The Dynamics of a Shock Wave and Aluminum Foam Layer Interaction

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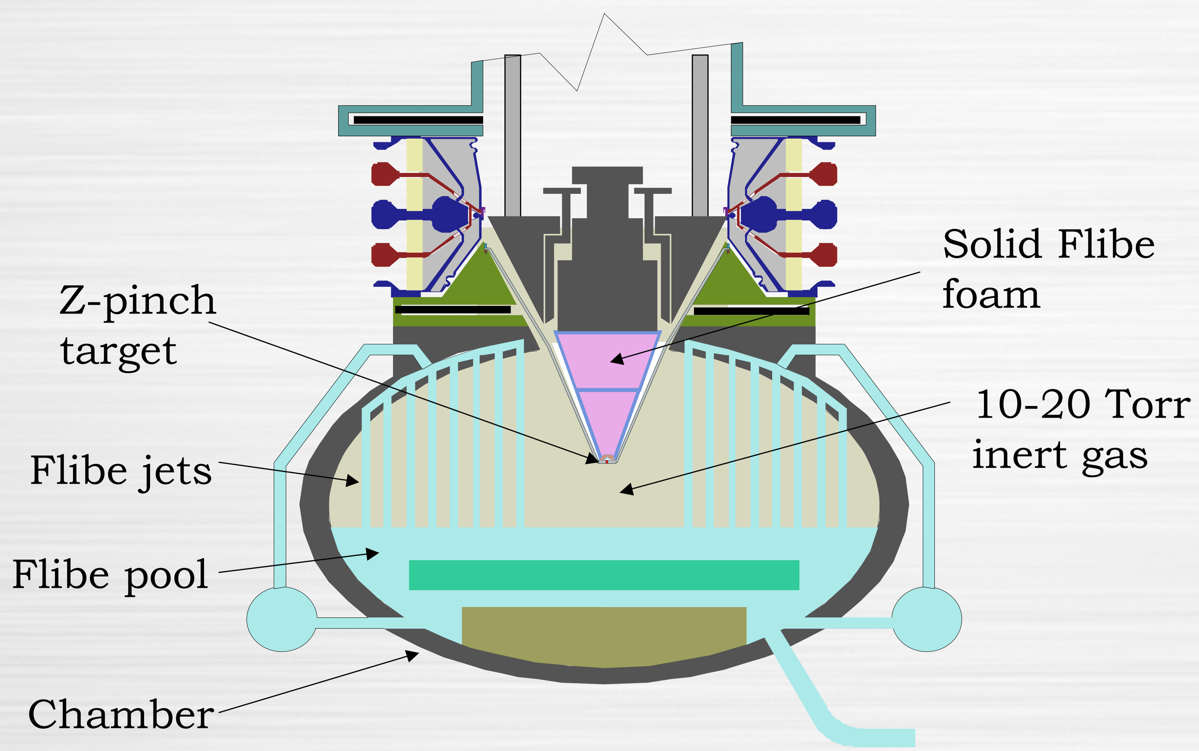
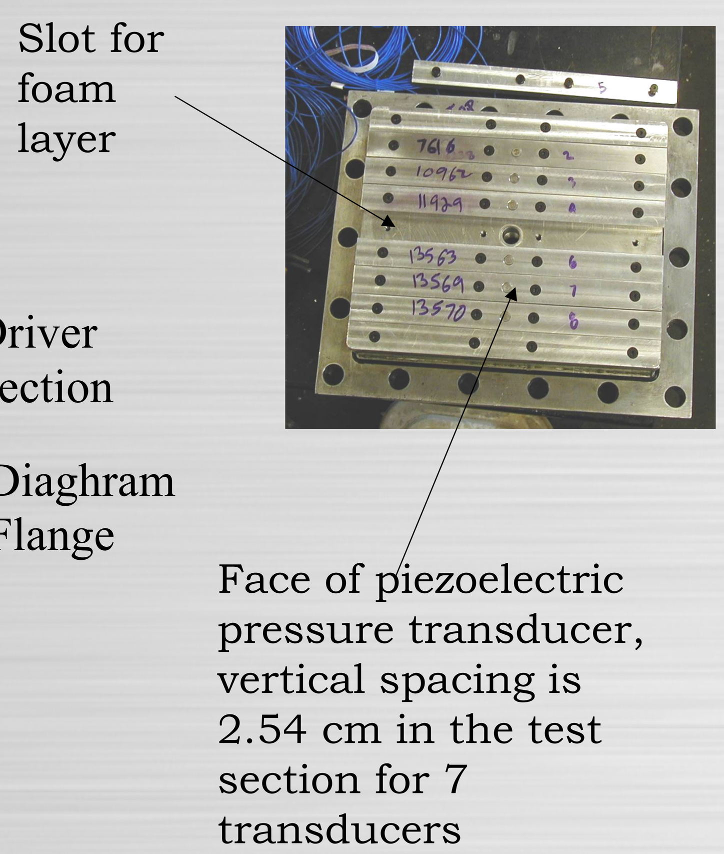
Motivation

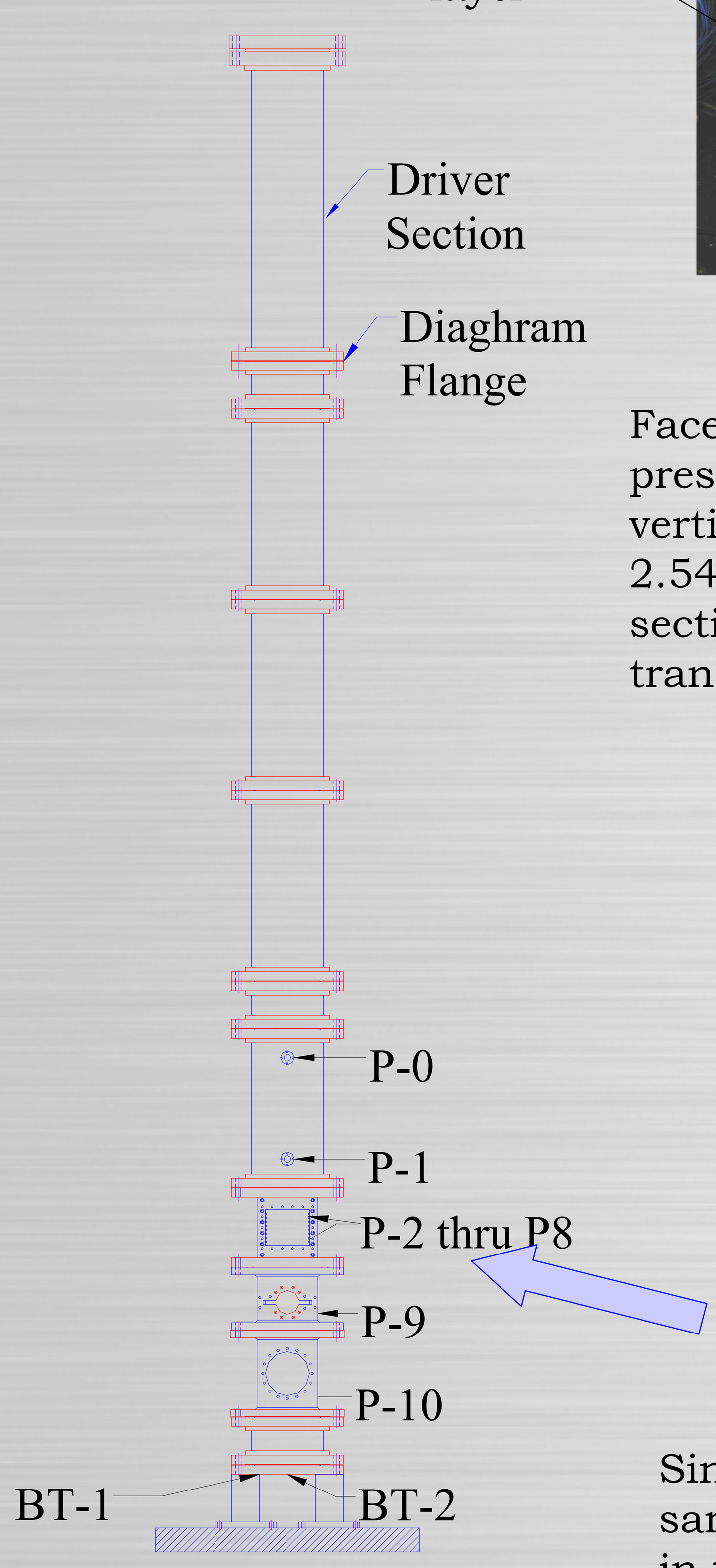
The Z-Pinch inertial fusion energy (IFE) reactor concept utilizes high-yield (~3 GJ) targets at a low repetition rate (~0.1 Hz) to generate energy. There is a hydrodynamic shock wave (due to both the low pressure chamber gas and the coolant ablation that occurs from thermal radiation) that results from each of the nuclear fuel implosions that must be attenuated to protect the target chamber. The primary protection mechanism consists of the coolant (Flibe- fluorine-lithium-beryllium compound) in a bubbly pool (bottom of the reactor), a liquid jet array (the circumference of the reactor), and a solid foam above the target, shown in purple in the schematic.



The Shock Tube

- 9.2 m long, vertically oriented.
- Square internal cross section, 25 x 25 cm.
- Up to Mach 5 into atmospheric air.
- Piezoelectric pressure transducers.

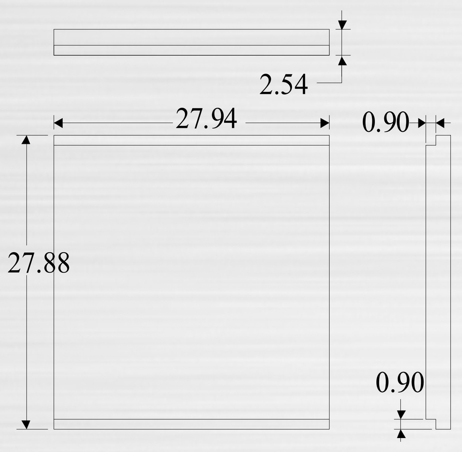


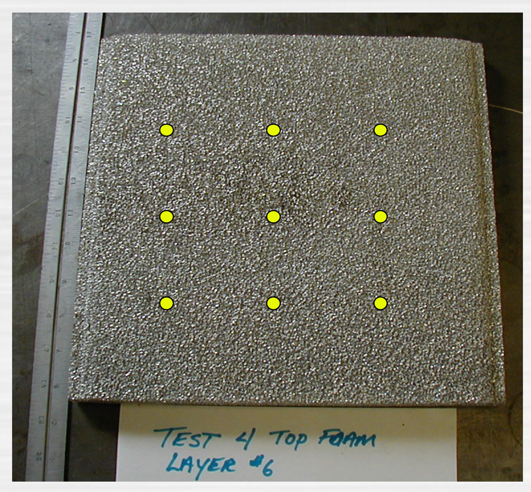


Single layer foam sample in slots in test section

Foam Sample

The foam samples were dimensioned as shown (in cm); the two reduced-thickness edges are for mounting, in a press-fit configuration, into slots in the walls of the shock tube test section. The yellow dots represent locations where micrometer displacement measurements were taken before, and after, the experiment.





40 PPI Aluminum foam
418 grams, 8.6% density

Test Matrix

Ten foam samples were tested in several configurations with the following parameters being varied: pore size, number of layers (and layer spacing), and initial pressure of the driven section. The samples failed in two of the experiments.

Exp. No.	Porosity Ppi	No. of Layers	Space Between Layers	Initial M (Nominal)	Initial Pressure	Fractured?
4	40	1	n/a	1.45	1 bar	Yes
6	40	1	n/a	1.34	1 bar	No
7	40	1	n/a	1.34	1 bar	No
8	40	2	3 in	1.34	1 bar	No
9	40	2	1 in	1.34	1 bar	No
10	20	1	n/a	1.34	1 bar	No
11	10	1	n/a	1.34	1 bar	No
16	40	1	n/a	3.66	42 torr	Yes

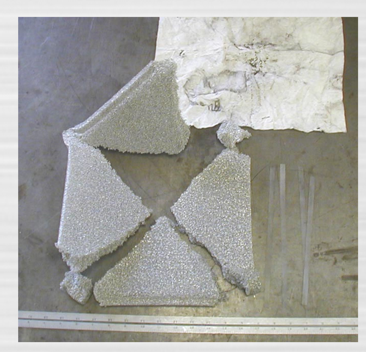
Foam Material Model

The manufacturing process for solid Flibe foam is still under development so for these shock mitigation experiments an open-cell aluminum foam was studied. The Duocell (ERG) aluminum foam has a nominal cellular density (ρ_c) of 8.6% that of solid Al (ρ_s=2,700 kg/m^3) corresponding to a porosity of $\phi=1-\rho_c/\rho_s=0.914$. Three materials of different cellular dimensions were used: 10, 20, and 40 ppi (pores per inch). The more cells per linear dimension resulted in both smaller cell size and also smaller ligament diameters. For incompressible flow applications (e.g. heat exchangers), a smaller cell size results in a higher pressure drop across the material per unit length; it was desired to investigate if an analogous type of relationship existed for shock attenuation for the eventual design of the Flibe foam to be used in the IFE reactor.

Place Foam
Samples Here

Shock Strength Design

With the measurement of shock attenuation being the primary goal of the experiment, the shock strength was chosen so that the foam layer did not fail structurally during the test. The M=1.45 shock strength (in atmospheric pressure Ar) was chosen based on a shear strength failure calculation. The first experiment resulted in a bending mode failure with a classical diagonal fracture pattern. The shock strength was then reduced to M=1.34 for future tests.



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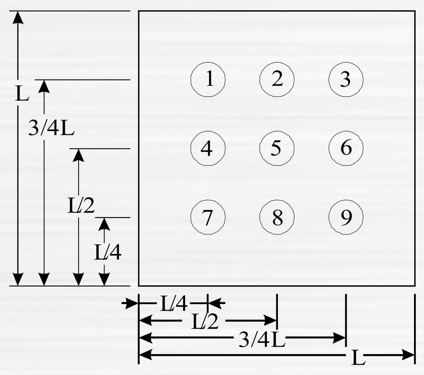
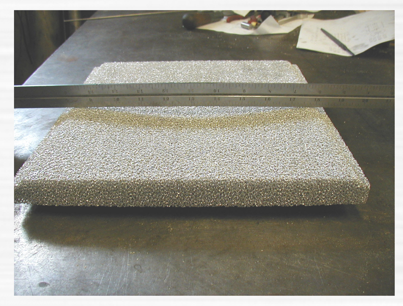
Deformation Results

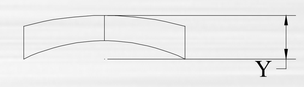
Some measurements for Exp. 6 are shown and the shocked layer is visibly cupped-concave down in the direction of incident shock propagation. The maximum compression was observed at the center of the sample, where the initially 25.4 mm thick layer was reduced to 15.52 mm (0.6112 in).



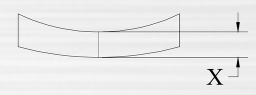


Pre-Shock Foam Test 6
1 - 0.989 2 - 0.990 3 - 0.9894
4 - 0.9886 5 - 0.989 6 - 0.9898
7 - 0.988 8 - 0.9886 9 - 0.9886

Post-Shock CC Up
1 - 1.1362 2 - 1.1940 3 - 1.1258
4 - 1.2046 5 - 1.3498 6 - 1.1894
7 - 1.1544 8 - 1.2118 9 - 1.1462



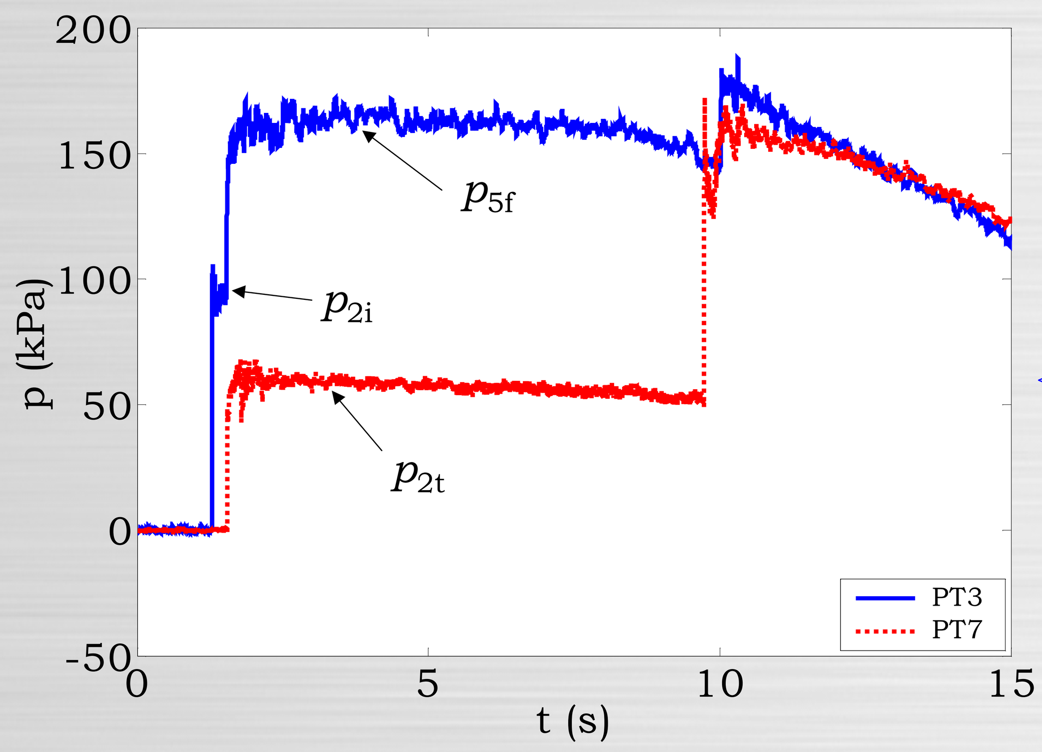
Post-Shock CC Down
1 - 0.8328 2 - 0.7614 3 - 0.8192
4 - 0.7934 5 - 0.6112 6 - 0.7742
7 - 0.8530 8 - 0.7930 9 - 0.8408



Pressure and Wave Speed Results

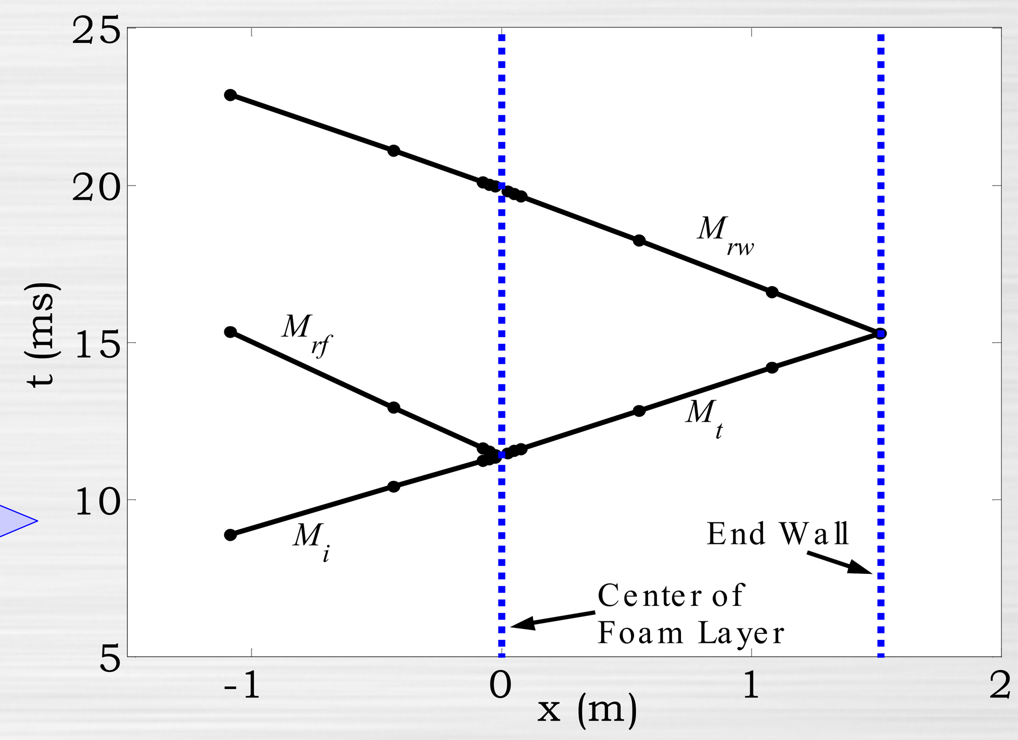
The pressure traces along the wall were used to determine wave speeds as well as pressure: W_i, incident wave speed; M_i incident Mach number based on W_i; W_t, wave speed transmitted to the other side of the foam; M_t, transmitted Mach number; $W_r=(W_i-W_t)/W_i$, wave speed reduction; W_{rf}, the wave reflected from the top surface of the foam layer; W_{rw}, reflected wave speed from the end-wall of the shock tube; p_{2i}, pressure behind W_i; p_{2t}, pressure behind W_t; $p_{2r}=(p_{2i}-p_{2t})/p_{2i}$, pressure reduction; p_{5f}, pressure behind W_{5f}; and p_{5w}, pressure behind W_{5w}.

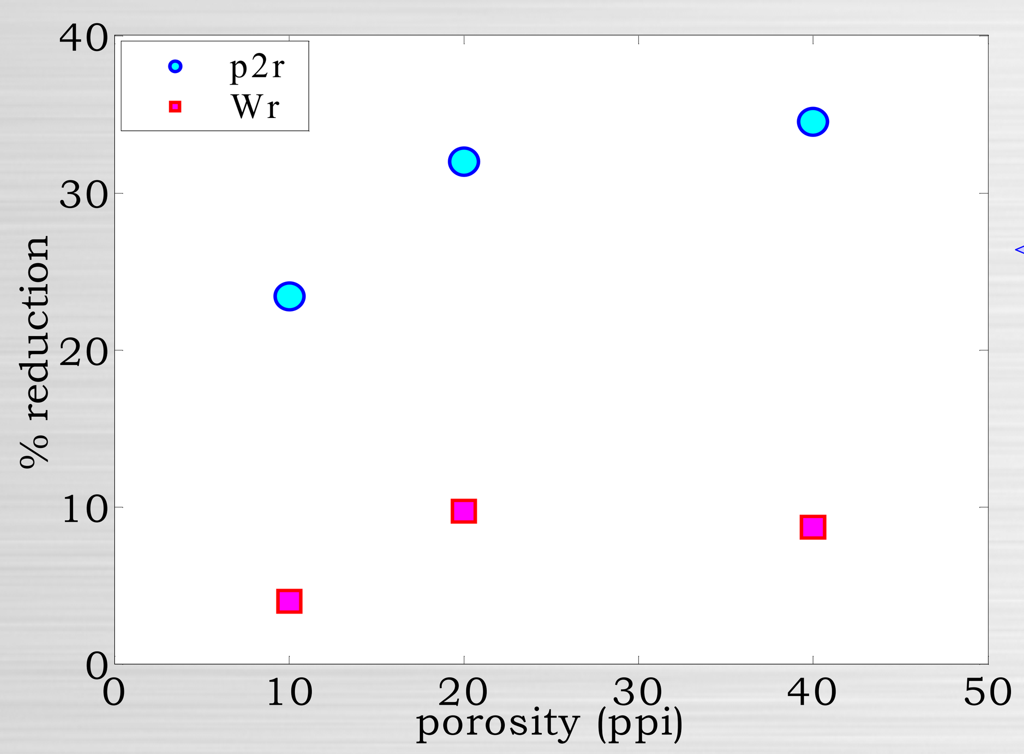
Exp. No.	W_i (m/s)	M_i	W_t (m/s)	M_t	W_r (%)	W_{rf} (m/s)	W_{rw} (m/s)	p_{2i} (kPa)	p_{2t} (kPa)	p_{2r} (%)	p_{5f} (kPa)	p_{5w} (kPa)
4	459	1.42	409	1.27	**10.6**	n/a	n/a	121	77.8	**35.9**	n/a	n/a
6	426	1.32	389	1.21	**8.3**	273	326	91.7	60.1	**34.5**	163	143
7	432	1.34	393	1.22	**9.0**	271	323	94.6	61.9	**34.6**	169	148
8	432	1.34	368	1.14	**14.9**	272	318	92.7	46.1	**50.3**	181	108
9	435	1.35	373	1.16	**14.1**	274	319	97.1	48.8	**49.7**	194	113
10	431	1.34	392	1.21	**9.7**	269	323	93.7	63.7	**32.0**	160	152
11	405	1.25	386	1.20	**4.0**	270	322	69.1	52.9	**23.4**	103.6	123.9
16	1,180	3.65	853	2.64	**27.7**	n/a	n/a	58.7	27.6	**53.0**	n/a	n/a



Exp. 6
Sample Pressure Traces

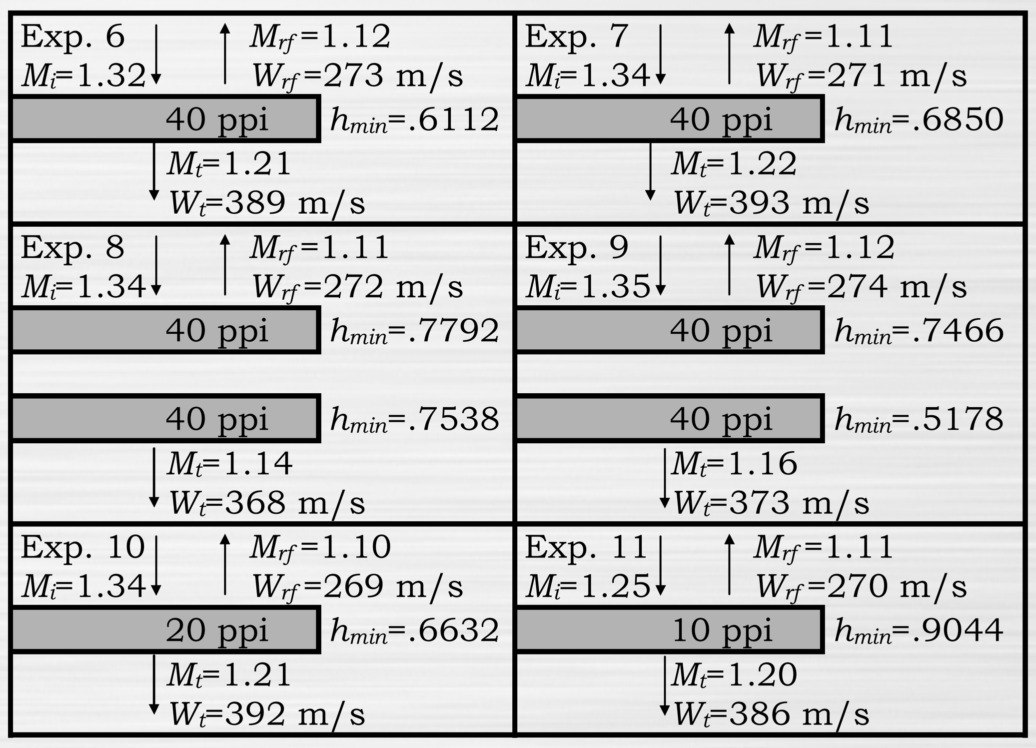
x-t diagram





Attenuation

Summary Table



Conclusions and Future Work

Transmitted wave speed attenuation was modest but the pressure reduction was significant, 35% and 50% for the single- and double-layer experiments, respectively. At this shock strength, which was chosen to approach the failure strength of the foam, some of the shock energy is translated into plastic deformation of the cell structures and reduction of the sample layer thickness; however, most of the attenuation is believed to be due to frictional increases for the flow in the open-cell, porous foam. There is no quantitative information obtained that may be directly used to predict wave speed and pressure reduction for changes in shock strength or foam thickness, however, these data may be used to assist in the benchmarking of codes that could then be used for investigations into other regimes. Future work will study the behavior of the shock wave as it transmits through a much thicker foam sample (10 cm) subjected to a much higher shock strength (M_i≈6) with a resultant pressure load of several MPa.