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14. ABSTRACT
To support a renewed effort in Pressure-Shear Plate Impact studies with normal-impact Hugoniot and isentropic compression experiments that determine the equation of state, wave profiles, and/or sound speed of soda-lime glass up to 75 GPa
The budget envisioned approximately three normal-impact experiments per year, using the 40 mm projectile gun that reaches pressures of ~50 GPa for Ta impactors on soda-lime glass targets. We exceeded this goal significantly with 5 successful equation-of-state shots with partial release information on the 40 mm gun, one partly successful equation-of-state shot at higher pressure on the two-stage light gas gun, two successful thick-flyer experiments yielding temperature and shock velocity, and the first-of-its-kind "thin- flyer" shot on a silicate glass material, detecting both a high-precision shock temperature and a very clear rarefaction overtake.

15. SUBJECT TERMS

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December 3, 2019

Re: Final Technical Report for ONR award Number N00014-16-1-2751
Title: Failure of Soda-Lime Glass at Extreme Conditions: New Experimental Frontiers

Major Goals:

To support a renewed effort in Pressure-Shear Plate Impact studies with normal-impact Hugoniot and isentropic compression experiments that determine the equation of state, wave profiles, and/or sound speed of soda-lime glass up to 75 GPa

Accomplishments Under Goals:

The budget envisioned approximately three normal-impact experiments per year, using the 40 mm projectile gun that reaches pressures of ~50 GPa for Ta impactors on soda-lime glass targets. We exceeded this goal significantly with 5 successful equation-of-state shots with partial release information on the 40 mm gun, one partly successful equation-of-state shot at higher pressure on the two-stage light gas gun, two successful thick-flyer experiments yielding temperature and shock velocity, and the first-of-its-kind "thin- flyer" shot on a silicate glass material, detecting both a high-precision shock temperature and a very clear rarefaction overtake.

The shock velocity data, compared to previous low-pressure results by Alexander and Bourne and previous high-pressure results by Kobayashi, suggest that our soda-lime glass stays on the extension of the low- pressure (low-density structure) configuration to significantly higher particle velocity than expected (>3 km/s) and then drops onto the high-pressure (high-density structure) Hugoniot, matching Kobayashi's result. The shock temperature data are generally consistent with Kobayashi's experiments, except that our results suggest a much lower slope, perhaps because our lower-pressure point probes a different (lower-density) shock state than Kobayashi's experiment in this pressure range. Our newest result exceeds the precision of an individual measurement by Kobayashi by a factor of five.

The sound speed result is most easily fit by adjusting the volume (V) dependence of the Grünseisen parameter (γ), the quantity used to express the thermal pressure coefficient of a material. We have been actively investigating constraints on the anomalous volume dependence of gamma in silicate liquids under compression for some time, using finite difference between offset Hugoniots in a material. The sound speed measurement gives us a direct, instantaneous measure, with no finite differencing required. Remarkably, we fit this sound speed with the exponent q in $(\gamma / \gamma_o) = (V / V_o)^q$ yielding a best value of –2.00. All silicate liquids we have examined using the finite offset method give $-2.5 < q < -1$. So, this is quite consistent, but very precise and forms the first basis of a test to evaluate whether the Mie-Grüneisen approximation is valid in this case.

We also developed a new theoretical form for more accurate interpretation of these data and their use to extrapolate and interpolate liquid properties under conditions not directly observed. Our molecular dynamics simulations of a different silicate glass composition show clearly that the Mie-Grüneisen approximation does not hold for silicate liquids. Although the experimental data to not yet require this, the simulations show that there is no real justification for the approximation but also suggest a simple, integrable, four-parameter function (the Mie-Grüneisen model we have been using has three parameters). We have seen that this model allows optimal fitting of solid shock, liquid shock, liquid sound-speed, and temperature data for geological silicate liquids. It also fits the soda-lime data and makes new and different predictions for the behaviors of soda-lime material under the test conditions of interest to the ONR-332 soda-lime consortium.
A complete data table is appended to this report.

Training Opportunities:

A visiting scientist in our lab, Xiaojuan Ma, learned advanced shock wave experimental methods and theory of silicate glass compression on this project.

Postdoctoral scholar Jinping Hu took over the project after Ma left the lab and has added advanced shock wave methods and pyrometer to his toolkit. Given his interest in shocked meteorites and high-pressure mineralogy, this is important for his future career plans.

Graduate student Olivia Pardo, whose main project involves silicate glasses and liquids of geological interest, has observed our experiments on soda-lime glass as part of her preparation to do similar experiments on her own samples.

Results Dissemination:

Results have so-far been disseminated at the annual ONR-332 reviews in February 2018 and 2019 and at the biennial American Physical Society topical group meetings on Shock Compression in Condensed Matter in St. Louis and in Portland. A manuscript is still in preparation at this time, pending further (NSF-funded) experiments and calculations.

Follow-up plans:

A White Paper has been submitted to ONR describing potential next steps.

Sincerely,

Paul Asimow

Eleanor and John R. McMillan Professor of Geology and Geochemistry

shot number (all Mo flyers)	ufp	up	Us	P	V	rho	T	T error	sound speed	sound speed error	γ	γ error
	km/s	km/s	km/s	GPa	cm^3/g	g/cm^3	K	K	km/s	km/s		
559	4.24			61.1			3118	27	7.964	0.37	0.93	0.24
547	4.739			71.6			3619	39	7.951	0.24	1.18	0.11
1114	1.257	1.039	4.872	12.572	0.317	3.157						
1115	1.969	1.642	4.965	20.255	0.269	3.712						
1117	2.605	2.136	5.744	30.481	0.253	3.955						
1116	2.640	2.167	5.791	31.172	0.252	3.969						
1118	1.214	0.926	4.893	11.252	0.326	3.064						
539	4.795	3.697	7.905	72.600	0.214	4.667	3900	292				
540	4.227	3.283	7.390	60.267	0.224	4.470	3530	248				
533	3.800	3.019	7.487	56.151	0.240	4.163						
release data												
1114		1.014	1.869	1.086	0.317	3.157						
1115		2.447	4.083	5.724	0.301	3.318						
1117		3.143	5.058	9.107	0.286	3.495						
1116		3.030	4.902	8.508	0.276	3.626						
1118		1.295	2.336	1.734	0.339	2.954						

All flyers and drivers are Mo
Uncertainty on flyer velocity is typically ±0.005 km/s
Uncertainty on particle velocity is typically ±0.01 km/s
Uncertainty on shock velocity is typically ±0.05 km/s
Uncertainty on pressure is typically ±1 GPa
Uncertainty on shock density is typically ±0.03 g cm−3