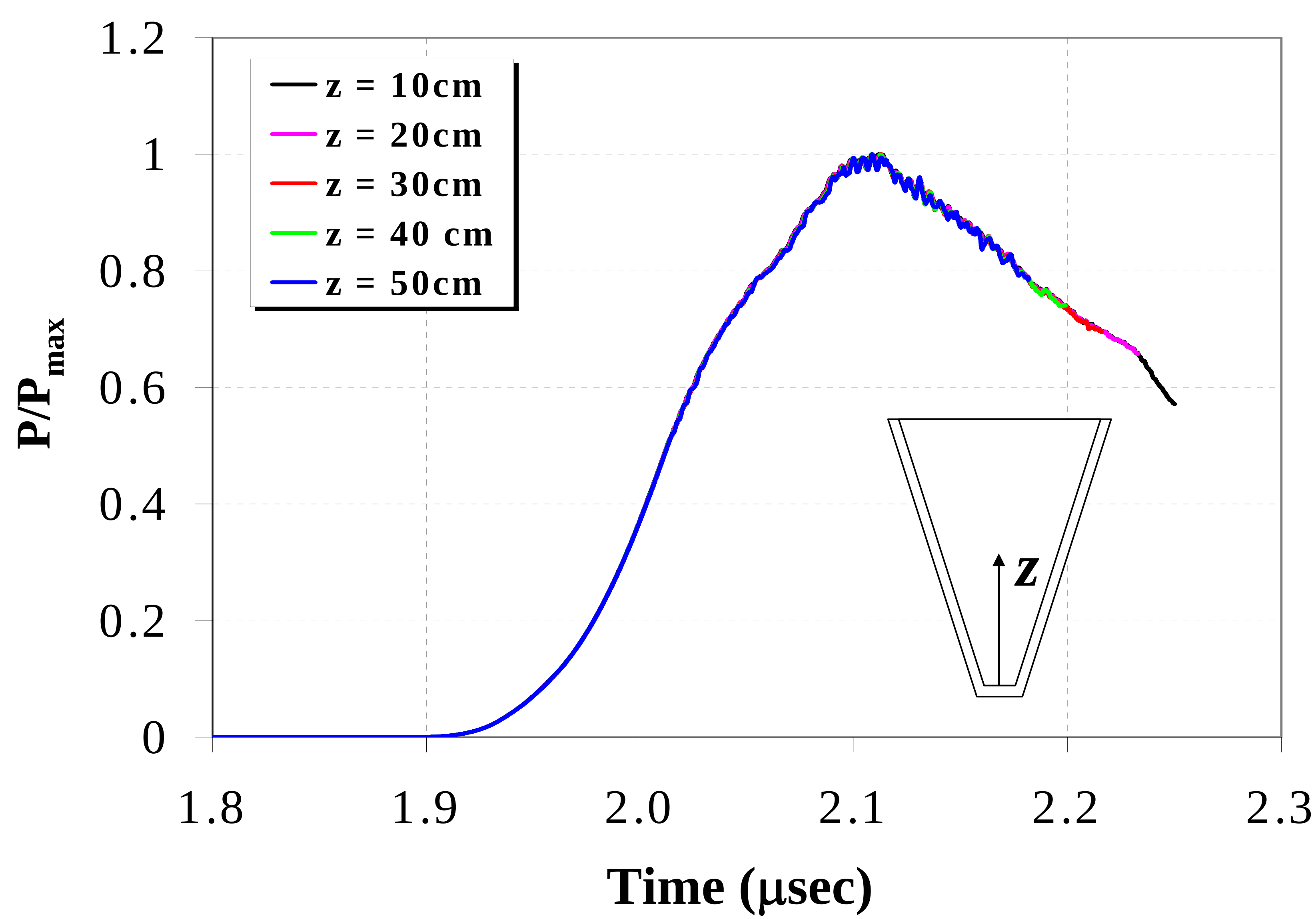
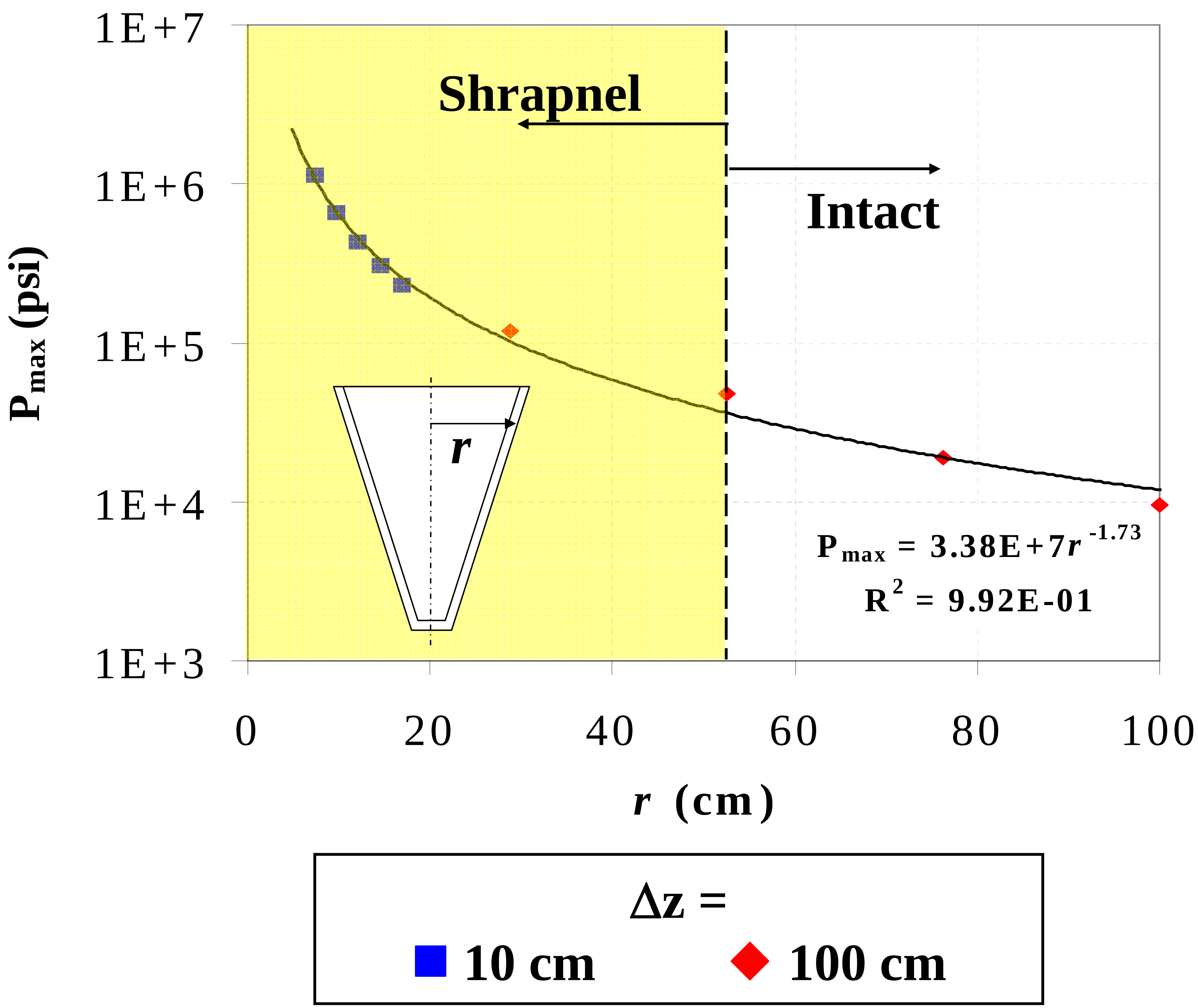
Normalized Magnetic Pressure Histories



- Similarity of curves confirmed
  - Normalize by peak pressure
- Facilitates 2D CTH modeling
  - Need relationship for P_{max}
- Pressure decay behavior unknown
  - Treated parametrically

P_{max} Functionality



- P_{max} plotted as $f(r)$
  - Eliminates dependence on RTL cone angle
  - Still depends on shell thickness and gap
- Approximate yield limit predicts half of RTL ⇒ shrapnel
  - Based on earlier CTH results
    - ZR-like electrical loading
    - Steel shells with thickness of 635 μm and gap of 3 mm

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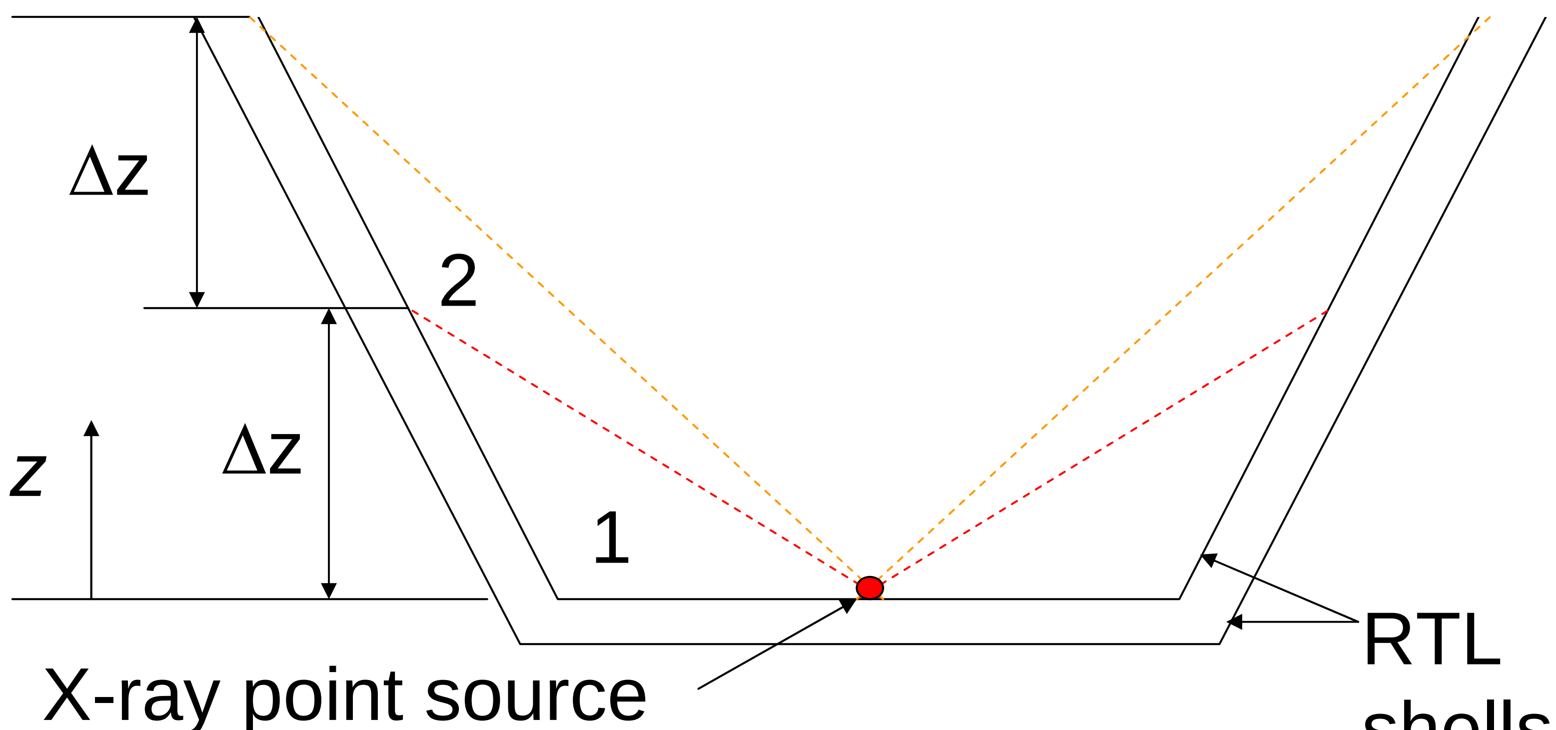
X-ray Energy Deposition



Label	*z* (cm)	Percentage of Total Energy
1	10	80
2	20	9.4
3	30	2.8
4	40	1.4
5	50	0.7

- **Estimate E_{dep} with solid angles**
- **Deposition into first band**
  - **For 3 MJ x-rays, 1.5 MJ x 0.8 = 1.2 MJ**
  - **Occurs at peak pressure**

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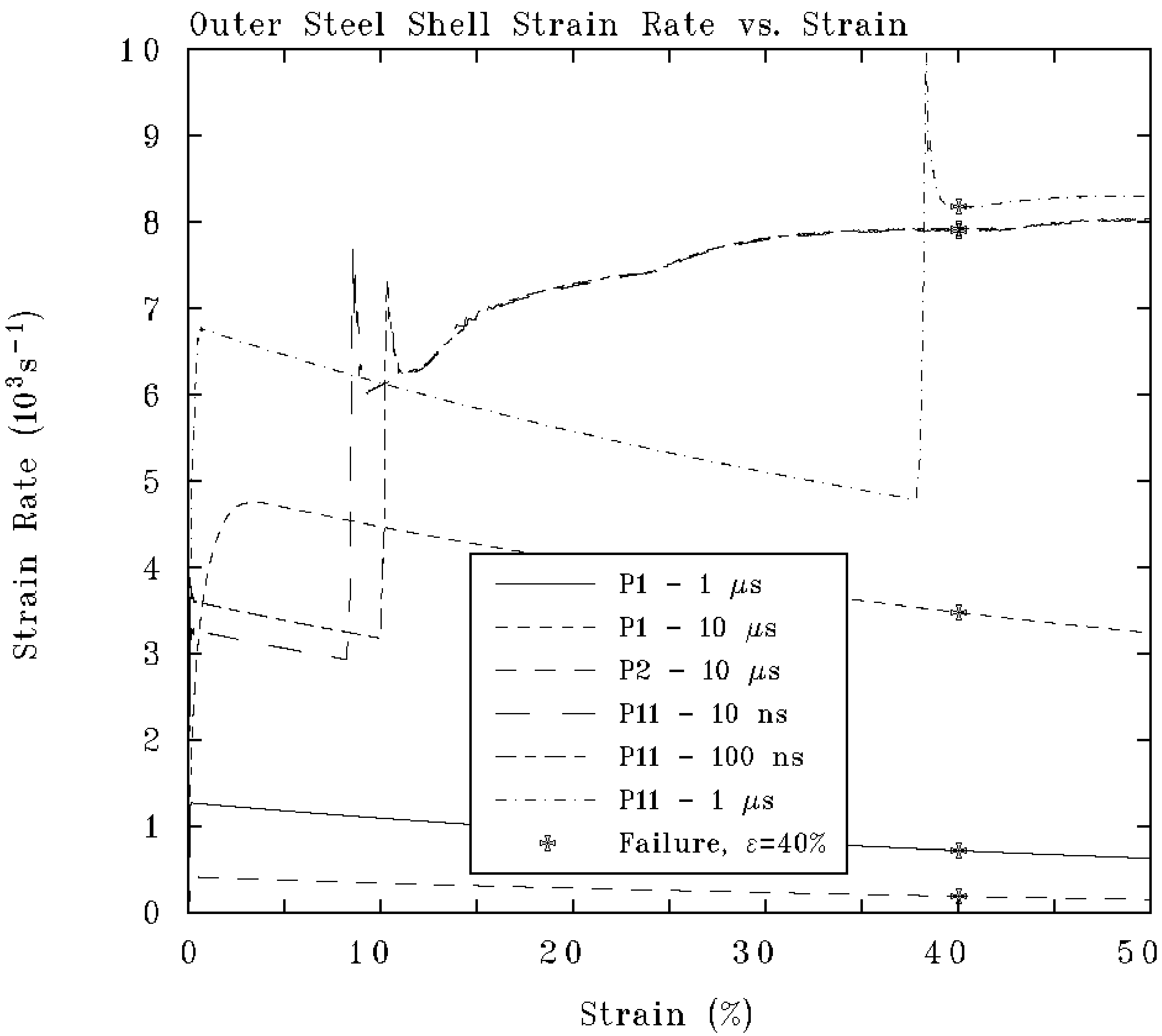
Fragment Size Estimation



- **Average fragment estimation**

$$-S = \left[\frac{\sqrt{24} K_{IC}}{\rho c \dot{\varepsilon}} \right]^{2/3}$$

Where:

- ***S* = Avg. fragment size**
- **K_{IC} = Fracture toughness**
- **ρ = Material density**
- ***c* = Material speed of sound**
- **$\dot{\varepsilon}$ = Strain rate at failure**

– Grady, D.E., "The Spall Strength of Condensed Matter", *J. Mech. Phys. Solids*, 36, 353- 384, (1988).
– Kipp, M.E., Grady, D.E. and Swegle, J.W., "Experimental and Numerical Studies of High-Velocity Impact Fragmentation", Sandia National Laboratories Report, SAND93-0773, (August 1993).

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CTH Model Results

Case	Decay Time	X-Ray Dep.	Initial Shell Radius (mm)	Failure Shell Radius (mm)	Circumference of Shell at Failure (mm)	Strain Rate at Failure (1/s)	Average Fragment Size (mm)	Fragment Number	Fragment Velocity (m/s)
P1	1 μs	No	173	242	1520	730	133	11	175
	10 μs	No	173	242	1520	3500	47	32	845
P2	10 μs	No	413	578	3630	200	320	11	115
P11	10 ns	Yes	77	108	680	7900	27	25	860
	100 ns	Yes	77	108	680	7900	27	25	860
	1 μs	Yes	77	108	680	8200	27	25	890

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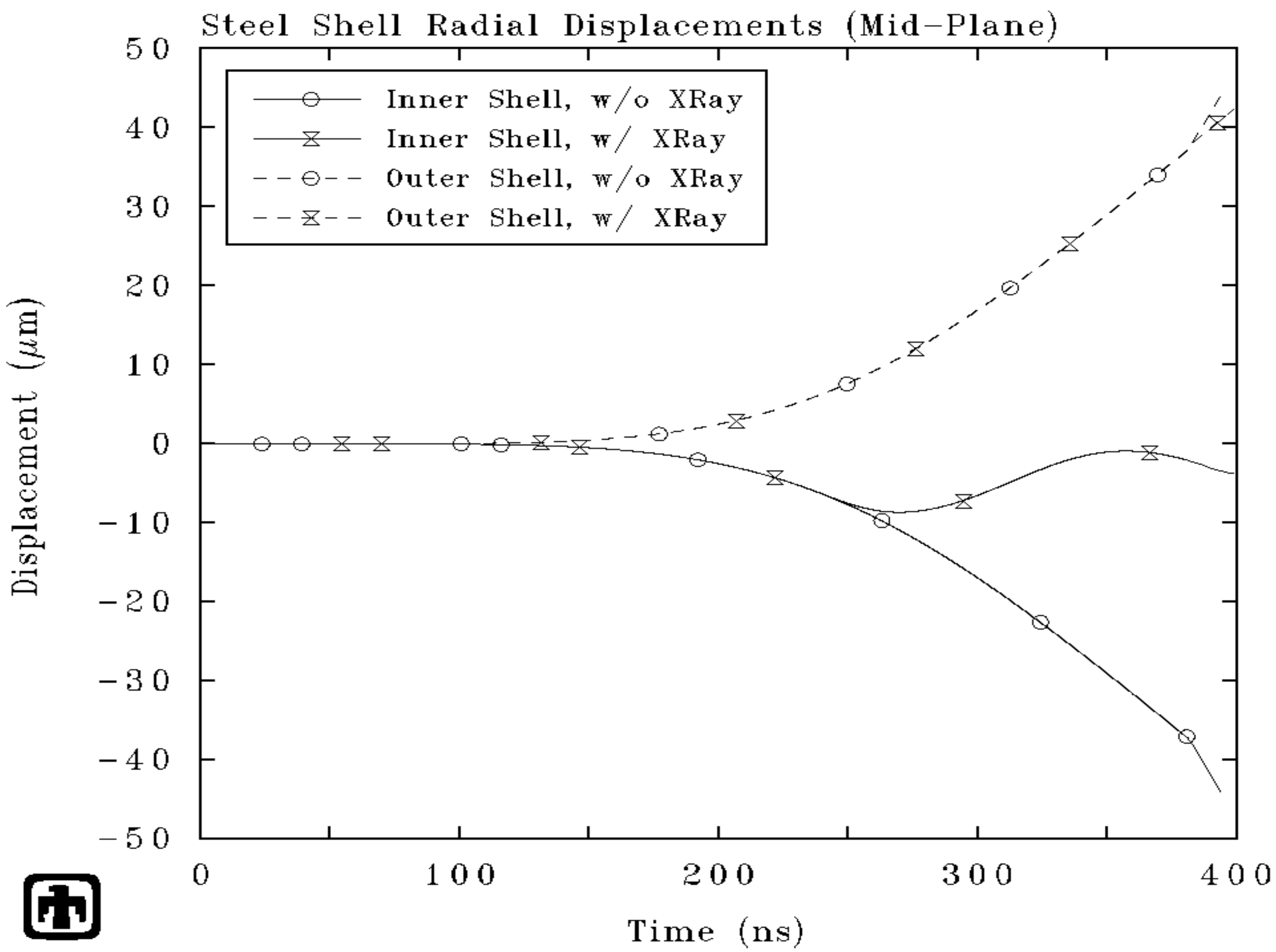
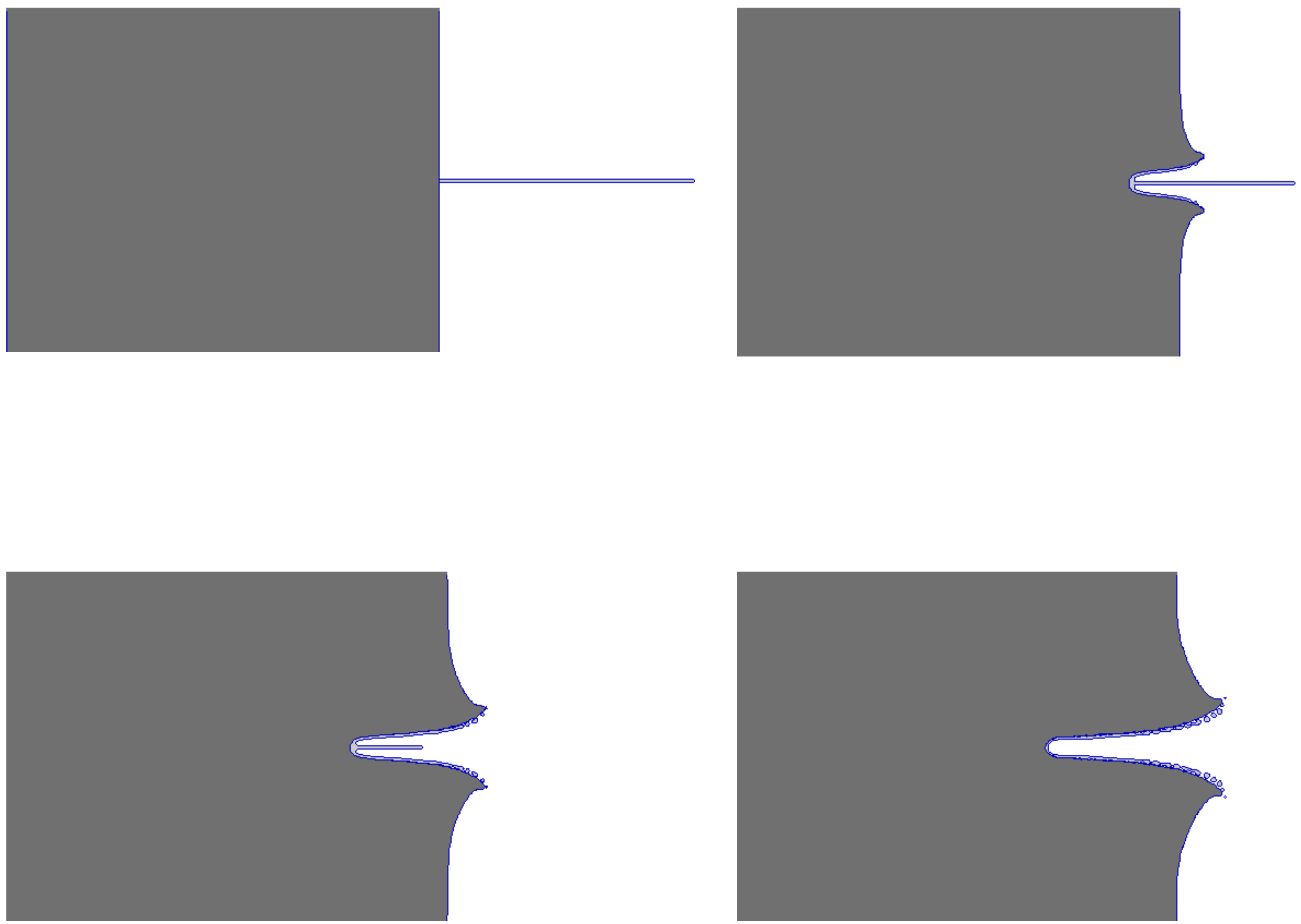
CTH Model Displacements



P11 level (10 ns pressure decay)

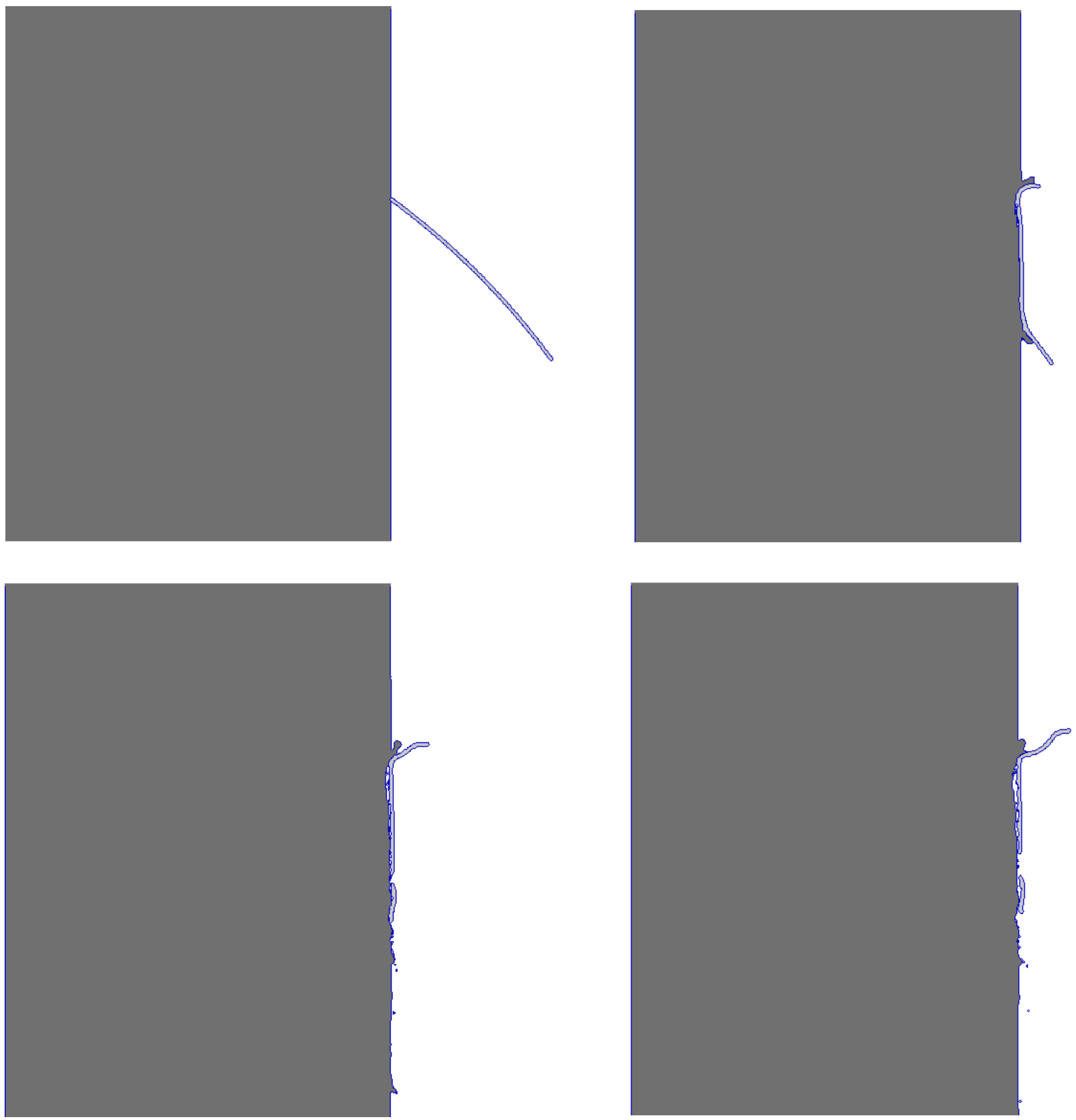
- **Failure based on strain of 40%**
  - **Typical for steel**
- **Fragment size estimated from strain rate at failure**
  - **Current estimates near RTL tip: 30 mm shards at approx. 900 m/s**
    - **Roughly same mass as M16 round**
    - **Typical muzzle of M16 is 930 m/s**
    - **Sound of speed in STP air 344 m/s**

Flat Fragment Edge-On Impact



- Worst case scenario
  - Unlikely given curved RTL surfaces
- Fragment 30 × 0.45 mm
  - Typical of P11
  - Velocity = 850 m/s
  - Erodes as it penetrates
- Steel target 50 mm thick
  - Penetration of 16 mm

Curved Fragment Oblique Impact



- Fragment 30 × 0.45 mm
  - Radius of curvature = 100 mm
  - Typical of P11
  - Velocity = 850 m/s
- Slight penetration into steel target
  - Depth = 1 mm

Summary

- Modeling efforts have demonstrated estimates of shrapnel threat
  - Using simplified geometry and decoupled modeling
  - Accounts for induced magnetic pressure, x-ray deposition, and material fracture mechanics
    - Does not include vaporization
- RTL generates a considerable shrapnel threat
  - Shards of up to 30 mm at 900 m/s
  - Initial fragment impact studies indicate potential for severe pitting

Scalable Shrapnel Model for Pulsed Power Transmission Lines

Practical working designs for in-chamber components have been the cost-effective choice to date in pulsed power equipment. As overall power levels along with the sophistication of chamber and instrumentation increase, survivability from target-generated shrapnel becomes a driving factor to be considered. Development of a predictive capability to diagnose the shrapnel threat would allow future components to be designed with much more insight and confidence. This multidisciplinary program proposes to advance the current modeling campaign, including ALEGRA-HEDP, with an integrated experimental program to quantify and understand the shrapnel threat. This model development effort would not only benefit the current pulsed power program but may also prove to be an important stepping stone in the realization of achievable Z-generated inertial fusion energy in the future.

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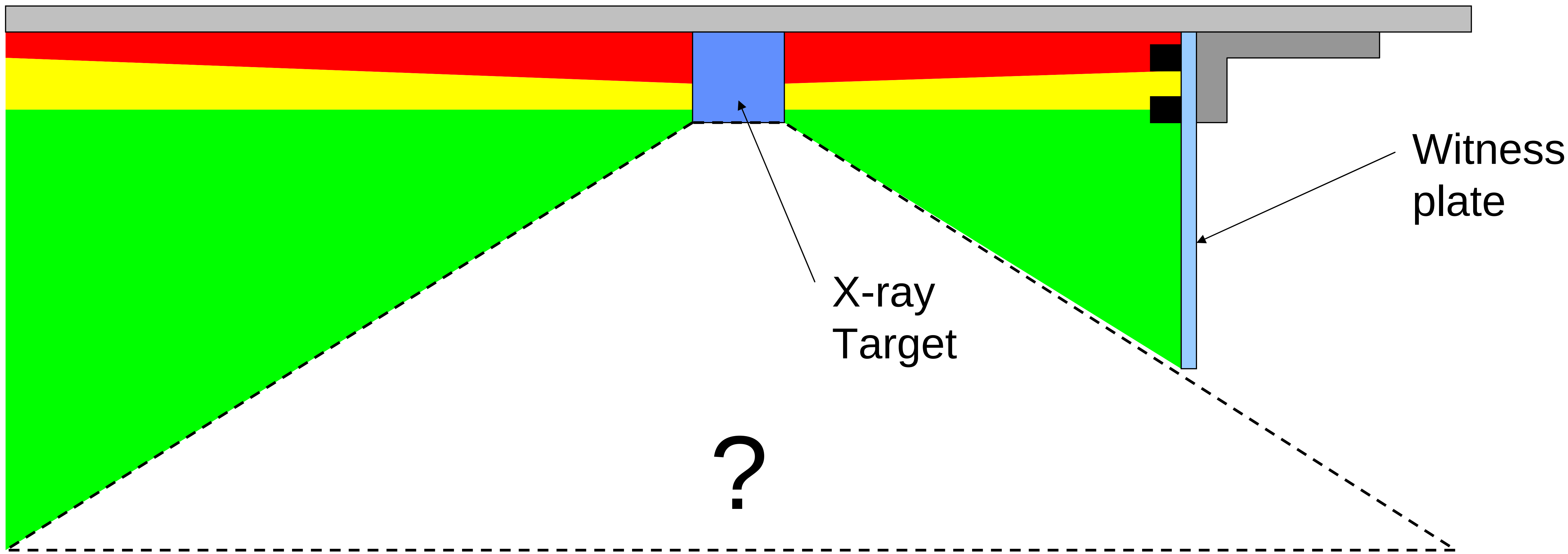
Saturn Impulse Experiment*

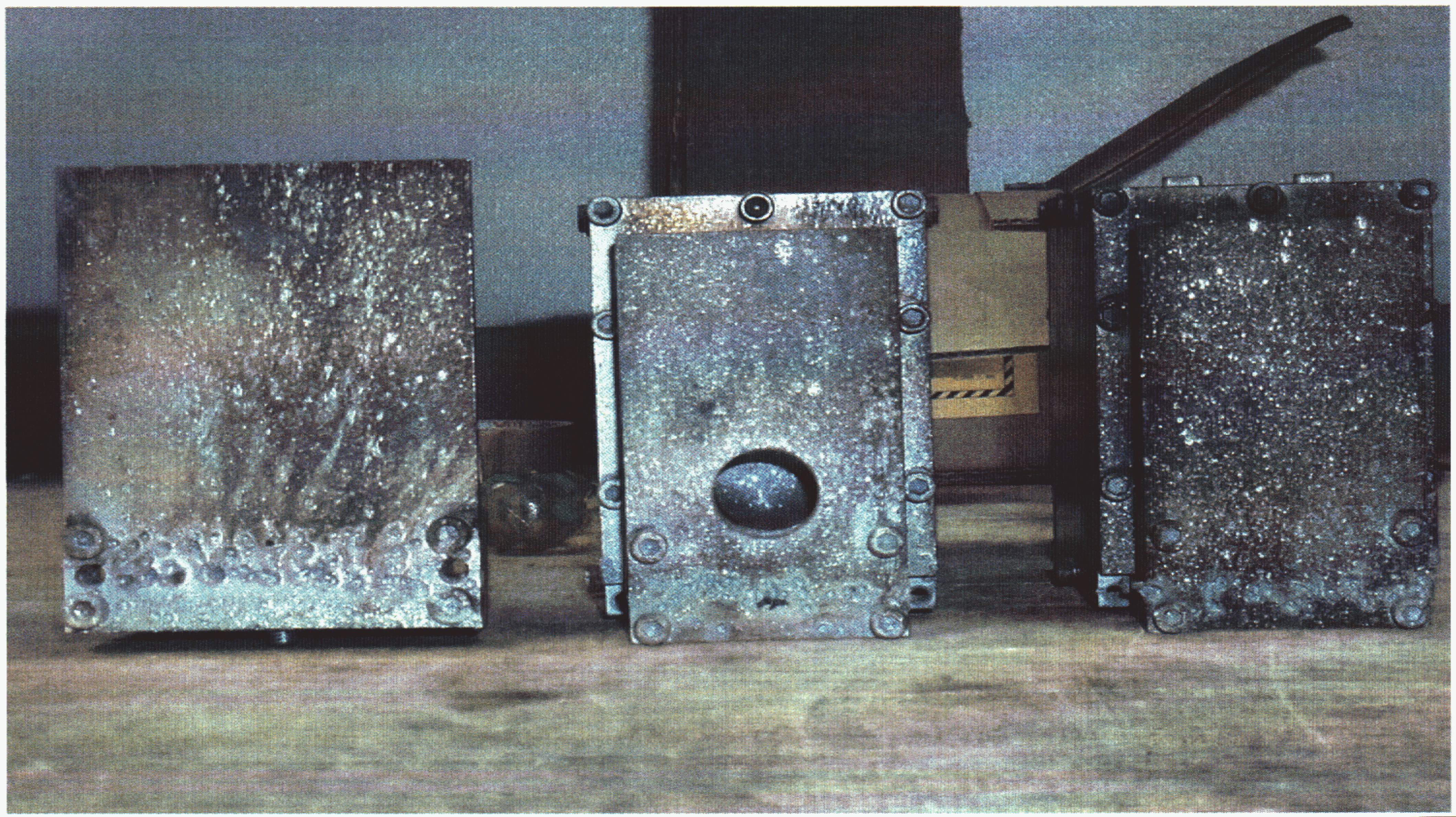


- **Also fielded pressure gages and optical impulse monitor**
- **Approximately ½ of can mass deposited "in-plane"**
- **X-ray energy ⇒ ½ to can ⇒ ½ to debris**

Concentrated Debris
Clear Gouging
Limited Splatter

*** SAND 2002-1600P**

Debris constitution is a major concern for simulation applications*



"The purpose of this work is to evaluate the potential utility of z-pinch debris as an impulse simulation source... [of] external hostile environments on reentry systems." – Harper-Slaboszewicz, et al. SAND2001-1906C

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* SAND 2002-0600P