THERMODYNAMIC PROPERTIES OF WARM DENSE MATTER

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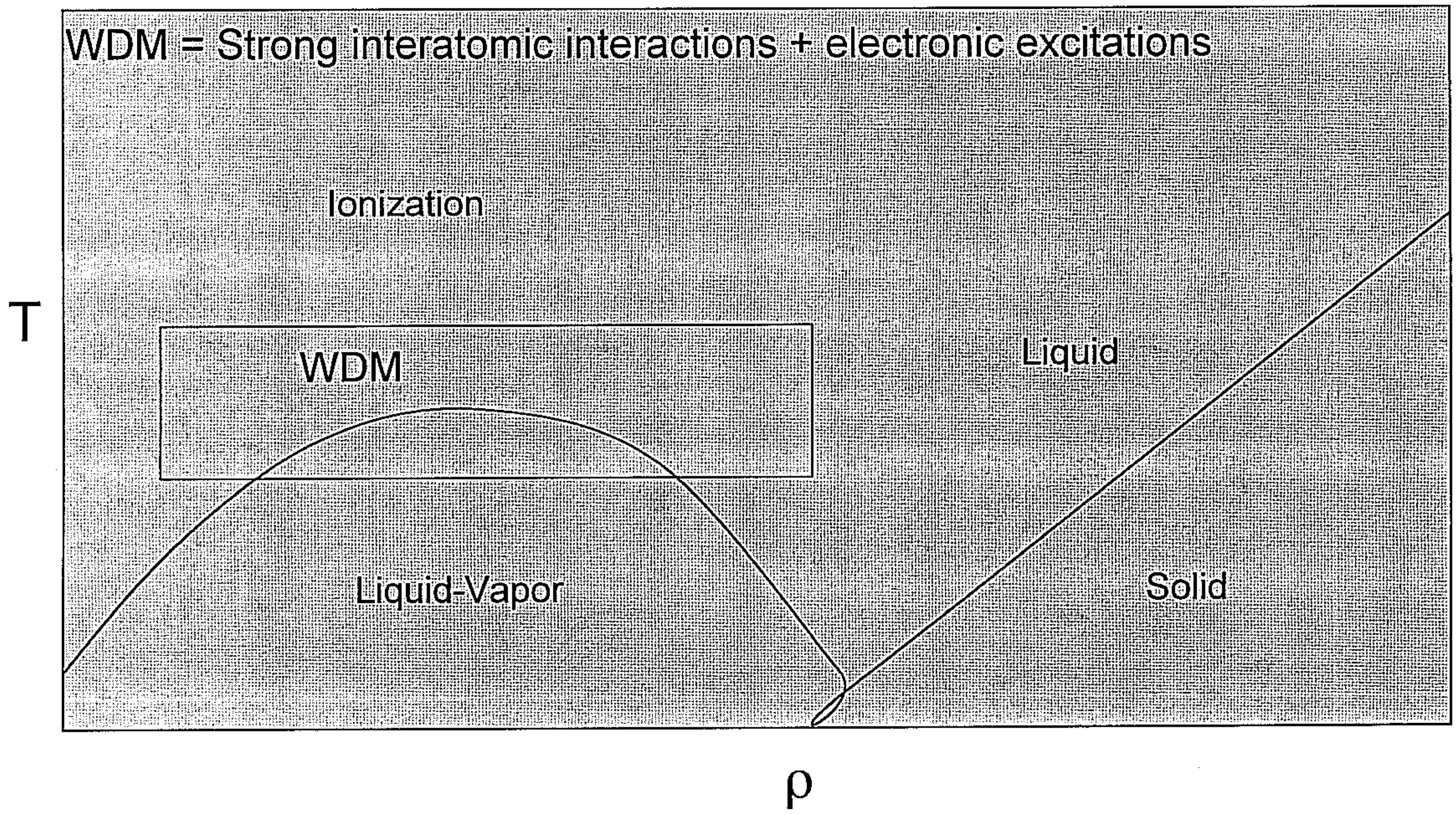
WHAT IS "WARM DENSE MATTER"?



WHY ARE WE INTERESTED?

- At LLNL, we build GLOBAL Equation of State tables and we need to cover the WDM region
- There is a steadily rising demand for more accurate EOS tables
- New experiments drive new theory
- Applications:
  - ablation physics
  - shocked gases and foams
  - releases from strong shocks

WDM EXPERIMENTS ARE CHALLENGING

The problem:

1) deliver enough energy to produce a WDM state

2) make accurate measurements on this state

Conventional explosives and gas guns are just barely able to enter the WDM regime

New methods to produce higher energy densities are needed for WDM research

WDM THEORY IS CHALLENGING

Plasma model

T = ∞ basis
excitation, ionization, Coulomb coupling, mixing
LLNL model: ACTEX

WDM

Neither basis
Is adequate

Solid-State model

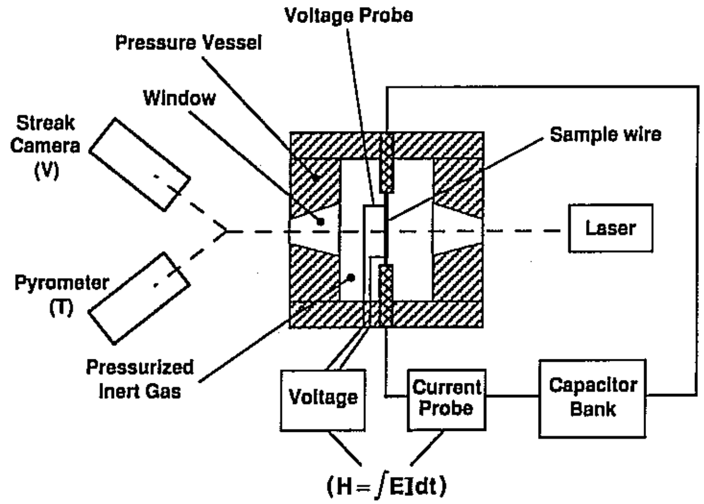
T = 0 basis
Fermi gas, cold curve, lattice dynamics, dense fluids
LLNL model: XEOS

WDM EXPERIMENTAL DATA

- Isobaric expansion data
- Isochore data
- Gas Shock data
- Porous Shock Hugoniot
- Porous Shock Hugoniot release

ISOBARIC EXPANSION EXPERIMENTS
SOFT-SPHERE THEORY

IEX Experiment



Soft-Sphere liquid model

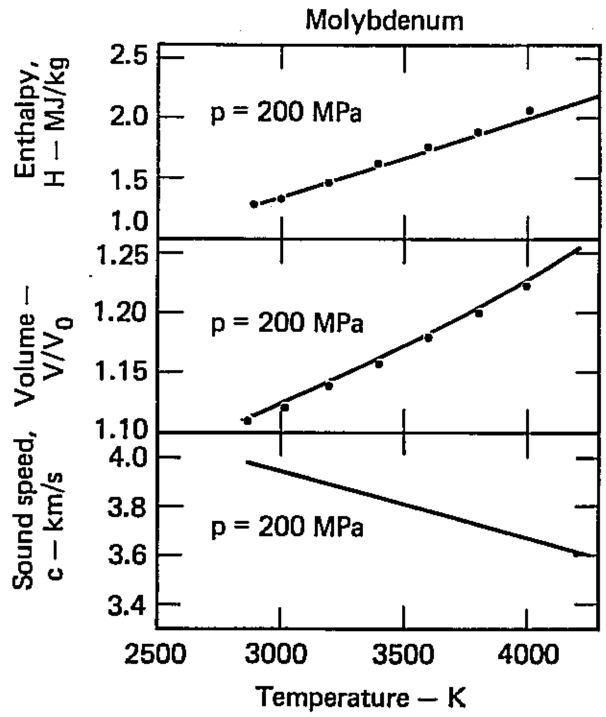
$\phi(r) = \varepsilon(\sigma/r)^n$

$E(\rho,T) = NkT\ [3/2 + C_n\rho^{n/3}(\varepsilon/kT)^{1/3}$
$+ (1/6)Q(n+4)\ \rho^{n/9}(\varepsilon/kT)^{1/3} - \rho^m(\varepsilon/kT)]$

ISOBARIC EXPANSION EXPERIMENTS
SOFT-SPHERE THEORY FITS

Molybdenum

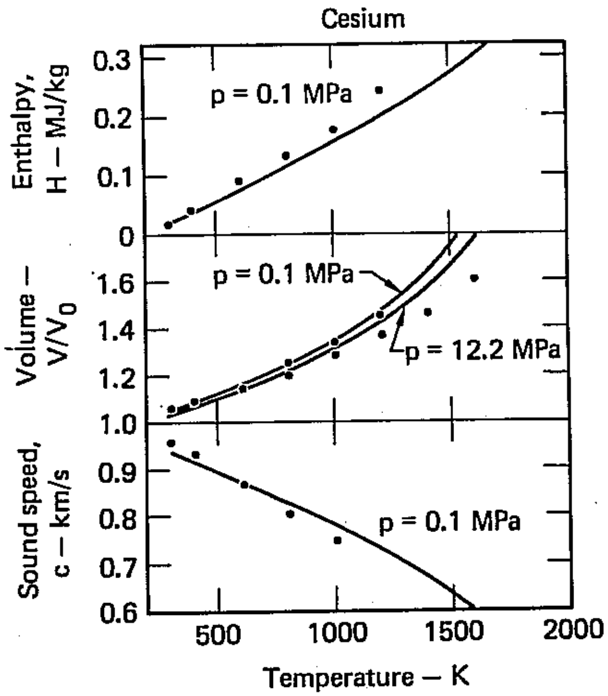
IEX Experiment
From Livermore
(1977)

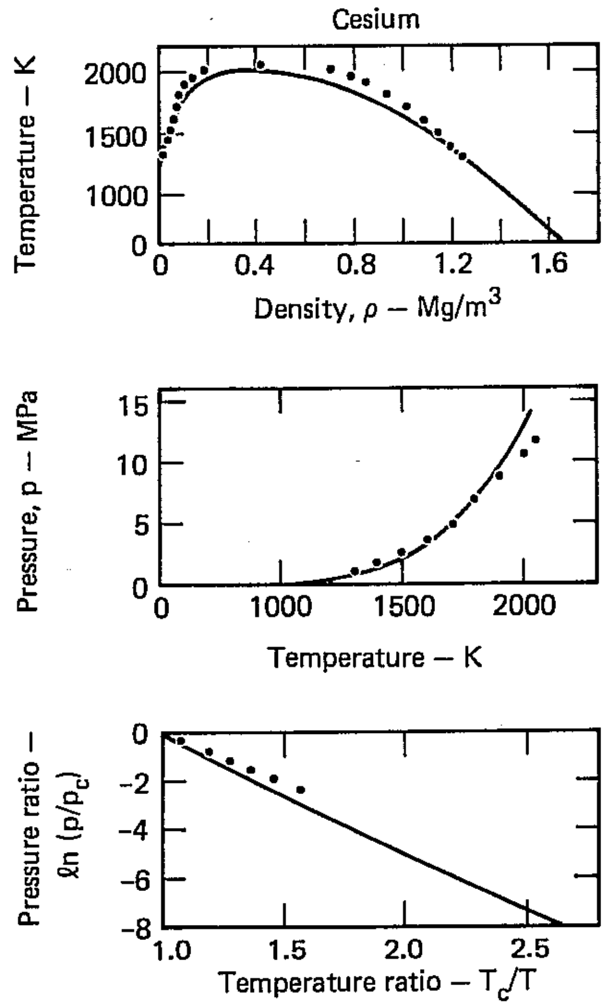


ISOBARIC EXPANSION EXPERIMENTS
SOFT-SPHERE THEORY FITS

Cesium

Isobars and Coexistence Curves





SOFT-SPHERE THEORY PREDICTIONS OF CRITICAL POINTS

We can estimate critical points from the soft-sphere model

	T_c(expt) K	T_c(SS) K	P_c(expt) kb	P_c(SS) kb
Cs	2048	2018	0.116	0.136
Hg	1740	2074	1.41	1.78
Pb	(5300)	5158	(1.70)	2.26
Mo	(13300)	8002	(9.6)	9.70
Ta		9284		9.99
U		6618		4.16

GLOBAL EOS MODELS

Global EOS model represents solid, fluid, and plasma states

Approximate decomposition into cold, ion thermal, and electron thermal pieces:

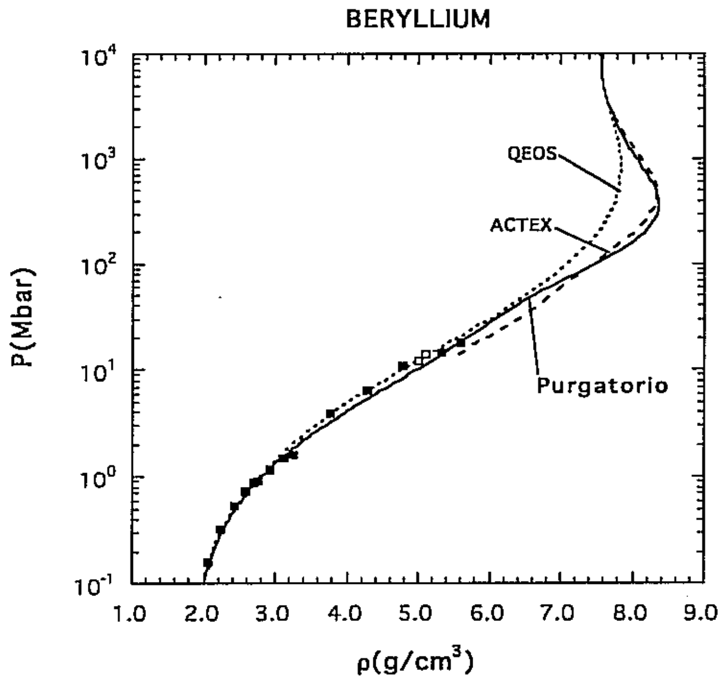
$$E_{tot}(\rho,T) = E_c(\rho) + E_i(\rho,T) + E_e(\rho,T)$$

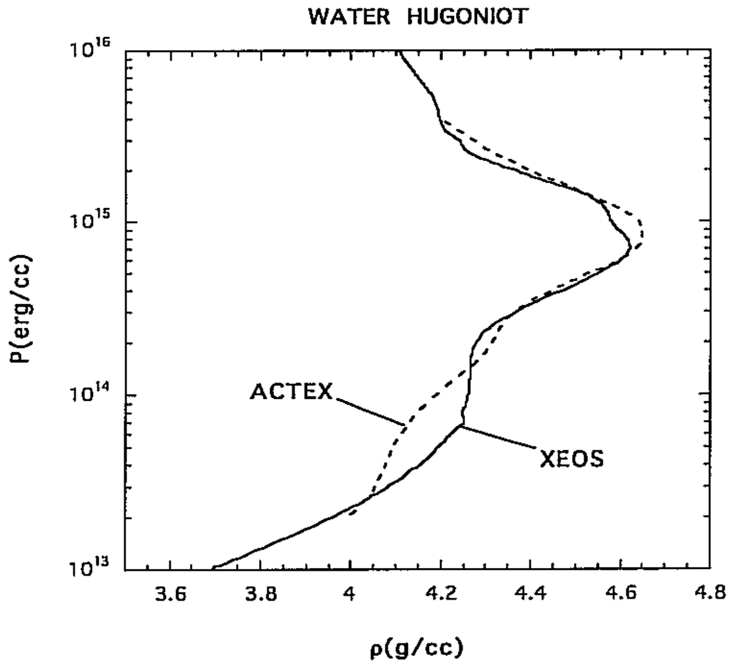
$E_c(\rho)$	$E_i(\rho,T)$	$E_e(\rho,T)$
Based on Thomas-Fermi + bonding model	Debye-Gruneisen Model+Lindemann Melt+scaling fluid	Thomas-Fermi or Dirac atom model

LLNL global EOS physics: QEOS (ca. 1980), XEOS (2005)
These EOS's use the same cold and ion models and either Thomas-Fermi (QEOS) or relativistic quantum (XEOS) electron models

XEOS PHYSICS

Comparison of XEOS shock Hugoniots with ACTEX plasma physics results is good, showing that XEOS is accurate in the plasma region. Thomas-Fermi physics (QEOS) is inaccurate.

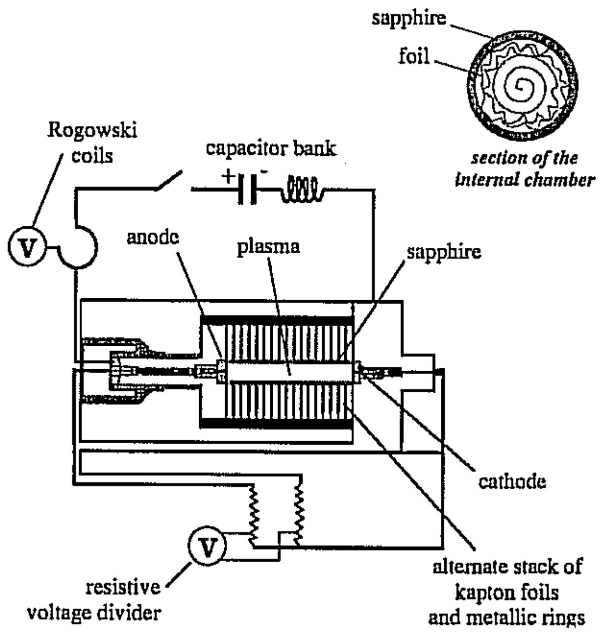




ISOCHORE EXPERIMENTS

Isochore experiments explore the low-density state of metals

A global EOS model is needed to understand the results



V. Recoules, et al., Phys. Rev. E 66, 056412 (2002)

ISOCHORE EXPERIMENTS
GLOBAL EOS MODELS

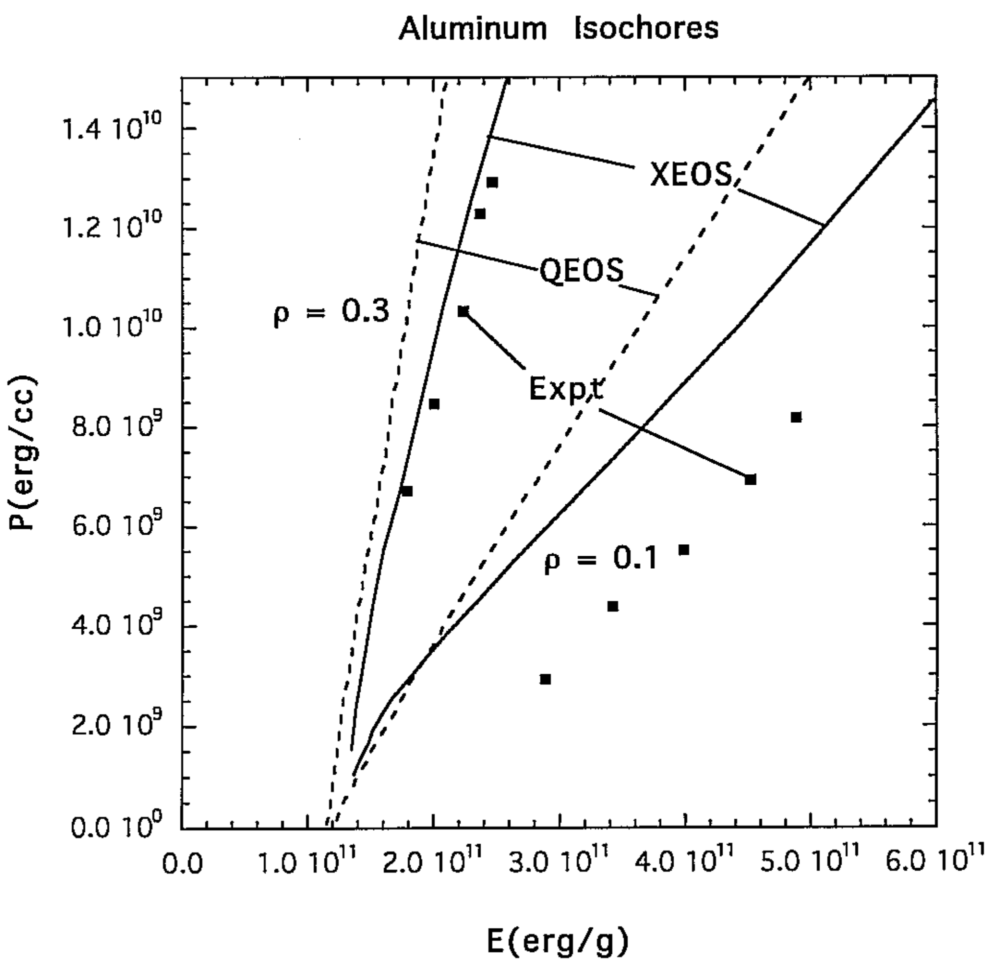
French Isochore Experiments

T_{max} = 2.5 eV

XEOS predictions for aluminum

E_{coh} is measured

Renaudin, et al. Phys. Rev. Lett. 91, 075002 (2003)

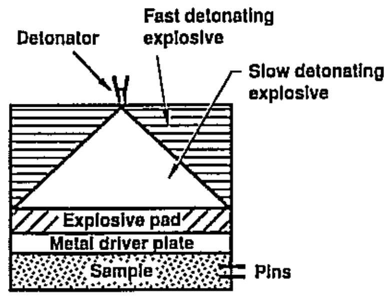


ISOCHORE EXPERIMENTS
GLOBAL EOS MODELS

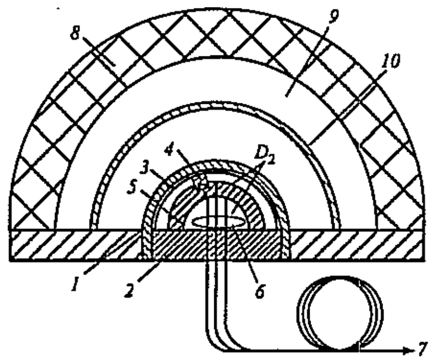
- Models do not do well!
- Isochore is perhaps the best example of a WDM experiment
- Binding energy curve is important
- Strong impetus for improved theory
- We hope that the experiments will continue

SHOCK EXPERIMENTS

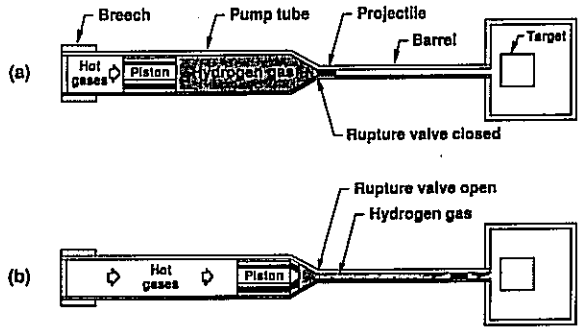
Planar geometry explosive-driven shock wave



Hemispherical convergent-geometry shock wave



Two-stage gas gun
High-velocity impactor-driven shock wave



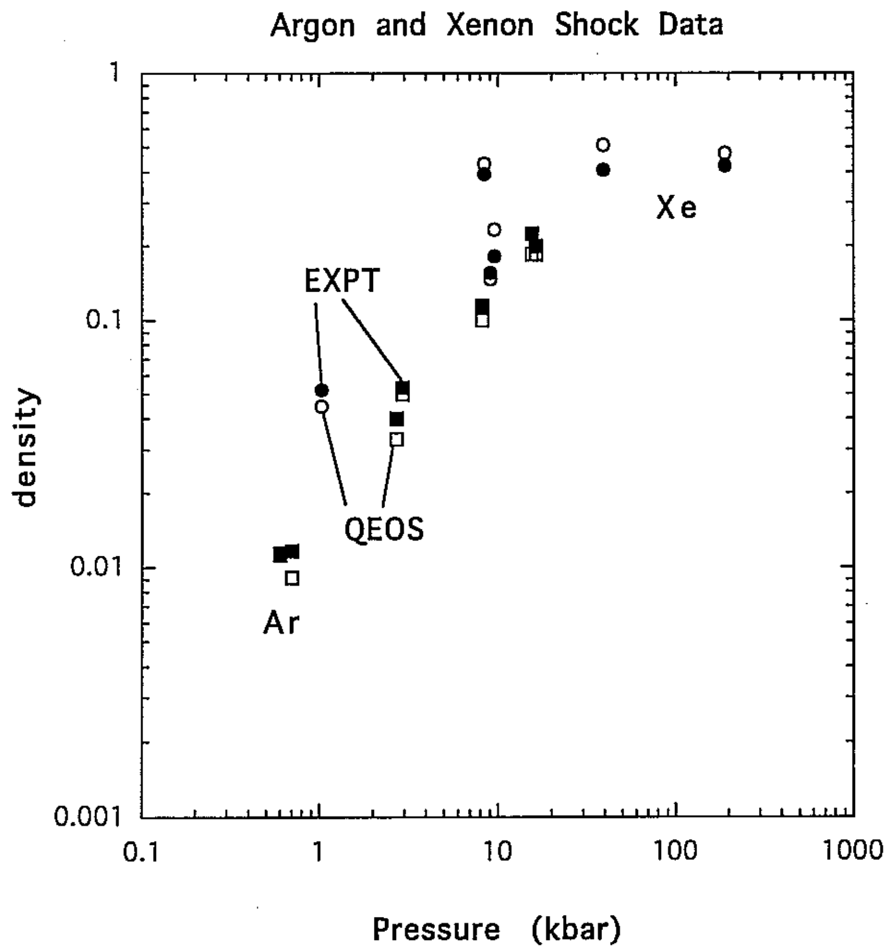
SHOCKED GASES

Russian shock Experiments on Ar and Xe

T_{max} = 5 eV

Comparison with QEOS

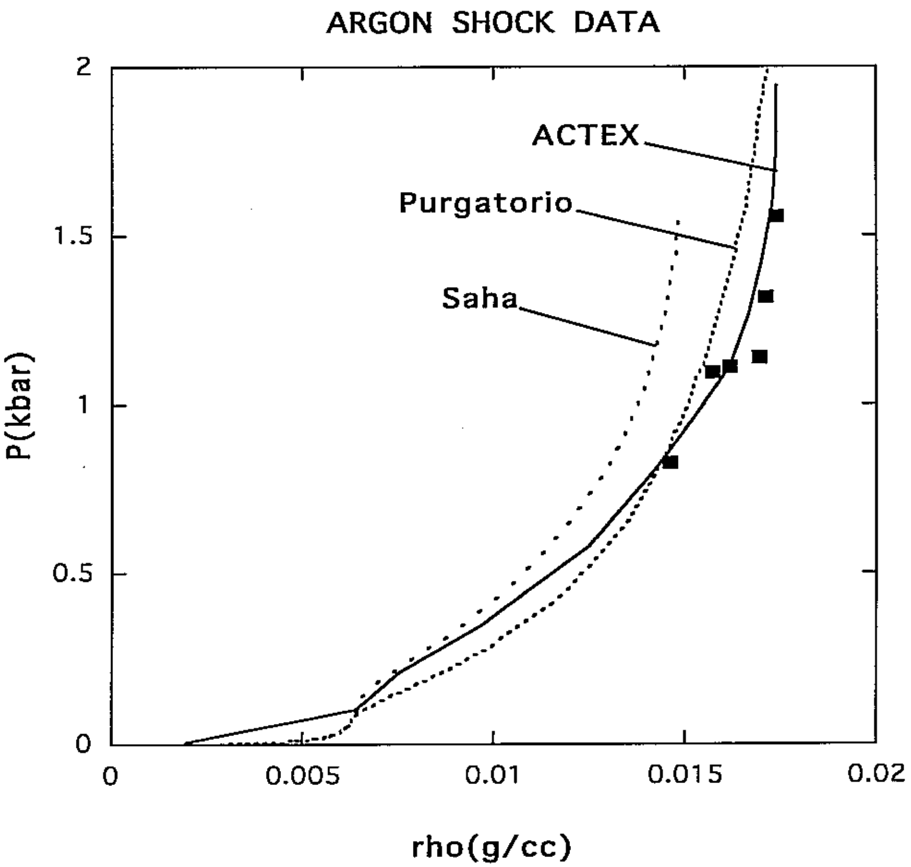
Gryaznov, et al. Sov. Phys. JETP 51, 288 (1980)



SHOCKED GASES

LLNL shock Experiments on Ar

D. Erskine, LLNL 1995

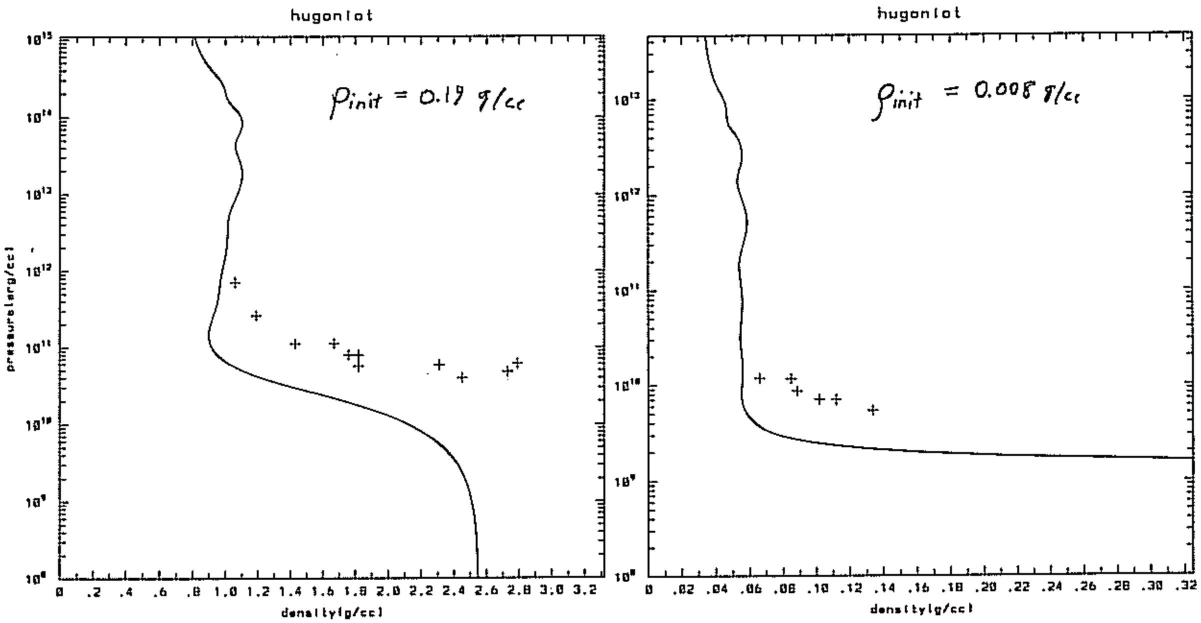


SHOCKED FOAMS

Russian shock Experiments on SiO_2 aerogel

T_{max} = 2 eV

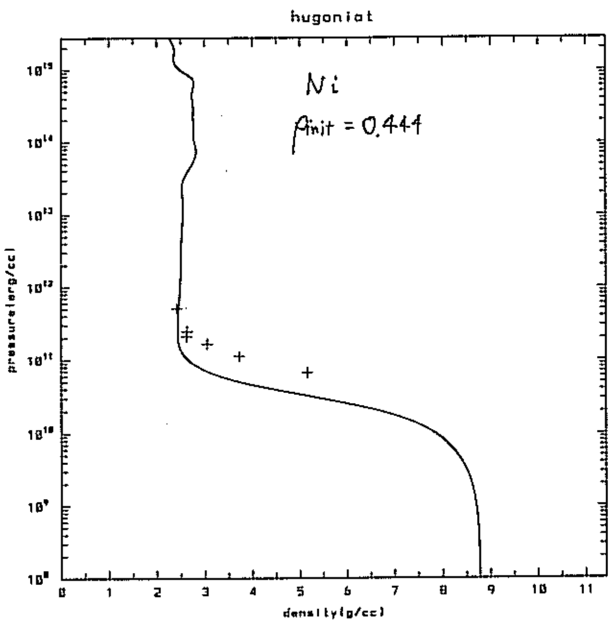
Comparison with Saha EOS

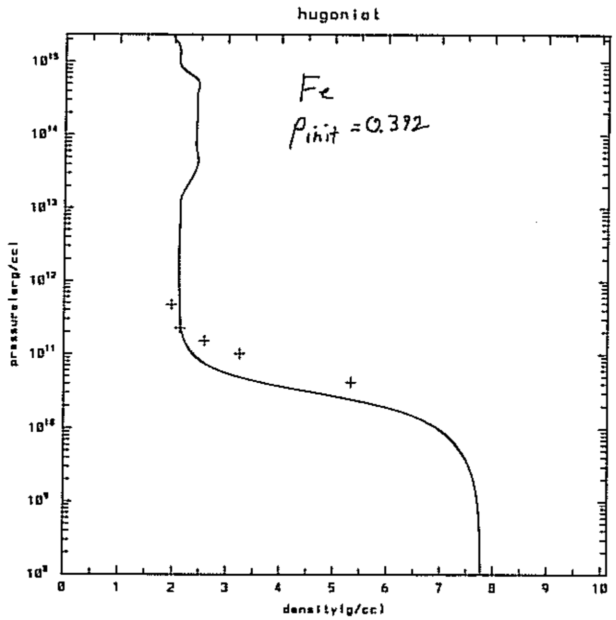


Nikolaev, et al., APS Shock Wave Conference 1999
Vildanov, et al., APS Shock Wave Conference 1995

SHOCKED METALLIC FOAMS

Russian shock Experiments on Ni and Fe foams At .05ρ_0





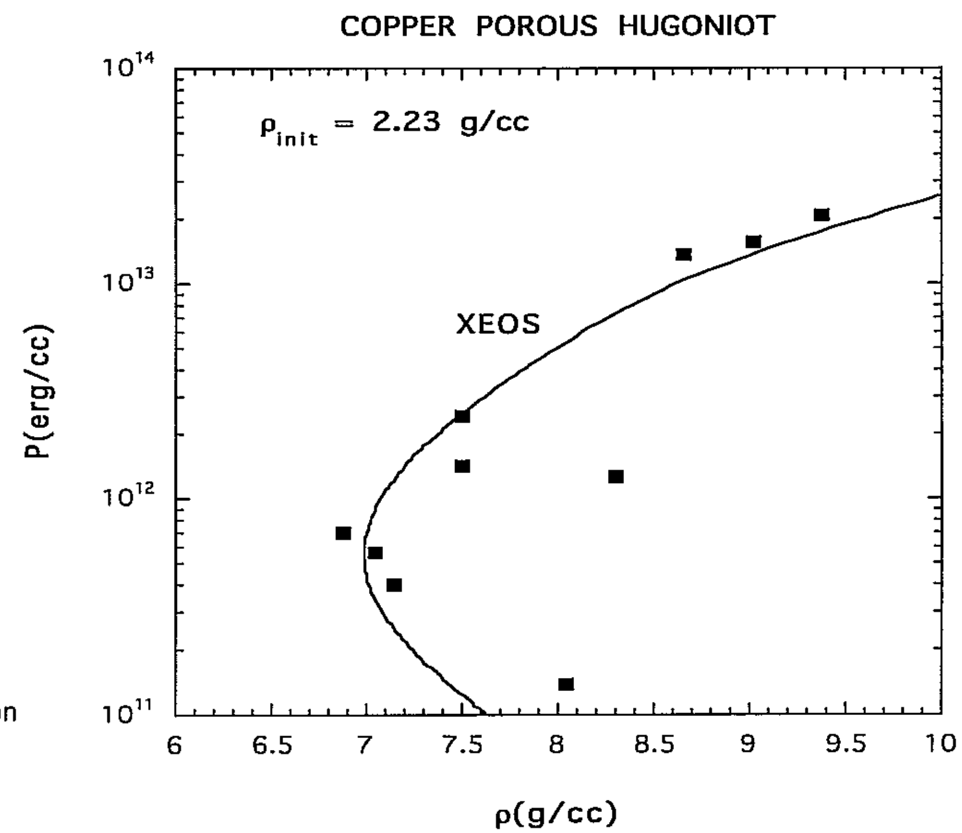
Comparison with Saha EOS

Trunin, Experimental Data on Shock Compression and Adiabatic Expansion Of Condensed Matter (Sarov, 2001)

SHOCKED METALLIC FOAMS

Russian shock Experiments on Cu foam

Comparison with XEOS

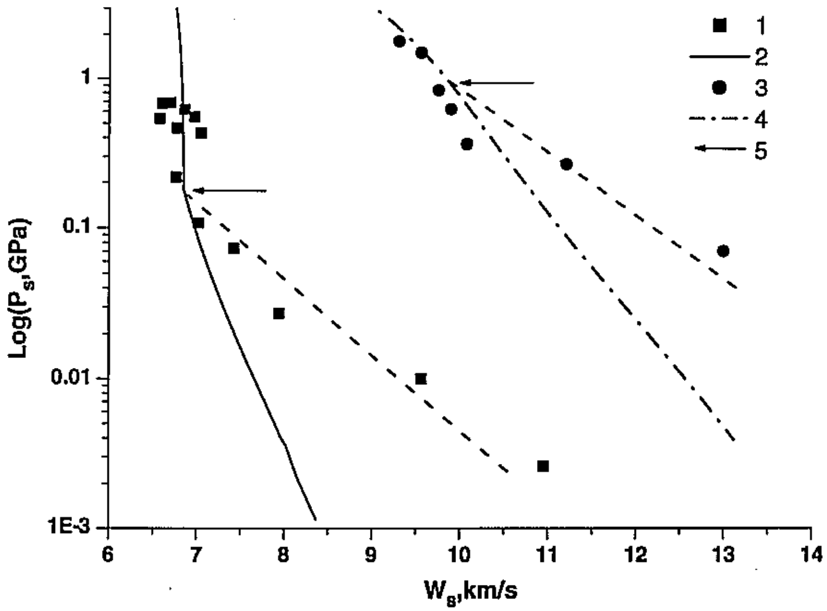


Trunin, Experimental Data on Shock Compression and Adiabatic Expansion Of Condensed Matter (Sarov, 2001)

RELEASE FROM STRONG SHOCKS

Russian release experiments on Molybdenum to determine coexistence curve

Estimated critical Point:
T_c = 13,300 K
P_c = 9.6 kbar



Emelyanov, et al., Int. J. Thermophys. 26,1985 (2005)

WHERE WE STAND

- A small suite of experimental data exists - much more data with higher energy density are needed
- EOS models are adequate for global coverage, but improvements in WDM region are needed
- Strong international effort
- Strong symbiosis between experiment and theory