Z-Pinch Power Plant Shock Mitigation Experiments, Modeling, and Code Assessment

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Introduction

- Problem Statement
- Aluminum Foam Experiments
- Analytic Models
- Aluminum Foam Simulations
- Conclusion

Problem Statement

- Mitigate the powerful shock wave that is generated inside the Z Pinch Power Plant.
- Fusion of deuterium-tritium pellets:

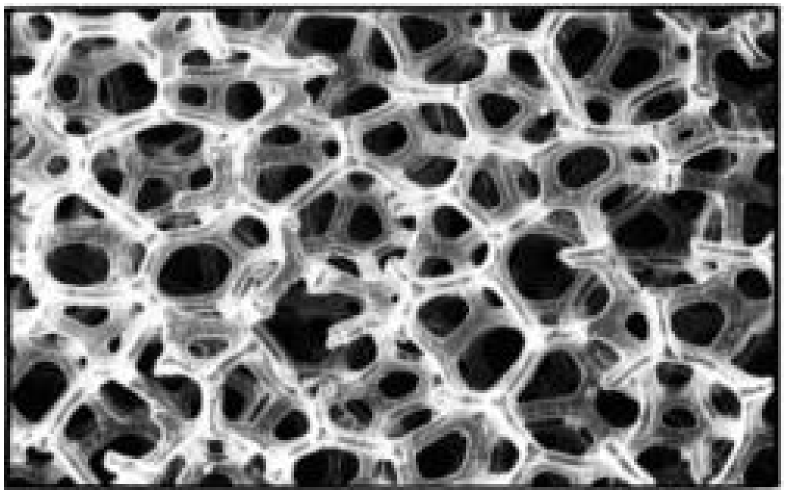
$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + E$$

- Each D-T capsule will release about 3 gigajoules (and perhaps more…).
- This is the equivalent energy released by a 1,500-lb bomb…
- …Or 1,911 jelly doughnuts.
- As a first step, we will conduct shock experiments to
  - Obtain data with which to benchmark structural analysis codes.
  - Explore the feasibility of metal foams as a shock mitigation medium in IFE chambers.
  - Validate EOS and constitutive equations.

Metal Foam Experiments

- The University of Wisconsin has already done shock experiments on thin liquid-water films.
- Metal foam appears promising in terms of shock mitigation. Consequently, we conducted a series of shock tests at the Shock Tube Facility in the UW.
- A variety of porosities, materials, test configurations, and shock wave magnitudes are being considered.
- 20.3-cm thick samples will be tested in about three weeks. Because they are thicker, they will be subjected to higher shocks.
- A foamed thick-liquid water experiment will also be conducted.

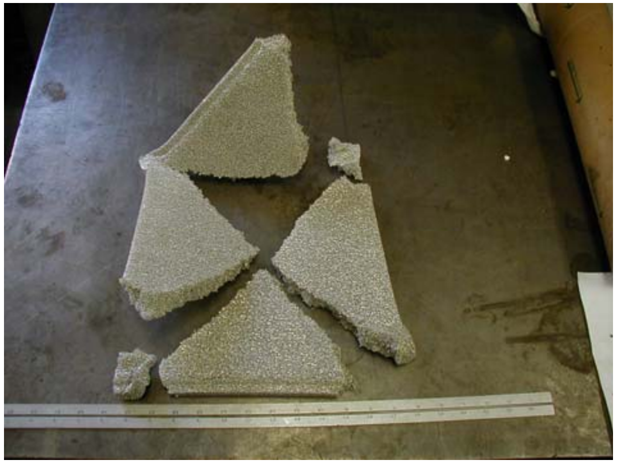
Metal Foam Shock Mitigation Tests

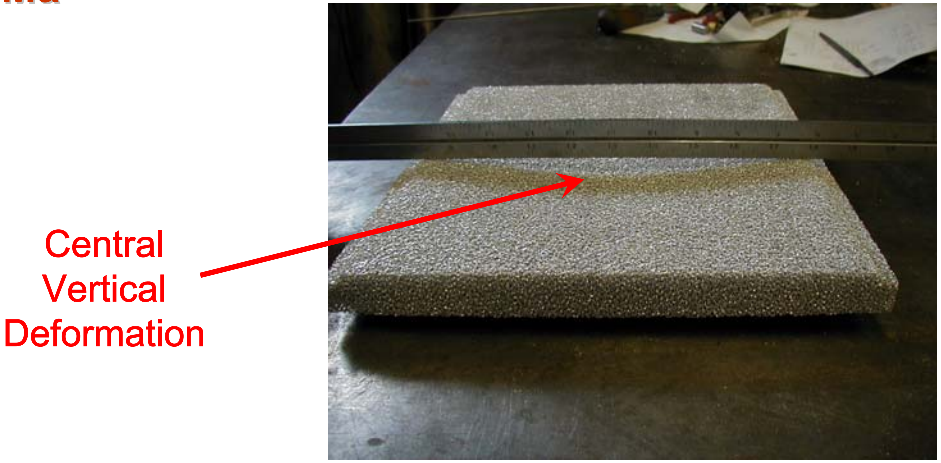


- **Purpose**
  - Provide data to benchmark codes
  - Explore feasibility as a shock mitigation medium
- **Test specimens**
  - 6101-T6 Aluminum
  - 10, 20, 40 ppi
  - 2.54 cm thick
- **Performed at WiSTL**
  - Single and dual layers

Metal Foam Shock Mitigation Tests

- **Single layer**
  - 1.45 Ma – Sample failure
  - 1.34 Ma
    - Reflections subsonic
    - Transmitted shocks : 1.19-1.20 Ma
    - Deformation
      - ♦ *20, 40 ppi   31% - 38%*
      - ♦ *10 ppi   8%*
- **Double layer – 1.34 Ma**
  - Transmitted shocks: 1.14, 1.16 Ma
  - Deformation
    - Top: 21& & 25%
    - Lower: 24% & 48%
  - 48% deformation
    - Off center
    - 1" separation
    - Intra-layer reflections?





Metal Foam Shock Mitigation Tests

Test	Sample No.	Porosity (ppi)	Configuration	Trans. Shock (Ma)	Central Deformation (cm / %)
4	3	40	Single layer (Ma 1.45)	No data	Material failed
6	5	40	Single layer	1.19	0.961 / 38
7	10	40	Single layer	1.20	0.777 / 31
8	6 & 7	40	2 layer 3" separation	1.14	0.538 / 21 0.593 / 24
9	8 & 9	40	2 layer 1" separation	1.16	0.618 / 25 1.20 / 48*
10	2	20	Single layer	1.20	0.840 / 33
11	1	10	Single layer	1.19	0.212 / 8

* Off-center deformation in lower layer.

Code Selection and Analytic Models

- We will use ALEGRA, ABACUS, BUCKY, CTH, and DYNA2D to simulate Shock Tube Test 6.
- We will investigate the following models, and perhaps others:
  - Mie-Grüneisen US UP (EOS)
  - Elastic Plastic Power Law Hardening (constitutive equation)
  - P-α (constitutive equation appropriate for void fractions less than 20%)

Analytic Models

- **Mie-Grüneison (MG) US UP EOS Model:**
  - **Pressure**

$$P(\rho,E)=P_H(\rho)+\Gamma_0\rho_i\left[E-E_H(\rho)\right]$$

  - **Energy**

$$E(\rho,T)=E_H(\rho)+C_v\left[T-T_H(\rho)\right]$$

  - **Shock and Particle Velocity**

$$U_S=C_O+S_1u_P$$

(P_H = Hugoniot pressure, E_H = Hugoniot energy, T_H = Hugoniot temperature, T = material temperature, E = material energy, P = material pressure, ρ_i = initial density, ρ = density, Γ_0 = Grüneisen parameter, C_V = specific heat, U_S = shock velocity, c_O = bulk sound speed, S_1 = slope of the U-u Hugoniot, and u_P = particle velocity.)

•In ALEGRA, the MG model can be easily modified to incorporate the P-α model.

Analytic Models

C_L = compressive wave velocity, C_S = shear wave velocity,

C_O = bulk sound speed, B = bulk modulus,

G = shear modulus, E = Young's modulus,

ν = Poisson's ratio, A ~ 1, E_0 and ρ_0 pertain to solid.

$$From\ C_L = \sqrt{\frac{B + \frac{4}{3}G}{\rho}},$$

$$C_S = \sqrt{\frac{G}{\rho}},$$

$$B = \frac{E}{3(1-2\upsilon)},$$

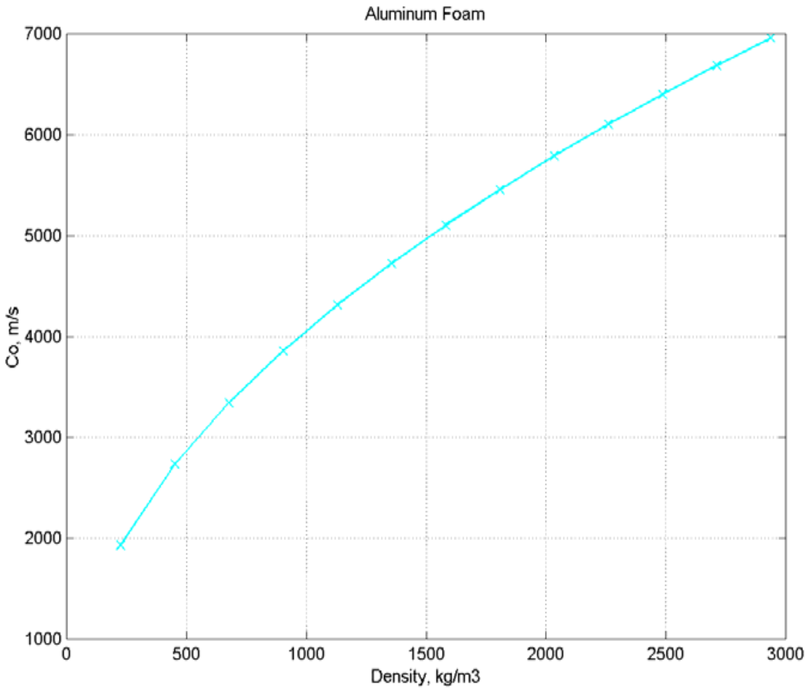
$$G = \frac{E}{2(1+\upsilon)},\ \ and$$

$$E = AE_0\left(\frac{\rho}{\rho_0}\right)^2\ \ (Gibson - Ashby\ \ Data\ \ Fit)$$

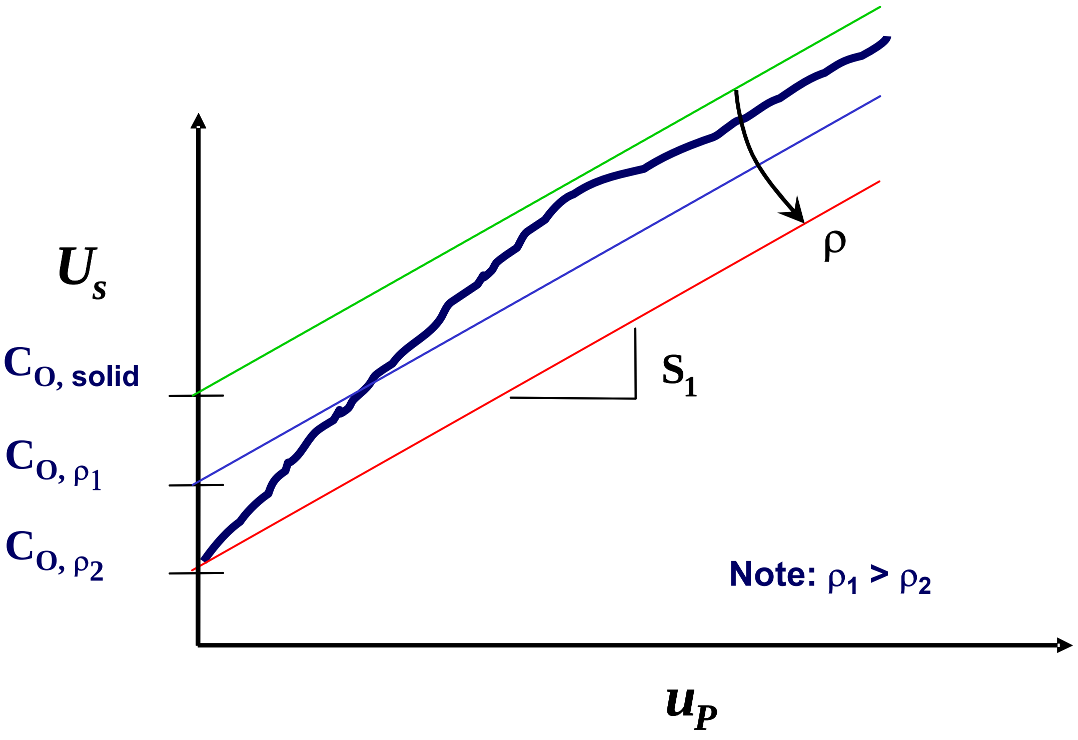
$$\Rightarrow C_L = \frac{1}{\rho_0}\left[\frac{\rho A E_0 (1-\upsilon)}{(1-2\upsilon)(1+\upsilon)}\right]^{\frac{1}{2}}\ \ and$$

$$\Rightarrow C_S = \frac{1}{\rho_0}\left[\frac{\rho A E_0}{2(1+\upsilon)}\right]^{\frac{1}{2}}.$$

$$Approx:\ \ C_O \approx \sqrt{C_L^2 + C_S^2}\ \ for\ \ mild\ \ shocks$$



Analytic Models



Relationship Between Effective Density and the U-u Hugoniot.

Analytic Models

- **Stress-Strain Model: Elastic, Perfectly Plastic with Lüders Strain.**

$$\sigma = \sigma_{ys} + C(\varepsilon^{P} - \varepsilon^{L})^{n}$$

σ = effective stress

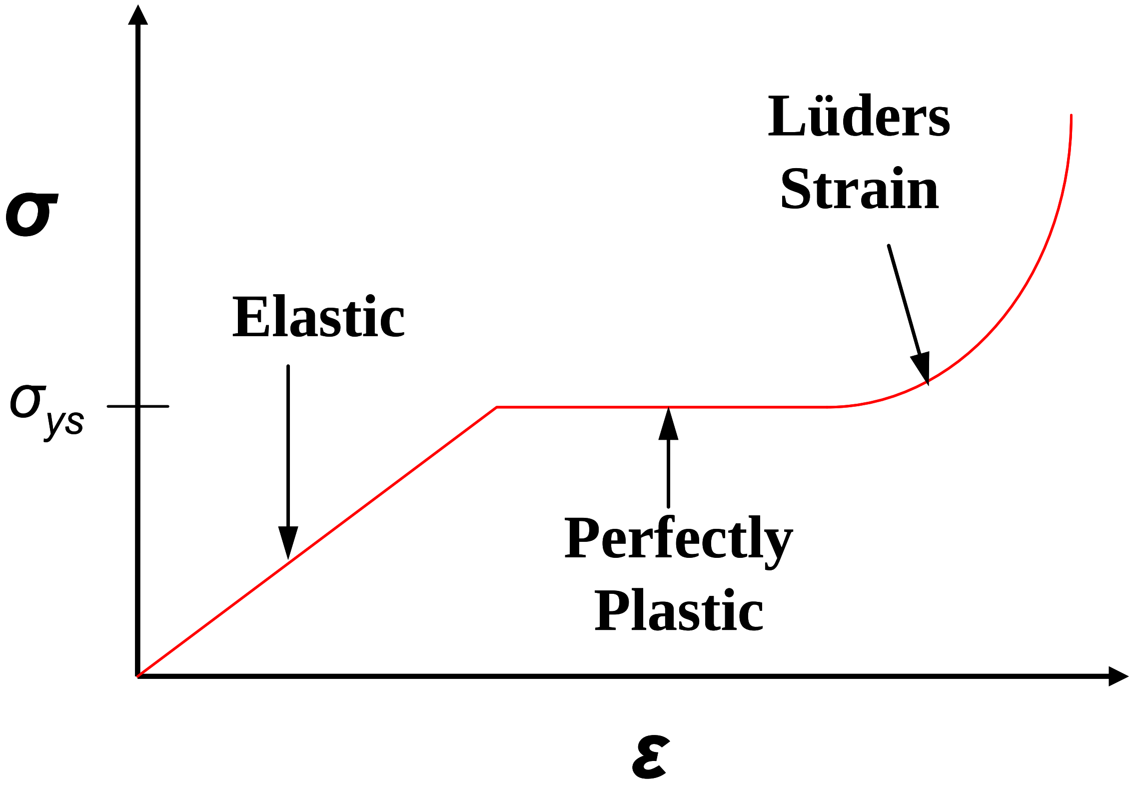
σ_{ys}= initial yield stress

ε^{P}= equivalent plastic strain

ε^{L}= Lüders strain

C, n = material constants

Analytic Models



Elastic, Perfectly Plastic with Lüders Strain Hardening

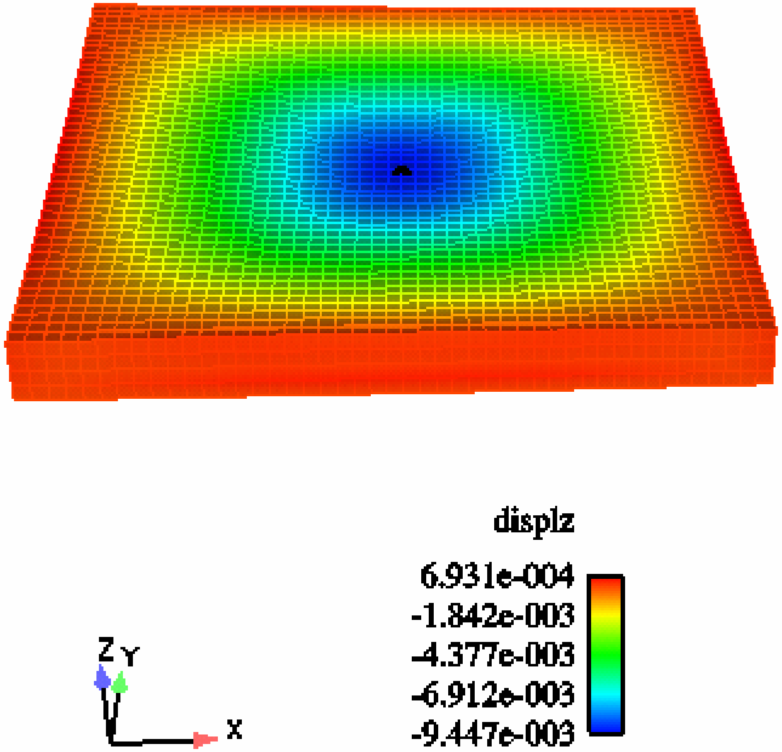
Model Material Properties

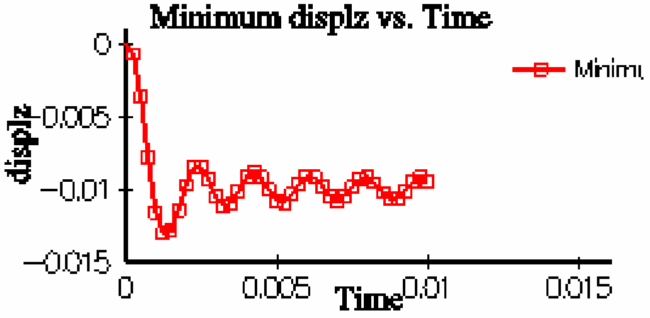
40 PPI Aluminum Foam Material Properties.

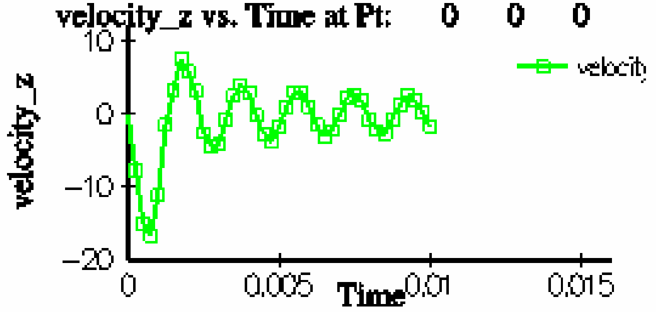
Property	Value	Source
Young’s modulus	452e6 N/m^2	Reference 2 (data/Gibson-Ashby Equations).
Poisson’s ratio	0.33	Reference 6.
Yield stress	1.4e6 N/m^2	Reference 2 (data/Gibson-Ashby Equations).
Lüders strain	0.002	Reference 8.
Hardening exponent	0.2	Reference 8.
Hardening constant	1.00e09 dyne/cm^2	Reference 8.
Initial density	226 kg/m^3	8.1% of value in Reference 5.
C_O	1,928.3 m/s	Derived from Reference 5 using initial density.
S1	1.338	Reference 5.

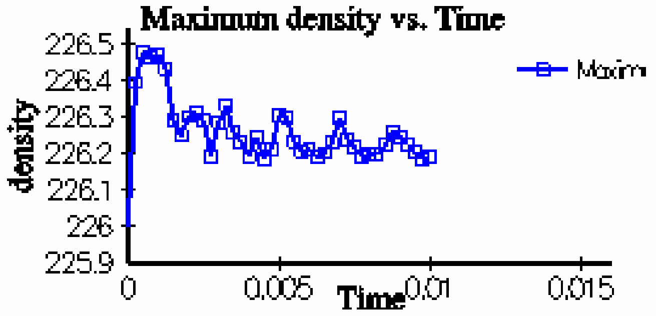
2. T. G. Nieh, K. Higashi, and J. Wadsworth, “Effect of Cell Morphology on the Compressive Properties of Open-Cell Aluminum Foams”, Materials Science & Engineering, A283, 105 – 110, 2000.
4. Paul W. Cooper, “Explosives Engineering”, Wiley-VCH, Inc, 1996.
6. Michael F. Ashby et al, “Metal Foams A Design Guide”, Butterworth-Heinemann, 2000.
8. Charles M. Stone, Gerald W. Wellman, and Raymond D. Krieg, “A Vectorized Elastic/Plastic Power Law Hardening Material Model Including Luders Strain, Sandia National Laboratories, Sand90-0153, March 1990.

ALEGRA Simulation of Test 6.









Code Output Comparison

Comparison of Data vs. ABAQUS, ALEGRA, and CTH.

Parameter	**Data**	**ABAQUS**	**ALEGRA**	**CTH**
Max. Displacement (m)	0.00961	0.0110	0.0105	0.0075
Max. Foam Velocity (m/s)	Not measured	12.0	7.4	8.75

Conclusion

- The shock experiments show that foamed metal can be used to mitigate shocks.
- Analyses of the data indicate that because the shocks were mild, u_p was small, as evidenced by the small change in the calculated density and hand-calculation of the particle velocity via the U-u Hugoniot.
- Because the shock was mild, the magnitudes of the compressive and expansive waves were small.
- The foam absorbed a small fraction of the shock energy because part of the shock wave encountered air-filled cells (as opposed to aluminum filaments).

Conclusion

- The elastic plastic power law hardening constitutive equation and MG US UP EOS are suitable for modeling metallic foam. The P-α model is not suitable for our study because its usage is limited to void fractions less than 20%.
- The ALEGRA, ABAQUS, and CTH results show that the codes were able to calculate the displacement with reasonable success.