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THE HUGONIOT EQUATION OF STATE OF ROCKS

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SUMMARY

In considering peaceful applications for nuclear explosions detonated underground, one is concerned with the action of strong shocks which proceed from the center of detonation into the surrounding medium. The propagation of such shocks and their effect on the medium are directly related to the useful purposes to which nuclear explosives can be put. Furthermore, in planning experimental explosions it is highly desirable to predict with good accuracy the effects of the shock. Predictions are based partly on a knowledge of the Hugoniot equation of state.

For these reasons, the equations of state of several common rocks have been measured by Alder's group at Livermore. Plane hydrodynamic shocks were produced by conventional high explosive techniques and transmitted to pellets of the rock by aluminum plates. Shock times-of-arrival at aluminum and rock surfaces, and free-surface velocities were recorded by an argon flash-block technique and a sweep camera. This method has been discussed by various authors. Shock velocity and free-surface velocity are measured in these experiments.

Measurements have been made at pressures ranging from 70 kb to 900 kb. Rock salt, granite, tuff, marble, dolomite, limestone, basalt, and other rocks have been studied; several points on the P-V curve for each have been measured. Particularly interesting data for granite and basalt have been obtained. Further work is in progress.

The desirability of making in situ peak pressure measurements on shocks generated by actual nuclear explosions has led to the development of an instrument which employs pin-contactors to measure shock velocity and free-surface velocity at locations in the rock medium not far from the explosion. The instrument has performed satisfactorily in high explosive tests. It is hoped that shock stresses from below 100 kb to over 1 Mb can be measured in this fashion.

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*Work was performed under auspices of the U. S. Atomic Energy Commission.

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The Hugoniot Equation of State of Rocks

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I. INTRODUCTION

In developing ideas for nonmilitary applications of nuclear explosives, one becomes concerned with the behavior of strong shocks in solids. The shock stresses involved range from a few kilobars to several megabars, and their duration can be as long as several milliseconds. Most of the benefits which can be obtained from such explosions are attributable wholly or partly to the effects of shocks on the surrounding rock. Crushing, cracking, and heating are among these effects. Furthermore, the effects of the shock on existing underground structures such as mines and tunnels must be considered when nuclear devices are detonated underground; the action of shocks is also important in the theory of craters caused by buried charges.[1] An understanding of strong shocks in solids is therefore prerequisite to the efficient design of underground explosions for peaceful industrial purposes, and also prerequisite to accurate predictions of the effects of such explosions.

In describing the propagation of hydrodynamic shocks through a solid material, one must know the isentropic equation of state for the material, i. e., the dynamic pressure-volume relationship. The theory of strong shocks in solids is discussed at length by Rice, McQueen, and Walsh.[2] Their review article also describes various experimental techniques by which the dynamic equation of state is measured. It is assumed that many of those to whom this paper is addressed are familiar with these techniques and the theory of hydrodynamic shocks. For those who are not, a very brief review of techniques and theory will be helpful in view of the material to be discussed.

Strong shocks are commonly generated in the laboratory by high explosive charges placed next to the specimen to be shocked. The transit time of the shock front through the specimen (of known preshot density and thickness) is measured. The shock velocity U is thus established. In a simple experiment one also measures the free-surface velocity at the side of the sample away from the explosive. In a more sophisticated arrangement a second material, one with a well-known equation of state, is inserted between the H. E.

and the specimen, and the free-surface velocity of the "standard" material is measured. In either case, one uses the free-surface velocity to compute the particle velocity u (or mass velocity) in the specimen.

From the conservation of mass, energy, and momentum one can derive the so-called "Rankine-Hugoniot" conditions,

$$P = \rho_0 u U \tag{1}$$

$$V/V_0 = 1 - u/U \tag{2}$$

$$E - E_0 = P(V_0 - V)/2 \tag{3}$$

where P, V, and E are the pressure, specific volume, and specific internal energy respectively, the subscript $_0$ refers to preshot conditions ahead of the shock front, $\rho_0 \equiv 1/V_0$, and P_0 has been assumed negligibly small compared to P.

The pressure, compression, and specific internal energy associated with a particular shock can therefore be computed from a measurement of ρ_0, U, and u. The locus of P, V points characteristic of a material is called the Hugoniot (or dynamic) equation of state. The stress P is assumed to be isotropic; the theory is valid, therefore, only for shock stresses which far exceed the ability of the material to support shear. Such shocks are called "hydrodynamic."

In solid materials, in certain shock stress ranges, (different for each material) U may be less than sound velocity in the unshocked material. Shocks of these magnitudes will travel at less than the sound speed and will be preceded by a sonic disturbance called an "elastic precursor." The amplitude of the precursor is commonly taken as a measure of the dynamic yield strength of the material. Furthermore, some materials under shock conditions undergo polymorphic transitions. If the higher pressure phase has a lower shock velocity than the lower pressure phase, the well-known double-shock structure will develop.[2] However, if the pressure is high enough that U for the high pressure phase exceeds U for the other phase, the disturbance will revert to a single-shock structure.

Equation of state measurements for several rock types which have been made at LRL during the past 3 years will be discussed in Section II, and compared with other published measurements. Section III deals with an instrument which has been designed for measuring peak shock pressures in the rock near underground nuclear explosions.

II. EQUATION OF STATE DATA

The interest of Plowshare in underground nuclear explosions has led Alder's group at Livermore to undertake measurements of the Hugoniot equations of state for several common rocks.[3] Their experimental method is described in Christian's report.[4] However, the work on rocks is not finished and many more experiments must be performed before the data can be called complete. Results to date are being published now at the request of several workers in the rock mechanics field. A note of caution is in order for those who would interpret the data. There is sometimes considerable variation in experimental results from one specimen to the next, even when both specimens come from the same piece of rock; this is especially true of rocks with coarse grain structure and other gross inhomogeneities. These empirical variations are frequently as large as variations between samples of the same general type from different locations. A mineralogical and chemical description of the samples has been omitted here except where particular properties of a rock could be correlated with the results.

Alder's data[3] for several rock types is tabulated as an Appendix to this report, and discussion of some of it seems in order. Equation of state data obtained in shock experiments can be — and commonly is — graphically summarized in several ways; but the plot of shock velocity vs particle velocity has several advantages. Where the data is good in the hydrodynamic region and where no transitions occur, the points always appear to lie on a straight line, although no explanation of why this should be so has yet been advanced. Where polymorphic transitions exist, the points for each phase lie on a separate line; each characterized by a different slope. Transitions are thus easy to spot in such a plot. (Within the past three years, two polymorphic transitions in rocks have been reported, one in gabbro by Hughes and McQueen,[5] the other in marble by Dremin and Adadurov.[6])

The LRL data for rock salt of various purities (including New Mexico red potash ore) are plotted in Fig. 1. The data seem to lie about a straight line but the scatter is too great to show the transformation in pure NaCl suggested by Christian's work.[4] Figure 1 also shows some equation of state data for Louisiana rock salt, obtained at the Stanford Research Institute by Grine,[7] using the wedge method for lower pressures.[8] The large grain size of the rock salt probably accounts for as much of the scatter evident in Fig. 1 as do variations between rock types. Grine is planning further low-pressure experiments, some of which incorporate technological improvements.[7]

In Fig. 2, the work in marble recently published by the Soviet workers Dremin and Adadurov is contrasted with data from two types of marble measured at LRL. The Soviet marble had a density of 2.70 g/cm^3; the LRL marble varied between 2.84 and 2.90. Note that the Soviet data can be fitted nicely with two straight lines, indicating a polymorphic transition between 146.5 and 155.8 kilobars. The LRL marble evidently has a different equation of state. But the scatter suggests that the experiments must be repeated; perhaps a modification of the method will be necessary, as will a careful selection of samples to assure optimum homogeneity. Needless to say, further work is under way.

A plot of granite data (Fig. 3), taken at LRL and by Grine at SRI, tells a different story. Most of this material came from a formation at the AEC Nevada Test Site. Above 330 kb the points lie nicely about the expected straight line. Below this pressure the scatter is extremely bad; there are several possible reasons, and the poor experimental results are probably due to a combination of circumstances. Grine has reported a 29- to 36-kb elastic precursor in granite[9,7]; this means that there is a two-wave structure up to about 350 kb, above which U exceeds the sonic velocity; no precursor, therefore, will precede shocks greater than about 350 kb. Furthermore, if a polymorphic transition exists somewhat above 50 kilobars (which is likely since such a transition is known in quartz[10]), a three-wave structure will develop which could further confuse measurements. Additional complications arise from different dynamic strengths along different quartz axes. If there are transitions in other mineral components of granite in this pressure range, even more complications could develop. The coarse grain structure doubtless contributes to the difficulties. Variations from sample to sample are large and it is not surprising that our experiments to date have not given a clear picture of the equation of state at the lower pressures. Grine's observations of granite[7] suggest a rather complicated wave structure, which varies from sample to sample. Equation of state data for three rocks (granite, basalt, and limestone) are plotted in Fig. 4. A comparison of the limestone and basalt is especially interesting, because their equations of state agree quite well, in spite of their dissimilar compositions, at pressures above about 230 kb. It seems probable that these two equations of state do not agree at lower pressures, but further investigation must precede a more meaningful analysis. Granite has been included in Fig. 4 because, even though granite is more nearly like basalt in composition and density than is limestone, its high-pressure equation of state is very definitely different.

Basalt is an interesting rock, similar in composition to gabbro but with a relatively fine grain structure. Basalt is typical of hard rocks in which Plowshare might carry out nuclear cratering experiments. The small amount of basalt data presently available is plotted again in Fig. 5 along with the Los Alamos results for gabbro.[2] The Los Alamos data were taken from a graph in the Hughes and McQueen article,[5] and its accuracy may have suffered in the transposition. Gabbro and basalt are similar above the gabbro transition but different below. It is not clear why this should be so.

Our information on tuff is somewhat more complete than that on basalt (Fig. 6). Tuff is noteworthy because most of our experience with underground nuclear explosions is in this medium. The equation of state is strongly dependent upon water content. The latter was about 5 percent by weight for the driest of the tuff shots and over 20 percent for the wettest. However, the densities for both "wet" and "dry" tuff, as measured before the shots, fluctuated several percent. Furthermore, this series of shots had been completed before it was discovered that oven-dried tuff samples rapidly absorb water from the atmosphere. Some of the "dry" samples were doubtless wetter than supposed when the shots were fired, since their densities were measured immediately after oven drying, more than 24 hours before shot time. It is probable also that some of the "saturated" samples dried out somewhat prior to shot time. The water content of <u>in situ</u> tuff at the Nevada Test Site varies from 7 to 35 percent within the space of a few feet in the same formation.[11] The great variability in water content of <u>in situ</u> tuff complicates the calculations for nuclear explosions in this medium. It is interesting to note in Fig. 6 that the "wet" tuff point A was the sample with the lowest preshot density of the "wet" samples (1.79 g/cm^3). Point B of the "dry" tuff group in Fig. 6 represents the densest of the "dry" samples (1.88 g/cm^3).

It should again be emphasized that this equation of state work is still in progress at LRL, and imperfect though it is at the present time, it is being presented here in response to requests from our colleagues in rock mechanics, and for the purpose of setting forth some of the difficulties encountered in measuring the dynamic equations of state of rocks.

III. PEAK PRESSURE MEASUREMENTS NEAR NUCLEAR EXPLOSIONS

In planning subsurface nuclear explosions, one is faced with the problem of predicting their effects. For reasons of economy and safety it is necessary to estimate ahead of time such parameters as the shock strength at various distances, the extent of crushing and cracking, and the size of the cavity. John Nuckolls at LRL has constructed a theory[12] which, with the aid of digital computers, can make such predictions. Unfortunately, there is at present only a limited amount of empirical data with which to compare the predictions of the code. While there is good agreement to date for explosions in volcanic tuff, it will be highly desirable to make appropriate measurements on shocks generated by future nuclear explosions in as yet untested media.

One important quantity which should be measured is peak shock stress as a function of distance from the center of detonation. Various transducers commonly employed in seismic work can be used at great distances. Closer in, for shock stresses up to a few kilobars, stress histories can be measured with crystal transducers.[13] For stronger shocks, where such transducers fail, the only *in situ* measurements known to the author have consisted of shock time-of-arrival transducers placed at various distances from the shot.[14] If the equation of state of the medium is known, the time-of-arrival data can be used to determine peak pressure as a function of distance. The accuracy of this method, however, is not high, since peak pressure is not a strong function of shock velocity. (For instance, as the stress increases by a factor of 8.5 the shock velocity U increases by only 1.8.)

A technique which suggests itself for accurate *in situ* peak-pressure measurements is that adapted from the one employed in the Laboratory for equation of state determinations. A simultaneous measurement (on the native medium) of shock velocity and free-surface velocity should yield good precision. The difficulty of recovering film from a recording camera near an underground explosion precludes the use of optical techniques. Signals from self-shorting pin-contactors, however, can be transmitted by cable and/or telemeter to recording stations a safe distance away. Pins have been widely used for equation of state measurements in the laboratory.[1,15] Oscillographic methods are employed to record the time of arrival at each pin of the shock front or the free-surface.

The peak-pressure instrument which we have developed consists of a 5-inch-diameter, 1-inch-thick disk machined from rock obtained from the formation in which the experiment is to be carried out (see Fig. 7). A cylindrical depression is machined into the center of the disk. A plastic pin-holder supports pins at various distances from the flat bottom of this depression. Here, these pins will measure the free-surface velocity u. Other pins, installed in small holes in the rock will measure shock velocity U. The peak pressure is calculated with the aid of equation (1). Figure 8 is a photograph of a completed pin assembly, ready for testing with high explosives.

For field use the entire assembly, suitably potted, will be inserted in a 6-inch-diameter hole drilled radially toward the shot point. When the assembly is near the bottom of the hole, grout will be forced around it to insure good contact with the surrounding rock (Fig. 9). A special grout must be developed for each medium in which the measurement is made, since the shock impedance of the grout must match that of the medium in order to insure a reliable experiment. This impedance match is attained by adjusting the grout mixture until its Hugoniot equation of state matches that of the rock in the stress range where the in situ measurement will be made.

Two peak pressure determinations will be made in connection with the Gnome experiment (a 5-kt nuclear explosion in bedded salt) which is planned for sometime next winter (pending presidential approval) near Carlsbad, N. M. Two of these instruments will be emplaced, one at about 600 kilobars and one at about 300 kilobars. Laboratory tests, using New Mexico red halite rock and granite from the Nevada Test Site have been successful in yielding data which agree nicely with the measured Hugoniot equations of state (Figs. 1, 3). An accuracy of ± 2% in pressure can be achieved in the laboratory. Accuracies in the field may not be quite as good due to degeneration of the signals by 3000 ft of cable, but barring unforeseen complications a precision of better than ± 5% can be expected. If the peak pressure measurement is successful in Gnome, an attempt will be made to perform a more comprehensive experiment on a subsequent underground detonation.

IV. CONCLUSIONS

It is clear that more data must be collected before we can have much confidence in our equations of state for most of these rocks. It has been shown that careful work on very fine grained rocks can yield good results. Since water content has a drastic effect on experimental results in at least one instance, we must evidently be more careful in the control of future experiments, at least when dealing with permeable materials. Furthermore, in planning experiments with all kinds of rocks, we should exercise greater control in the selection of specimens, particularly with regard to homogeneity.

In situations where large elastic precursors or multiple shock systems exist, it may be necessary to employ precision pin techniques or other methods of observing the appropriate velocites, in order to obtain reliable data. At the lower stress levels, where materials behave plastically rather than hydrodynamically, it will be difficult to obtain and interpret meaningful dynamic equations of state. For example, some experimental records of some plastic shock fronts suggest that they may not be very steep.[13]

An instrument for measuring in situ peak pressures has been developed to a point where one can hope to do accurate work by using pins to measure the shock and free-surface velocities. Experience in the field and further refinement of the instrument will hopefully yield even better precision. High explosive tests of the instrument have yielded highly satisfactory results.

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Appendix. TABULATION OF EQUATION OF STATE DATA FOR VARIOUS ROCK TYPES

	U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0	Source
ROCK SALT (several sources):*						
	4.652	0.891	2.155	0.089	0.809	1
	5.018	1.170	2.143	.126	.767	2
	5.382	1.392	2.142	.1609	.741	2
	5.325	1.377	2.145	.162	.755	2
	5.511	1.400	2.151	.166	.746	2
	5.874	1.747	2.152	.220	.7026	2
	5.870	1.79	2.155	.226	.695	1
	6.07	1.99	2.145	.258	.672	2
	6.122	1.98	2.145	.260	.677	2
	6.088	1.996	2.156	.262	.672	2
	7.07	2.87	2.155	.437	.594	2
	7.10	2.85	2.157	.436	.599	2
	7.17	2.96	2.158	.457	.587	2
	7.465	2.98	2.152	.479	.601	2
	8.24	3.49	2.155	.620	.577	1
	8.425	3.90	2.156	.709	.537	1
	8.73	3.92	2.148	.735	.551	2
	9.118	4.445	2.151	.856	.5089	2
	9.157	4.596	2.053	.865	.498	3
	9.025	4.54	2.153	.882	.497	3

*1. Louisiana dome salt; Carey Mine. 2. Origin undetermined. 3. New Mexico red potash ore.

	U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0	Source
GRANITE (two or more sources):**						
	5.383	0.485	2.614	0.068	0.915	1
	5.37	1.31	2.612	.182	.756	1
	5.825	2.220	2.614	.337	.6189	1
	5.71	0.490	2.676	.0743	.914	2
	5.58	.822	2.683	.123	.853	2
	5.48	.960	2.695	.143	.826	3
	5.506	1.15	2.669	.148	.791	4
	5.658	1.63	2.669	.246		4
	5.64	1.625	2.683	.247	.712	3
	5.61	1.715	2.674	.2565	.693	4
	6.31	2.63	2.676	.446	.584	3
	7.64	3.35	2.680	.680	.558	4
	8.27	4.00	2.673	.884	.5164	2

**1. Pink quartz monzonite, surface, NTS Area 15. 2. Origin undetermined. 3. SRI exploratory core, 1005 ft, NTS Area 15. 4. Gray granodiorite, surface, NTS Area 15.

		U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0	Source
TUFF (two sources):*							
	Dry	2.627	0.869	1.7	0.0389	0.6695	1
	Dry	3.33	1.340	1.661	.074	.598	2
	Dry	3.433	1.329	1.690	.077	.613	2
	Dry	3.78	1.73	1.604	.105	.542	2
	Dry	3.71	1.72	1.713	.109	.536	2
	Dry	4.299	1.626	1.882	.132	.6218	1
	Dry	4.76	2.31	1.65	.181	.515	2
	Wet	4.05	1.236	1.869	0.094	0.695	2
	Wet	4.13	1.27	1.898	.095	.692	2
	Wet	4.09	1.230	1.901	.096	.699	3
	Wet	4.411	1.61	1.861	.130	.635	2
	Wet	4.40	1.60	1.897	.133	.636	2
	Wet	4.61	1.59	1.855	.136	.655	2
	Wet	5.01	2.02	1.869	.171	.597	2
	Wet	4.79	2.24	1.796	.1965	.542	2
	Wet	5.23	2.25	1.903	.224	.570	2

*1. Tunnel U12A, NTS. 2. Tunnel U12B, NTS, mined near Rainier. 3. Origin undetermined.

DOLOMITE (from surface, NTS Area 12):

7.14	1.10	2.842	0.223	0.846
7.546	1.935	2.843	.4165	.7436

LIMESTONE (from 3rd Fragmental formation, Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada):

3.707	0.570	2.505	0.053	0.846
4.927	1.055	2.501	.130	.786
5.83	2.01	2.508	.294	.655
6.56	2.64	2.532	.439	.598
8.05	3.31	2.596	.692	.589
8.60	3.67	2.589	.817	.573

ANDESITE (quarried in Marin County, California):

2.70	0.51	2.60	0.042	0.815
5.038	.619	2.642	.0829	.877
5.344	.82	2.641	.115	.846

BASALT (Buckboard hole No. 3, 36 ft, 40-Mile Canyon, NTS):

4.867	0.794	2.673	0.103	0.837
5.24	1.63	2.668	.234	.689
7.97	3.29	2.667	.684	.578
8.588	3.71	2.665	.769	.524

	U,mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P,Mbars	V/V$_0$
MARBLE (from surface, NTS Area 15):					
Light	6.620	0.913	2.840	0.171	0.862
	7.347	1.422	2.843	.297	.8065
	7.658	1.93	2.846	.418	.7480
Dark	5.464	0.983	2.905	.156	.820
	7.304	1.425	2.852	.296	.8049
	7.737	2.13	2.840	.468	.725
TACONITE;* (banded, Mesabi Range, Erie formation):					
Iron	4.360	0.683	4.263	0.126	0.843
	5.33	1.61	4.153	.246	.657
	7.511	3.02	4.150	.940	.229 (?)
	7.98	3.25	4.375	1.14	.5928
Rock	4.294	0.947	1.820	0.074	.780
	4.23	1.59	1.875	.200	.624
	7.409	4.05	2.413	.679	.453

*Note: The banding was of the same dimensions as the samples, hence the "iron" samples are almost pure iron while the "rock" samples contain little iron.

OIL SAND;** (McMurray formation, Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada):

U,mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P,Mbars	V/V$_0$
4.372	1.215	1.843	0.098	0.722
5.69	2.21	1.925	.242	.612
5.48	2.26	1.863	.231	.588
7.45	3.80	1.908	.540	.490
7.31	3.78	1.975	.546	.483
7.79	4.25	1.915	.634	.455

**Content somewhat variable.

OIL SHALE (dry); (Pony Creek No. 2 core, Richfield Oil Co., Alberta, Canada): (Ore grade)*

	U,mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P,Mbars	V/V$_0$
High	4.86	1.27	1.621	0.096	0.739
	5.333	1.595	1.596	.1355	.701
	5.96	1.97	1.636	.189	.669
	6.23	2.26	1.579	.219	.637
Medium	5.30	1.09	2.307	.119	.794
	5.274	1.43	2.350	.170	.729
	6.09	1.75	2.250	.242	.713
	6.29	2.00	2.222	.279	.682

	U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0
OIL SHALE (dry) (continued):					
Low	5.08	1.09	2.315	0.130	0.785
Low	5.358	1.405	2.321	.1755	.738
Low	6.04	1.75	2.333	.241	.710
Low	6.41	1.98	2.351	.286	.691
	3.96	1.605	1.837	.117	.595
	4.82	2.69	1.687	.219	.442

*Note: This is a qualitative term denoting the relative oil yield per unit volume of rock.

OIL SHALE (wet); (Pony Creek No. 2, Richfield Oil Co., Alberta, Canada):

	U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0
	4.43	1.638	1.514	0.110	0.630
	5.16	2.68	1.514	.222	.507
	5.25	2.115	1.502	.164	.590

OIL SHALE (mud); (Pony Creek No. 2, Richfield Oil Co., Alberta, Canada):

	U, mm/μsec	u, mm/μsec	ρ_0, g/cm^3	P, Mbars	V/V_0
Wet	6.45	3.48	1.533	0.344	0.461
Dry	5.90	3.49	1.656	.341	.409

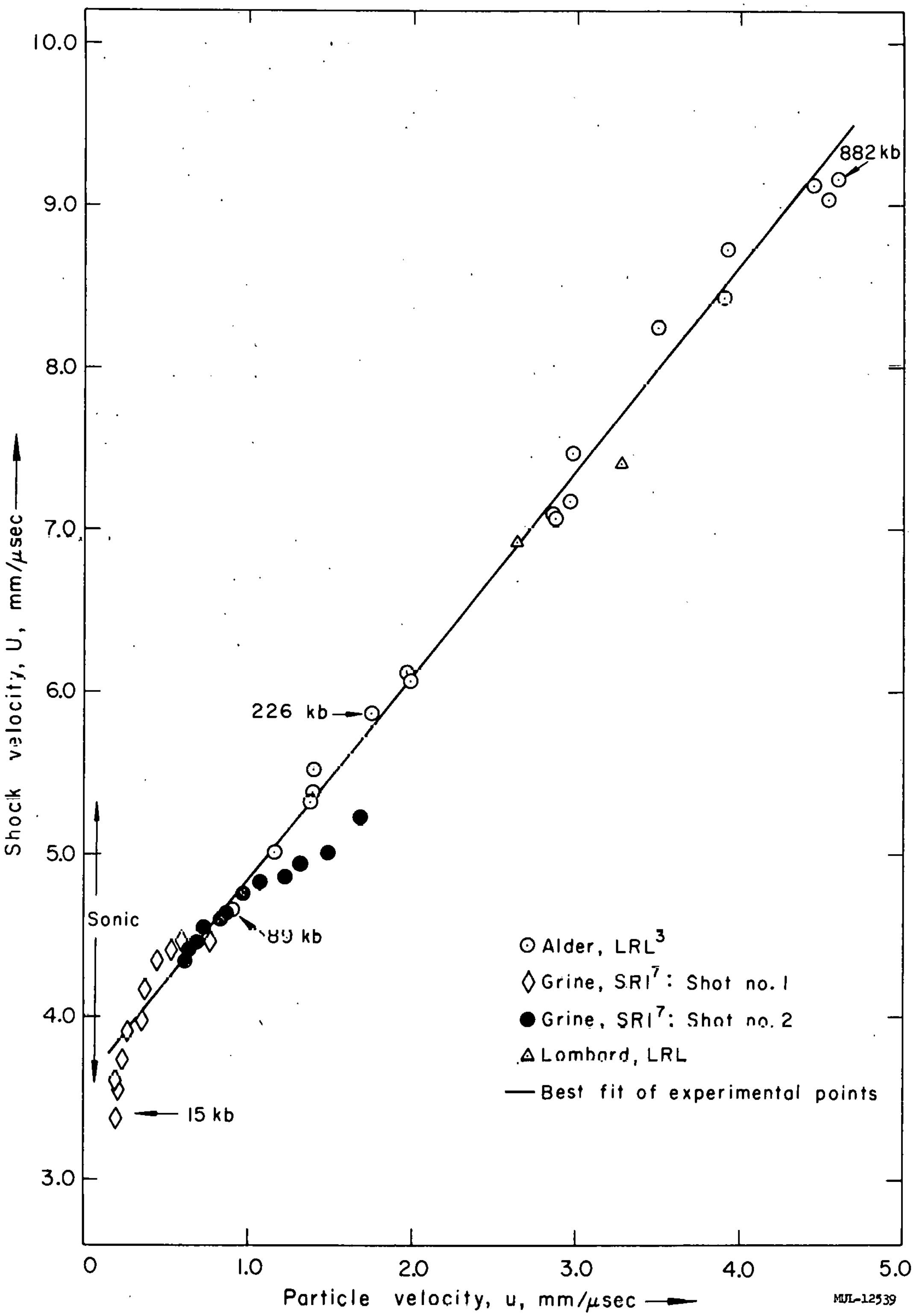


Fig. 1. Dynamic equation of state: various rock salts.

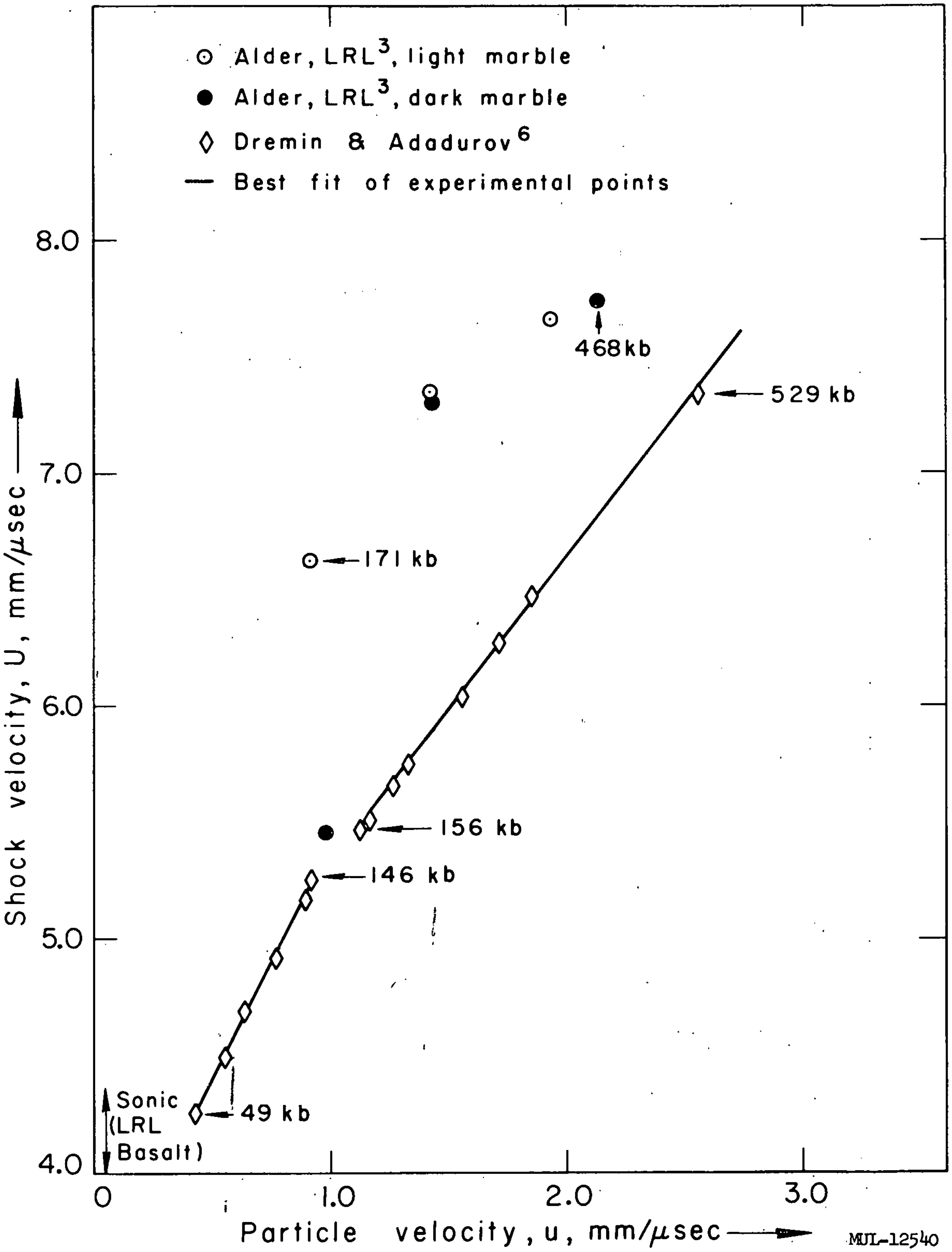


Fig. 2. Dynamic equation of state: marble.

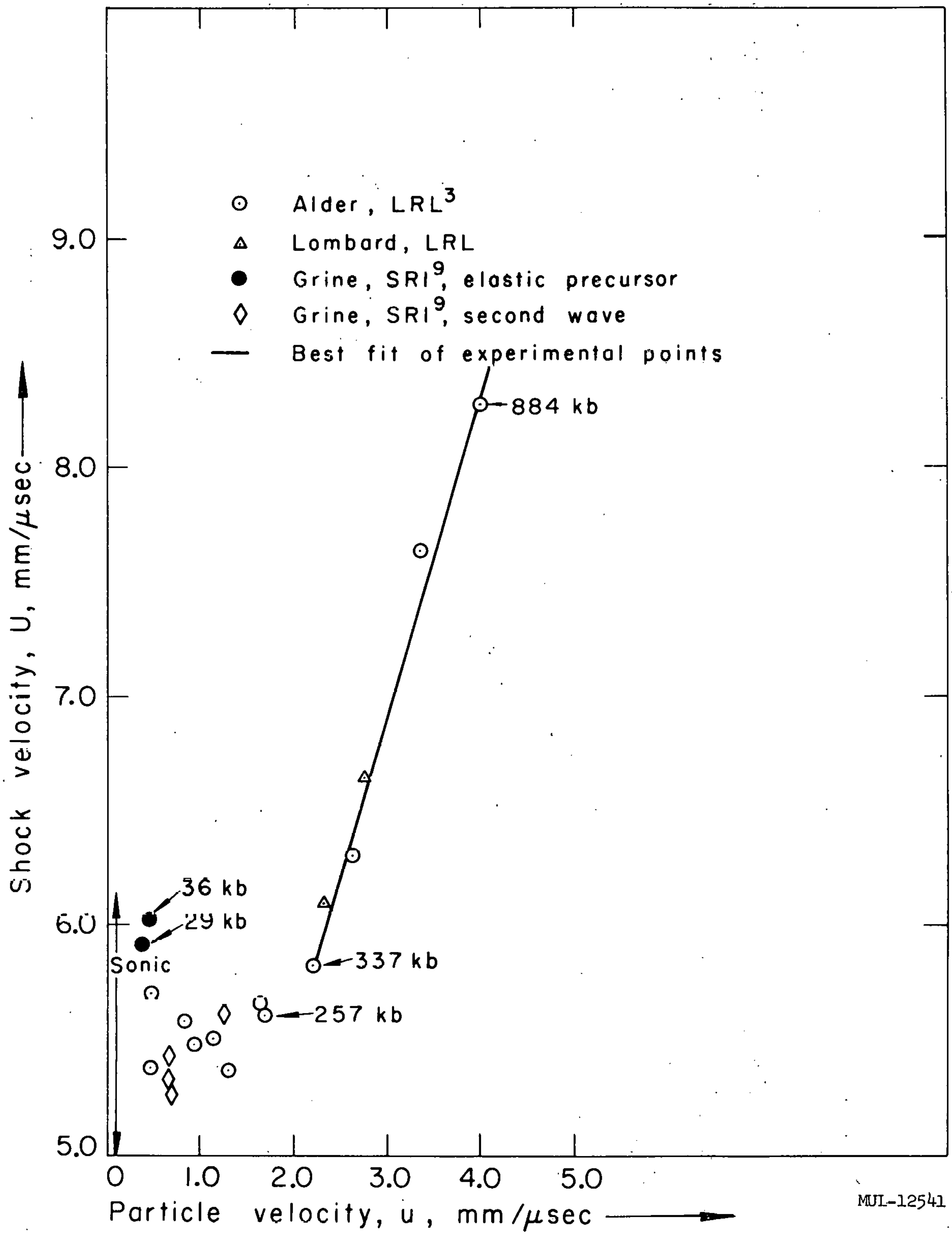


Fig. 3. Dynamic equation of state: granite.

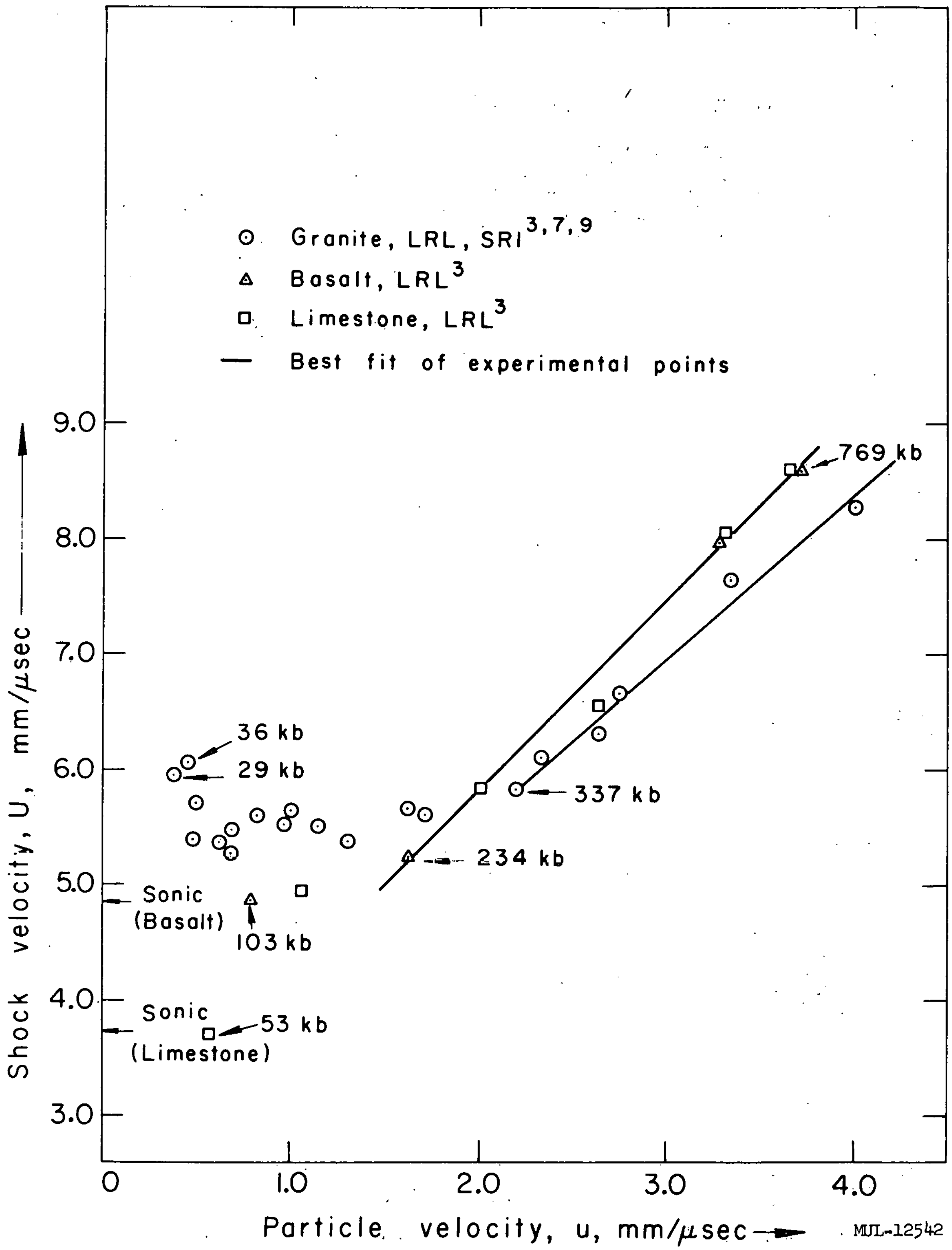


Fig. 4. Dynamic equation of state: granite, basalt, and limestone.

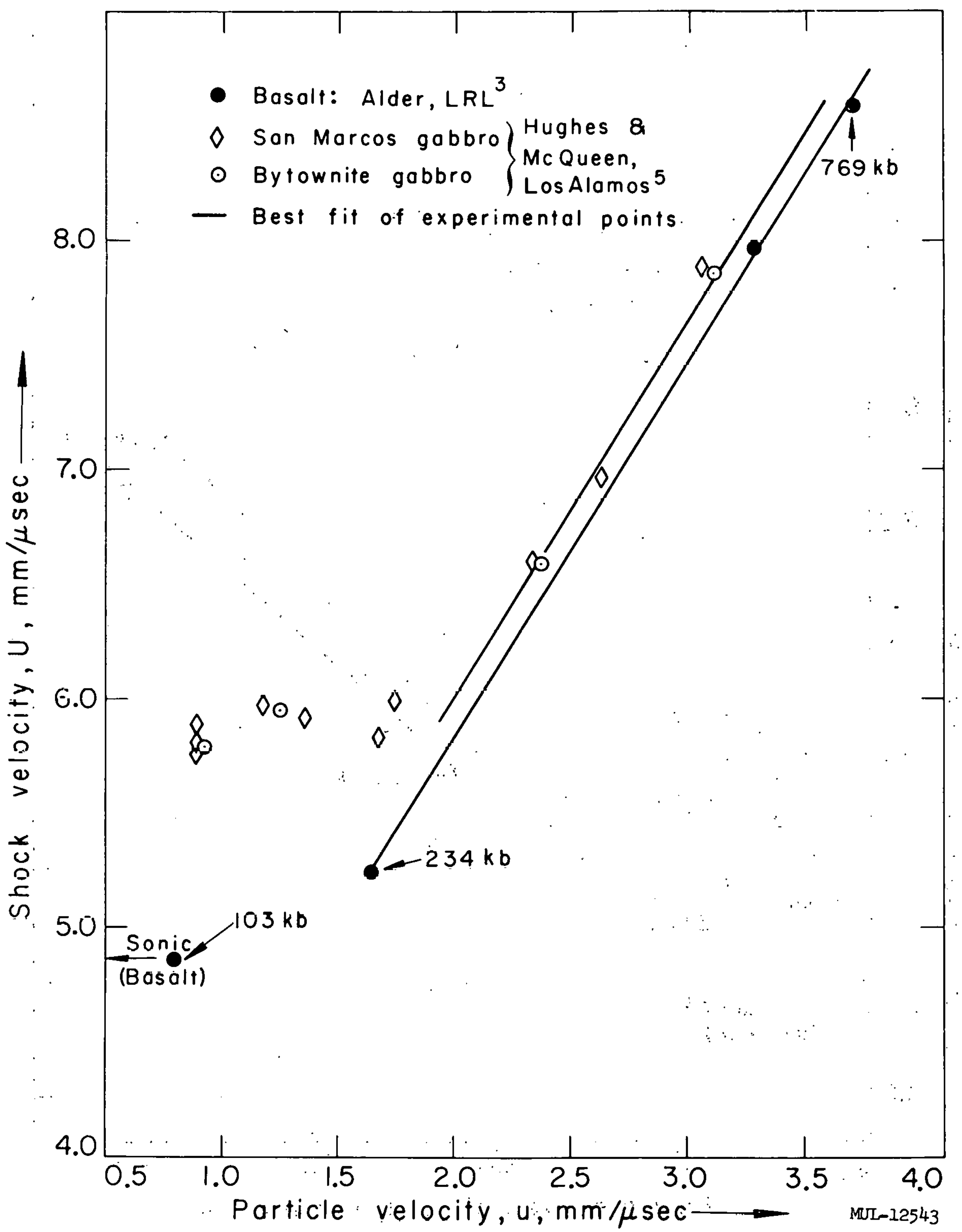


Fig. 5. Dynamic equation of state: basalt and gabbro.

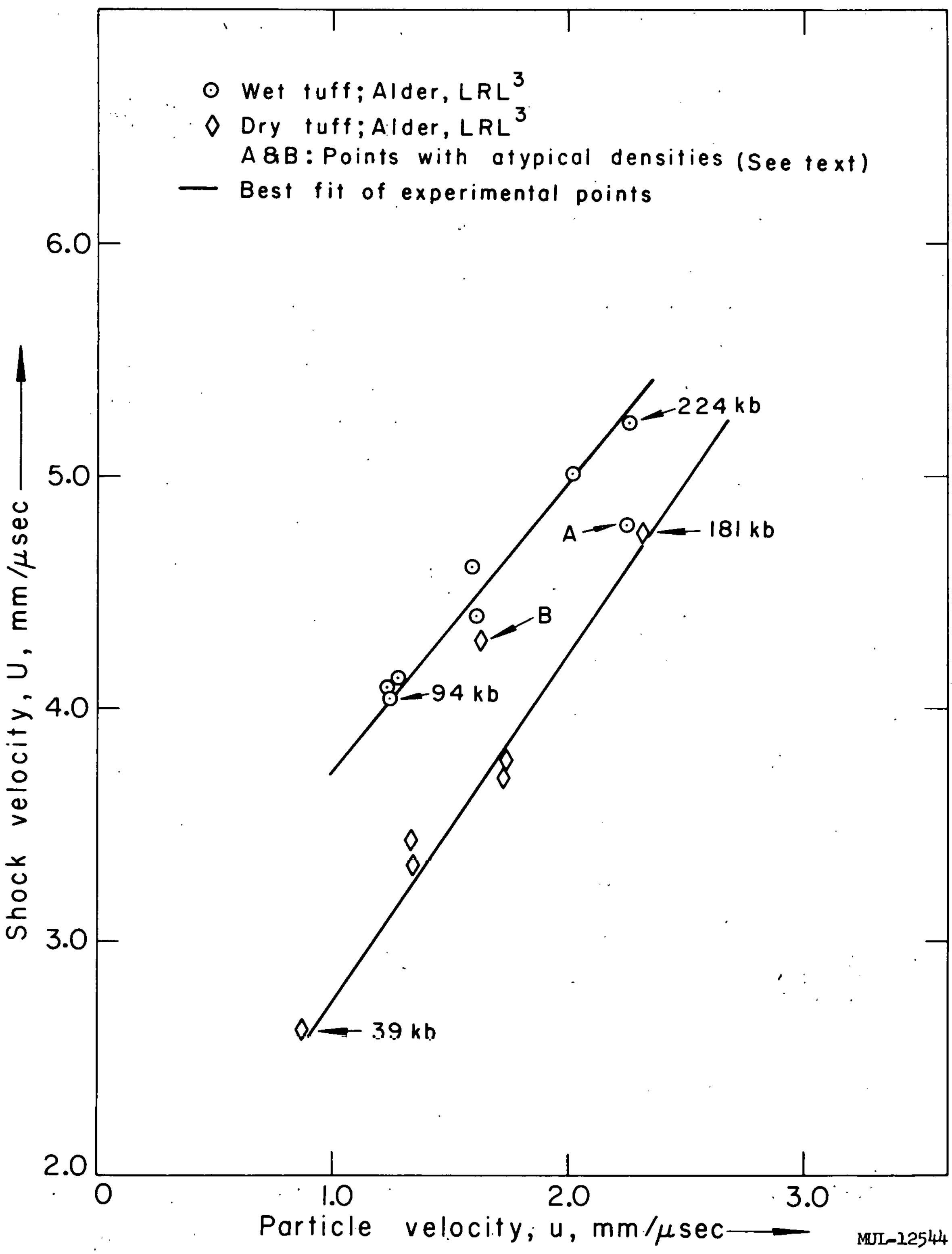
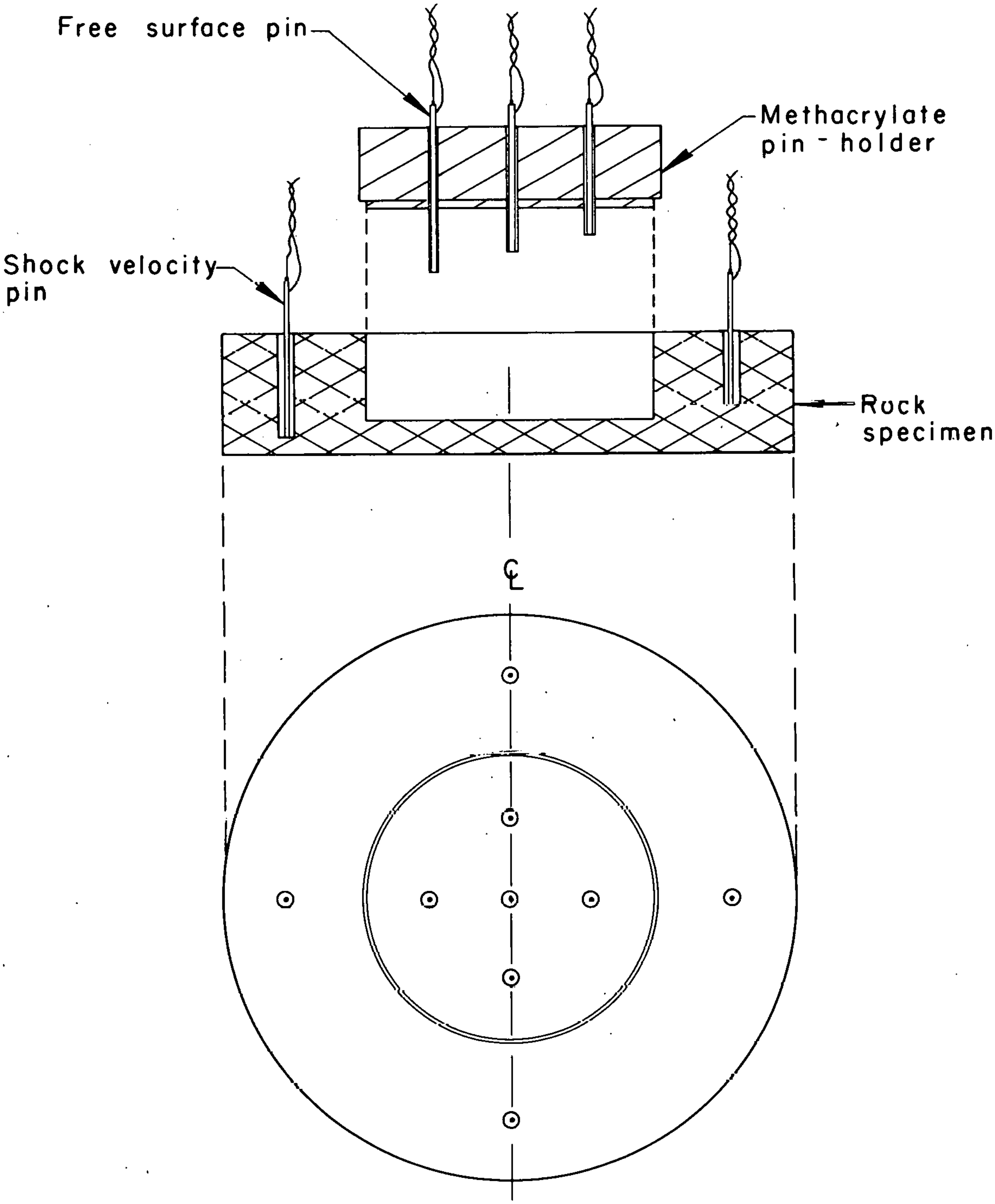


Fig. 6. Dynamic equation of state: tuff.



MUL-12545

Fig. 7. Sketch of peak pressure instrument.

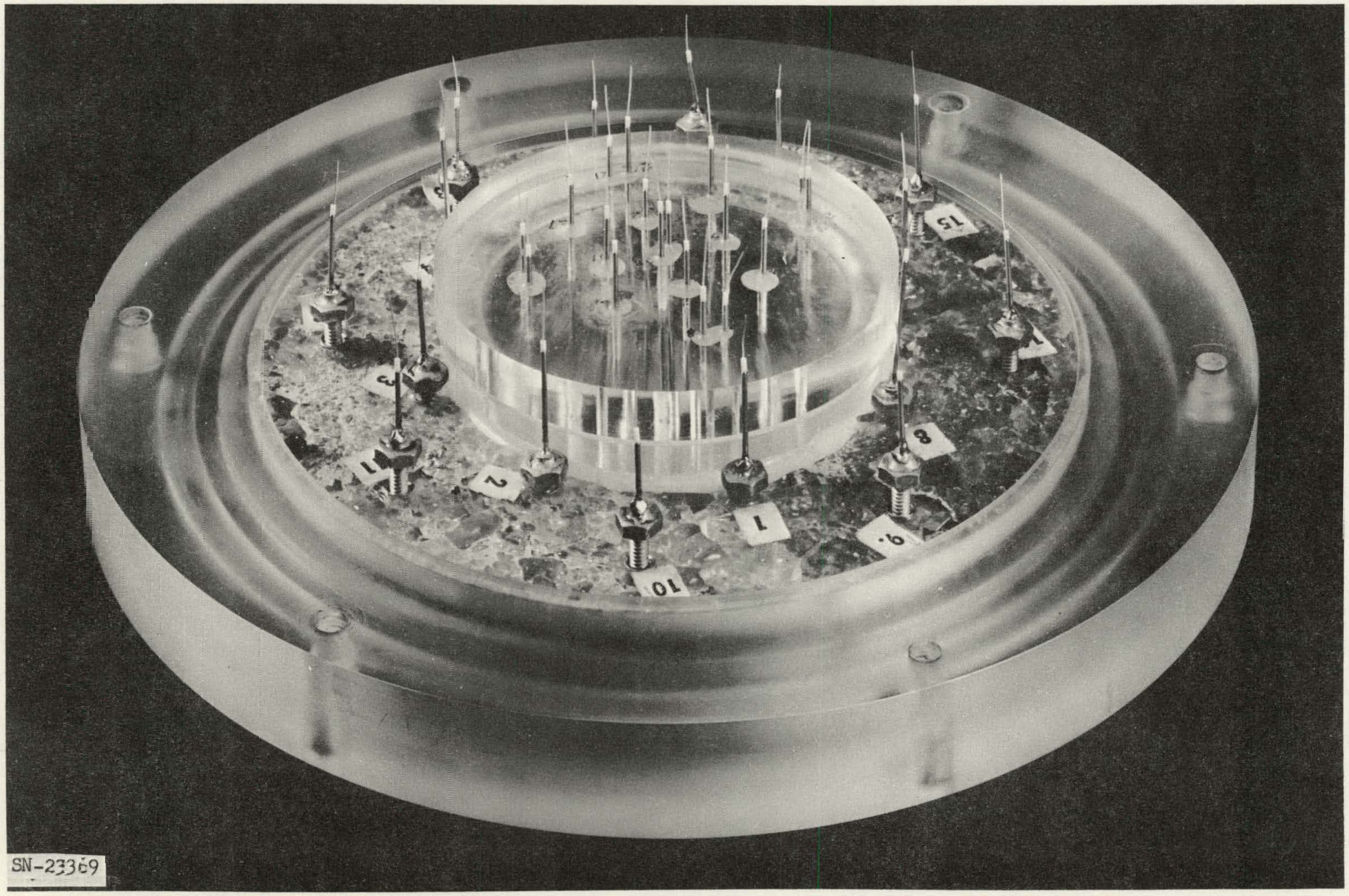
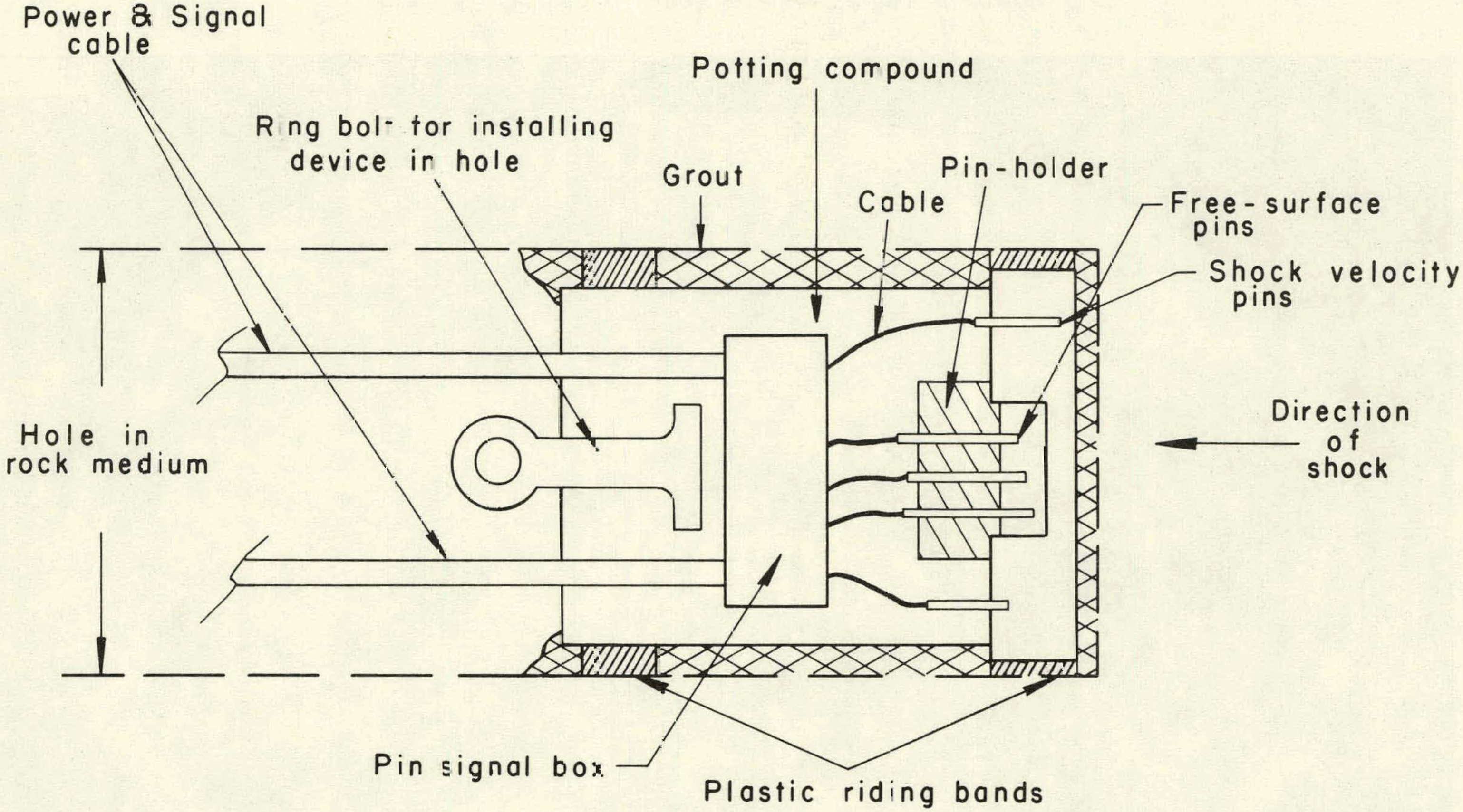


Fig. 8. Photo of peak pressure instrument.



MUL-12546

Fig. 9. Sketch of peak pressure instrument, emplaced.

LIST OF PREVIOUS PLOWSHARE AND/OR RELATED REPORTS

Report No.	Title
UCRL-4659	Deep Underground Test Shots.
UCRL-5026	Non-Military Uses of Nuclear Explosions.
UCRL-5124 Rev. I	Phenomenology of Contained Nuclear Explosions.
UCRL-5253	Industrial Uses of Nuclear Explosives.
UCRL-5257 Rev.	Peaceful Uses of Fusion.
UCRL-5281	Temperatures and Pressures Associated with the Cavity Produced by the Rainier Event.
UCRL-5457	Large Scale Excavation with Nuclear Explosives.
UCRL-5458	Mineral Resource Development by the Use of Nuclear Explosives.
UCRL-5538	Evaluation of the Ground Water Contamination Hazard from Underground Nuclear Explosions.
UCRL-5542 Rev.	Properties of the Environment of Underground Nuclear Detonations at Nevada Test Site. Rainier Event.
UCRL-5623	Radioactivity Associated with Underground Nuclear Explosions.
UCRL-5626	Underground Nuclear Detonations.
UCRL-5709	Hydroclimatology and Surface Hydrology of San Clemente Island.
UCRL-5757	Geologic Studies of Underground Nuclear Explosions Rainier and Neptune.
UCRL-5766	The Neptune Event. A Nuclear Explosive Cratering Experiment.
UCRL-5840	Industrial and Scientific Applications of Nuclear Explosions.
UCRL-5882	Chemical Reactions Induced by Underground Nuclear Explosions.
UCRL-5917	Excavation with Nuclear Explosives.
UCRL-5928	Nuclear Explosives and Mining Costs.
UCRL-5932	The Soviet Program for Industrial Applications of Explosions.
UCRL-5949	An Application of Nuclear Explosives to Block Caving Mining.
UCRL-5968	An *In Vacuo* Electromagnetic Dispersion Experiment.
UCRL-6013	Probing the Earth with Nuclear Explosions.
UCRL-6030-T	Application of Nuclear Explosions as Seismic Sources.
UCRL-6054	Fracturing of Rock Salt by a Contained High Explosive.

Report No.	Title
UCRL-6175	The System H_2O-NaCl at Elevated Temperatures and Pressures.
UCRL-6215	Can Peaceful Nuclear Explosions be Conducted Safely?
UCRL-6240	Cavity Definition, Radiation and Temperature Distributions Resulting from the Logan Event.
UCRL-6249-T	Distribution of Radioactivity from a Nuclear Excavation.
UCRL-6274	Final Report on the Pinot Experiment.
UCRL-6311	The Hugoniot Equation of State of Rocks.
	Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium (Held at San Francisco, May 13-15, 1959):
UCRL-5675	Part I: Phenomenology of Underground Nuclear Explosions.
UCRL-5676	Part II: Excavation.
UCRL-5677	Part III: Recovery of Power and Isotopes from Contained Underground Nuclear Explosions.
UCRL-5678	Part IV: Industrial Uses of Nuclear Explosives in the Fields of Water Resource, Mining, Chemical Production, and Petroleum Recovery.
UCRL-5679	Part V: Scientific Applications of Nuclear Explosives in the Fields of Nuclear Physics, Seismology, Meteorology and Space.

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