High-Precision Measurements of the Equation of State of Hydrocarbons at 1 to 10 Mbar Using Laser-Driven Waves

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Abstract

The equation of state (EOS) of polystyrene and polypropylene was measured using laser-driven shock waves with pressures from 1 to 10 Mbar. Precision data resulting from the use of α-quartz as an impedance-matching (IM) standard tightly constrains the EOS of these hydrocarbons, even with the inclusion of systematic errors inherent to IM. The temperature at these high pressures was measured, which, combined with kinematic measurements, provide a complete shock EOS. Both hydrocarbons were observed to reach similar compressions and temperatures as a function of pressure. The materials were observed to transition from transparent insulators to reflecting conductors at pressures of 1 to 2 Mbar.

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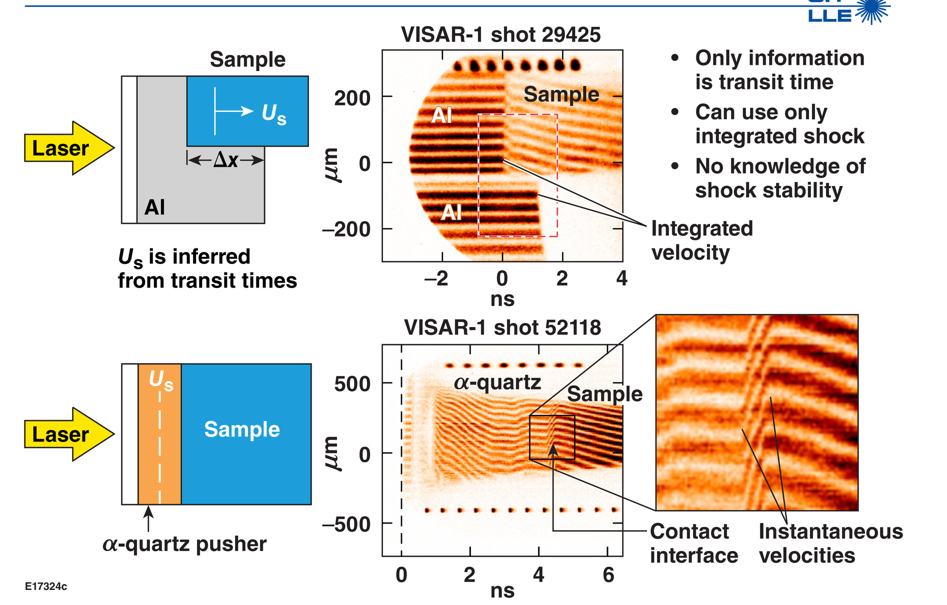
Random Errors

Higher precision is obtained with a transparent standard compared to an opaque standard



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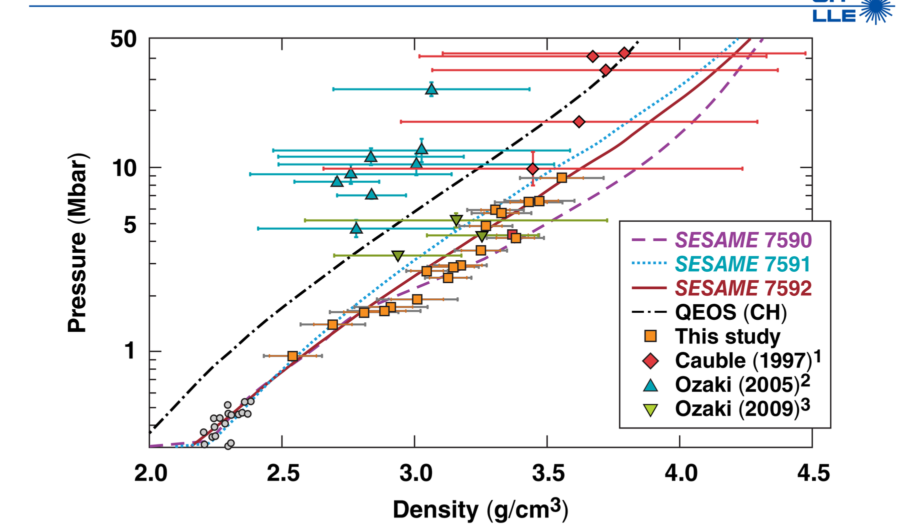
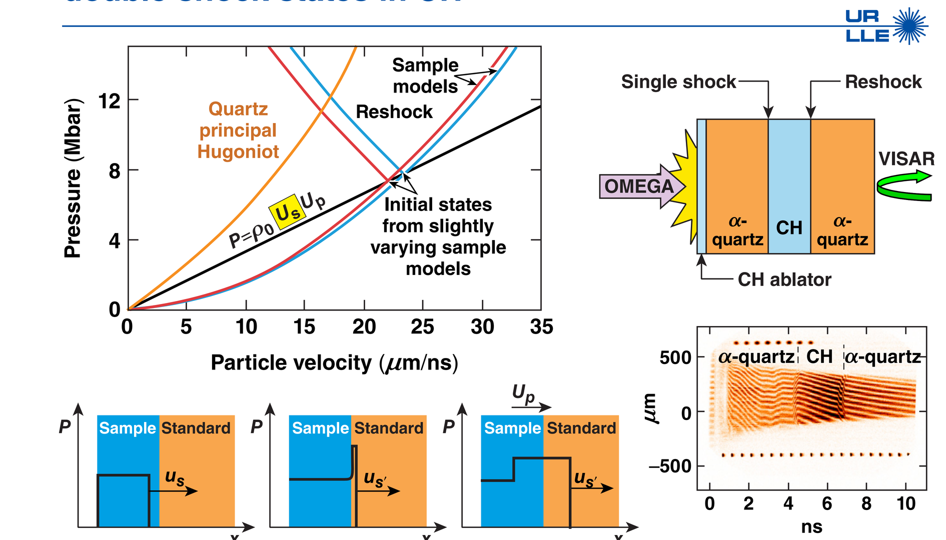
The polystyrene results have higher precision than previous studies



[1]R. Cauble *et al.*, Phys. Plasmas 4, 1857 (1997).
[2]N. Ozaki *et al.*, Phys. Plasmas 12, 124503 (2005).
[3]N. Ozaki *et al.*, Phys. Plasmas 16, 062702 (2009).

E18350a

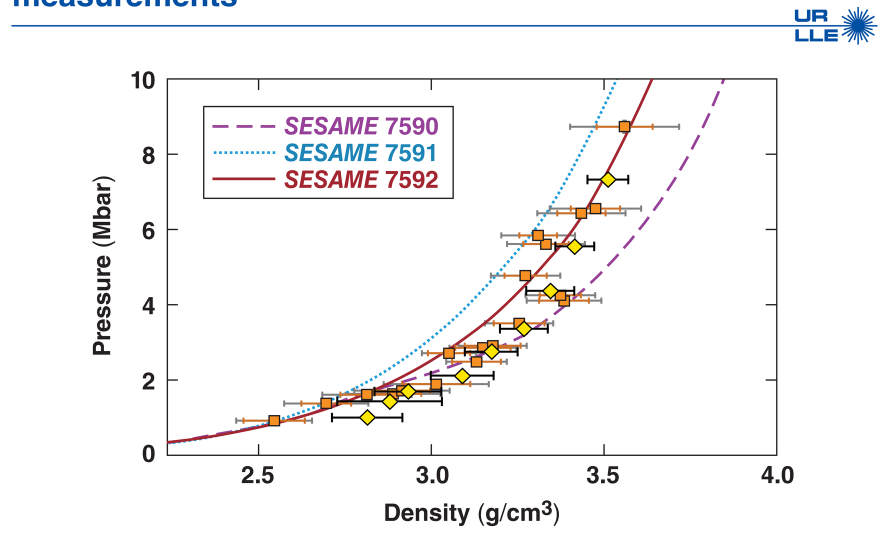
Reflected shocks are used to create double shock states in CH



Small differences in models are amplified using reshock to move off the Hugoniot.

E18057b

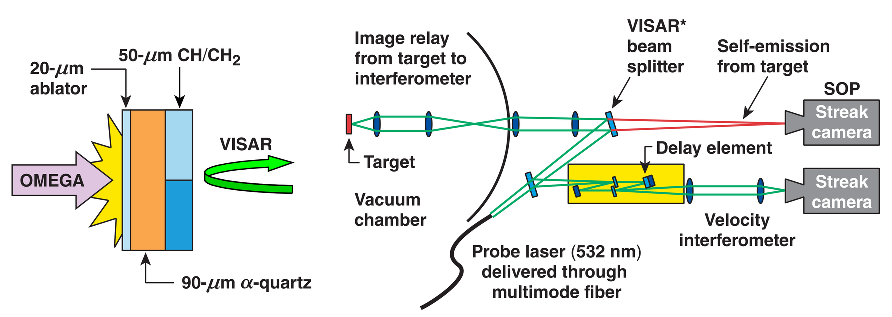
Inferred principal Hugoniot results for polystyrene from reshock data are consistent with single-shock measurements



E18909

OMEGA Experiments

Hydrocarbon EOS experiments were performed using laser-driven shock waves on OMEGA



- Experiments used laser energies between 200 to 1130 J delivered in a nominally 2-ns square pulse.
- Average laser irradiances on target were 0.3 to 1.1 × 10^{14} W/cm^2

VISAR* has time resolution of <30 ps and shock-velocity precision of ~1%.

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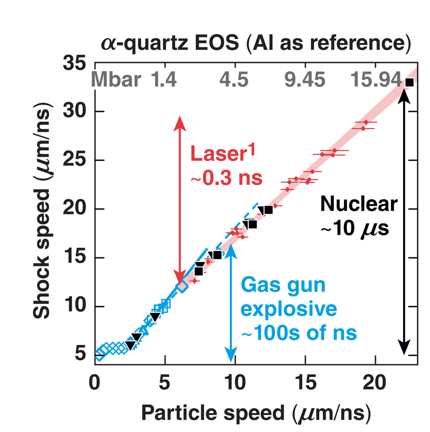
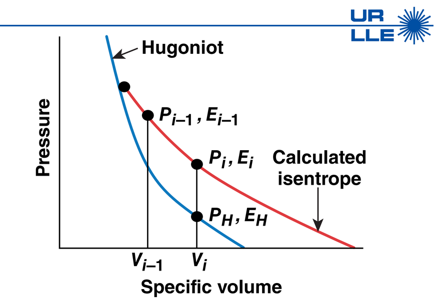
*Velocity Interferometer System for any Reflector

Systematic Errors

α-quartz's experimental principal Hugoniot is used, and its release isentrope is approximated using the Mie-Grüneisen EOS





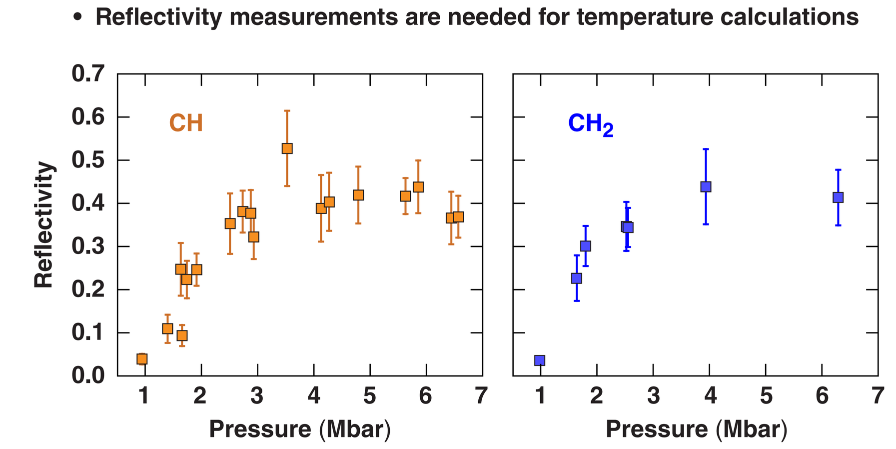
- Γ describes pressure differences between equal volume states on the Principal Hugoniot $\Gamma = V\left(\frac{dP}{dE}\right)_V$
- Combining the above with the first law of thermodynamics, $dE = TdS - PdV$, with $dS = 0$, leads to a recursion relation describing a loci of isentropes in the P–V plane
- Based on models, Γ is assumed to be constant in the high-pressure fluid regime, with value $\Gamma = 0.64 \pm 0.11$

[1]D. G. Hicks *et al.*, Phys. Plasmas 12, 082702 (2005).

E17325c

Shocked CH and CH_2 become reflective at 1 to 2 Mbar

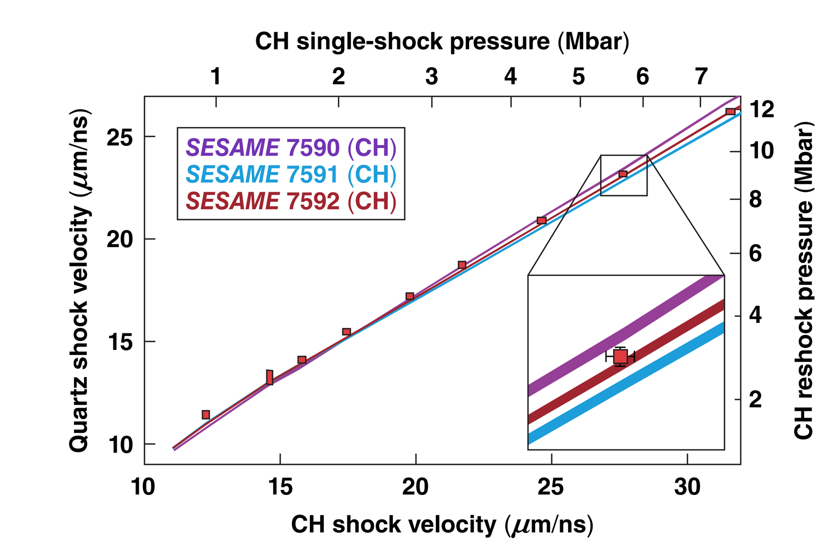
- Reflectivity measurements are needed for temperature calculations



Expected behavior of dielectrics undergoing insulator-conductor transition.

E18351a

Polystyrene (CH) double-shock data are in agreement with single-shock results



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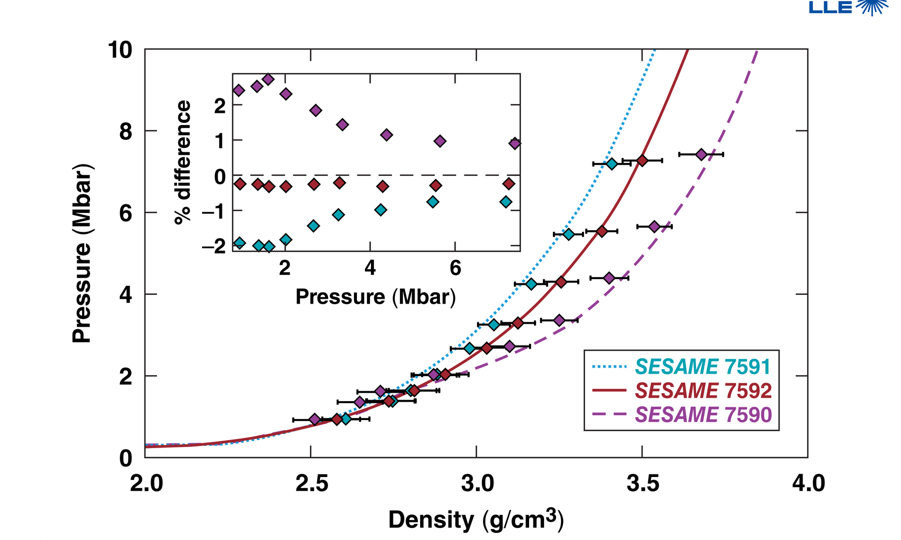
Accuracy of the inversion method is tested by using the effective gamma and shows to be in agreement with single-shock states, as predicted by models



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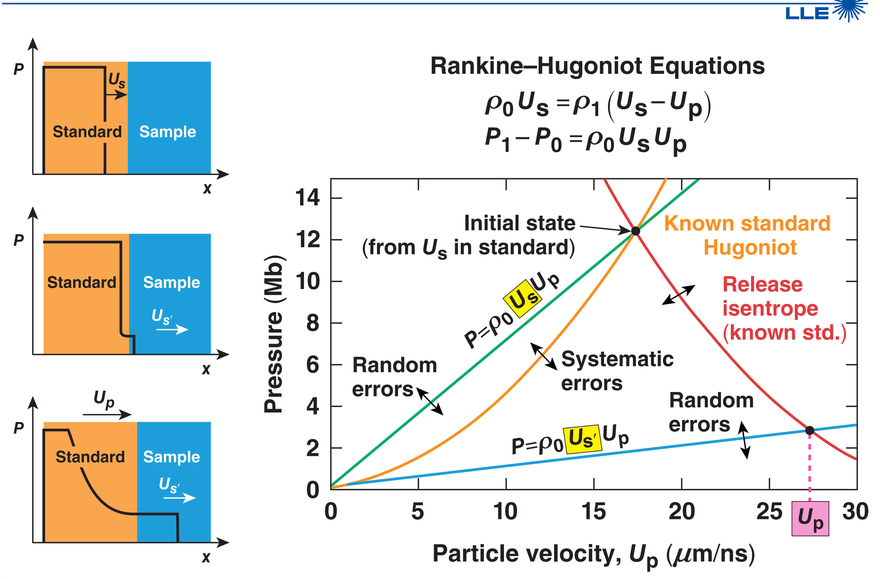
Impedance Matching $U_s = F(U_p)$

EOS data are obtained from the impedance-matching technique



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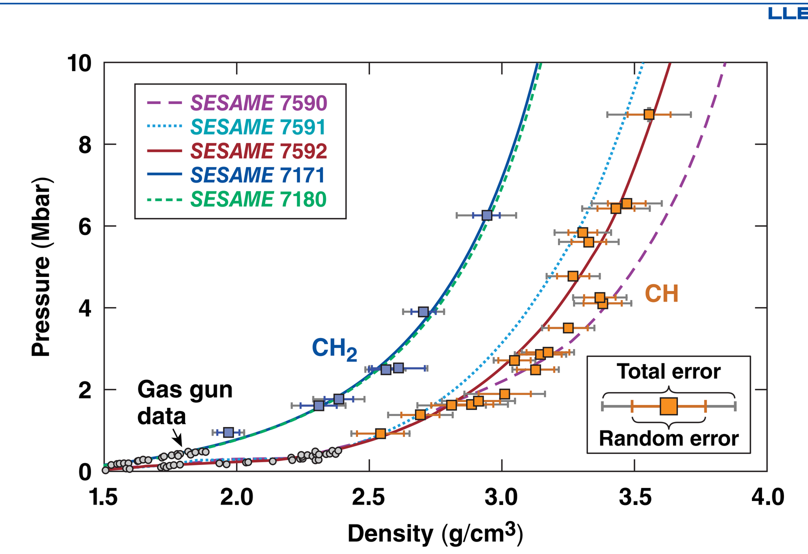
Precision EOS data tightly constrain polystyrene (CH) and polypropylene EOS models



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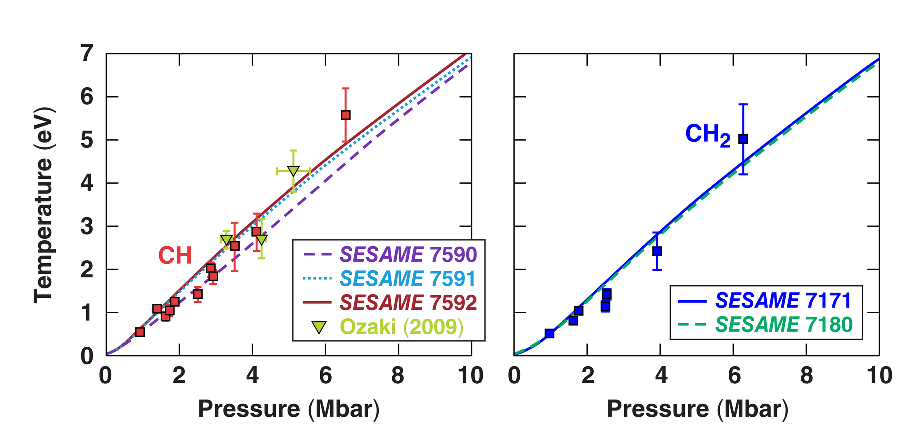
The measured brightness temperatures are consistent with models; but differences among models are too small to be discerned



This provides a complete EOS of CH and CH_2.

E18364a

Single-shock states are inferred from double-shock data via an inversion method

Hugoniot relations for single- and re-shock states

$$\rho_1 (U_{s1} - U_{p1}) = \rho_0 U_{s1} \qquad \rho_2 (U_{s2} - U_{p2}) = \rho_1 (U_{s2} - U_{p1})$$
$$P_1 = \rho_0 U_{s1} U_{p1} \qquad P_2 - P_1 = \rho_1 (U_{s2} - U_{p1})(U_{p2} - U_{p1})$$

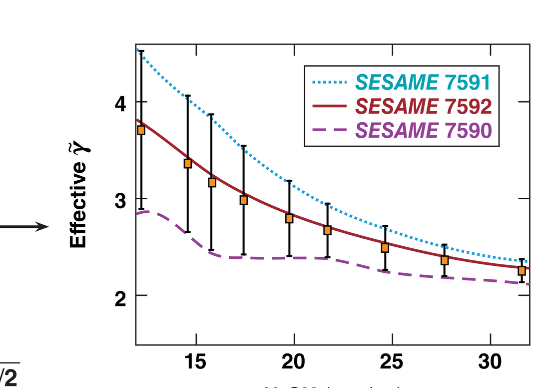
5 unknowns

Hugoniot equation:

$$\Delta E_{21} = \frac{1}{2}(P_2 + P_1)\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$

Energy difference from effective gamma:

$$\Delta E_{21} = \frac{P_2/\rho_2 - P_1/\rho_1}{\tilde{\gamma} - 1}$$



Eliminating ΔE_{21}:

$$\frac{P_2}{\rho_1} = 1 + \frac{P_2 - P_1}{P_1 + (\tilde{\gamma} - 1)(P_2 + P)/2}$$

E18926

Summary/Conclusions

Precision equation-of-state (EOS) measurements are obtained on various hydrocarbons at 1 to 10 Mbar

- Precise knowledge of ablator EOS is required for ICF target designs
- Laser-driven shock waves produce EOS data using the impedance-matching (IM) method
- CH data allows for model discrimination, favoring *SESAME* 7592
  - mild softening is not accounted for between 2 to 4 Mbar
  - single- and double-shock results display similar behavior
  - inferred single-shock results from double-shock data is in agreement with principal Hugoniot measurements
- Stoichiometry effects between CH and CH_2 are well-predicted by models
- Both CH and CH_2 reach similar compressions and temperatures as a function of pressure

E18910