LA-UR- 04-4281

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Title: RESULTS OF EXPLOSIVELY-DRIVEN ISENTROPIC COMPRESSION EXPERIMENTS (HEPP-ICE)

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Submitted to: ICOPS 2004
July 1, 2004

Los Alamos
NATIONAL LABORATORY

To be presented at the 31st IEEE International Conference on Plasma Science (ICOPS 2004) to be held in Baltimore, MD, June 28 to July 1, 2004.

Results of Explosively-Driven Isentropic Compression Experiments (HEPP-ICE)*

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Using the Los Alamos high explosive pulsed power (HEPP) system, isentropic equation of state (EOS) data may be obtained for a wide range of materials. Current pulses with risetimes of ~500 ns and current densities exceeding 400 MA/m, create continuous magnetic loading of samples at megabar pressures. We will summarize the technique and the problems that had to be overcome to perform the HEPP-ICE experiments at these pressures. We will then present our EOS results obtained with the conventional Lagrangian analysis and the Hayes' "Backward" integration method,[1] and compare the data with the published principal isentrope of OFHC copper.

* This work was supported by the U.S. Department of Energy, LA-UR-04-0157

[1] "Backward Integration of the Equations of Motion ... ," Dennis Hayes, Sandia National Labs., SAND2001-1440, May 2001

LA-UR-04-0157

Results of Explosively-Driven Isentropic Compression Experiments (HEPP-ICE)

ICOPS 2004

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DX-2, *P-22

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Overview

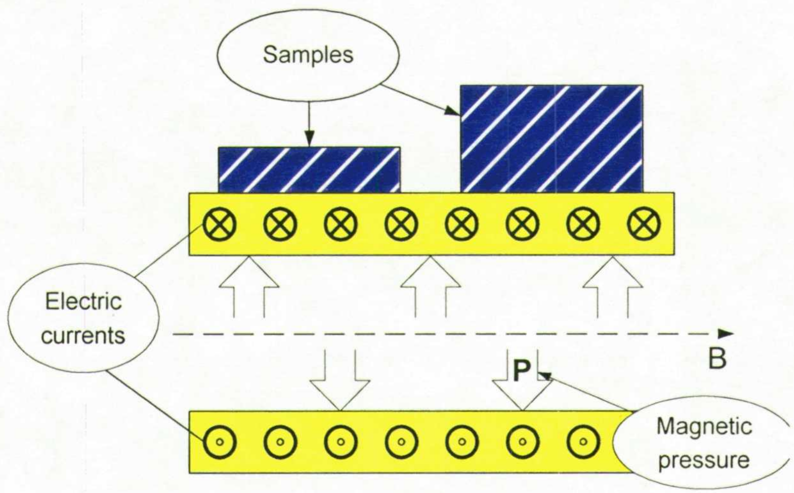
- What is HEPP-ICE?
- Technique described, physics, circuit specifications
- Experimental design
- Timing issues
- Results compared to principal isentrope of OFHC copper
- Future capabilities
- Summary

What is HEPP-ICE?

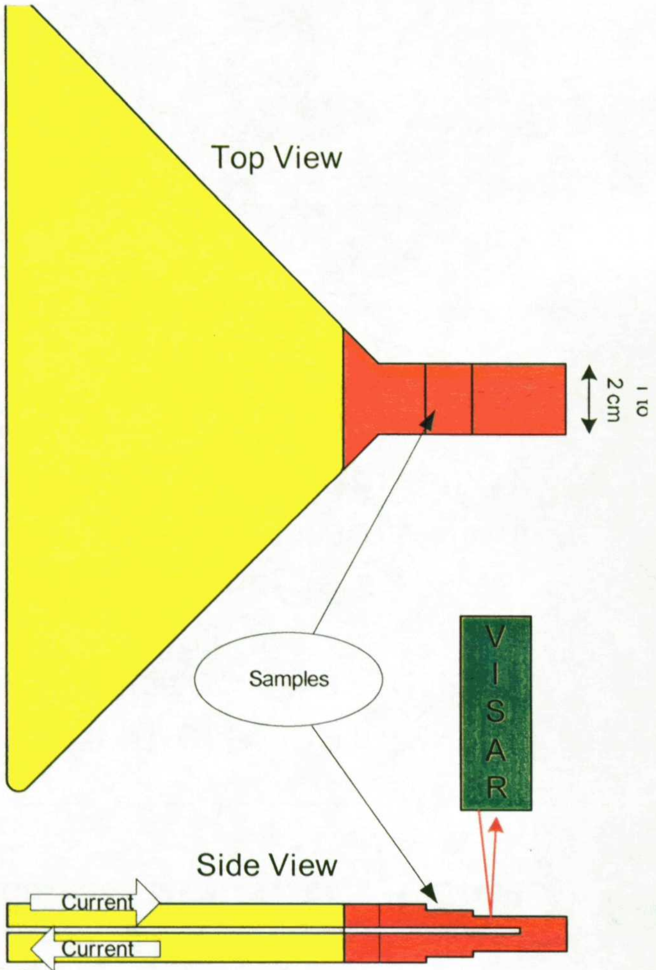
- Purpose:
  - To obtain isentropic equation-of-state (EOS) data for various materials at megabar pressures.
- Why?
  - At megabar pressures isentropic EOS data are significantly different to shock (Hugoniot) EOS data.
- Concept:
  - Use magnetic pressure to achieve shock-free loading of materials.
- Method:
  - Use high explosive pulsed power (HEPP) to develop current densities >= 5MA/cm with risetimes of ~500 ns.

Magnetic compression - parallel plates

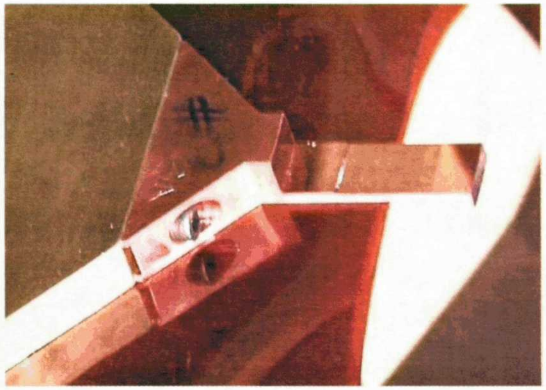
- Magnetic pressure P = 2π GPa (63 kbar) for J = 10^8 A/m (1 MA/cm) -
  - $P = \frac{1}{2}\mu_0 J^2$ Pa (J: current density, A/m), SI units,
  - P = ~3 Mbar @ 7 MA/cm (B = 880 T).



HEPP ICE load section



- Planar design (not coaxial).
- Tapered to minimize inductance.



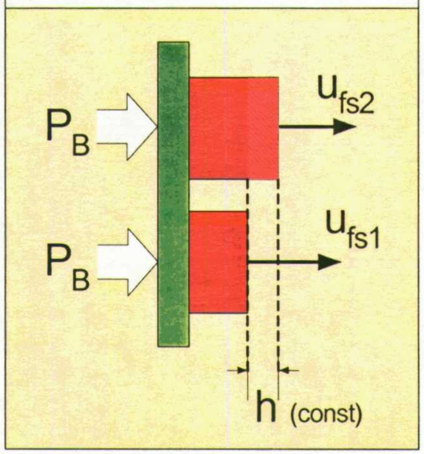
HEPP-ICE gap exaggerated, is ~ ½ mm

EOS data recovery – standard method

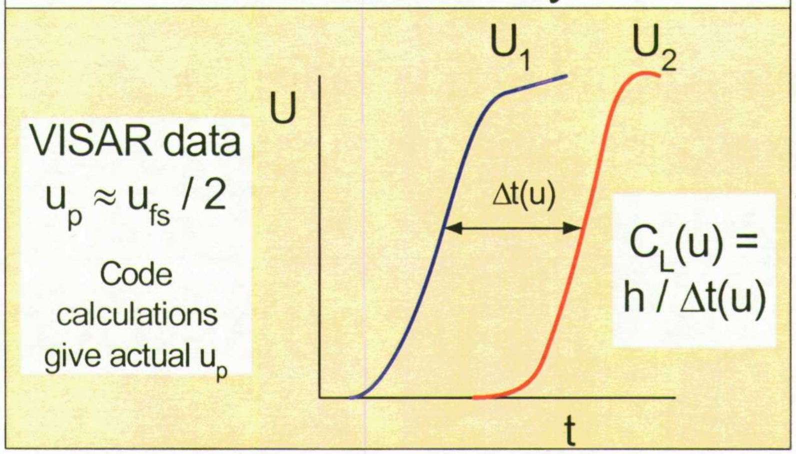
- 2 or more sample thickness compressed in each experiment
  - Note: Pressures (P_B) must be equal so B field MUST be uniform.
- VISARs used to measure particle velocities at back faces
  - with or without windows.
- Lagrangian analysis gives pressure etc., with h = constant.

$$c_L(u) = \frac{h}{\Delta t(u)} \qquad d\sigma = \rho_0 c_L(u) du \qquad c_E = \left(\frac{\rho_0}{\rho}\right) c_L$$

EOS Pairs



VISAR data analysis

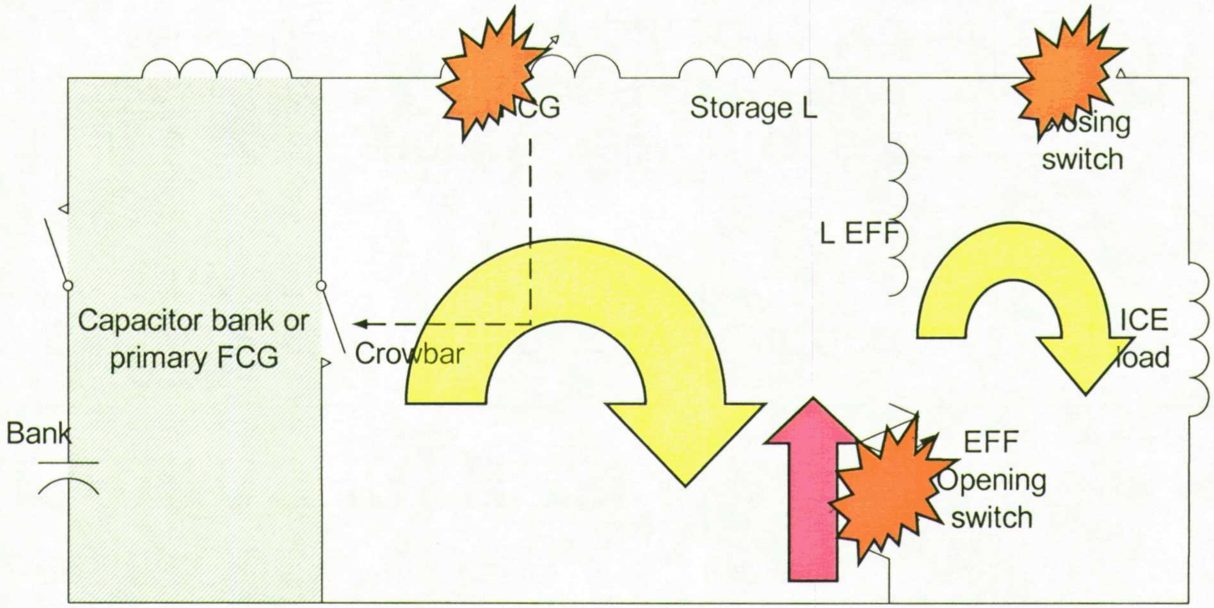


Risetime issues

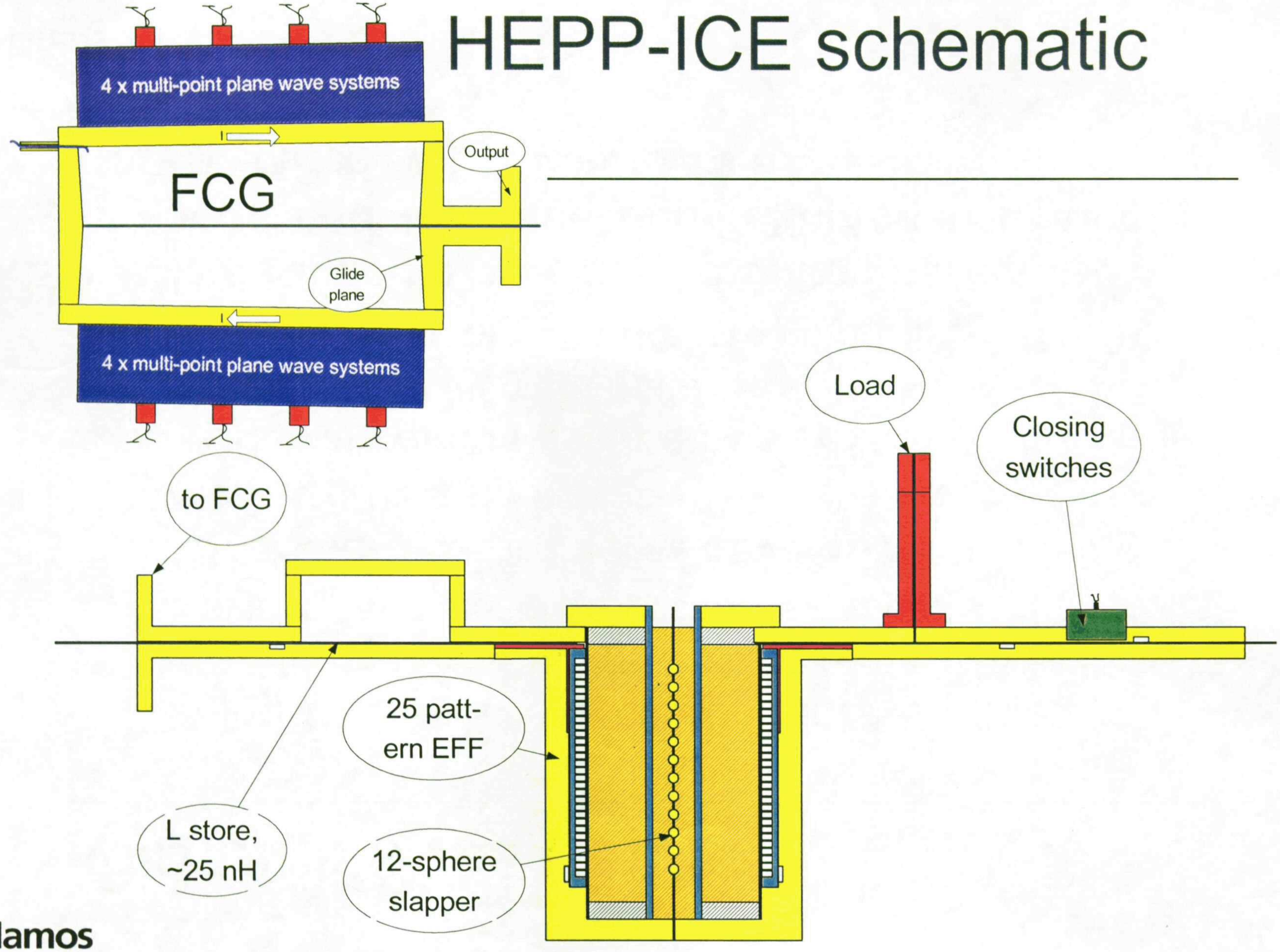
- Pressure P_B >> strength of any conductor (1 - 10 kbar), so conductors fly apart.
- ONLY inertia holds them together for a short time (i.e., time for relief waves to return from free surface). So current risetimes must be short compared to transit time.
- BUT if risetime is too short than shocks develop prematurely
  - 300 to 600 ns optimum for ICE for mm-thick samples.
- This is a challenge for HEPP, 5 μs is more typical.
- Have developed a "baseline" system to meet this requirement.

LANL HEPP-ICE Circuit

- Plate flux compression generator (FCG) and pulse conditioning
  - FCG produces large current at low voltage,
  - Then explosively-formed fuse (EFF) produces high voltage,
    - for fast risetime,
  - At peak voltage, current switched to load by staged closing switch,
    - for shaped (controlled) current rise.



HEPP-ICE schematic



Circuit issues (timing)

- Timing of the various components is critical
  - Desired jitter of the flux compressor, opening switch, and closing switches is ~ 50ns.
- We had serious problems developing a closing switch to these specs.
  - Original switch was based on explosively-driven jet puncture of insulation,
  - Jitter was as high as **600 ns** with this switch.
- We designed a new closing switch based on shock-induced conduction in Kapton insulation
  - Reduced switch jitter to **20 ns.**

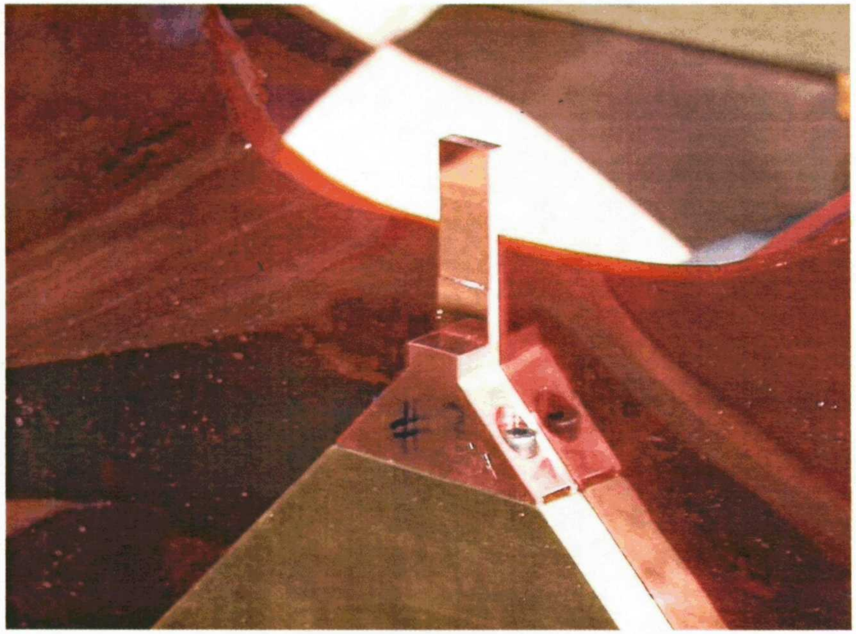
Progress with HEPP-ICE system - 1

- We systematically eliminated various problems associated with insulation systems, corona, and closing switches.
- From ICE-10 on there have been **six successful shots in a row – the design has been proven reliable.**
- Having achieved reliability we were able to build accurate circuit models to analyze and optimize HEPP-ICE performance
  - These models incorporate all the physics of the FCG, EFF, closing switches, AND the load (including acoustic wave interactions).
- Performance of complete experiment can now be modeled
  - Allows accurate predictions of HEPP-ICE capabilities.
  - More on this later …

Progress with HEPP-ICE system - 2

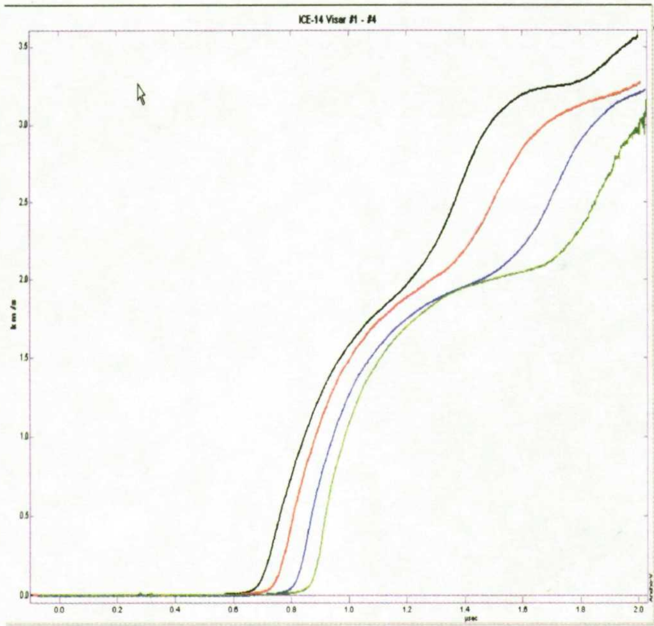
ICE	Seed MA	FCG MA	Veff kV	Load	Load MA	Risetime ns	P mag Mbar
4	1.90	6.90		OFHC Cu	3.00		
5	1.90	6.90	120	OFHC Cu	3.00		
6	1.92	9.14	100	OFHC Cu	3.00		
7	1.92	9.14	90	W	3.30		
8	1.90	9.00	102	OFHC Cu	3.10	1812	0.37
9	1.90	9.70	96	Brass	5.30	2074	1.09
10	**1.90**	**9.95**	**60**	**Brass**	**5.70**	**680**	**1.27**
11	**1.95**	**9.05**	**100**	**Brass**	**4.87**	**860**	**0.92**
12	**1.88**	**9.05**	**91**	**OFHC Cu**	**5.96**	**964**	**1.38**
14	**1.88**	**9.06**	**82**	**OFHC Cu**	**5.00**	**648**	**0.97**
15	**1.95**	**9.85**	**125**	**OFHC Cu**	**5.39**	**662**	**1.13**
16	**1.95**	**9.91**	**80**	**OFHC Cu**	**5.15**	**670**	**1.03**

RESULTS: For ICE-14 copper load

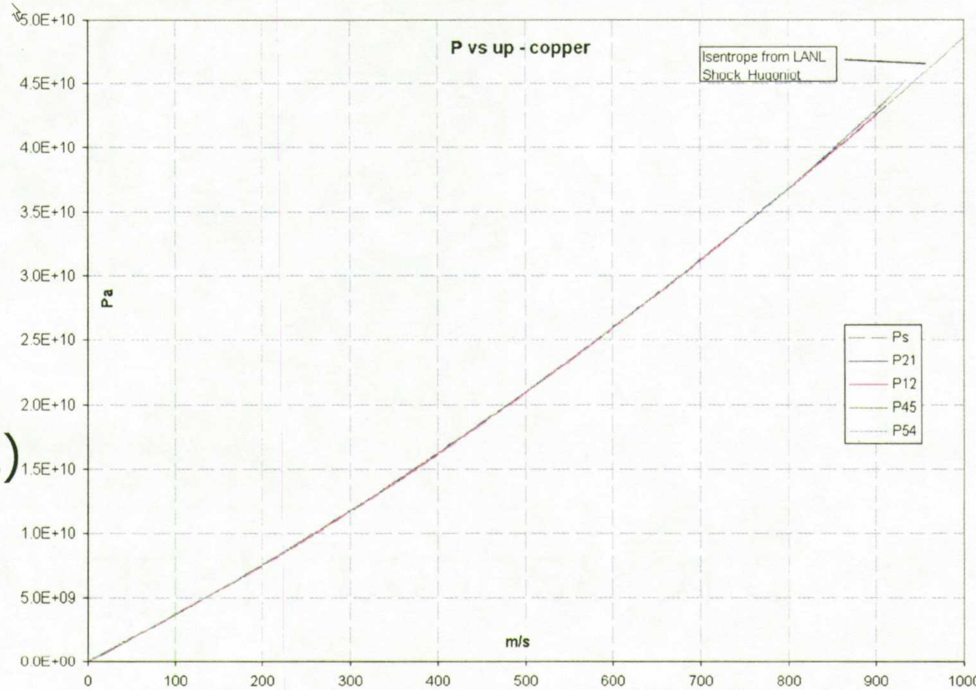


- 4 OFHC copper samples, 2 on each face with different thicknesses (1.8 – 2.5 mm thick).
- Width here 1.27 cm.

ICE-14 Visar data and EOS results



- Free surface velocities at back faces of samples 1 to 4 in OFHC copper
  - Thicknesses: 1791, 2005, 2283, 2517 µm.

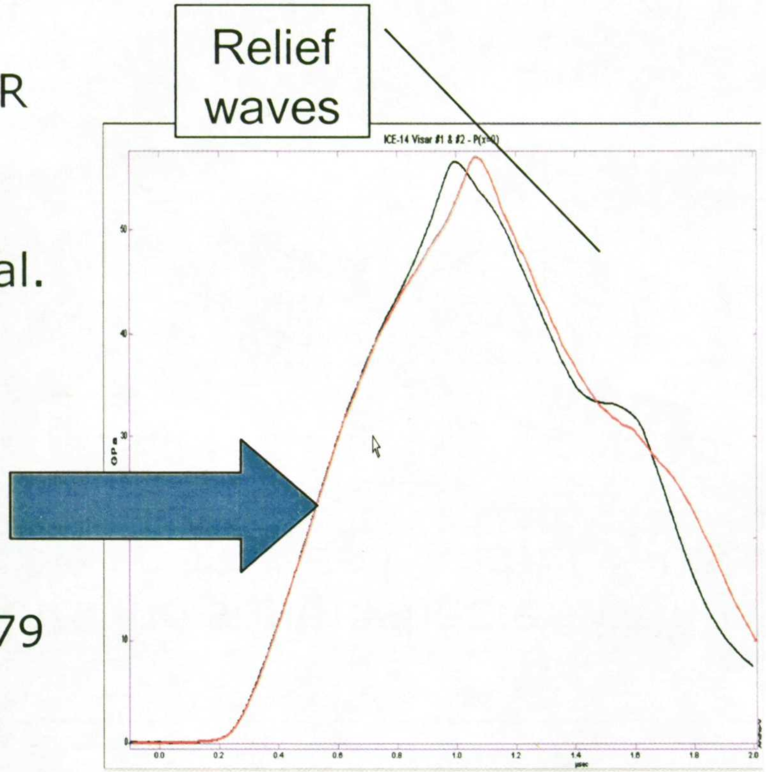


- Excellent agreement between published (LANL) EOS and ICE-14
  - Within 0.2%

Verification of results with "Backward" calculation

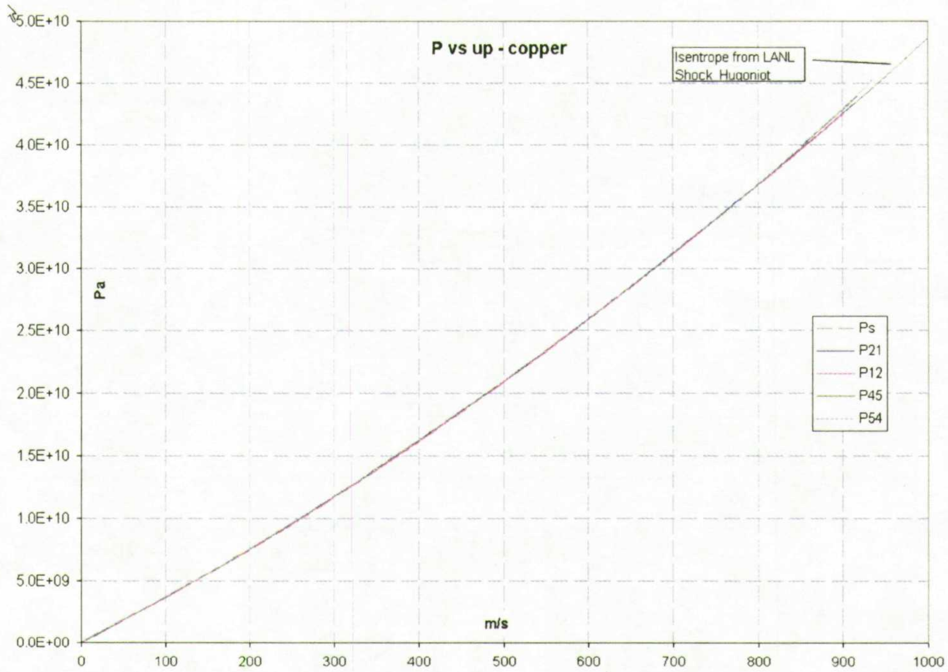
- If we have the correct EOS (and the loading is shock-free) we can calculate backwards from the VISAR surface to the magnetic drive surface.
- There the pressures should be equal.

- Stresses obtained with "Backward" and principle isentrope from published data, for OFHC copper
  - RMS deviation between samples 79 MPa, or 0.2% of 40 GPa,
  - Results indistinguishable from published data.



Summary

- Good data obtained. Results indistinguishable, within experimental error of ~0.2%, from published EOS data for OFHC copper, up to 40 GPa.
- Further improvements are possible.



Future work

- This baseline system, based on a 12-MA flux compressor, is limited to ~2.5 Mbar.
- Tandem or parallel flux compression generator (FCG) modifications can extend pressure range beyond 4 Mbar.
- A scaled-up design, based on the 90-MA Ranchero FCG, will allow us to reach significantly higher pressures.

Acknowledgements

- We truly appreciate the invaluable assistance and support of the LANL DX-2 shock physics group who provided and fielded the VISAR diagnostics.
- We are extremely grateful to Rendell Carver (LANL X-division) for his continued encouragement, enthusiasm, and financial support.
- We are indebted to Dennis Hayes for invaluable contributions to the data analysis.