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Measuring the Dynamic Compression and Release Behavior of Rocks and Grouts Associated with HYDROPLUS

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Abstract

Gas-gun impact tests were performed on twelve rocks and rock simulants pertinent to the HYDROPLUS nuclear yield measurement program: a variety of tuffs, rhyolites, carbonates, grouts, an epoxy-alumina mixture and quartzite permafrost samples recovered in an apparently preserved frozen state from northern Canada. The present report presents results for all of these materials except for the carbonates. Two classes of impact techniques were employed for measuring equation-of-state properties for these materials. Both use velocity interferometry diagnostics. One, employing a sample-in-projectile geometry, provides high-precision Hugoniot data and continuous release trajectories for dry or water-saturated materials. The majority of the experiments were performed with this geometry. The other, employing a sample-in-target geometry, provides loading path and Hugoniot data as well as limited release data. Uncertainties in the results have been estimated by analyzing the effects of errors in observables and ancillary material properties.

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Measuring the Dynamic Compression and Release Behavior of Rocks and Grouts Associated with HYDROPLUS

1.0 Introduction

1.1 Motivation

Laboratory measurements of rock and grout equation of states are fundamental to the Defense Nuclear Agency HYDROPLUS program objective of determining yield from field, groundshock measurements. Such laboratory measurements provide a calibration for material models used in calculations of shock attenuation. These calculations are then used to relate the observed groundshock measurements to the energy released by an underground detonation. The models may be applied to other groundshock problems as well, such as range-to-effect, test containment, and CORTEX-type yield measurements.

Physically, the experimental data provide constraints on the hysteresis A of the stress-volume path followed by an element of rock or grout (Fig. 1.1), which governs the rate of energy loss from the spherically-propagating shock. The release is essential for calculating groundshock attenuation rates and characterizing release overtake velocities. Other material properties essential for calculating attenuation rates include the precursor state and the Hugoniot. For many of the materials of interest for HYDROPLUS, precursors are negligi-

Figure 1.1. Rate of decay of groundshock energy.

ble over the stress ranges of interest. Hugoniot measurements are also needed for choosing appropriate grouts for gauge emplacement and stemming, and for correcting gauge response for impedance mismatches.

The methods and results described here are essentially uniaxial. Thus, it is not completely correct to refer to “pressure”; the operative quantity is axial stress. “Density” does retain its old meaning here. Hence, these data do not provide constraints on hoop stresses and other phenomena characteristic of divergent wave phenomena.

Furthermore, these experiments do not explicitly address scaling issues. Rate-dependant behavior is not evaluated in the present study.

1.2 Previous work and broad-brush background

Techniques for measuring Hugoniot properties alone have been in use for at least 35 years¹. Many studies were conducted at the National Laboratories, among other organizations, to evaluate Hugoniot properties of geological materials. These relied largely on transit-time measurements. Hugoniot data measured at Los Alamos for approximately 44 geological materials (depending on how “different” materials are defined) may be found in Marsh¹; van Thiel² reports properties for 60 -70 materials measured at Lawrence Livermore. The Soviets/Russians produced a wealth of careful Hugoniot data as well³. The rock physics which can be extracted from these studies has been summarized elsewhere^{4,5}.

More recently, time-resolved interferometry (VISAR) techniques for measuring shock wave structures^{6,7,8} have made it possible to conduct impact experiments giving far more information for constraining material models^{9,10,11} than previously, as have the somewhat lower-resolution piezoresistive and electroinductive gauge techniques¹².

These newer techniques have allowed the measurement of a wider variety of material properties under dynamic loading. In addition to Hugoniot data, information can be obtained about yield strengths, shock viscosity, release trajectories, multiwave structures and the strength and sound velocities of materials in the shocked state. Techniques have been developed to determine the dynamic material properties at strain rates of 10^5 to 10^{10} sec^{-1} at stresses approaching 250 GPa¹³. Release hystereses can be characterized, as can rate-dependent effects for certain classes of phenomena such as transition fractions.

The outstanding feature of the shock response of silicate rocks is the phase transition apparent at 20-50 GPa, marking the quartz-stishovite transition. This is more accurately described as the $^{\text{IV}}\text{Si} \rightarrow ^{\text{VI}}\text{Si}$ transition inasmuch as it is observed for silicate rocks other than quartz and the final product may be a dense glass or other structure not displaying the long-range order of stishovite. The zero-pressure density of stishovite is 58% greater than that of quartz, so the effect of this transition is marked. Phenomenological aspects of this transition under dynamic loading and release have been modeled by Swegle¹⁴, who expressed the kinetic factors as a combination of strength softening and hysteretic $^{\text{IV}}\text{Si} \leftrightarrow ^{\text{VI}}\text{Si}$ reactions. The factors providing a best fit to experimental data for quartz and granite samples represent some strength softening and a hysteresis intermediate between frozen

quench of ^{VI}Si and equilibrium back-transition. The experiments were reverse-ballistic experiments quite similar to those described in Section 2.1 of the present report.

For lower pressures, strength effects have been seen to be important for certain rock materials. These are ideally manifested as precursors to the main loading wave and hysteretic releases to a failure envelope, followed by release nearly parallel to the Hugoniot. In practice, a sharp corner at the failure envelope is rarely seen. For granites and other strong geological materials, these effects are seen to be important; for tuffs, they are less so.

The combination of strength effects and $^{IV}Si \rightarrow ^{VI}Si$ hysteresis produces releases below the Hugoniot ("hysteretic"; $|P/V|$ is larger along the release than along the Hugoniot) over pressure ranges from near zero to 40 - 80 GPa, with releases above the Hugoniot ("normal") above this pressure. At extremely high pressures, thermal effects cause releases to lie above the Hugoniot. Factors controlling the pressure above which releases are normal may include strength (e.g. Section 3.3.3) and dewatering temperatures¹⁵.

A few representative studies are mentioned. It would be difficult to summarize all of the pertinent work in this section. Much early compression/release testing was performed with rock materials at Stanford Research Institute, using magnetic pickup loops to monitor particle velocity¹⁶. Ahrens et al¹⁵ measured Hugoniot and partial release states in granite and muscovite over a wide range of pressures, using streak camera and VISAR techniques. They found the granite releases (one point/release) to be consistent with a quench of ^{VI}Si down to 10 GPa or lower. The muscovite releases were hysteretic for Hugoniot points to nearly 100 GPa, but normal above that point, which the authors take as consistent with dewatering of the muscovite at around that pressure level. Erskine and Nellis¹⁷ evaluated Hugoniot and sound speeds in a wet and semi-dry Nevada Test Site (NTS) tuff. Upon modeling their rock as a Mie-Grüneisen solid, they found that releases from Hugoniot states in the range 6 - 27 GPa required a Grüneisen gamma between -1.5 and -3 (i.e. the releases were hysteretic). This is consistent with the results found by Grady and Furnish¹⁸ for MJ-2 grout, and by Furnish¹⁹ for another suite of tuffs from the NTS. Both of those studies used techniques similar to those described in Section 2. Individual rock-forming minerals have been studied by various investigators through the years; to summarize these is beyond the scope of the present report.

1.3 Scope

This paper outlines the types of experimental impact measurements which have been made on materials related to the HYDROPLUS program, to summarize aspects of these techniques important for understanding how these data may be used (including error measurements), and to present the data for non-carbonate materials which has been obtained at Sandia in support of HYDROPLUS. In particular, data are presented for experiments which we have conducted on tuffs, rhyolites, grouts and quartzites related to the HYDROPLUS program. Data for carbonate materials studied in connection with HYDROPLUS may be found elsewhere²⁰.

The two experimental VISAR-based techniques described in the next section provide information about many of the properties mentioned in Section 1.2 above. We have made

use of these techniques to develop a useful database for groundshock calculations in the materials of interest. The techniques have evolved during this study as well, as has our understanding of them; this evolution is discussed throughout the report.

1.4 Summary of HYDROPLUS materials studied

Table 1.1 presents a summary of materials tested at Sandia National Laboratories under the HYDROPLUS program. "RB" and "FB" refer to "reverse-ballistic" and "forward ballistic" (see Section 2). All of these materials are discussed in the present report except as noted.

Table 1.1. Materials Studied at Sandia Under HYDROPLUS Program.

Series (Shot designators)	Stress (GPa)	Experimental Suite*	Comments
U20bd#1 2198' Tuff (TFA)	2 - 101	10 RB	Tuff. 3 tests w/Ta buffers. Saturated Samples from U20bd#1 2198'.
U19ba 2001' Rhyolite (RY)	4 - 15	5 RB	Partially saturated (maintained as-received). Samples from U19ba 2001'.
U12p.04 IH20 145' Tuff (TFC)	4 - 55	5 RB	Tuff. Saturated. Samples from U12p.04 IH20 144.4-145.8
Limestone (JL) [†]	4 - 20 GPa	9 FB; 1 RB	Saturated. Compare EOS of frozen and warm Ft. Knox limestones UTP Boring CB-7, 601.2-602.3 ft.; 642.3-642.9 ft. for Louisville Fm.; 523.2-523.45 ft. for Jeffersonville Fm
Marble (DM)*	10 - 100	2 FB; 4 RB	Assess precursor and EOS. Dry Samples of Montclair Danby, Vermont Marble, Proctor, VT
Epoxy/Al ₂ O ₃ (AEP)	4 - 26	5 RB	Fair-poor data for 4 tests (heterogeneities?). Dry. 3 sample from NTS crew; 1 from P. deCarli
Silicate Grout (GTA)	5 - 19	4 RB	Saturated. U19BA Bex GC-1 Hole#2 poured Feb. 1 1991
HPNS12 (HP)	3-13	5 RB	Silicate grout. Saturated
DM Grout (GTB)	1.5 - 8.5	2 FB; 4 RB	Silicate/Borate Grout. Saturated
Quartzite Permafrost (PF)	2 - 8 GPa	12 FB, 2 RB	Impure quartzite. Tested warm, frozen (preserved frozen; thawed & refrozen). Thawed, Preserved: LU1B 1.64-1.76 Refrozen LU1A 2.60-2.62

*RB = reverse-ballistics; FB = forward-ballistics (see Section 2)

[†]These series not included in the present report; see Furnish(20, 21)

Table 1.1. Materials Studied at Sandia Under HYDROPLUS Program (Continued)

Series (Shot designators)	Stress (GPa)	Experimental Suite	Comments
U12n.24 samples: U12n.24 HP3 36' Tuff (TFD) U12n.24 GI#1 Tuff (TFE)	1 - 57 GPa	3 FB; 12 RB	Zeolitized Tuff U12n.24 HP3 36' (2.05 gm/cm ³) {4J stratigraphic unit} U12n.24 GI#1 (1.85 gm/cm ³) {4H stratigraphic unit}
Totals 11 series		24 FB; 53 RB	(Total of 77 Hugoniot points, 63 release trajectories)

Table 1.2 summarizes selected other pertinent materials studied recently at Sandia. The U20bb SH-1 1965' tuff is discussed in the present report; other materials are documented as noted; references are to the bibliography at the end of this report.

All reverse-ballistic tests listed in these tables yielded Hugoniot data, and nearly all yielded release paths. All forward-ballistic tests listed yielded Hugoniot data. The forward-ballistic tests for limestone, marble and HT tuff gave partial release states, while those for quartzite permafrost gave continuous release curves.

For this suite of experiments (summarized in Tables 1.1 and 1.2), impact velocities ranged from 0.15 km/sec to 6.84 km/sec, requiring the use of a 4 inch bore compressed-gas gun, an 89 mm bore powder-driven gun and a 28 mm bore 2-stage light gas gun.

Table 1.2. Materials Studied at Sandia Related to HYDROPLUS Program*.

U20bb SH-1 1965' Tuff (TFB)	3 - 45	5 RB	Tuff. Saturated; 1 w/Ta buffer U20bb SH-1 1965.2-1965.8
MJ-2 Grout (DNA) ¹⁸	4 - 66	15 RB; 3 FB	Partially dried, then resat. to higher p 6 RB w/Ta buffers; others w/Al.
Indiana Limestone ^{20,21} (ILS; DLS)	1 - 12	17 RB, 4 FB	18% porosity. 9 dry, 15 wet. Very good data. Bedford quarry, Indiana
P-Tunnel tuffs (RT,PT) ¹⁹	1.5 - 13	11 RB	Partially dried, then resat. to lower ρ
N-Tunnel (NT) ¹⁹	2 - 12	5 RB	Partially dried, then resat. to lower ρ
Snow (SNW) ²²	0.2 - 4	8 FB	Density 0.5 gm/cm ³
Lightweight Concrete ²²	0.2 - 4	8 FB	Snow Simulant; density 0.7 gm/cm ³
Snow Matching Grout ²²	0.04 - 1.34	10 FB	Snow Simulant; density 0.2 gm/cm ³
Other snow simulants ²²	0.04 - 1.0	8 FB	4 other simulants for AGT
Totals 9 series		41 FB; 43 RB	

* Includes several series sponsored for containment studies. Funded by DNA except for DOE-funded testing of U20bb SH-1 1965' Tuff (TFB) and Indiana Limestone.

2.0 Techniques for Evaluating Hugoniot and Release of Geological Materials

2.1 Reverse-ballistic method

Consider an impact experiment with the design shown in Figure 2.1. The wave interactions and observed velocity history for this design are also shown in Figure 2.1. The sample is mounted in the projectile, contained in an aluminum cup to protect it from gun vacuum and backed by a closed-cell, high strength foam. In this way water saturation is maintained during the experiment. Upon impact, a shock propagates through the aluminum cup, through the sample and into the foam backer. A release is reflected forward through the sample, the aluminum cup and target components and into the lithium fluoride window. A VISAR monitors the velocity history of the aluminum/lithium fluoride interface.

Figure 2.1. Configuration of Reverse-Ballistics Configuration (Powder gun adaptation shown)

2.1.1 Information available from the reverse-ballistic method

The most basic form of generally usable data produced by this experiment is a velocity profile. Material models may be validated by comparing computer code simulations of the experiment with the observed wave profiles. Utilizing these data requires a detailed knowledge of such experimental particulars as component dimensions and projectile velocity.

Hugoniot data are derived from these profiles by standard impedance-match methods²³ (Figure 2.2). Information required is the projectile velocity, the initial sample density and the velocity level of the long plateau in the observed velocity profile. In addition, the Hugoniot and release properties of the cup and window materials are required, although these are known to good precision for materials such as aluminum and lithium fluoride (better than 1 percent stress at a given particle velocity over the range 6 - 150 GPa).

Figure 2.2.
Impedance match diagram
for standard reverse-
ballistics configuration.

Provides σ , U_p
If loading wave is steady, then:
 $U_s = \sigma / \rho_0 U_p$
 $\rho = \rho_0 U_s / (U_s - U_p)$

Release trajectories are derived by modeling the experiment computationally¹⁸. We have used the wavecode WONDY V, a one-dimensional Lagrangian wavecode. After the Hugoniot state has been determined, an empirical model of the sample is constructed with a Mie-Grüneisen loading behavior and a Lagrangian release modulus described by:

$$(-V_0) \left. \frac{\partial \sigma}{\partial V} \right|_S \equiv B_S = B_0 (1 + \chi B_1 + \chi^2 B_2 + \chi^3 B_3) \quad (\text{where } \chi \equiv \frac{\sigma}{\sigma_H} - 1) \quad (\text{Eq. 2.1}).$$

Here, B_0 has units of pressure and the other B_i are nondimensional. B_0 is adjusted to match the observed release arrival time on the VISAR record; the Eulerian sound speed at the Hugoniot state may be expressed as $C_b = (\rho_0 / \rho) \sqrt{B_0 / \rho_0}$. Here, subscript "b" (bulk) is an artifact of the simplistic splitting of the release into longitudinal and bulk portions, and means that the fitting generally ignores initial release structure. Next, B_1 is adjusted to match the initial slope of the release signature; then B_2 and B_3 are adjusted to match the observed curvature of the release curve signature. Within the uncertainties of the fitting process, B_0 and B_1 are generally determined accurately, while B_2 and B_3 are less well defined. The release path in stress/density space may then be determined by integrating Eq. 2.1; particle velocity may be obtained by integrating the differential $dU_p = \sqrt{d\sigma dV_S}$ over volume from the Hugoniot state. In practice, this fitting process is iterative, requiring 5 - 20 runs of the wavecode. About 600 zones are used for typical models.

Figure 2.3 gives an indication of the role of each of the B_i in fitting the profile, and the relation between fitting precision and effects on the calculated release trajectories in various spaces. The particular example is for a test on a rhyolite (density 2.276 Mg/m^3) shocked to a Hugoniot stress of 11.6 GPa . The initial arrival of the release wave corresponds to the sound speed, which may be calculated as discussed by Furnish¹⁹.

Figure 2.3. Effects of changing respective B_i coefficients in WONDY fits (case of test RY-5)

Empirical material models may be derived directly from a set of Hugoniot points and release curves. Consider the axial release modulus, $K \equiv -V(\partial\sigma/\partial V)|_S$, and its first three stress derivatives, $K^{(n)} \equiv (\partial^n K/\partial\sigma^n)|_S$. These are functions of stress along the release. Their values at the Hugoniot stress may be expressed²⁴ in terms of the B_i described above, the Hugoniot stress P_H , and the ratio of initial to Hugoniot density, ρ_0/ρ_H . Each of the $K^{(n)}$ may then be expressed as a function of Hugoniot stress (each experiment generates one set of the $K^{(n)}|_{\sigma_H}$); this then gives an experiment-based description of the release behavior of the material for shocks of arbitrary strength within the experimental range. This technique has been used to estimate errors caused by using an approximation that a grout release lies along the Hugoniot when correcting gauge stress or particle velocity to *in-situ* conditions²⁴.

2.1.2 Limitations of the reverse-ballistic method

With reverse-ballistics, releases are limited by the nonzero shock impedance of the foam. In turn, the foam selected is governed by strength requirements; it must support the acceleration of the sample and cup during launch. Releases may thus be measured down to as low as 20 percent of the Hugoniot stress for low-velocity launches (to 0.7 km/sec; Hugoniot stresses to ~3 GPa, depending on the impedance of the test material). On the other hand, tests with the 2-stage gun at 4 - 7 km/sec only provide releases down to 60-75 percent of the Hugoniot stress, since a relatively dense (0.7 gm/cm^3) plastic/glass microballoon composite must be used for the 1 - 2 mega-G launch environment.

From such data, geologic materials may be characterized by the fraction of the Hugoniot specific energy retained at half-stress on the release. Higher fractions correspond to greater groundshock attenuation rates.

The sample must also be able to withstand the launch. For most rock materials studied, this has not been a problem. More distended materials, however, may present problems with this technique²².

The Grüneisen gamma, an important parameter in many material models, can be only approximately determined from these data. There are two reasons for this. The first is experimental: this technique is optimized to measure a release trajectory and single Hugoniot state rather than a difference between the Hugoniot and the release trajectory. Any flexibility in choosing a Hugoniot corresponds to an uncertainty in progressing from a release curve to a Grüneisen parameter (example in Section 3.3.3). The second reason, common to uniaxial experiments, lies with the inability of this technique to distinguish between the strength of the material and the effects of shock heating or phase changes.

Finally, such properties of the loading wave as precursors (e.g. an elastic wave or a phase-transition induced precursor) and the rise time are not measured by this method. For most of the NTS materials tested, this is not a significant concern because the strengths (substantially less than 0.1 GPa) are very small compared to the Hugoniot stresses (1 to 100 GPa). More competent materials, such as granites, dunites or many single-crystalline samples, do show multiwave structures in forward-ballistic experiments (shock transmitted through sample to window). Carbonates may show precursors related to a $\text{CaCO}_3 \text{ I} \rightarrow \text{III}$ transition. Reverse-ballistic testing of these materials must be interpreted in light of the two-wave structure. Impedance-match calculations in the stress-particle velocity plane give the correct Hugoniot stress and particle velocity, but the shock velocity and Hugoniot density must be calculated to account for the wave structure. Releases may be derived by the iterative wavecode modeling method described above if the description of the loading behavior in the wavecode is correct.

There are three primary reasons we have used the reverse-ballistic configuration where possible. First, it is very robust against experimental error. Information about absolute timing of the trace and projectile velocity is supplied redundantly, affording cross-checking. This advantage is due to the first part of the experiment being an aluminum/aluminum impact, whose properties are well-known. Second, the wave interactions are relatively simple. This is partly due to the very good impedance match between the aluminum buffer

and the lithium fluoride window. While the experimental analyses makes corrections for all wave interactions, it is useful to know that the sample has been subjected to a simple load/unload path with little in the way of extraneous shocks and releases. In particular, the main release wave travels through an almost uncontaminated Hugoniot state for the entire sample thickness (compare with the case for forward-ballistic VISAR experiments, below). This second advantage does not hold if a high-impedance buffer, such as tantalum, is used instead of aluminum so as to achieve higher shock stresses. As mentioned below, it also may not hold for forward-ballistics geometries. Third, this method provides an intrinsic averaging of the response of a heterogeneous material through the buffer and cup not afforded by experiments with high time-resolution stress gauges, while providing a high time resolution not afforded by larger stress gauges.

2.1.3 Uncertainties associated with reverse-ballistic data

Consider the data as reduced and reported in three stages: wave profile, Hugoniot data and release trajectories. Uncertainties in each stage of reduction affect that and subsequent stages.

The wave profile is uncertain in timing and amplitude. Impact time (which is defined as zero time) may be established by two methods: an electronic fiducial generated by a flush pin, and assumed shock velocities through the buffer separating the impact surface from the window and the interface monitored by VISAR. For these experiments, assumed buffer shock transit times have generally been used, with an uncertainty estimated at about 10 nsec (mainly due to uncertainty in interpreting the raw VISAR fringes). Fiducial time determinations have exhibited appreciable discrepancies with the buffer transit time determinations (up to 200 nsec); this is ascribed to small bowing of projectile components.

Wave profile amplitudes are uncertain insofar as the velocity-per-fringe (VPF) is uncertain. In turn, this is a combination of error in calibrating of the VISAR leg delay and error in the assumed index-of-refraction correction for the window ($1+\Delta v/v_0$), which is about 1.28 for LiF, 0.99 to 1.00 for PMMA, 1.03-1.06 for fused silica and 1.75-1.78 for sapphire^{25,26}. The combined errors here are limited to about 1 percent.

The Hugoniot point is calculated as discussed above. The principal uncertainties are the projectile velocity (about 0.5 - 1 percent), the average value of the velocity plateau on the VISAR record, the initial density, and errors in the assumed equations of state for the ancillary materials (aluminum, lithium fluoride, and (where appropriate) tantalum or copper. Errors in ancillary material EOS have been taken arbitrarily as 1 percent in stress at a given particle velocity; this may understate the error somewhat at stress levels $\sigma_{xx} \lesssim 4$ GPa, where strength becomes important. Projectile velocities are measured by pins (1 or 2 independent measurements per shot) and from the first (short) plateau in the velocity history; uncertainties are taken as 0.5 percent unless the spread of these readings justifies a larger uncertainty. Often the most difficult uncertainty to assign is the (Hugoniot) plateau velocity. When there is an apparent step in the middle, an average value is taken, with uncertainties sufficient to bracket both elevations. If a high-impedance buffer is used, a clean step may correspond to aluminum ringing, and the two elevations may be used separately¹⁸ (see also Section 8.3.1). A large hump at the end of the plateau, as found in some

tests, is not included in any averaging. We are still uncertain as to why this is found.

As an example, errors for the U20bd#1 2198' tuff (Tuff A) Hugoniot are broken down according to principal causes in Figure 2.4, for each of the four Hugoniot quantities. The principal contributions to overall Hugoniot uncertainties are projectile velocity and velocity plateau level for typical tests. The initial density error is a far less important quantity in this analysis.

Figure 2.4. Fractional error contributions to Tuff A (U20DB#1 2198') Hugoniot error by various uncertainties. Larger values mean more of the error in that calculated value (e.g. stress) is due to errors in that particular observable (e.g. projectile velocity). For example, in Test 11 most of the stress uncertainty was due to plateau velocity uncertainty

Release uncertainties are difficult to present explicitly. We have assessed them by performing a perturbation-type analysis¹⁸. The principal uncertainties (broken down as observables) are the projectile velocity, the plateau velocity (hence the Hugoniot state), the profile timing relative to impact and the fitting of the calculated profile to the experimental profile in the release interval. Other uncertainties are less important: ancillary material equations of state (which tend to "cancel out"), initial density, and sample thickness (which may be measured very closely prior to the experiment). Figure 2.5 shows the effects of perturbations of the observed plateau velocity on the reported release curve (case of BEX-5). A 2σ error in plateau velocity (taken here loosely as meaning about an 80 percent confidence interval) gives approximately a 4 percent error in $f = E(\sigma_H/2)/E(\sigma_H)$. This is for the present test, and can vary depending on the oscillation amplitude of the VISAR record in the plateau region and the existence/absence of such anomalies as a two-plateau structure or a large bump at the end of the plateau. Similar analyses for errors in impact velocity, timing and in fitting the release profile show 2σ contributions of about 2 percent, 1 percent and 1 percent, respectively. These fittings are shown in Figures 2.6, 2.7 and 2.8 (respectively). The fitting error, of course, is difficult to estimate for the general case. Adding these in quadrature, and including small uncertainties for the other

Figure 2.5. Sensitivity of inferred releases to errors in plateau velocity

Figure 2.6. Sensitivity of inferred releases to impact velocity errors

Figure 2.7. Sensitivity of inferred releases to profile timing errors

Figure 2.8. Sensitivity of inferred releases to release curve-fitting errors

Figure 2.9. Half-pressure retention of Hugoniot energy for U19ba 2001' rhyolite, Grout A, epoxy/alumina and MJ-2 grout

observables and the ancillary materials, a total 3σ error in f of 7-10 percent for a given test may be assumed. As an example, we conclude that Grout A had a significantly less hysteretic release than the rhyolite or epoxy/alumina, but that the differences within these last two families of releases may not be significant (cf. Fig. 2.9)

2.2 Forward-ballistic method using VISAR

There are many situations where the reverse-ballistics configuration is unsuitable. For example, experiments with refrigerated or heated samples, or fragile samples, must be done with the sample in the target. Any material tested under conditions where a precursor (elastic or phase-transition) exists at a large fraction of the Hugoniot stress will not give a simple centered release wave in a reverse-ballistics experiment; the precursor will reflect a strong release wave before the plastic loading wave has finished traversing the sample. If the shock state of the precursor is not known, the Hugoniot shock velocity and density cannot be calculated from the results of the reverse-ballistic experiment. For these situations, a forward-ballistic experiment is required.

The information available from such experiments varies with the particular experiment. Usually it includes a loading history (including strain rate and the shock states of any precursors), the Hugoniot state, either a reshock state or a partial release state of the sample, and a release or recompression trajectory from this state. In some cases it is possible to measure a release directly from the Hugoniot state.

Consider the configuration of Fig. 2.10. This is the most practical geometry for use with VISAR since a window must be used (free surfaces of geological materials are not adequate reflectors after shock arrival). Often a buffer is desirable to average the effects of heterogeneities and to provide better survivability for the reflecting surface, although very low-porosity materials (e.g. granites and marbles) may be used without buffers.

Figure 2.10. Forward-Ballistics Configuration (Gas gun adaptation shown)

The best available window materials for use with geological materials are PMMA, lithium fluoride and fused silica (although Z-cut sapphire may be used in its elastic regime below ~12 GPa for extremely high-impedance samples such as iron). If an inappropriate window is chosen, an excessively large reshock or a release wave is sent back into the sample (see Fig. 2.10, releases labeled (a)) and the primary release is contaminated by the affected volume of sample. In this respect, *in-situ* stress or particle velocity gauges hold advantages over VISAR diagnostics; sandwiching the gauge between disks of the sample will give a perfect impedance match. If an impactor of higher impedance than the sample is used, the release will be abbreviated by the wave interaction leading to the reshock labeled (b) in Fig. 9. Hence choice of ancillary materials is important.

Calculation of the Hugoniot and partial release/reshock states proceeds as illustrated in

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3.0 Tuff A (U20bd#1 2198') - Dynamic Experiments

3.1 Material studied

We conducted a set of experiments to determine dynamic compression and release behavior of "Tuff A", sampled from Nevada Test Site (NTS) bore U20bd#1 at the 2198 foot level. This is an unwelded, altered tuff taken from just below the water table (~2190 foot level). It is described as a "calcaline ash-fall tuff, fine-grained, sparse lithics, competent, zeolitized, massive, rare chalcedony along fractures."³⁰ Terra Tek measured critical material properties, as follows²⁷. In-situ saturation for this material ranges from 97-99%. Porosity ranges from 33-42%, with air voids representing 0.4-1.0% of the volume. Densities are 1.80-1.996 gm/cm³ (112.4 - 124.6 lb/ft³, or 1.004 - 1.113 gigaslugs/furlong³, if the reader will). In general, densities decrease and porosities increase with increasing depth, although a marked change in lithological character occurs at the 2000 foot level. Ultrasonic velocity measurements were 2.317 and 1.050 km/sec (P, S-Wave, respectively) immediately adjacent to the samples tested at Sandia; these values are lower than those at 2207' (3.021 and 1.228) and those at 2003' (2.812 and 1.214), although this is labelled as scatter. Irreversible compaction is typically 2 -3 times the air void volume under uniaxial loading to 0.2 - 0.3 kb.

The samples used were provided as 4 inch diameter core, foiled and encased in beeswax to preserve water saturation. The bore designation is U20bd#1 (2198 foot level)*. The Sandia Laboratories grinding shop prepared disk-shaped samples from this core. Based on our experience with other altered tuffs (from the vicinity of the NTS N- and P-tunnels) suggesting that partially dried tuffs are not readily resaturated to their original saturation, we instructed the shop to keep the samples immersed except during active machining, and to use water coolant (without rust inhibitors, cutting oils or other potential contaminants) during the machining process. The samples were machined cleanly, with tight tolerances (0.0005") applied to plane-parallelism of the disk faces. Sample diameters were approximately 69.7 mm (powder gun tests) and 24.1 mm (2-stage light-gas gun). Sample densities as tested ranged from 1.824 to 1.880 gm/cm³ (1.838 to 1.851 gm/cm³ for the larger powder-gun samples). These correspond well with the 1.826 gm/cm³ density measured for the same level by Terra Tek²⁷.

3.2 Experiments conducted

Experiments conducted are listed in Table 3.1. They required the use of the 89 mm powder gun and the 28 mm 2-stage light gas gun at the Sandia STAR Facility. All were reverse-ballistics experiments (Section 2.1).

The intent of this series was to map out the dynamic response of this material to Hugoniot stresses ranging up to 100 GPa. As discussed in Section 2, the aluminum-buffered geom-

*Personal communication with Kirt Sinz (LLNL), based on information from Bill McKinnis (NTS) questions this designation, suggesting that it should be U20BD#2 (2198 - 2203'). This is because McKinnis suggested that no waxed cores were recovered from U20BD#1. Our records are consistent with the designation U20bd#1 2198'.

Table 3.1. Impact experiments conducted to characterize Tuff A (U20bdd#1 2198')

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density ¹ (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ² Thick (mm)	Velocity ³ Per Fringe (km/sec)
TFA 1 ⁴	Powder	0.54	0.320	6.0	Tuff	1.845	6.005	2.027	Al	2.621	31.756	0.094795
TFA 2 ⁴	Powder	2.10	0.640	6.0	Tuff	1.838	5.974	2.032	Al	2.679	31.634	0.094795
TFA 3	2-Stage	4.00	0.763	2.984	Tuff	1.844	4.032	0.9906	Al	1.023	18.828	0.270444
TFA 4	2-Stage	5.67	0.763	2.987	Tuff	1.880	3.971	1.0287	Al	1.021	25.411	0.270444
TFA 5	2-Stage	5.26	0.763	2.995	Tuff	1.864	4.018	1.0378	Al	1.008	18.948	0.198883
TFA 6	2-Stage	6.84	0.763	3.021	Tuff	1.824	4.032	1.034	Ta	3.127	18.860	0.198883
TFA 7 ⁴	2-Stage	2.94	0.763	3.007	Tuff	1.880	4.023	1.037	LiF	3.020	19.032	0.298883
TFA 8	Powder	1.804	0.320	6.299	Tuff	1.830	5.993	2.004	Ta	6.355	31.760	0.094795
TFA 9	Powder	2.26	0.640	6.330	Tuff	1.851	5.989	2.007	Ta	6.332	31.670	0.094795
TFA 10	Powder	1.04	0.320	6.284	Tuff	1.827	5.988	1.986	Al	1.509	31.844	0.094795

Notes:

¹Nominal densities; 0.320 = 20 lbs/ft³, 0.640 = 40 lb/ft³; 0.763 = "syntactic" (glass microballoon foam; Sylgard 184 GMB Syntactic)

²Window is composed of lithium fluoride throughout this suite of tests

³Velocity per fringe (VPF) corresponds to a setting of the VISAR

⁴Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment.

etry was preferred; it was therefore used whenever possible. Test TFA-6 made use of a tantalum buffer to allow reaching extremely high pressures. Tests TFA-8 and 9 also used such buffers to provide data in the stress range 13-18 GPa, which is difficult to reach otherwise because of the gap between the 2.25 km/sec maximum launch velocity of the powder gun and the ~3.0 km/sec minimum launch velocity of the 2-stage light gas gun.

Test TFA-7 was conducted to provide a very low-stress test on the 2-stage gun system to verify that there was no systematic data shift between the two gun systems. The data presented for MJ-2 grout by Grady and Furnish¹⁸ showed a two-phase structure, with this transition range coinciding with the range of the expected $^{IV}\text{Si} \rightarrow ^{VI}\text{Si}$ transition, but also coinciding with a change of gun systems from the powder gun to the 2-stage light gas gun. This had given rise to concerns in the community that the two-phase structure was an experimental artifact. A LiF buffer was selected to provide a slightly lower Hugoniot stress than could be reached with an aluminum buffer.

3.3 Dynamical material properties results

3.3.1 Velocity profiles observed

The velocity profiles observed are presented in Figure 3.1, broken into separate plots according to the gun system and buffers used. The features found for the aluminum and lithium fluoride buffer tests are typical of this configuration.

Two of the powder-gun Al-buffer tests showed signatures of a gap forming between the cup and sample (see Section 3.3.3), as did the LiF-buffer test. While undesirable, such a gap does not seriously affect the Hugoniot measurements. Its width may be calculated, and wave interactions modeled so as to account for the gap.

The tantalum buffer tests do not show a clean plateau corresponding to the aluminum/tantalum impact because of release overtake. The tantalum buffer thicknesses were chosen as great enough to avoid spalling the sample; a consequence of this is the overtake mentioned.

3.3.2 Hugoniot conditions

Calculations of Hugoniot states were performed assuming a modified Mie-Grüneisen model for the ancillary materials (6061-T6 aluminum, lithium fluoride, and tantalum). The defining parameters for the models used are given in Table 3.2.

The calculated Hugoniot conditions for the aluminum- and lithium fluoride-buffer tests are listed in Table 3.3 below. These were calculated by methods discussed in Section 2 (including hydrodynamic Mie-Grüneisen properties for the aluminum, a reasonable assumption under the present impact conditions). For the lithium fluoride test, a straight impedance match was used.

Hugoniot conditions for the tantalum buffer experiments may be calculated according to the impedance match procedure described in Grady and Furnish¹⁸ to give the values presented in Table 3.4 (note that the values for tests 8 and 9 will be further examined on following pages).

Figure 3.1. Velocity profiles from impact tests on U20BD#1 2198' tuff

Table 3.2 Ancillary Material Equation-of-State Parameters Assumed*

Material	ρ_0 (kg/m ³)	C_0 (m/sec)	S	γ_0	Y (GPa)
Lithium Fluoride	2641	5148	1.35	1.63	0.2
Aluminum	2698	5370	1.34	2.1	0.3
Tantalum	16680	3293	1.31	1.6	0.7
PMMA**	1185	2571	1.53	0.97	---
Copper	8805	3940	1.489	1.99	0.3

*Assuming linear shock velocity/particle velocity relation ($U_s = C_0 + S U_p$). Y = dynamic yield strength

**For pressures up to 6 GPa, use viscoelastic PMMA model of Schuler and Nunziato, 1974²⁸

Table 3.3. Hugoniot conditions for U20bd#1 2198' Tuff experiments with aluminum or lithium fluoride buffers

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
1	0.54(2)	0.154(4)	1.845(5)	0.39(2)	2.25(7)	2.10(3)	3.15(19)	1.1399	0.475(7)
2	2.10(1)	0.692(8)	1.838(5)	1.43(2)	11.5(2)	2.73(4)	4.37(10)	1.4937	0.366(6)
3	4.00(7)	1.427(15)	1.844(5)	2.61(7)	27.5(5)	3.38(16)	5.73(20)	1.8359	0.295(15)
4	5.67(7)	2.145(15)	1.880(6)	3.58(7)	46.9(8)	3.86(17)	6.97(19)	2.0519	0.259(12)
5	5.26(3)	1.941(20)	1.864(6)	3.36(4)	41.0(8)	3.83(13)	6.55(17)	2.0541	0.261(9)
7	2.94(4)	1.019(10)	1.880(6)	1.92(4)	17.5(4)	3.11(10)	4.85(16)	1.6531	0.322(10)
10	1.04(1)	0.330(8)	1.827(5)	0.72(2)	5.03(15)	2.25(3)	3.83(16)	1.2315	0.444(6)

(Note that values in parenthesis represent uncertainties in the last 1-2 digits of the quantity)

Table 3.4. Hugoniot conditions for U20bd#1 2198' Tuff experiments with tantalum buffers (fast cup ringdown approximation)

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
6	6.8400	1.9141	1.824	5.606	101.165	4.208	9.8942	2.3071	0.2376
8	1.8040	0.3426	1.830	1.588	12.885	2.853	4.4320	1.5585	0.3505
9	2.2650	0.4444	1.851	1.985	17.154	3.219	4.6698	1.7391	0.3107

These calculations were made assuming that the “ringing” in the aluminum cup was essentially completed early in the experiment. For two of the experiments with tantalum buffers, however, wavecode simulation revealed that the relatively thick (2 mm) cup caused essentially every point in the sample to be shocked to a point above the predicted Hugoniot stress, then released to the predicted stress, then finally further released by a wave coming forward from the foam/sample interface. This is illustrated for test TFA-8 in Figure 3.2; test TFA-9 shows similar wave interactions.

Figure 3.2: Test TFA-8 Wave Interactions

Hugoniot calculations for those tests assuming very thick cups give the values presented in Table 3.5.

Table 3.5. Hugoniot conditions for U20bd#1 2198' Tuff experiments with tantalum buffers
(slow cup ringdown approximation)

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Hugoniot Conditions			Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
				Particle Vel km/sec	Pressure GPa	ρ gm/cm ³			
8	1.8040	0.3359	1.830	1.700	16.085	2.727	5.1699	1.4898	0.3667
9	2.2650	0.4421	1.851	2.108	21.384	3.008	5.4798	1.6253	0.3324

For those tests, I believe that the best Hugoniot values lie between the above values, and have chosen the pressure and particle velocity values to lie 1/3 of the way from the "rung up" values (reported first above) to the "thick cup" values. Other values are computed from these. The results are:

Table 3.6. Hugoniot conditions for U20bd#1 2198' Tuff experiments with tantalum buffers
(“Averaged” aluminum cup ringdown treatment)

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Hugoniot Conditions					Specific Vol cm ³ /gm
				Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
8	1.8040	0.3404	1.830	1.625	13.950	2.800	4.6910	1.5300	0.3572
9	2.2650	0.4436	1.851	2.026	18.564	3.133	4.9502	1.6928	0.3191

It is nevertheless clear from these difficulties in identifying “the” Hugoniot state reached in these samples (with tantalum buffers and aluminum cups) that such a geometry is not ideal. What can improve this experiment? Making the aluminum cup as thin as possible improves the interaction. Figure 3.3 presents the same experiment as does Figure 3.2, except that a thinner aluminum cup is used (1 mm thick vs. 2.004 in Figure 3.2). This decreases the amount of sample subject to a succession of stress states prior to the arrival of the main release. Figure 3.4 shows the calculated wave interactions for test TFA-6, which uses a fairly thin aluminum cup.

Using no cup avoids these difficulties, but is not an option if the sample must be protected from vacuum (e.g. to avoid water loss). One other option is to make the cup as well as the buffer from tantalum. This is predicted to eliminate the “ringing” problem, protect the sample from contact with vacuum and still achieve much higher pressures for a given impact velocity than aluminum buffers and cups (by a factor of approximately 1.4 for typical rock materials with densities around 2 gm/cm³). It is not useful for impact velocities above about 4.6 - 5.2 km/sec, however, because partial to complete melting induced in the tantalum in symmetric impacts at such velocities. Hence, for water-saturated samples to be compressed to the megabar range, it is best to use a tantalum buffer with as thin an aluminum cup as practical.

These Hugoniot data are plotted, together with data for the U20bb SH-1 1965' tuff (see Section 4) in Figures 3.5 and 3.6.

Uncertainties in these Hugoniot data have been calculated by methods described in Section 2.1.3; for the aluminum and lithium fluoride buffer experiments, the contributing factors are summarized in Figure 2.4. To summarize; the primary contributing uncertainties for the Hugoniot quantities are plateau velocity (for stress); projectile velocity (for particle velocity), and a combination of plateau velocity and projectile velocity (shock velocity and density).

Figure 3.3 Test TFA-8 wave interactions (1 mm aluminum cup supposed)

Figure 3.4. Test TFA-6 wave interactions

Figure 3.5: Shock velocity/particle velocity fits for U20bd#1 2198' and U20bb SH-1 1965' tuffs (older data for comparison)

Figure 3.6: Pressure-density data for U20bd#1 2198' and U20bb SH-1 1965' tuffs
(older data for comparison)

3.3.3 Release paths

These tests have been modeled with the wavecode WONDY V and parameters varied to extract information about the release behavior of this material. Details of the method are discussed in Section 2.1.1; we reproduce the critical equation here for reference:

$$(-V_0) \left. \frac{\partial \sigma}{\partial V} \right|_S \equiv B_S = B_0 (1 + \chi B_1 + \chi^2 B_2 + \chi^3 B_3) \quad (\text{where } \chi \equiv \frac{c}{\sigma_H} - 1) \quad (\text{Eq. 3.1}).$$

The resulting modelings of the wave profiles are shown in Figs. 3.8 and 3.9 for the aluminum and lithium fluoride buffer experiments, as well as for TFA-6 (the highest-velocity tantalum buffer experiment). Where necessary, gaps have been introduced into the models and adjusted until a correct fit is made to the gap signature (e.g. 1.3 - 1.5 μsec after impact for test TFA-1).

Associated release results are summarized in Figure 3.10, where the highest-pressure release has been eliminated to allow the use of a scale for properly representing the other releases. All of the releases are plotted in Figure 3.11 pressure/volume space, as well as the lower-pressure releases in spaces involving specific energy. The specific energy has been calculated by integrating σdV along the release trajectory. These release paths are tabulated in filtered form in Appendix A.

Sound velocities computed from these releases are shown in Figure 3.7. These velocities are calculated two ways: (1) From the WONDY modeling of the tuff, using the equation $C_b = (\rho_0/\rho) \sqrt{B_0/\rho_0}$ (see Section 2.1.1); and (2) from explicit position/time calculations (see Ref. 11). The interesting point from these results is that the release is hysteretic (higher sound velocity than release $\equiv$ Hugoniot would give) for pressures up to 40-45 GPa, and normal at higher Hugoniot pressures. We associate this with the relatively decreasing importance of strength and the $^{IV}\text{Si} \rightarrow ^{VI}\text{Si}$ transition.

Figure 3.7. Sound velocities at the Hugoniot state for Tuff A.

Figure 3.8. WONDY Velocity history models for TFA 1, 2, 3, 4 (B_0 in units of 10 GPa; other B_i unitless)

Figure 3.9 WONDY Velocity history models for TFA 5, 6, 7, 10 (B_0 in units of 10 GPa; other B_i unitless)

Figure 3.10. Inferred Releases for U20bd#1 2198' Tuff Tests (Highest-pressure test eliminated for clarity; lower-pressure tantalum buffer experiments eliminated for reasons discussed in text).

Figure 3.11. Inferred Releases for U20bd#1 2198' Tuff Tests (Highest-pressure test eliminated for clarity except in P/V plot; lower-pressure tantalum buffer experiments eliminated for reasons discussed in text).

The Hugoniot values for the tantalum-buffered experiments are ambiguous, as discussed in Section 3.3.2. How does this affect the interpretation of the release profiles? Specifically, since different sections of the samples were subjected to different pressure histories (with position-dependant peak stresses; see Figs. 3.2 - 3.4), how do we deconvolute the results of the several experiments we seem to be performing on the sample?

The direct answer is that the deconvolution is not practical. However, we are definitely able to construct a compression/release model and assess whether it reproduces the data. This model is not unique. Fig. 3.12 shows the fit and corresponding pressure-density Hugoniot and release properties of two candidate models.

Fig. 3.12. Two WONDY simulations of test TFA6

“Thin Cup” uses Hugoniot calculated assuming Al cup thin, giving complete ringdown
 “ $2/3 \times (\text{Thin Cup} + 1/2 \text{ Thick Cup})$ ” uses Hugoniot which is a weighted average between thin cup and Hugoniot calculated assuming no ringdown occurred.

These release results may be expressed systematically, as mentioned in Section 2.1.1 and discussed in detail for MJ-2 grout in reference 12. Recall that this method requires converting the B_i coefficients to moduli and their derivatives along the release (experiment by experiment). The axial release modulus is, $K \equiv -V(\partial\sigma/\partial V)|_S$, and its first three stress derivatives are $K^{(n)} \equiv (\partial^n K/\partial\sigma^n)|_S$ ("S" referring to the - approximately - isentropic nature of the release). The term "axial" refers to the uniaxial strain nature of the experiment. Using the methods of Reference 24, we calculate a family of values for the moduli and derivatives as plotted in Figure 3.13. Also plotted in Figure 3.13 are three sets of curves. One, calculated from the Hugoniot, assumes that the release will lie along the Hugoniot. The Hugoniot slope is given by McQueen et al.²³ as:

$$\frac{dP_H}{d\eta} = (\rho_o C_o^2 \eta) / (1 - s\eta^2) \quad (\text{where } \eta \equiv 1 - \rho_0 V). \quad (\text{Eq. 3.2})$$

The second is calculated from a Mie-Grüneisen equation of state²³ using the Hugoniot as given along with the assumption that the Grüneisen parameter $\gamma \equiv V(\delta P/\delta E)|_V$ has a value of 1. Finally, the third set of curves is a piecewise fit to the calculated modulus or derivative values. The piecewise fits are given in the following table:

Table 3.7. Systematic Modulus Fits to Tuff A Releases

Modulus	Fit Curve	Pressure Range (GPa)
K_H (GPa)	$K_H = 10.0 \text{ GPa} + 5.889 P_H$ $K_H = 165.43 \text{ GPa} + 2.435 P_H$ $K_H = -169.73 \text{ GPa} + 5.748 P_H$	$0 \leq P_H < 45$ $45 \leq P_H < 101.7$ $101.7 \leq P_H$
K'_H	$K'_H = 18.0 - 0.15556 P_H \text{ GPa}^{-1}$ $K'_H = 14.092 - 0.0687 P_H \text{ GPa}^{-1}$ $K'_H = 2.5256 + 0.04562 P_H \text{ GPa}^{-1}$	$0 \leq P_H < 45$ $45 \leq P_H < 101.7$ $101.7 \leq P_H$
K''_H (GPa ⁻¹)	$K''_H = 11.328 \text{ GPa}^{-1}$ $K''_H = (29.5 - 0.15375 P_H \text{ GPa}^{-1})/P_H$	$0 \leq P_H < 2.5694$ $2.5694 \leq P_H$
K'''_H (GPa ⁻²)	$K'''_H = 2.0 \text{ GPa}^{-2}$ $K'''_H = (13.217 - 0.00534 P_H \text{ GPa}^{-1})/P_H^2$	$0 \leq P_H < 2.5694$ $2.5694 \leq P_H$

The release curves are then calculated according to Equation (2.7) from Furnish²⁴, reproduced here as Eq. 3.3:

$$V(P) = V(0) \times \int_0^{P_H} \frac{d\xi}{B_s(\xi)} = V(P_H) \times \exp \left[\int_{(P-P_H)}^0 \frac{d\xi}{K_s(\xi)} \right] \quad (\text{Eq. 3.3})$$

$$= V(P_H) \times \exp \left[\int_{(P-P_H)}^0 \frac{d\xi}{K_s(P_H) + \xi K'_s(P_H) + \frac{1}{2} \xi^2 K''_s(P_H) + \frac{1}{6} \xi^3 K'''_s(P_H)} \right]$$

Figure 3.13. Axial Moduli and Pressure Derivatives Along Release for Tuff A

The match between these systematically fit release curves and the releases derived shot-by-shot is given in Figure 3.14. Note that the shot-by-shot Hugoniot points disagree slightly with the starting points of the systematic releases for the intermediate pressure regions, while the release slopes in general show good agreement between the shot-by-shot calculations and the systematically fit releases. The Hugoniot disagreement is due to the use of the fit U_s/U_p Hugoniot in determining the starting points for the systematically calculated releases.

Figure 3.14. Tuff A releases from modulus fits ("systematic") vs. shot-by-shot

How well these experiments constrain the Grüneisen parameter γ ? Briefly, they do not constrain it well. This was mentioned in Section 2.1.2. It is useful to examine the highest-pressure test, which is most sensitive to thermal effects. As shown in Figure 3.15, adjusting the Grüneisen parameter gives significant changes in the time of the release. A "best fit" value for γ may be chosen. However, adjusting the description of the Hugoniot in a way that fits the point in question and is within the uncertainties of the family of the data changes this best-fit γ by about 0.5; the value of γ is likely to be 0.71 ± 0.2 (30%; we loosely take this as 1σ variation). This experiment is a poor design for choosing the Grüneisen γ because it does not measure the Hugoniot and release curves near the Hugoniot state except as a small difference of large quantities.

Figure 3.15. Effects of adjusting the Grüneisen parameter g on the velocity profiles and on the P/ρ release paths for two choices of Hugoniot (case of test TFA-6).

4.0 Tuff B (U20bb SH-1) - Dynamic Experiments

4.1 Material studied

A second set of tuff samples, taken from NTS bore U20bb SH-1 (1965.2 - 1965.8 foot depth), was characterized for dynamic properties. This material was significantly denser than Tuff A, although it was also a zeolitized, nearly water-saturated tuff. Densities decreased with depth, possibly abruptly, from 2.01 - 2.05 gm/cm³ (1720 - 1750 foot depth) to 1.96 - 1.99 gm/cm³ (1960 - 1980 foot depth); our samples are from the latter depth range²⁰. Porosity increased (26 - 30% changing to 32 - 35%) over the same range. Grain densities were 2.45 - 2.48 gm/cm³ throughout. Sample densities recorded for the present series of experiments varied from 2.000 gm/cm³ to 2.025 gm/cm³ (details in Table 4.1). Water saturation was nominally²⁹ 99% or more, based on Terra Tek measurements of adjacent cores samples (1961 feet and 1966 feet).

Phenocryst sizes ranged to 3 mm (weathered feldspar crystals), with numerous smaller phenocrysts contained in a light-colored groundmass. We felt that our experiments were able to measure average properties of the samples based on the relatively small variations in the velocity plateau and shot-to-shot consistency. The material machined well. As with Tuff A, we requested that the samples be kept water-saturated during machining and that tap water without oils or rust inhibitors be used as a coolant. Tolerances were the same as for Tuff A (section 3.1).

4.2 Experiments conducted

The suite of experiments conducted on Tuff B may be described as a short version of the suite conducted on Tuff A. Five experiments were performed, all in the reverse-ballistic geometry, utilizing the 4 inch compressed-gas gun, the 89 mm powder gun and the 28 mm 2-stage light gas gun at the Sandia STAR Facility. As with all of the tuffs documented in this report, aluminum cups were used to prevent dewatering by the gun vacuum. Parameters are listed in Table 4.1.

Experimental conditions were chosen to produce Hugoniot stresses in the range 3 - 45 GPa. Historically, the powder gun facility was available to us long before the two-stage light gas gun; programmatic pressures thus made a tantalum buffer test on the powder gun worthwhile. Using such a buffer allowed us to reach a stress level above that achievable with an aluminum buffer on the powder gun, although at the expense of achieving a single shock state in the material (see Section 3.3.2).

4.3 Dynamical material properties results

4.3.1 Velocity profiles observed

The velocity profiles observed are presented in Figure 4.1, broken into several plots according to the gun system and buffers used. Only Test TFB-4 showed any evidence of a gap forming between the sample and the cup (estimated as 0.1 mm thick).

Table 4.1. Impact experiments conducted to characterize Tuff B (U20bb SH-1 1965')

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density ¹ (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ² Thick (mm)	Velocity ³ Per Fringe (km/sec)
TFB 1 ⁴	Powder	1.383	0.320	6.0	Tuff	2.000	5.994	1.997	Al	1.486	31.622	0.094795
TFB 2 ⁴	Powder	2.23	0.640	5.02	Tuff	2.010	6.009	2.014	Al	1.493	31.832	0.094795
TFB 3	Powder	2.211	0.540	4.958	Tuff	2.001	6.007	2.017	Ta	6.346	25.569	0.094795
TFB 4	2-Stage	5.32	0.763	2.995	Tuff	1.995	4.017	1.022	Al	1.366	25.411	0.42756
TFB 5	Gas	0.605	0.320	6.0	Tuff	2.025	6.017	2.045	Al	1.450	31.747	0.05599

Notes:

¹Nominal densities; 0.320 = 20 lbs/ft³, 0.640 = 40 lb/ft³; 0.763 = "syntactic" (glass microballoon foam; Sylgard 184 GMB Syntactic)

²Window is composed of lithium fluoride throughout this suite of tests

³Velocity per fringe (VPF) corresponds to a setting of the VISAR

⁴Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment.

Figure 4.1. Velocity profiles from impact tests on U20bb SH-1 1965' Tuff

4.3.2 Hugoniot conditions

For the aluminum buffer experiments, the following Hugoniot values were calculated:

Table 4.2. Hugoniot conditions for U20bb SH-1 1965' Tuff experiments with aluminum buffers

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel. km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
TFB1	1.38(1)	0.492(4)	2.000(5)	0.90(1)	7.8(1)	2.53(3)	4.30(10)	1.266	0.395(4)
TFB2	2.23(2)	0.803(5)	2.010(5)	1.45(2)	13.6(2)	2.91(5)	4.69(10)	1.446	0.344(6)
TFB4	5.32	2.077	1.995	3.28	44.8	3.84	6.84	1.925	0.260
TFB5	0.605(7)	0.199(6)	2.025(5)	0.41(1)	2.9(1)	2.29(2)	3.51(18)	1.133	0.436(4)

At a much later time, these values were recalculated including effects of the 6061-T6 aluminum strength, using the model $Y = Y_0(1+Y_1\varepsilon)(1-\varepsilon/Y_2)$ for the yield strength Y , where $Y_0 = 3$ kb (initial yield strength), $Y_1 = 0$ (strain hardening) and $Y_2 = 11.8$ MJ/kg (thermal softening). Poisson's ratio was taken as 0.333. This gave the following slightly revised values (all revisions well within uncertainty bounds):

Table 4.3. Hugoniot conditions for U20bb SH-1 1965' Tuff experiments with aluminum buffers (aluminum strength included)

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel. km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
TFB1	1.38	0.492	2.000	0.90	7.7	2.53	4.29	1.266	0.395
TFB2	2.23	0.803	2.010	1.44	13.6	2.91	4.68	1.446	0.344
TFB4	5.32	2.077	1.995	3.28	44.8	3.84	6.84	1.925	0.260
TFB5	0.605	0.199	2.025	0.41	2.9	2.29	3.48	1.133	0.436

Revising the aluminum EOS to match the Marsh¹ Hugoniot data for 6061 ($C_0 = 5.33$, $S = 1.344$, $\rho_0 = 2.703$), and including the aluminum strength effects, gives essentially the same results (shock velocities lowered very slightly; to 4.28, 4.68, 6.83 and 3.47, respectively). All of these changes are well within the error bounds originally calculated; in fact, they are invisible to the precision shown.

As discussed in Section 3.3.2, the tantalum-buffer experiment is more difficult to interpret as producing a single Hugoniot state, due to the "ringing" that occurs in the aluminum cup. For the purposes of the present section, we may use the same "best value" convention as

before ("best" is $2/3 \cdot \text{thin} + 1/3 \cdot \text{thick}$). The section of the plateau read depends on which approximation is used; for the thin-cup, the entire plateau is used, while for the thick cup, only the section of that plateau preceding a minor "step" up is used (here difficult to isolate; take as about 2.6 μsec from wavecode predictions). Thus, the thin-cup, thick cup and "best" Hugoniot values are:

Table 4.4. Hugoniot conditions for U20bb SH-1 1965' Tuff experiment with tantalum buffer TFB-3 (aluminum and tantalum strength included)

← Hugoniot Conditions →									
Shot Model	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
Thin	2.21	0.486	2.000	1.903	18.95	3.24	4.98	1.618	0.309
Thick	2.21	0.466	2.000	2.025	21.97	3.19	5.42	1.596	0.313
Best	2.21	0.466	2.000	1.944	19.96	3.22	5.13	1.609	0.311

The Hugoniot values for this material (including the "best" value for TFB 3) are plotted against the results for earlier tests of Tuff A and other materials in Figures 3.5 and 3.6 (preceding chapter). Uncertainties for TFB3 were taken as just large enough to bracket the extreme cases shown in Table 4.4.

4.3.3 Release paths

Following the procedure described in Section 3.3.3, release paths were inferred for the Tuff B tests by modeling with WONDY V.

The aluminum-buffer experiments were matched well by the wavecode, as shown in Figure 4.2. As with the Tuff A tests, the lower-velocity tests gave releases down to a lower fraction of the plateau velocity (corresponding to a lower fraction of the Hugoniot pressure) than did the higher-velocity tests. The extreme case is TFB 5 (605 m/sec impact velocity) opposed to TFB 4 (5320 m/sec impact velocity). The resulting releases are shown in pressure/particle velocity and pressure/volume space in Figure 4.3 (and tabulated in edited form in Appendix A). They are slightly more hysteretic than the corresponding Tuff A releases (Figure 3.10), although the difference is probably not significant.

The four releases for aluminum-buffer experiments (corresponding to the bottom three points and the top point) are consistent with the Hugoniot points. This is a nontrivial matter because the wavecode calculation begins with an assumed linear U_s/U_p relationship, but not with a specific Hugoniot point (although the U_s/U_p relationship is tailored to fit the observed Hugoniot point).

The tantalum experiment does not show this consistency. As discussed in the previous section, it is problematic to assign a single Hugoniot state for this material. Figure 4.4 illustrates several alternative possibilities, and is analogous to Figure 3.12.

Figure 4.2. WONDY hydrocode matches to observed velocity profiles for Tuff B (B_0 in units of 10 GPa; other B_i unitless)

Figure 4.3. Release paths for Tuff B (U20bb SH-1 1965') tests

Figure 4.4. Thin- and thick-cup interpretations of Tuff B tantalum-buffer experiment

In addition, the release is not as well constrained in test TFB-3 as in the aluminum buffered experiments. Experiments with a high-impedance buffer generally spall the buffer (or the sample, if appropriately designed). This spall reduces the sensitivity of the velocity profile to the sample release properties, and is a disadvantage to this configuration.

5.0 Tuff C (U12p.04 IH20) - Dynamic Experiments

5.1 Material studied

“Tuff C” is a zeolitized tuff from near the middle of the Paintbrush Tuff formation (MC-1 unit), a Tertiary unit which consists of repetitive sequences of ash-fall tuff, reworked ash-fall tuff and tuffaceous sandstone³¹. Our samples were extracted from hole U12p.04 IH20 (144.4 - 145.8' interval, which is above the water table). Densities ranged from 1.874 to 1.889 gm/cm³. Materials characterization studies were made on materials from nearby bores; samples of comparable density to those used in this study had porosities of 35 - 37% and were 97 - 100% water-saturated. Sample textures resembled those of Tuffs A and B.

As with the experiments on Tuffs A and B, water saturation was maintained during all stages of sample preparation and testing until impact. Samples were stored underwater (tap water) and not allowed to dry out.

5.2 Experiments conducted

The test matrix is summarized in Table 5.1. Five experiments conducted were designed to span the pressure range of 4.5 to 55 GPa. Reverse-ballistic aluminum buffer experiments were chosen to optimize Hugoniot and release data. Forward-ballistic experiments were not included in this suite of experiments because of the anticipated low strength of this material (10 - 40 MPa range anticipated) relative to the stress levels of interest.

5.3 Dynamic material properties results

5.3.1 Observed velocity profiles

The velocity profiles observed for these tests are shown in Figure 5.1.

Both of the powder gun tests (the lowest-velocity impacts of the series) show the expected features. The plateaus are especially smooth for tuff samples, probably corresponding to fairly uniform material. An apparent rarefaction shock at the end of the release deserves comment. I do not feel this is a physical feature of the velocity history experienced by the reflecting interface; it occurs as the intensity of the light beam received by the velocity interferometer abruptly goes to zero.

The profiles associated with the two-stage light gas gun tests all show gap signatures (due to an apparent gap between the sample and the cup). More unfortunately, however, the release signatures (1 - 1.4 μ sec) are quite abbreviated. It is unclear why; although these tests used a syntactic foam of the relatively high density about 0.7 gm/cm³, the release is predicted to be longer. This will be discussed more in Section 5.3.2. Finally, although the Hugoniot plateaus (0.4 - ~1.1 μ sec) for TFC4 and TFC5 are fairly level, the plateau for

Table 5.1. Impact experiments conducted to characterize Tuff C (U12p.04 IH 20 145')

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ¹ Thick (mm)	Velocity ³ Per Fringe (km/sec)	Gap ⁴ Width (mm)
TFC 1	Powder	0.986	0.580	10.172	Tuff	1.874	5.9862	1.975	Al	0.995	25.599	0.15528	N. A.
TFC 2 ²	Powder	2.203	0.589	10.153	Tuff	1.8744	6.0092	1.9674	Al	1.0074	25.615	0.15528	0.060
TFC 3	2-Stage	4.363	0.770	3.0224	Tuff	1.878	4.0124	1.0059	Al	0.555	25.457	0.2704	N.A.
TFC 4 ²	2-Stage	4.984	0.762	2.9916	Tuff	1.889	3.9842	0.9948	Al	0.5304	25.454	0.35295	0.110
TFC 5 ²	2-Stage	6.219	0.771	3.0032	Tuff	1.882	4.0131	1.0052	Al	0.5172	12.770	0.4297	0.3645

Notes:

¹Window is composed of lithium fluoride²Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment; calculated width in last column.³Velocity per fringe (VPF) corresponds to a setting of the VISAR⁴Gaps width and existence were determined after-the-fact during data reduction. These gaps, which occasionally form between the sample and the cup, are not emplaced deliberately and somewhat increase experimental Hugoniot and release uncertainties. This data included to facilitate later modeling of these tests.

Figure 5.1. Velocity profiles for Tuff C (U12p.04 IH20 144.4 - 145.8')

TFC 3 has a distinct step in the middle. Since the construction of the shots was similar, this probably corresponds to variabilities in the sample.

5.3.2 Hugoniot and release properties

Hugoniot states were computed as described in Section 2.1.1. The plateau velocities used in this calculation are shown as fit lines in Figure 5.1. These states, and the data from which they were calculated, are reported in Table 5.2 and plotted in Figure 5.2 (together with release curves).

In all of these spaces, the Hugoniot of this material appears to be very similar to that of Tuffs A and B. This is sensible in view of the density (1.88 gm/cm^3) of this material being intermediate between that of Tuff A ($1.84 - 1.88 \text{ gm/cm}^3$) and Tuff B (2.00 gm/cm^3).

Figure 5.2. Hugoniot and release properties of Tuff C (U12p.04 IH20 144.4 - 145.8') (properties of Tuffs A and B shown for comparison)

Table 5.2. Hugoniot conditions for Tuff C (U12p.04 IH 20 145')

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
1	0.986	0.314	1.874	0.681	4.76	2.292	3.732	1.223	0.4362
2	2.203	0.745	1.874	1.477	12.49	2.786	4.513	1.486	0.3589
3	4.363	1.586	1.878	2.813	31.48	3.558	5.958	1.895	0.2811
4	4.984	1.857	1.889	3.169	38.66	3.709	6.458	1.963	0.2696
5	6.219	2.409	1.882	3.860	54.94	3.844	7.562	2.043	0.2601

Release paths are calculated as before. WONDY fits to the velocity profiles are shown in Figure 5.3. for all tests except TFC3. For the powder gun tests, the releases are only matched to the beginning of the terminal step; i.e. to the end of the credible data. Among the two-stage tests, TFC5 gave a clean matching. TFC4 only yielded the beginning of the

Figure 5.3. WONDY modeling of the Tuff C (U12p.04 IH20 144.4 - 145.8') tests except for TFC3

release curve. Since a time-of-arrival of the release and an initial slope could be isolated, the initial slope and curvature of the release trajectory in pressure-volume space could be determined, but the path could not be reliably drawn below about 80% of the Hugoniot stress.

Test TFC3 was even more problematic because of the difficulty of determining a meaningful Hugoniot state. Figure 5.4 illustrates two fits which may be applied, depending on whether the Hugoniot plateau level is taken as the average velocity over the entire interval (labeled TFC3) or some average value for the last section of the plateau (plot labeled TFC3a). The release path for TFC3a is slightly more hysteretic (the release velocity is higher). The case TFC3a is problematic, however, because it is based on the assumption that the entire sample is represented by the final segment of the Hugoniot plateau. The model labeled TFC3 in Figure 5.4 is more self-consistent, and is taken here as "correct."

Figure 5.4 Alternative WONDY modelings of Tuff C test TFC3

While the Hugoniot of this material is nearly that of Tuffs A and B, the releases do not appear to be hysteretic. This matches the behavior of Tuff A, but contrasts with the behavior of Tuff B.

6.0 Tuffs D (U12n 24 HP #3) and E (U12n 24 GI #1) Dynamic Experiments

6.1 Materials studied

Two tuffs were studied in this suite of experiments. Both were taken from units of the Thirsty Canyon group, a Tertiary unit of a high-silica sodium-rich rhyolite (Pahute Mesa and Rock Wash members) and a comenditic rhyolite ash-flow tuff (Trail Ridge member). Units labels provided³² in the area of interest are 4J (higher density, more recent member) and 4H (lower density, older member).

The samples tested are designated U12N 24 HP#3 36' (sample of 4J member with density 2.04) and U12N 24 GI#1 (sample of 4H member with density 1.85). The 4J sample provided was taken from a location about 4.5 feet from the contact with 4H³². Rock samples provided as options for testing were extremely variable, in density, texture and overall mineralogy. The 4J sample used was chosen on the basis of its density (2.00 - 2.05 gm/cm³ desired to correspond to bulk properties in the field), competence (some of the cores were in very poor condition as received), ability to provide enough material for a complete testing program, and lack of gross heterogeneities (> 1 cm) which would cause gas-gun data to be suspect. On the whole, these samples were less competent than the other materials tested.

Materials property data (porosity, saturation, grain density) are not available at present. The samples were taken from above the water table, but were treated as saturated.

6.2 Experiments conducted

An extensive suite of experiments was undertaken to provide loading, Hugoniot and release information for these materials. The 4H sample was provided first, and testing began with this material over the 1.5 - 8 GPa level using a reverse-ballistic configuration. Upon receipt of 4J samples, a series of reverse-ballistic experiments covering the stress range of 4 to 57 GPa was performed, along with three forward-ballistic experiments covering the stress range of 1.7 to 5.5 GPa. At a later time, we were asked to perform two supplemental tests in the 20 - 25 GPa range; we performed three, of which two gave quality results (the third was performed with a sample in poor condition to document the operational status of new diagnostic equipment).

This suite of tests is summarized in Table 6.1. It includes a total of 13 tests, using the four inch compressed gas gun, the 89 mm powder gun and the 28 mm two-stage light gas gun.

Table 6.1. Impact experiments conducted to characterize Tuffs D and E (U12n.24 HP3 36' and U12n.24 GI#1)
(see following page for notes)

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID ⁸	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material ¹	Buffer Thick (mm)	Window ² Thick (mm)	Velocity ³ Per Fringe (km/sec)
TFD4	Gas	0.852	0.2895	5.006	"New" Tuff	1.995	6.027	2.609	Al	1.638	31.836	0.055995
TFD5	Powder	1.525	0.6247	5.031	"New" Tuff	1.977	5.998	1.998	Al	1.612	25.581	0.197508
TFE1	Gas	0.416	0.289	4.981	"Old" Tuff	1.811	8.037	2.591	Al	1.601	31.830	0.055995
TFD6	Powder	1.824	0.6224	5.032	"New" Tuff	1.981	5.999	1.908	Al	1.605	25.523	0.27044
TFD7	Powder	2.251	0.617	5.043	"New" Tuff	1.996	5.998	1.992	Al	1.604	25.586	0.27044
TFD8	2-Stage	4.414	0.776	2.970	"New" Tuff	2.048	3.988	0.988	Al	1.439	19.281	0.273642
TFD9	2-Stage	5.868	~0.78	3.039	"New" Tuff ⁶	2.032	3.983	1.017	Al	1.411	25.413	0.427558
TFD10	2-Stage	6.455	0.776	3.025	"New" Tuff	1.850	4.018	1.008	Al	1.456	18.925	0.427558
TFE2	Gas	0.843	0.292	5.092	"Old" Tuff	1.773	7.980	2.591	Al	1.619	25.626	0.55995
TFE3	Powder	1.500	0.626	5.040	"Old" Tuff	1.823	7.992	2.642	Al	1.616	25.636	0.1975083
TFD11	2-Stage	~3.63 ⁹	0.779	2.252	"New" Tuff	2.002	4.030	0.624	Al	1.513	19.733	0.3098
TFD12	2-Stage	2.97	0.779	2.245	"New" Tuff	2.026	4.016	0.607	Al	1.527	19.153	0.3098
TFD13	2-Stage	2.92 ¹⁰	0.776	2.243	"New" Tuff	2.003	4.041	0.604	Al	1.153	19.150	0.3098
Shot #	Gun Facility	Impact Velocity (km/sec)	Flyer Plate Thick ⁴ (mm)	Cup Thick (mm)	Sample ID ⁵	Sample Density (gm/cm ³)	Sample Thick (mm)			Buffer ⁵ Thick (mm)	Window ⁵ Thick (mm)	Velocity Per Fringe (km/sec)
TFD1	Gas	0.405	12.304	2.029	"New" Tuff	1.993	8.015			3.010	26.084	0.07240
TFD2	Gas ⁷	0.850	12.581	2.047	"New" Tuff	2.000	7.992			2.990	25.982	0.22652
TFD3	Powder	1.062	12.585	2.052	"New" Tuff	1.985	7.997			3.069	25.918	0.19876

6.3 Dynamic property results

6.3.1 Observed velocity profiles

The reverse-ballistic results here are divided according to velocity regime for clarity. Figure 6.1 presents the powder- and gas-gun results, Figure 6.2 presents the two-stage results, and Figure 6.3 shows the forward-ballistic test results.

As a reminder, these profiles represent the particle velocity histories at the interface between the buffer and the lithium fluoride window (see Figure 2.1) for reverse-ballistic tests, and between the sample or buffer and the window (see Figure 2.10) for forward-ballistic tests. They are also displayed separately in Figures 6.11 - 6.13 (Section 6.3.2).

All seven of the powder gun and compressed gas gun tests showed clean Hugoniot plateau levels. Gaps between the sample and the cup developed in all of these except for TFD 5. Widths of the gaps were determined from the velocity signatures, and are listed in Figures 6.11 - 6.13. The four tests on Tuff D (4J) all showed clean release signatures. The three tests on Tuff E (4H) did not. These three samples were inadvertently cut to ~8 mm thickness instead of the required ~6 mm, and the error was not recognized as a problem until after the tests were completed. The extra thickness added enough additional time prior to the release arrival at the window that only test TFE3 among the three Tuff E tests recorded a release signature, and that release was only recorded down to about 80% of the plateau level in the velocity profile (vs. 35% desired for the Tuff D tests).

All six of the two-stage light gas gun tests were conducted with the Tuff D (4J) samples. Five of these tests (all except for TFD13) yielded quality results for both Hugoniot and release signatures, although they all showed cup/sample gap signatures as well. TFD 12 showed a slight elevation of the Hugoniot plateau level shortly prior to the release arrival.

Notes for Table 6.1:

¹Standard aluminum used is 6061-T6 throughout assembly.

²Window is composed of lithium fluoride for reverse-ballistic tests in this study.

³Velocity per fringe (VPF) corresponds to a setting of the VISAR. Assuming $\Delta v/v=0.28$ (LiF), 0.00 (PMMA, test TFD3), -0.01 (PMMA, tests TFD1, TFD2)

⁴In the forward-ballistic tests, the flyer plate is backed by a void (gas gun) and a void with a phenolic support tube (31.75mm ID, 44.45 mm OD) (powder gun).

⁵Buffer and window are composed of PMMA for forward-ballistic tests in this study.

⁶Sample for TFD9 (repeat) was slightly damaged; radius of 0.47" reduced to 0.45" by missing material.

⁷Test TFD2 uses the SPL (fiber-optic) VISAR.

⁸"New" Tuff is nominal density 2.04 (4J; U12N 24 HP 3 36'); "Old" Tuff is nominal density 1.85 (4H; U12N 24GI#1)

⁹Reading from Al/Al plateau; 1 Mavis coil malfunctioned, preventing interval velocity measurement.

¹⁰Experimental test (preceding TFD11 and 12); sample chosen was in poor condition. Also tilt was inordinately large (4.7°), possibly due to specimen imbalance.

Two-stage test TFD13, however, showed extremely poor tilt and produced a VISAR fringe record which was slightly ambiguous insofar as where to place velocity jumps. The tilt problem may be due to the poor condition of the sample used, and a possible consequent imbalance of the projectile. The sample used was the only sample of Tuff D still available after the preparation of samples for TFD 11 and 12. As mentioned in Section 6.2, this test was not intended as a data test.

The forward-ballistic tests have been timed from electronic fiducials, taking account of tilt, pin projections and such experimental factors. Velocity-per-fringe jumps have been added in places consistent with the VISAR record to provide physically sensible partial release points. As with the reverse-ballistic experiments, there is no significant ambiguity to the jumps chosen. We do not see evidence of precursors. The rounding of the top of the loading is consistent with the viscoelastic effects of PMMA deduced by Schuler and Nunziato²⁸, and does not seem to be due to properties of the tuff.

These forward-ballistic tests yielded slightly irregular plateaus (corresponding to partial release states for this experimental geometry). No precursors were observed, consistent with a very low elastic strength for this material.

Figure 6.1. Velocity profiles for TFD and TFE tests performed on powder and compressed-gas guns (solid lines for TFE tests)

Figure 6.2. Velocity profiles, 2-stage light gas gun Tuff D reverse-ballistic experiments

Figure 6.3. Forward-ballistics velocity profiles for Tuff D (U12N 24 HP#3 36')

6.3.2 Loading, Hugoniot and release properties

Hugoniot states were calculated for these materials according to the methods described in Section 2 (including aluminum strength), and are listed in Table 6.2 (for reverse-ballistic experiments) and Table 6.3 (for forward-ballistic experiments). These results are also plotted in Figures 6.4 through 6.9, together with release paths.

The highest-pressure test (TFD 10) is an outlier in several respects. Although it is a sample of the 4(J) material, it has an anomalously low density (1.85 gm/cm^3). Due to an extremely tight supply of sample material, we did not have an alternative sample available. Also, the instrumentation velocity of this projectile (6.22 km/sec) does not properly model the aluminum/aluminum peak height; a velocity of 6.46 km/sec is required to correctly model this peak. There is no ambiguity in the choice of how many fringe jumps to assign here; the velocity-per-fringe of 0.428 km/sec is large enough that other choices are unreasonable. As can be seen in Figures 6.8 and 6.6, the release results from this test are inconsistent with those of the other tests, as well as the Hugoniot results.

Disregarding test TFD 10, the results appear to be consistent with those for the other silicate materials. The $\text{IVSi} \rightarrow \text{VSi}$ (quartz - stishovite) transition region appears to begin at a particle velocity of about 1.9 - 2.0 km/sec (stress of 20 GPa). Releases in Tuff D are

slightly hysteretic to non hysteretic, as are those in Tuff E as we were able to measure them.

**Table 6.2. Hugoniot Conditions for Tuffs D and E
(U12n.24 HP3 36' and U12n.24 GI#1):
Reverse-Ballistic Tests**

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	Hugoniot Conditions						Specific Vol cm ³ /gm
			ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
TFD4	0.852(5)	0.282(6)	1.995(20)	0.57(1)	4.2(1)	2.37(3)	3.66(13)	1.186(10)	0.423(6)
TFD5	1.53(2)	0.537(10)	1.977(0)	1.00(2)	8.5(2)	2.57(4)	4.32(14)	1.30(2)	0.389(6)
TFD6	1.83(3)	0.65(1)	1.981(16)	1.18(3)	10.7(2)	2.67(7)	4.56(19)	1.35(3)	0.374(9)
TFD7	2.25(1)	0.825(8)	1.996(20)	1.44(1)	14.0(2)	2.84(5)	4.85(11)	1.42(2)	0.352(6)
TFD8	4.41(3)	1.73(2)	2.048(20)	2.72(3)	35.0(4)	3.60(11)	6.29(14)	1.76(5)	0.277(8)
TFD9	5.87(6)	2.37(2)	2.032(20)	3.55(6)	53.4(5)	3.89(16)	7.42(17)	1.92(7)	0.257(10)
TFD10	6.46(23)	2.48(1)	1.850(19)	4.02(24)	57.2(4)	3.88(44)	7.68(48)	2.10(24)	0.257(33)
TFD11	3.63	1.36	2.002	2.29	25.8	3.38	5.62	1.69	0.296
TFD12	2.97	1.13	2.026	1.86	20.5	3.08	5.45	1.52	0.325
TFD13	2.92	1.15	2.003	1.8	21	2.9	5.8	1.5	0.34
TFE 1	0.416(5)	0.115(4)	1.811(18)	0.300(7)	1.61(8)	2.02(3)	2.95(16)	1.113(8)	1.496(6)
TFE 2	0.843(4)	0.243(6)	1.773(18)	0.602(8)	3.6(1)	2.16(3)	3.34(13)	1.22(1)	0.462(7)
TFE 3	1.50(2)	0.491(5)	1.823(18)	1.02(2)	7.7(1)	2.41(5)	4.15(12)	1.32(2)	0.414(9)

**Table 6.3. Hugoniot and Partial Release Conditions for Tuff D
(U12n.24 HP3 36')
Forward-Ballistic Tests**

Shot #	Proj. Velocity km/sec	Plastic TOA μ sec	Hugoniot Conditions						Specific Vol cm ³ /gm
			ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
TFD 1	0.405(4)	3.880(8)	1.993(0)	0.27(1)	1.71(7)	2.18(1)	3.15(1)	1.095(5)	0.458(2)
TFD 2	0.850(8)	3.442(15)	2.000(0)	0.56(2)	3.94(17)	2.38(2)	3.51(2)	1.190(10)	0.420(3)
TFD 3	1.062(5)	3.118(20)	1.985(0)	0.68(2)	5.44(20)	2.39(2)	4.03(4)	1.203(9)	0.419(3)

Shot #	Partial Release Conditions				
	Plateau Velocity km/sec	Stress (GPa)	Particle Vel. km/sec	Release Slope GPa/(km/sec)	Hugoniot P/Up GPa/(km/sec)
TFD 1	0.338(4)	1.24(2)	0.338(4)	-7.4(3.2)	6.3(3)
TFD 2	0.704(6)	3.04(4)	0.704(6)	-6.2(2.6)	7.0(3)
TFD 3	0.846(8)	3.88(6)	0.846(8)	-9.4(3.1)	8.0(3)

Figure 6.4. U_s/U_p plot of Tuff D and Tuff E Hugoniot data.

Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Figure 6.5. U_s/U_p plot of Tuff D and Tuff E Hugoniot data (low-range detail).

Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Figure 6.6. P/ρ plot of Tuff D and Tuff E Hugoniot and release data. Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Figure 6.7. P/ρ plot of Tuff D and Tuff E Hugoniot and release data (low-range detail). Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Figure 6.8. P/U_p plot of Tuff D and Tuff E Hugoniot and release data. Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Figure 6.9. P/U_p plot of Tuff D and Tuff E Hugoniot and release data (low-range detail). Other silicate data (Tuffs A-C and HPNS12 and MJ-2 grouts) are shown for comparison.

Releases deduced from the forward-ballistic experiments (partial release point displayed in Table 6.3) are consistent with the pressure-particle velocity curved deduced from the reverse-ballistic experiments. They are similar in magnitude to the loading slopes in pressure-particle velocity space (the only space where one can define a release slope for these experiments).

The WONDY V wavecode matches to the observed reverse-ballistic velocity profiles are shown in Figures 6.10 through 6.12 (release reduction for Test TFD13 was not performed due to bad tilt and poor sample used).

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Figure 6.10. WONDY modeling of the Tuff D and Tuff E tests

Figure 6.11. WONDY modeling of the Tuff D and Tuff E tests (continued)

Figure 6.12. WONDY modeling of the Tuff D and Tuff E tests (continued)

7.0 Rhyolite (U19ba 2001') - Dynamic Experiments

7.1 Material studied

Samples of a partially devitrified rhyolite lava were provided for testing. This material was taken from hole U19ba at the 2001' level. Material characterizations at the 2009' and 2010' levels reveal a material composed of about 80% groundmass, 14% feldspar and 6% quartz, about 77% saturated, with a porosity of 19.1% and a density of 2.274 gm/cm^3 .

The raw cylinder provided for the present experiments was 1.75 inches in diameter and 3 15/16 inches long, with one crack 3/32" wide, 3/8" deep and 1" long and a second 1/16" wide, 1/8" deep and 1/2" long. The overall density was 2.32 gm/cm^3 , suggesting a lower porosity or higher saturation than the 2009' - 2010' material described above.

It is difficult to store a partially saturated sample without allowing either water uptake or water loss. The final average density of the five samples tested was 2.31 gm/cm^3 ; a slight amount of water may have been lost (0.45% of the initial mass of the samples). Densities of the individual samples varied from 2.2705 to 2.385, as may be seen in Table 7.1.

7.2 Experiments conducted

A series of five reverse-ballistic powder gun and gas gun tests was conducted to measure Hugoniot and release properties of these samples over the stress range 4 - 15 GPa. Parameters are summarized in Table 7.1. All tests used aluminum buffers and cups.

7.3 Dynamic material properties results

7.3.1 Observed velocity profiles

Profiles observed are shown in Figure 7.1. They are generally clean, with good release signatures. Four of the five tests appeared to be free of gaps between the sample and the cup; a gap of estimated width 0.032 mm appeared in the lowest-velocity test (RY 2).

7.3.2 Hugoniot and release properties

Hugoniot properties for this rhyolite are tabulated in Table 7.2, and plotted with release paths in Figures 7.2 and 7.3. The plots provide a comparison of the Hugoniot and release states of this material with a Grout A (a silicate grout of density approx. 2.41 gm/cm^3 - Section 8) and an epoxy/alumina composite (density approx. 2.3 gm/cm^3 - Section 9).

On the whole, responses of these three materials appear similar. The grout has a slightly higher shock impedance, while the epoxy/alumina has a less hysteretic release.

Figures 7.4 and 7.5 show the WONDY V wavecode match with the velocity profiles corresponding to the rhyolite releases shown in Figures 7.2 and 7.3.

Table 7.1. Impact experiments conducted to characterize Rhyolite (U19ba 2001')

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ¹ Thick (mm)	Velocity ³ Per Fringe (km/sec)
RY 1	Powder	1.578	0.273	6.395	Rhyolite	2.385	5.0624	1.994	Al	1.4362	26.998	0.1552833
RY 2	Gas	0.737	0.284	6.3376	Rhyolite	2.306	5.078	1.994	Al	1.4420	31.934	0.0559948
RY 3	Powder	1.167	0.284	9.933	Rhyolite	2.3244	5.060	2.0091	Al	1.474	31.835	0.1088897
RY 4	Powder	2.2164	0.526	4.937	Rhyolite	2.2705	5.049	2.000	Al	1.4706	25.130	0.1088897
RY 5	Powder	1.823	0.284	9.935	Rhyolite	2.2767	5.0638	1.9857	Al	1.4654	31.651	0.1088897

Notes:

¹Window is composed of lithium fluoride²Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment.³Velocity per fringe (VPF) corresponds to a setting of the VISAR

Figure 7.1. Velocity profiles for U19ba 2001' Rhyolite experiments

Figure 7.2. Shock velocity/particle velocity Hugoniot data for rhyolite (epoxy/alumina and Grout A for comparison)

Table 7.2. Hugoniot conditions for Rhyolite (U19ba 2001')

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle			Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
				Vel km/sec	Pressure GPa	ρ gm/cm ³			
1	1.5780	0.613	2.385	0.981	9.96	3.098	4.261	1.299	0.3228
2	0.7370	0.261	2.306	0.483	3.92	2.672	3.519	1.159	0.3742
3	1.1680	0.416	2.324	0.763	6.46	2.940	3.644	1.265	0.3401
4	2.2164	0.850	2.270	1.386	14.57	3.241	4.629	1.427	0.3085
5	1.8230	0.700	2.277	1.140	11.60	3.057	4.468	1.343	0.3271

Figure 7.3. Hugoniot and release data for rhyolite (epoxy/alumina and Grout A for comparison)

Figure 7.4. WONDY V modeling of rhyolite (U19ba 2001') dynamic tests (solid curve) vs. experiment (discrete points)

Figure 7.5. WONDY V modeling of rhyolite (U19ba 2001') dynamic tests (solid curve) vs. experiment (discrete points) (continued)

8.0 Epoxy-Alumina - Dynamic Experiments

8.1 Material studied

This test series was designed to characterize the dynamic response of a composite of epoxy (BY 5022 resin and HY-5022-1 hardener) and alumina (Al_2O_3) grains. Weight ratios of these materials were not provided, but appear to be governed by sedimentation of the alumina within the epoxy. The material provided was pure epoxy through the top ~10% of the total volume, with a uniform-appearing packing of epoxy grains elsewhere. Samples were prepared from sections of the provided material which were well within the alumina-rich region. There were many nearly spherical gas bubbles ranging from 1 mm to 4 mm in diameter. Samples which had obvious voids in the central 5-8 mm were not tested, but it was impossible to determine if there were internal voids in the same area of other samples.

The density of the samples provided was about 2.286 gm/cm^3 . During the series, however, we were provided additional samples³⁴ of density 2.476 gm/cm^3 . These were inserted into the testing sequence. The difference between the two batches of samples is apparently one of how well the just-mixed material is agitated or stirred to eliminate bubbles. A larger batch of material which was to have been represented by our samples had a density of approximately 2.35 gm/cm^3 , so interpolation is needed to define the properties of that material from the present results.

8.2 Experiments conducted

A series of five reverse-ballistic powder gun tests was conducted to measure Hugoniot and release properties of these samples over the stress range 4 - 27 GPa. Parameters are summarized in Table 8.1. Two of these tests used aluminum buffers, one used a copper buffer and the remaining two tests used tantalum buffers to achieve high Hugoniot stress levels.

8.3 Dynamic material properties results

8.3.1 Observed velocity profiles

Profiles observed are shown in Figure 8.1. On the whole, they are of inferior quality.

Test AEP 2 (aluminum buffer) produced an intelligible wave profile, although the Hugoniot plateau is slightly noisy. The other aluminum-buffer test, AEP 1, has a broad, shallow signature resembling that of a sample/cup gap, but very shallow and broad. This might be interpreted as a bubble or concentration of epoxy sparsely populated with higher-impedance alumina near the velocity sensor. The release structure of AEP 1 begins so gradually that it is extremely difficult to model. Such a slow release would require a very strongly curved release path in pressure/volume space.

Test AEP 4, which utilized a copper buffer, shows a distinct Hugoniot plateau, although it is followed by a large bump at 3 - 3.5 μsec , making release interpretation questionable.

Table 8.1. Impact experiments conducted to characterize Epoxy/Alumina

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ¹ Thick (mm)	Velocity ⁴ Per Fringe (km/sec)
AEP 1 ²	Gas	0.880	0.281	4.958	Epoxy/Al ₂ O ₃	2.2864	6.058	2.0058	Al	1.496	25.562	0.0559948
AEP 2 ^{2,3}	Powder	1.807	0.450	9.982	Epoxy/Al ₂ O ₃	2.4760	5.1498	2.027	Al	1.446	25.583	0.1088897
AEP 3	Powder	2.211	0.682	6.362	Epoxy/Al ₂ O ₃	2.2262	6.0614	2.002	Ta	6.354	25.529	0.1088897
AEP 4	Powder	2.073	0.700	6.3696	Epoxy/Al ₂ O ₃	2.2848	6.0464	2.0184	Cu	6.259	25.647	0.1088897
AEP 5 ³	Powder	2.270	0.587	10.012	Epoxy/Al ₂ O ₃	2.4760	5.1472	1.962	Ta	6.3488	25.549	0.1088897

Notes:

¹Window is composed of lithium fluoride²Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment.³Test samples for AEP2 and AEP5 provided by P. deCarli and substituted into the series in mid-run⁴Velocity per fringe (VPF) corresponds to a setting of the VISAR

Figure 8.1. Velocity profiles observed for alumina/epoxy impact experiments

Tests AEP 3 and 5 utilized tantalum buffers. The velocity profile for test AEP 5 is reasonable in view of the expected two-platform structure predicted by modeling the ringing of the aluminum cup (see Figures 3.2 - 3.4, Section 3.3.2). Test AEP 3, however, shows a major valley structure prior to finally settling at a plateau at about 3.3 μ sec after impact.

8.3.2 Hugoniot and release properties

Hugoniot properties of this material as determined from these profiles are presented in Table 8.2. The plateau velocities quoted correspond to those shown in Figure 8.1. These values were plotted in Figures 7.2 and 7.3, along with the Hugoniot states of Grout A (BEX GC-1) and the U19ba 2001' rhyolite described in Section 7.3.2.

Table 8.2. Hugoniot conditions for Epoxy/Alumina

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	Hugoniot Conditions				Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
			ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³			
1	0.8805	0.306	2.286	0.583	4.64	2.746	3.482	1.201	0.3642
2	1.8070	0.732	2.476	1.092	12.22	3.266	4.518	1.319	0.3062
3	2.2110	0.569	2.286	1.861	22.64	3.514	5.324	1.537	0.2846
4	2.0729	0.597	2.286	1.654	17.17	3.596	4.541	1.573	0.2781
5	2.2700	0.633	2.476	1.868	25.59	3.739	5.532	1.510	0.2675

Release modeling was done for all tests except AEP 3 (for which it seemed no single material model would credibly represent the experiment and match the observed data). A high-confidence modeling of test AEP 1 could not be produced owing to the ambiguous early-time saddle and the very shallow release. The release is probably a product of the coarse composite nature of this material. Wave profile modeling for AEP 2 (using the variable-coefficient modulus treatment used throughout this report) and for AEP 5 (using a Mie-Grüneisen model) are presented in Figure 8.2. Note that the velocity profile predicted for AEP-5 has a markedly flat plateau. As noted earlier, AEP 4 release interpretation is uncertain because of the late-time hump. Test AEP 2 was the most amenable to sensible modeling; its release is plotted in Figure 7.3 and tabulated in Appendix A.

Figure 8.2. WONDY modeling of test AEP 2 and AEP 5 (Alumina/Epoxy)

9.0 Grout A (BEX GC-1) - Dynamic Experiments

9.1 Material studied

We were provided cylinders (4 inches in diameter) of a high-density grout produced by Waterways Experiment Station for dynamical characterization. The composition of this grout was³⁵:

Table 9.1. Composition of Grout A (BEX GC-1)

Ingredient	Pounds per cubic foot of grout
Chem comp cement	25.11
Bauxite Sand	72.54
Silica Flour	18.60
Gel	1.63
D-19	0.46
Plastiment	0.8 oz.
Water	25.35

The density of this material was measured as 2.41 - 2.42 gm/cm³. We treated it as fully saturated, storing it underwater and assuring adequate water was placed in the sample chamber of the test apparatus to prevent its dewatering.

9.2 Experiments conducted

A series of four reverse-ballistic powder gun tests was conducted to measure Hugoniot and release properties of these samples over the stress range 5 -20 GPa. Parameters are summarized in Table 9.1. Three of these tests used aluminum buffers and the remaining test used a copper buffer to achieve higher Hugoniot stress levels than would be possible on this gun system with an aluminum buffer.

9.3 Dynamic material properties results

9.3.1 Observed velocity profiles

Velocity profiles generated in this series of experiments are shown in Figure 9.1 All tests showed evidence of gaps forming between the sample and the cups, but were otherwise of good quality. Good release signatures were available on all of these tests.

It should be reemphasized that these gaps, although not desirable, do not compromise the quality of the resulting data other than by slightly increasing uncertainties. It seems to be difficult to avoid them when performing reverse-ballistic tests with water-bearing samples.

Table 9.2. Impact experiments conducted to characterize Grout A

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ¹ Thick (mm)	Velocity ³ Per Fringe (km/sec)
GTA 1 ²	Gas	0.878	0.280	4.969	Si Grout	2.4215	6.0480	1.9868	Al	1.4728	25.581	0.0559948
GTA 2 ²	Powder	1.453	0.288	4.9544	Si Grout	2.413	6.0556	2.164	Al	1.478	25.572	0.1088897
GTA 3 ²	Powder	2.238	0.433	4.968	Si Grout	2.4205	6.0344	1.9822	Al	1.4694	25.576	0.1088897
GTA 4	Powder	2.026	0.685	6.368	Si Grout	2.4087	6.0485	2.0142	Cu	6.163	25.189	0.1088897

Notes:

¹Window is composed of lithium fluoride²Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment.³Velocity per fringe (VPF) corresponds to a setting of the VISAR

Figure 9.1. Velocity profiles for Grout A (BEX GC-1) tests

9.3.2 Hugoniot and release properties

The Hugoniot properties are derived as described earlier from the experimental wave profiles, the sample initial density, the projectile velocity, and the ancillary material properties. They are summarized in Table 9.3.

Release paths have been evaluated for the three aluminum-buffer experiments. The results of the wavecode matching are shown in Figure 9.2. The release paths are unusually clean down to quite low stress levels.

The copper-buffer experiment has been resistant to successful modeling. In the simulation, there is a great deal of large-amplitude ringing which gives a “walking” in density/pressure space which is unphysical. Modifications to the WONDY V code eliminated this for most of our simulations, but the present test has not been credibly modeled yet.

Table 9.3. Hugoniot conditions for Grout A

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	Hugoniot Conditions						Specific Vol cm ³ /gm
			ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
1	0.8780	0.330	2.421	0.557	5.02	2.847	3.724	1.176	0.3512
2	1.4530	0.573	2.413	0.895	9.23	3.051	4.278	1.264	0.3278
3	2.2380	0.905	2.421	1.354	15.68	3.375	4.786	1.394	0.2964
4	2.0260	0.639	2.409	1.577	18.57	3.556	4.888	1.476	0.2812

Figure 9.2. WONDY V simulations of Grout A (BEX GC-1) aluminum-buffer tests

10.0 Grout B (BEX GC-1(R)) - Dynamic Experiments

10.1 Material studied

We were provided cylinders (4 inches in diameter) of a second high-density grout produced by Waterways Experiment Station for dynamical characterization. The composition of this grout was³⁶:

Table 10.1. Composition of Grout B (BEX GC-1(R))

Ingredient	Pounds per cubic foot of grout
Chem comp cement	25.81
Bauxite Sand	77.84
Silica Flour	18.72
Aquagel	0.41
PSP	0.21
Plastiment	0.82 fl. oz.
Water	26.12

The density of this material was measured as 2.29 - 2.32 gm/cm³. We treated it as fully saturated, storing it underwater and assuring adequate water was placed in the sample chamber of the test apparatus to prevent its dewatering.

Some difficulty was experienced machining this material due to the hardness of the bauxite grains³⁶ and the consequent tendency for them to either protrude from the surface of the sample under grinding or be plucked, leaving a gap. Such irregularities will cause an overestimate of sample thickness, leading to a low final calculated density.

Figure 10.1. BEX GC-1(R) Grout - Grinding Behavior

10.2 Experiments conducted

A series of four reverse-ballistic and two forward-ballistic compressed gas and powder gun tests was conducted to measure loading, Hugoniot and release properties of these samples over the stress range 2 - 10 GPa. Parameters are summarized in Table 10.1. All

Table 10.2. Impact experiments conducted to characterize Grout B

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material ¹	Buffer Thick (mm)	Window ² Thick (mm)	Velocity ³ Per Fringe (km/sec)
GTB3	Gas	0.877	0.293	5.007	DM Grout	2.2956	6.004	1.87 ⁶	Al	1.619	25.586	0.055995
GTB4	Gas	0.876	0.291	4.976	DM Grout	2.2919	6.005	2.027	Al	1.636	25.602	0.055995
GTB5	Powder	1.095	0.285	5.038	DM Grout	2.2907	6.016	2.588	Al	1.618	25.574	0.15528
GTB6	Powder	1.423	0.625	5.050	DM Grout	2.3261	6.007	2.641	Al	1.632	25.440	0.19751
Shot #	Gun Facility	Impact Velocity (km/sec)	Flyer Plate Thick ⁴ (mm)	Cup Thick (mm)	Sample ID ⁵	Sample Density (gm/cm ³)	Sample Thick (mm)			Buffer ⁵ Thick (mm)	Window ⁵ Thick (mm)	Velocity Per Fringe (km/sec)
GTB1	Gas	0.493	12.591	2.046	DM Grout	2.3085	8.013			3.029	25.891	0.07240
GTB2	Gas	0.575	12.645	2.023	DM Grout	2.3116	7.995			2.990	25.723	0.07240

Notes:

¹Standard aluminum used is 6061-T6 throughout assemblies (both configurations).²Window is composed of lithium fluoride for reverse-ballistic tests in this study.³Velocity per fringe (VPF) corresponds to a setting of the VISAR.⁴In these forward-ballistic tests, the flyer plate is backed by a void.⁵Buffer and window are composed of PMMA for forward-ballistic tests in this study.⁶Pre-shot measurement unavailable. Calculated as 1.87 ± 0.05 mm from wave profiles.

Figure 10.2. Velocity profiles, Reverse-Ballistic Experiments, Grout BEX GC-1(R)

of the reverse-ballistic tests used aluminum buffers, while the forward-ballistic tests used aluminum impactors and PMMA buffers and windows.

10.3 Dynamic material properties results

10.3.1 Observed velocity profiles

The velocity profiles produced in the reverse-ballistic experiments are shown in Figure 10.2. On the whole they present no unpleasant surprises. The Hugoniot plateaus are somewhat irregular, but there is no systematic trend across them which forces the analyst to make any interpretation other than that the irregularities are due to random inhomogeneities. Hence the irregularities are ignored in this analysis.

Figure 10.3 shows the forward-ballistic velocity profiles. Weak precursors (particle velocity of about 4 m/sec) are seen at the toe of the main loading waves. Assuming that the levels of these precursors have not been severely changed by the buffers, these would correspond to an elastic limit of 30 - 40 MPa in the grout. This is low enough to be ignored in the Hugoniot and release analysis of the next section.

Figure 10.3. Forward-ballistic velocity profiles for BEX GC-1(R)

As with Tuff D, the viscoelastic properties of the PMMA have caused some rounding of the corner at the top of the main shock arrival. The plateau giving partial release information is present, although it is difficult to identify precisely where it ends. Nevertheless its height can be measured with reasonable confidence.

10.3.2 Loading, Hugoniot and release properties

The Hugoniot states for the reverse-ballistic experiments are summarized in Table 10.3., and plotted in Figure 10.4. Figure 10.4 also shows the Hugoniot states of other grouts discussed in this report and elsewhere¹⁸.

Release trajectories from these experiments are shown in Figure 10.5, along with corresponding properties of Grout A (BEX GC-1) and results from the forward-ballistic analysis. The forward-ballistic results are tabulated in Table 10.4.

**Table 10.3. Hugoniot Conditions for Grout B
Reverse-Ballistic Tests**

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Hugoniot Conditions					Specific Vol cm ³ /gm
				Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
GTB 3	0.877(3)	0.297(8)	2.296(11)	0.584(9)	4.4(1)	2.79(4)	3.30(15)	1.214(16)	0.359(5)
GTB 4	0.876(9)	0.310(5)	2.292(11)	0.57(1)	4.6(1)	2.73(3)	3.54(12)	1.192(11)	0.366(4)
GTB 5	1.095(11)	0.384(4)	2.291(11)	0.72(1)	5.9(1)	2.87(3)	3.56(8)	1.252(12)	0.349(4)
GTB 6	1.423(21)	0.535(12)	2.326(12)	0.90(2)	8.5(2)	2.99(6)	4.05(18)	1.285(25)	0.335(7)

The results of WONDY wavecode modeling of the four reverse-ballistic tests are shown in Figure 10.6. Widths of the gaps between the sample and the cup are calculated as shown.

Figure 10.4. Hugoniot states of Grout B, Grout A, MJ-2 grout and HPNS-12 Grout

Table 10.4. Hugoniot Conditions for Grout B
Forward-Ballistic Tests

Shot #	Proj. Velocity km/sec	Plastic TOA μ sec	ρ_0 gm/cm ³	Hugoniot Conditions					Specific Vol cm ³ /gm
				Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	
GTB 10.493(10)	4.189(10)	4.189(10)	2.309(9)	0.331(16)	2.13(10)	2.62(2)	2.785(10)	1.135(7)	0.382(3)
GTB 20.575(11)	3.694(5)	3.694(5)	2.312(9)	0.369(15)	2.82(11)	2.60(2)	3.305(9)	1.126(6)	0.384(2)

Partial Release Conditions

Shot #	Plateau		Particle Vel. km/sec	Release Slope GPa/(km/sec)	Hugoniot P/Up GPa/(km/sec)
	Velocity km/sec	Stress (GPa)			
GTB 1	0.401(7)	1.51(3)	0.401(7)	-8.7(4.4)	6.43(44)
GTB 2	0.441(7)	1.70(4)	0.441(7)	-15.6(6.1)	7.64(44)

Figure 10.5. Hugoniot and release properties for BEX GC-1 and BEX GC-1(R) grouts
 Reverse- and forward-ballistic test results are plotted as noted.

2 of 2

On the whole, the Hugoniot and release properties of BEX GC-1 and BEX GC-1(R) grouts are quite similar. The BEX GC-1(R) releases may be slightly more hysteretic. The primary difference appears to be in the initial release; the majority of the release is parallel to the Hugoniot in pressure-volume space.

It is worthwhile to return momentarily to the sources of uncertainties for the Hugoniot states. These are summarized in Table 10.5 for the present material.

Table 10.5. Major sources of uncertainties in Hugoniot quantities for Grout B

Hugoniot Quantity: ➡	Particle Velocity	Shock Velocity	Stress	Density
Observable ↓	***REVERSE BALLISTIC***			
Projectile Velocity	70-75%	25-30%	0%	40-45%
Initial Density	0%	4%	0%	30%
Plateau Velocity	20%	65-70%	80%	30%
Al release (esp. strength)	5-10%	3%	20%	0%

Table 10.5 (Continued)

Hugoniot Quantity: ➡	Particle Velocity	Shock Velocity	Stress	Density
Observable ↓	***FORWARD BALLISTIC***			
Projectile Velocity	20%	0%	20%	15%
Initial Density	0%	0%	0.5%	30%
Timing	0%	60-80%	0%	0%
Al release (esp. strength)	80%	0%	80%	50%
Plateau level	0%	10-20%	0%	0%
Existence of elastic wave	0%	4-10%	0%	0%

(Partial release state uncertainties due almost entirely to plateau level uncertainties)

Figure 10.6. WONDY V modeling matches to the observed velocity profiles for BEX GC-1(R) grout (Grout B).

11.0 HPNS 12 Grout - Dynamic Experiments

11.1 Material studied

We were provided cylinders (4 inches in diameter) of a lower-density grout produced by Waterways Experiment Station for dynamical characterization. The composition of this grout was³⁶:

Table 11.1. Composition of HPNS-12 Grout

Ingredient	Pounds per cubic foot of grout
Class A Portland Cement	35.00
NTS Gel	2.00
Barite	20.90
Silica Flour	30.41
PSP	0.15
Water	33.8

The density of this material was measured as 1.94 gm/cm^3 . We treated it as fully saturated, storing it underwater and assuring adequate water was placed in the sample chamber of the test apparatus to prevent its dewatering.

11.2 Experiments conducted

A series of five reverse-ballistic compressed gas gun and powder gun tests was conducted to measure Hugoniot and release properties of these samples over the stress range 3 - 13 GPa. Parameters are summarized in Table 11.1. All of these tests used aluminum buffers (our usual practice where cups must be used in reverse-ballistic experiments).

11.3 Dynamic material properties results

11.3.1 Observed velocity profiles

The velocity profiles produced in the reverse-ballistic experiments are shown in Figure 11.1. The Hugoniot plateaus are much smoother than those for Grouts A or B (BEX GC-1 and BEX GC-1(R)). Two of the tests showed evidence of gap formation between the sample and the cup.

It should be mentioned that a zero-width gap may form a gap signature because release waves propagating through aluminum will outrun following reshocks, unless the reshock is to a much greater stress than that preceding the release. Test HP 3 may be an example of the signature of a gap of essentially zero width.

Table 11.2. Impact experiments conducted to characterize HPNS12 Grout

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material	Buffer Thick (mm)	Window ¹ Thick (mm)	Velocity ³ Per Fringe (km/sec)	Gap Width (mm)
HP 1 ²	Gas	0.731	0.292	4.673	HPNS12	1.942	5.999	2.154	Al	1.484	25.529	0.055995	0.2344.
HP 2	Powder	0.846	0.282	4.982	HPNS12	1.939	6.010	2.034	Al	1.423	25.606	0.1088897	N. A.
HP 3	Powder	1.157	0.281	4.986	HPNS12	1.9365	6.002	2.0117	Al	1.451	25.529	0.1088897	N. A.?
HP 4 ²	Powder	1.795	0.280	4.981	HPNS12	1.9315	5.9964	1.9964	Al	1.461	25.606	0.1088897	0.0840
HP 5	Powder	2.185	0.626	4.996	HPNS12	1.9359	6.0071	2.0193	Al	1.449	25.590	0.1552832	N. A.

Notes:¹Window is composed of lithium fluoride²Velocity profile shows evidence that a gap appeared between the sample and the cup during the experiment; calculated width in last column.³Velocity per fringe (VPF) corresponds to a setting of the VISAR

Figure 11.1. Velocity profiles for HPNS-12 Grout experiments

All of the releases proceeded to very low stresses; in fact, particle velocities were recorded as going slightly negative on tests HP 1 - 4. Inspecting the fringe records for these tests shows that the laser light returned to the interferometer began to go extinct at about the zero-crossing time for these tests. This is reminiscent of the “rarefaction shock” in Figure 5.3 (test TFC 1), and is unphysical. The solution here is to follow the release profile down until anomalous behavior begins.

11.3.2 Hugoniot and release properties

Hugoniot properties are calculated in the usual manner, and are tabulated in Table 11.3 and plotted in Figure 11.2 (juxtaposed on the results for Tuff C, U12p.04 IH20 145’).

Releases were calculated by the usual material modeling procedure. The release paths are shown in Figure 11.2 and tabulated in Appendix A. The wavecode profiles corresponding to these release paths are shown in Figures 11.3 and 11.4.

Release properties of the two materials (Tuff C and HPNS-12 grout) appear very similar. Releases are very close to along the Hugoniot in both cases. Shock impedances are also close. There are differences in the Hugoniot. A linear U_s/U_p fit over the range $U_p = 0$ to 1.5 km/sec would give Tuff C showing a higher value of C_0 and a lower S than would HPNS12. Associated with this, the slight difference in the starting density of the two materials apparently crushes out by 12 - 14 GPa; at higher stress levels the materials may have very similar dynamic properties.

Table 11.3. Hugoniot conditions for HPNS12 Grout

← Hugoniot Conditions →									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
1	0.732	0.219	1.942	0.518	3.25	2.313	3.231	1.191	0.4323
2	0.846	0.253	1.939	0.600	3.79	2.376	3.263	1.225	0.4210
3	1.157	0.365	1.936	0.803	5.61	2.490	3.610	1.286	0.4016
4	1.795	0.606	1.931	1.204	9.85	2.699	4.234	1.397	0.3705
5	2.185	0.772	1.936	1.432	13.02	2.785	4.696	1.439	0.3590

Figure 11.2. Hugoniot and release results for HPNS12 grout and Tuff C

Figure 11.3. WONDY V matches to observed velocity profiles for HPNS-12 grout, corresponding to release paths in Figure 11.2

Figure 11.4. WONDY matching for HPNS 12 test HP 5

12.0 Quartzite Permafrost - Dynamic Properties

12.1 Materials tested and motivation

The overall purpose of these tests was to provide data for whether a frozen condition significantly changes the dynamic response of a rock, and further, whether thawing and refreezing a rock sample causes the sample to exhibit different dynamic properties than would a sample which has been preserved in a frozen state.

Samples of an impure quartzite from the Lupin Mine were machined by Terra Tek, and then provided to us for these gas gun experiments. Thawed samples came from hole LU1B (1.64 - 1.76 meters depth), as did the preserved samples (2.56 - 2.64 meters depth), while the thawed/refrozen samples are from hole LU1A (2.60 - 2.62 meters depth). Densities were measured at Terra Tek, and again at Sandia (measurements agreed closely between the two laboratories). These densities (2.74 - 2.75 g/cm³ for the frozen and the refrozen samples and 2.72 - 2.73 g/cm³ for the warm samples) are considerably higher than the density of crystalline quartz, so a significant component of heavier minerals (possible anorthite, biotite or calcite) must be present. Porosities are presumed very low in these samples. They were very fine-grained. No rigorous attempts had been made during sample mining, storage, machining or transportation to maintain water content, although the preserved frozen samples were carefully held below freezing. Storage at our facility was at a temperature of -10°C, although the frozen samples were received at -18°C.

12.2 Experiments and analyses conducted

A total of 15 experiments were performed. These are listed in the Table 12.1. All utilized velocity interferometry (VISAR) as the primary diagnostic. As with previous studies, forward-ballistics tests (sample in target) were performed to obtain Hugoniot states and loading information (see Section 2.2). In addition, since the sample shock impedance is very close to those of lithium fluoride and 6061-T6 aluminum (in fact, slightly softer), forward-ballistic tests also yield release information from a state very close to the Hugoniot state. Most of the tests were performed in this configuration because sample-in-projectile geometries do not seem practical for samples which must be kept at subfreezing temperatures. Two tests were performed with room-temperature samples in a reverse-ballistic configuration (sample in projectile - see Section 2.1) to allow cross-checking of the Hugoniot and release data between the two experiment types.

12.3 Dynamic material properties results

12.3.1 Velocity profiles observed

Velocity profiles resulting from these tests are shown in Figures 12.1 - 12.3. For the forward-ballistic experiments, timing was accomplished using an electronic fiducial triggered by a shorting pin flush with the impact surface. This timing has been corrected

Table 12.1. Impact experiments conducted to characterize Quartzite (Preserved Frozen, Thawed, Refrozen)
(see following page for notes)

Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID ¹	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material ²	Buffer Thick (mm)	Window Thick ³ (mm)	Velocity Per Fringe ⁴ (km/sec)
PFT6 ⁵	Gas	0.347	0.2917	5.062	Quartzite ^{#6} , RT	2.724	5.989	2.609	Al	1.624	25.450	0.055995
PFT7 ⁵	Gas	0.492	0.2934	4.988	Quartzite ^{#7} , RT	2.731	5.980	2.610	Al	1.2556	25.397	0.055995
Shot #	Gun Facility	Impact Velocity (km/sec)	Foam Density (gm/cm ³)	Foam Thick (mm)	Sample ID	Sample Density (gm/cm ³)	Sample Thick (mm)	Al Cup Thick (mm)	Buffer Material ²	Buffer Thick (mm)	Window Thick ³ (mm)	Velocity Per Fringe ⁴ (km/sec)
PFT1	Gas	0.151	12.705	2.703	Quartzite ^{#1} , RT	2.722	9.946					0.055995
PFT2	Gas	0.341	12.675	2.715	Quartzite ^{#2} , RT	2.732	9.915					0.055995
PFT3	Gas	0.483	12.665	2.774	Quartzite ^{#3} , RT	2.730	9.931					0.055995
PFT4	Gas	0.685	12.674	~2.75(4)	Quartzite ^{#4} , RT	2.724	9.880					0.055995
PFT5	Powder	1.108	12.648	2.652	Quartzite ^{#5} , RT	2.745	9.987					0.19825
PFP1A	Gas	0.178	12.679	2.690	Quartzite ^{#3} , PF	2.742	10.093		Test Lost	3.129	25.440	0.055995
PFP1	Gas	0.192	12.676	2.743	Quartzite, PF ⁸	2.738	9.934			2.990	25.352	0.055995
PFP2	Gas	0.346	12.671	2.586	Quartzite ^{#2} , PF	2.749	10.053			3.136	25.430	0.055995
PFP3	Gas	0.492	12.674	2.672	Quartzite ^{#1} , PF	2.746	10.062			3.153	25.298	0.055995
PFP4	Gas	0.694	12.672	2.682	Quartzite ^{#4} , PF	2.752	10.015			3.167	25.300	0.055995
PFP5	Powder	1.064	12.610	2.662	Quartzite, PF	2.742	9.929			3.128	25.467	0.19825
PFR1	Gas	0.339	12.670	2.705	Quartzite ^{#1} , RF	2.741	10.005			3.156	25.453	0.055995
PFR2	Gas	0.663	12.648	2.723	Quartzite ^{#2} , RF	2.737	10.366			3.272	25.337	0.055995

Notes for Table 12.1:

1. RT = room temperature, PF = preserved frozen, RF = thawed and refrozen. Superscript designations refer to Terra Tek labelings (RF samples from core Lu#1A; PF samples from core Lu#1B, RT samples from core Lu#1B 1.64-1.76m)
2. Standard aluminum used is 6061-T6 throughout assembly.
3. Window is composed of lithium fluoride for all tests in this study.
4. Velocity per fringe (VPF) corresponds to a setting of the VISAR. This VPF assumes $\Delta v/v_0 = 0.28$ (see text for discussion).
5. Gaps appeared between the sample and the cup in both reverse-ballistic tests. Estimated gap widths for PFT6 and PFT7 (respectively) are 0.070 and 0.045 mm.
6. Buffer and window are composed of LiF for forward-ballistic tests in this study.
7. In these forward-ballistic tests, the flyer plate is backed by a void (gas gun) and a void with a phenolic support tube (31.75mm ID, 44.45 mm OD) (powder gun)
8. Sample Q-5 (4.885 mm thick, $\rho_0=2.7422 \text{ gm/cm}^3$) backed by Sample Q-6 (5.049 mm thick, $\rho_0=2.735 \text{ gm/cm}^3$). Thicknesses added to within 0.001 mm.

Figure 12.1. Quartzite permafrost velocity profiles (forward-ballistic, gas gun)

for projectile tilt and data/fiducial travel time differences. Reverse-ballistic experiments were timed using the known shock velocity in the aluminum buffer.

Comments about the specific tests follow:

- Tests PFT1-4 (forward-ballistic tests with warm samples) were all conducted successfully.
- Reverse-ballistic tests PFT6-7 (warm samples) were conducted successfully. A gap appears to have formed between the cup and the sample in the projectile. While both Hugoniot and release conditions may be extracted correctly by taking account of the gap (whose width may be calculated), the gap is undesirable. Eliminating it is an elusive goal, and we are not completely sure why. It generally seems to be most prominent for relatively low-velocity tests (impact at less than about 1 km/sec).
- Test PFP-1 (preserved frozen sample) was lost. We do not understand exactly why; but it produced a nonsense velocity curve lasting $\sim 15 \mu\text{sec}$ (vs. 5 expected). This tests was successfully repeated on November 2 with a sandwich of two preserved-frozen quartzite samples as Test PFP-1A.
- Test PFP3 was conducted with a sample which had inadvertently been allowed to warm to $+1\text{-}2^\circ\text{C}$ for a period of 1-4 minutes. Whether this sample in fact thawed is

Figure 12.2. Quartzite permafrost velocity profiles (forward-ballistic, powder gun)

unclear (as is the question of whether temperatures of -10 - -20°C actually “freeze” such samples).

- Only one of the normal set of two orthogonal fringe records collected by the VISAR was acquired for test PFR2. I had to write two new programs to help me extract a velocity history for this test. There are two areas in which confidence in the history diminishes for such a test. First, near the sinusoid extrema in the fringe records, sensitivity goes down. For these tests, such extrema occur at intervals of about 28 m/sec. The more important, however, is that at such extrema it is necessary to guess what the sign of subsequent acceleration is. Since we know the expected form of the curve, this is not difficult. There is room for error (e.g. the velocity decline following 6.9 μsec after impact may actually be a velocity increase).

12.3.2 Loading, Hugoniot and release properties

The resulting Hugoniot conditions are tabulated as Table 12.2, with estimated errors as indicated. They are also plotted (with release paths, as discussed below) in Figures 12.4 - 12.6, and compared with other quartz data, as well as with aluminum and lithium fluoride, in Figure 12.7. Errors were calculated by adding in quadrature contributions from timing errors, LiF equation-of-state errors (see next section), projectile velocity errors and plateau measurement errors.

Figure 12.3. Quartzite permafrost velocity profiles (reverse-ballistic, gas gun)

Table 12.2. Hugoniot Conditions for Quartzite Permafrost (Lupin Mine)

Forward-Ballistic Tests:			Hugoniot Conditions						
Shot #	Proj. Velocity km/sec	Plastic TOA μsec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
PFT 1	0.151(1)	2.985(22)	2.722(0)	0.076(1)	1.09(1)	2.762(1)	5.27(5)	1.0145(5)	0.3621(2)
PFT 2	0.341(2)	3.120(13)	2.732(0)	0.181(1)	2.36(1)	2.839(2)	4.78(5)	1.0392(6)	0.3522(2)
PFT 3	0.483(3)	2.976(16)	2.730(0)	0.249(2)	3.53(3)	2.867(2)	5.19(3)	1.0503(9)	0.3488(3)
PFT 4	0.685(4)	2.919(5)	2.724(0)	0.356(2)	5.08(3)	2.922(2)	5.24(1)	1.0728(6)	0.3422(2)
PFT 5	1.108(10)	2.796(8)	2.745(0)	0.574(5)	8.65(9)	3.065(5)	5.49(3)	1.1166(20)	0.3263(6)
PFP 1	0.192(1)	3.135(100)	2.738(0)	0.101(3)	1.33(6)	2.797(6)	4.82(25)	1.0215(23)	0.3575(8)
PFP 2	0.346(2)	2.960(30)	2.749(0)	0.176(1)	2.54(2)	2.844(2)	5.26(9)	1.0346(8)	0.3516(3)
PFP 3	0.492(3)	3.057(18)	2.746(0)	0.257(2)	3.54(3)	2.894(2)	5.01(6)	1.0540(9)	0.3455(3)
PFP 4	0.694(5)	3.090(5)	2.752(0)	0.370(3)	4.95(4)	2.979(2)	4.86(3)	1.0825(9)	0.3357(3)
PFP 5	1.064(10)	2.816(4)	2.742(0)	0.555(5)	8.19(8)	3.057(4)	5.38(2)	1.1149(15)	0.3271(5)
PFR 1	0.339(2)	3.118(14)	2.741(0)	0.178(1)	2.39(2)	2.844(2)	4.90(5)	1.0376(6)	0.3516(2)
PFR 2	0.663(4)	3.098(14)	2.737(0)	0.348(2)	4.84(3)	2.938(3)	5.08(16)	1.0734(12)	0.3404(4)

Partial Release/Reshock Conditions

Shot #	Plateau Velocity km/sec	Stress (GPa)	Particle Vel. km/sec	Hugoniot P/Up GPa/(km/sec)
PFT 1	0.084(3)	1.23(7)	0.084(3)	1.0145(5)
PFT 2	0.185(3)	2.67(6)	0.185(3)	1.0392(6)
PFT 3	0.249(3)	3.62(6)	0.249(3)	1.0503(9)
PFT 4	0.354(4)	5.25(6)	0.354(4)	1.0728(6)
PFT 5	0.547(2)	8.51(5)	0.547(2)	1.1166(20)
PFP 1	0.094(2)	1.37(6)	0.094(2)	1.0215(23)
PFP 2	0.180(1)	2.60(4)	0.180(1)	1.0346(8)
PFP 3	0.250(5)	3.64(8)	0.250(5)	1.0540(9)
PFP 4	0.356(2)	5.28(5)	0.356(2)	1.0825(9)
PFP 5	0.555(3)	8.65(7)	0.555(3)	1.1149(15)
PFR 1	0.180(2)	2.60(5)	0.180(2)	1.0376(6)
PFR 2	0.346(3)	5.12(14)	0.346(3)	1.0734(12)

Reverse-Ballistic Tests:

Hugoniot Conditions

Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
PFT6	0.347(3)	0.177(1)	2.724(0)	0.174(3)	2.60(3)	2.814(5)	5.47(14)	1.033(2)	0.3554(6)
PFT7	0.492(4)	0.247(4)	2.731(0)	0.251(6)	3.67(8)	2.865(8)	5.37(22)	1.049(3)	0.3490(10)

Figure 12.4. Hugoniot and release results for quartzite permafrost experiments (σ/U_p space)

Figure 12.5. Hugoniot results for quartzite permafrost experiments (U_s/U_p space)

Figure 12.6. Hugoniot and release results for quartzite permafrost experiments (σ vs. ρ/ρ_0 space)

Figure 12.7. Hugoniot results for quartzite permafrost experiments (P/U_p space) compared with Hugoniot of other quartz materials, aluminum and lithium fluoride

Sample-related precursors are suggested in the loading wave profiles for tests PFT1 and PFR2, at respective velocities of 45 and 70 m/sec. Assuming these to be Hugoniot elastic limit (HEL) signatures, the material HEL is about 0.6 - 1.0 GPa. This corresponds to yield stresses $Y = \sigma_{HEL} \times (1-2\nu)/(1-\nu)$ ($\nu \equiv$ Poissons ratio) of 0.3 - 0.5 GPa. These HEL signatures are not well pronounced, and the other profiles do not show HEL signatures. The 10 - 20 m/sec precursors present in all of the velocity profiles are of amplitude consistent with the strength properties of the LiF buffer (see Section 12.3.3).

All of these tests have been modeled with the wavecode WONDY V to extract release properties. For this series of tests, these modelings have been done two ways.

The first modeling set follows the procedure used for other tests, fitting releases using a polynomial Lagrangian release modulus. Fits used are shown in Figures 12.8 - 12.11 for the 14 successful tests, with corresponding releases plotted in Figs. 12.4 and 12.6. Recall that time-of-arrival corresponds to the Hugoniot state and plateau level corresponds to a slightly released state for this material, with the overall release sensitivities very analogous to those for reverse-ballistic experiments (Figs. 2.7 and 2.8).

Figure 12.8. WONDY fits for reverse-ballistic quartzite permafrost tests (Polynomial release model)

The most obvious frozen/thawed contrasts evident from this analysis are the gentler release slopes of the thawed samples at the lowest and second-highest pressure levels (~1 and ~5 GPa), as shown in Figs 12.4 and 12.6. On close inspection of the fits used at the 5 GPa level, however, it is apparent that there is some subjectivity in assigning fits (mid-release vs. breakaway region).

The second modeling set performed treated the sample behavior according to a Mie-Grüneisen model ($\gamma_0 = 2.1$). At these pressure levels, this essentially compares the test results with a Hugoniot = Release approximation. This is useful for comparing responses of cold with warm samples. The results of the modeling are shown in Figures 12.12 - 12.15 for the 14 successful tests.

These modelings make apparent the more dispersed nature of the frozen-material wave-

Figure 12.9. WONDY fits for forward-ballistic quartzite permafrost tests (Polynomial release model)

Figure 12.10. WONDY fits for forward-ballistic quartzite permafrost tests (Polynomial release model, cont'd)

Figure 12.11. WONDY fits for forward-ballistic quartzite permafrost tests (Polynomial release model, cont'd)

Figure 12.12. WONDY fits for reverse-ballistic quartzite permafrost tests (Mie-Grüneisen release model)

forms (cf. PFT3 vs. PFP3; PFT4 vs. PFP4 and PFR2) as well as an earlier release arrival time for frozen material than for thawed material in the lowest-pressure tests (PFT1 vs. PFP1).

Two issues have not been exhaustively addressed in this analysis. The first is the effect of strength on the releases. Several of the velocity profiles (especially PFT2, 3, 4) show definite release structure likely associated with strength. The second is that the particle velocity plateau level (corresponding to a very slightly released state of the sample) significantly disagrees with numerical predictions in several tests (PFP1, PFT1, PFT2, PFT5, PFP5). The direction of discrepancy is not consistent.

12.3.3 Discussion - window material (LiF)

A difficulty of these experiments is choice of a window material. We elected to use (100) single-crystal LiF because of its expected close impedance match with the samples (see Figure 12.7). There are disadvantages to this choice, primarily pertaining to the gas-gun tests (vs. powder gun). This material is not completely characterized mechanically or optically in much of the region of interest (say, over 0 - 6 GPa). The lowest-pressure data point used in the generally accepted fits (which are close to $C_0=5.148$ km/sec, $S=1.353$, $\rho_0=2.641$ gm/cm³) is at about 7 GPa (Figure 12.16), while the optical properties under shock are known well from about 8 GPa up as represented by $\Delta v/v_0 = 0.28$ ²⁵. This quantity, incidentally, is used in the calculation of the velocity-per-fringe of a velocity interferometer system, cf. $VPF = \lambda_0/[2\tau(1+\Delta v/v_0)(1+\delta)]$ (where λ_0 is the incoming laser wavelength, τ is the etalon delay of one leg relative to the other, and $\delta=0.034$ is a dispersion correction for the case where glass etalons are used)²⁶. If this quantity is not constant, a rigorous derivation of an interface velocity requires an interactive modeling of the wave behavior. There is also an elastic precursor of about 0.2 GPa amplitude (6.5 km/sec wavespeed) which develops. The initial amplitude of this precursor is higher, but the pre-

Figure 12.13. WONDIY fits for forward-ballistic quartzite permafrost tests (Mie-Grüneisen release model)

Figure 12.14. WONDY fits for forward-ballistic quartzite permafrost tests (Mie-Grüneisen release model, cont'd)

Figure 12.15. WONDY fits for forward-ballistic quartzite permafrost tests (Mie-Grüneisen release model, cont'd)

Figure 12.16. Mechanical shock wave properties of lithium fluoride.

cursor appears to decay from 1 GPa to 0.2 GPa over about 0.4 - 0.6 mm³⁷. Additionally, the temperature dependence of the mechanical properties has not been carefully studied (of particular significance to the present task). The precursor is known to decay significantly more rapidly at liquid nitrogen temperature than at room temperature, however³.

The alternative windows, however, all pose disadvantages. Fused silica introduces a ramp up to 3 GPa; PMMA is much lower in impedance than the samples, and sapphire is much higher in impedance. Nitromethane is lower in impedance and poses safety and convection problems as well.

Optical data in the 0 - 6 GPa region is sparse, and is shown in Figure 12.17. In deriving velocity profiles in the present study, the fit $\Delta v/v_0 = 0.28$ was extrapolated to low pressures.

Figure 12.17. Optical shock wave properties of lithium fluoride.

Alternative fits to the LiF optical behavior were considered. For example, the optical properties of LiF may be represented according to the alternative piecewise fit shown in Figure 12.17. This produced the Hugoniot data plotted in Figure 12.18. The shock velocities for the reverse-ballistics experiments were unacceptably high compared with the forward-ballistics experiments. This is a sensitive consistency check since the Hugoniot properties of the forward-ballistic experiments are insensitive to the LiF optical and mechanical model used (relying only on shock transit time measurement), while the Hugoniot properties derived for the reverse-ballistic experiments are sensitive to both the optical and mechanical models of LiF. Softening the low-pressure model of LiF in the 0 - 6 GPa region allowed the reverse-ballistic points to be moved into agreement with the forward-ballistic points, but is physically unrealistic because the elastic-plastic properties of LiF implied by the existence of a precursor would have the opposite effect in this pressure region.

Figure 12.18. Hugoniot and release results (U_s/U_p space) for quartzite permafrost experiments, with piecewise representation of LiF optical properties (not used, as discussed in text)

Another available fit²⁵ to the LiF optical properties is continuous, yet captures some of the low-pressure behavior:

$$\frac{\Delta v}{v_0} = 0.2784 \times U_p^{0.031} \quad (\text{Eq. 12.1})$$

This curve is plotted against the data in Figure 12.17. It is intermediate between the other piecewise fit for stress levels below 6 GPa (the area of interest here). Hugoniot states have not been calculated using this, although they should lie between the values in Figure 12.18 and those in Figure 12.4 (with forward-ballistics experiments affected little).

12.4 Discussion and conclusions - quartzite permafrost

The results are open for interpretation. There do not seem to be any systematic differences in the Hugoniot states of the three types of samples (preserved frozen, thawed and thawed/refrozen). Regarding the releases, I would suggest that two trends are apparent, although weak. First, the releases appear to reach the window more rapidly for the frozen samples than for the thawed samples in the gas-gun tests for the lowest-pressure tests. The highest-pressure tests do not show such a trend. This would suggest a greater hysteresis for the fro-

Figure 12.19. Possibility of Misinterpreting LiF EOS (~3 - 4 GPa) from Al → AlLiF experiment

zen materials (and greater groundshock attenuation) in the 1 - 6 GPa region. The thawed samples, in fact, appear to be modeled well by the release = Hugoniot approximation. Second, the above-mentioned disagreement of predicted and observed plateau velocities (possibly due to the LiF behavior) is more marked for the warm samples than for the cold samples at the lower pressure levels. This plateau velocity corresponds to a weakly reshocked or weakly released state of the sample. The sign of the disagreement (experimental curve higher) is not consistent with an explanation based on sample elastic-plastic behavior alone. It is interesting that this disagreement occurs again at the highest (14 GPa) pressure level, although with the frozen sample displaying a lower-than-predicted plateau level.

The question of the LiF equation-of-state and optical properties is still open. At stress levels above 6 - 7 GPa, both properties are well established. Below 6 - 7 GPa, they are not. I found that taking $\Delta v/v_0 = 0.28$ and $C_0 = 5.148$ km/sec, $S = 1.353$ throughout gave consistency between the forward- and reverse-ballistics results. In a similar vein, I have found that reverse-ballistic projectile velocities calculated from the VISAR records making the same downward extrapolation of LiF properties tend to agree very closely with projectile velocities measured with pins. Yet these interpretations are not unique. All of these results can be reproduced as well assuming a pressure-dependent value of $\Delta v/v_0$, a LiF shock impedance lower than predicted by $C_0 = 5.148$ km/sec and $S = 1.353$ for pressures less than 6 - 7 GPa, and a greater-than-expected strength in the aluminum under these conditions (see Figure 12.14).

13.0 Conclusions, Discussions and Future Work

I have presented two methods for measuring equation-of-state properties necessary for benchmarking groundshock calculations, both based on velocity interferometry measurement techniques. These methods accommodate moderately heterogeneous materials, frozen materials, and materials which should not be allowed to lose water content. Materials with random, large heterogeneities of strongly contrasting shock impedance properties (such as the epoxy/alumina mixture of Section 8) are not handled well by this or (probably) by any other gas-gun technique. For a wide variety of rocks and grouts, however, these methods supply loading, Hugoniot and release properties with reasonably well defined uncertainties.

These methods have been applied to a large variety of rocks and grouts of interest in the HYDROPLUS nuclear yield verification program. Materials studied included several tuffs, a rhyolite, an epoxy-alumina potting mixture, three silicate grouts and an impure quartzite acquired from a permafrost environment. The quartzite was tested preserved frozen (never thawed during the entire process from coring to testing), thawed and refrozen, and thawed. Other materials studied, but documented elsewhere include a variety of carbonate rocks, other tuffs and grouts, and various other materials.

Many of these materials display releases along or slightly below the Hugoniot for Hugoniot stresses up to ~50 GPa, then above the Hugoniot at higher Hugoniot stresses. Many of the release profiles were dispersed, corresponding to a release path strongly concave upward in stress-volume space. A combination of strength effects, hysteretic phase transitions (particularly $^{IV}\text{Si} \leftrightarrow ^{VI}\text{Si}$, or quartz to stishovite), and thermal effects are probably the most important factors governing these behaviors. On the whole, the materials discussed in detail in the present report are relatively weak. The quartzite was expected to be a stronger material, but few direct signatures of this strength were observed in the loading portion of waveforms passed through this material. The signatures present suggest a Hugoniot Elastic Limit of about 0.6 - 1.0 GPa (yield strength of 0.3 - 0.5 GPa).

Not all of the problems of these experiments are resolved. Consider the "bump." Several of the reverse-ballistic experiments on tuffs gave waveforms with bumps immediately preceeding the release arrival at the window. Other sample materials generally did not give this feature, so it is probably not an edge effect. It is more likely to be a segregation of water during launch. However, it is more prominent for lower launch velocities than for higher. Slower launches have lower acceleration than do faster launches, but the acceleration is sustained over a longer time. Such bumps are also present on some of the forward-ballistic quartzite tests, again immediately preceeding the release arrival at the window. Here the sample is stationary until impact. The window is lithium fluoride in all of the cases in question, yet what is known about the optical and mechanical behavior of LiF does not provide an explanation for these bumps.

Future work is, frankly, difficult to define from the experimentalist's end of the groundshock study effort. Historically and logistically the experimentalist has been able to define his work only by viewing the world as a modeler. As I step into those shoes for a moment, mindful of experimental limits and possibilities, as well as of the sea change associated

with a shift in the focus of the groundshock community from a yield-measurement interest toward a nonproliferation verification interest (placing greater importance on groundshock behavior at lower stress levels), several thoughts come to mind:

(1) The HYDROPLUS community is lucky if the gas gun samples represent the large scale rockmass well. If large-scale joint systems, variations of rockmass properties, faults or contacts are found in the volume of interest, the problem is harder. Modelers have calculated the effects of certain discrete contacts or joints. We need to create and benchmark models for pervasive joint systems. The role of statistical variations in rockmass properties has been addressed³⁸, but is still not completely understood at the present time.

(2) The roles of hoop stresses in reducing mean stress and causing pullback, and other unique properties of divergent waves, need to be assessed. Wave divergence effects may be assessed with actual divergent wave environments. While such environments can be produced from impact experiments (e.g. propagating a shock along a rod), the more traditional divergent wave experiments (exploding wire or point charge) may allow a more straightforward relation to physical systems of interest. Planar impact tests, however, are still needed for benchmarking material models because the stress pulses are more readily tailored for particular measurements.

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Appendix A

Tabulated Release Paths

Release paths for the tests discussed in this report are presented in a filtered form in this Appendix. Each path is represented by the first (Hugoniot), second and last points on the portion of the release considered valid, with the interval between the second and last points covered by five equally spaced points. Units are GPa for pressure, cm^3/gm for volume, gm/cm^3 for density, km/sec for particle velocity U_p , and MJ/kg for specific energy. Particle velocity is presented both incrementing upward and incrementing downward from the Hugoniot value to facilitate comparison with the results of other experiments; the true sense for the reverse-ballistic experiments is upward incrementation since the shock and the release are propagating in opposite directions.

Shot names and numbers are the same as those used in the text and tables. They are arranged alphabetically. The B_i parameters are listed consecutively; e.g. for AEP 2, we have $B_0 = 31.0 \times 10^{10}$ Pa, $B_1 = 2.05$, $B_2 = 1.35$ and $B_3 = 0.25$, and for TFA 1, $B_0 = 3.90 \times 10^{10}$ Pa, $B_1 = 1.4$, $B_2 = 0.7$ and $B_3 = 0.1$, with a 0.163 mm gap between the sample and the cup.

AEP 2 B = 31, 2.05, 1.35, 0.25

Pressure	Volume	Density	Up (+)	Energy	Up (-)
0.12222E+11	0.30618E-03	0.32660E+04	0.10927E+04	0.59700E+06	0.10927E+04
0.12075E+11	0.30715E-03	0.32558E+04	0.11046E+04	0.58546E+06	0.10808E+04
0.10474E+11	0.30959E-03	0.32300E+04	0.11670E+04	0.55869E+06	0.10184E+04
0.88723E+10	0.31291E-03	0.31958E+04	0.12396E+04	0.52791E+06	0.94582E+03
0.72709E+10	0.31754E-03	0.31492E+04	0.13256E+04	0.49194E+06	0.85976E+03
0.56695E+10	0.32433E-03	0.30834E+04	0.14297E+04	0.44967E+06	0.75571E+03
0.40682E+10	0.33476E-03	0.29872E+04	0.15587E+04	0.40084E+06	0.62670E+03
0.24668E+10	0.35165E-03	0.28437E+04	0.17227E+04	0.34822E+06	0.46268E+03

GTA 1 B = 9, 1.9, 1.9, 0.8

Pressure	Volume	Density	Up (+)	Energy	Up (-)
0.50250E+10	0.35125E-03	0.28470E+04	0.55691E+03	0.15507E+06	0.55691E+03
0.50234E+10	0.35197E-03	0.28412E+04	0.55799E+03	0.15145E+06	0.55583E+03
0.42813E+10	0.35588E-03	0.28100E+04	0.61179E+03	0.13363E+06	0.50202E+03
0.35392E+10	0.36099E-03	0.27702E+04	0.67333E+03	0.11420E+06	0.44049E+03
0.27971E+10	0.36754E-03	0.27208E+04	0.74303E+03	0.94104E+05	0.37078E+03
0.20551E+10	0.37571E-03	0.26616E+04	0.82087E+03	0.75117E+05	0.29294E+03
0.13130E+10	0.38565E-03	0.25930E+04	0.90672E+03	0.59356E+05	0.20709E+03
0.57089E+09	0.39775E-03	0.25141E+04	0.10036E+04	0.48872E+05	0.11023E+03

GTA 2 B = 11, 1.3, 0.47, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.92340E+10	0.32776E-03	0.30510E+04	0.89455E+03	0.40011E+06	0.89455E+03
0.92305E+10	0.32832E-03	0.30458E+04	0.89595E+03	0.39497E+06	0.89316E+03
0.79171E+10	0.33374E-03	0.29963E+04	0.98034E+03	0.34955E+06	0.80877E+03
0.66038E+10	0.34038E-03	0.29379E+04	0.10736E+04	0.30305E+06	0.71550E+03
0.52904E+10	0.34864E-03	0.28683E+04	0.11777E+04	0.25571E+06	0.61138E+03
0.39771E+10	0.35917E-03	0.27843E+04	0.12952E+04	0.20886E+06	0.49389E+03
0.26637E+10	0.37289E-03	0.26817E+04	0.14293E+04	0.16540E+06	0.35973E+03
0.13504E+10	0.39119E-03	0.25563E+04	0.15843E+04	0.13086E+06	0.20482E+03

GTA 3 B = 26, 1.6, 0.7, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.15683E+11	0.29630E-03	0.33750E+04	0.13537E+04	0.91621E+06	0.13537E+04
0.15646E+11	0.29684E-03	0.33688E+04	0.13581E+04	0.90773E+06	0.13492E+04
0.13588E+11	0.30049E-03	0.33280E+04	0.14447E+04	0.85580E+06	0.12627E+04
0.11529E+11	0.30509E-03	0.32778E+04	0.15420E+04	0.80042E+06	0.11653E+04
0.94712E+10	0.31105E-03	0.32150E+04	0.16526E+04	0.74027E+06	0.10547E+04
0.74129E+10	0.31901E-03	0.31347E+04	0.17806E+04	0.67581E+06	0.92680E+03
0.53546E+10	0.33001E-03	0.30302E+04	0.19308E+04	0.60857E+06	0.77651E+03
0.32963E+10	0.34573E-03	0.28924E+04	0.21105E+04	0.54387E+06	0.59688E+03

GTB 3 B = 9.5, 1.7, 1.3, 0.243 Cup=1.873mm Gap=.3mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.44270E+10	0.35868E-03	0.27880E+04	0.58361E+03	0.17030E+06	0.58361E+03
0.44240E+10	0.35913E-03	0.27845E+04	0.58477E+03	0.16833E+06	0.58245E+03
0.37569E+10	0.36260E-03	0.27579E+04	0.63288E+03	0.15441E+06	0.53433E+03
0.30899E+10	0.36710E-03	0.27241E+04	0.68759E+03	0.13949E+06	0.47962E+03
0.24228E+10	0.37284E-03	0.26822E+04	0.74943E+03	0.12422E+06	0.41778E+03
0.17558E+10	0.37992E-03	0.26321E+04	0.81817E+03	0.11017E+06	0.34905E+03
0.10887E+10	0.38815E-03	0.25763E+04	0.89227E+03	0.99532E+05	0.27494E+03
0.42166E+09	0.39696E-03	0.25191E+04	0.96891E+03	0.94139E+05	0.19830E+03

GTB 4 B =10.0, 1.8, 1.05, -0.18 Gap=0.27mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.46260E+10	0.36590E-03	0.27330E+04	0.57076E+03	0.16288E+06	0.57076E+03
0.46121E+10	0.36610E-03	0.27315E+04	0.57243E+03	0.16196E+06	0.56909E+03
0.39098E+10	0.36964E-03	0.27053E+04	0.62352E+03	0.14719E+06	0.51800E+03
0.32075E+10	0.37440E-03	0.26709E+04	0.68126E+03	0.13073E+06	0.46026E+03
0.25052E+10	0.38082E-03	0.26259E+04	0.74839E+03	0.11293E+06	0.39313E+03
0.18029E+10	0.38915E-03	0.25697E+04	0.82482E+03	0.95846E+05	0.31670E+03
0.11006E+10	0.39869E-03	0.25083E+04	0.90669E+03	0.83990E+05	0.23483E+03
0.39826E+09	0.40790E-03	0.24516E+04	0.98707E+03	0.79751E+05	0.15445E+03

GTB 5 B =12.0, 1.7, 1.28, 0.365 Gap=0.12mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.58550E+10	0.34868E-03	0.28680E+04	0.71728E+03	0.25725E+06	0.71728E+03
0.58469E+10	0.34922E-03	0.28635E+04	0.71938E+03	0.25405E+06	0.71518E+03
0.50067E+10	0.35267E-03	0.28354E+04	0.77320E+03	0.23575E+06	0.66136E+03
0.41665E+10	0.35710E-03	0.28004E+04	0.83413E+03	0.21607E+06	0.60043E+03
0.33263E+10	0.36277E-03	0.27565E+04	0.90315E+03	0.19557E+06	0.53142E+03
0.24860E+10	0.37000E-03	0.27027E+04	0.98098E+03	0.17549E+06	0.45359E+03
0.16458E+10	0.37904E-03	0.26383E+04	0.10681E+04	0.15789E+06	0.36648E+03
0.80561E+09	0.39009E-03	0.25635E+04	0.11644E+04	0.14540E+06	0.27015E+03

GTB 6 B =22.0, 2.2, 1.5, 0.1

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.84670E+10	0.33467E-03	0.29880E+04	0.89796E+03	0.40317E+06	0.89796E+03
0.83675E+10	0.33563E-03	0.29795E+04	0.90772E+03	0.39520E+06	0.88820E+03
0.73942E+10	0.33785E-03	0.29599E+04	0.95384E+03	0.37809E+06	0.84207E+03
0.64210E+10	0.34079E-03	0.29344E+04	0.10073E+04	0.35837E+06	0.78867E+03
0.54477E+10	0.34480E-03	0.29002E+04	0.10697E+04	0.33520E+06	0.72623E+03
0.44744E+10	0.35041E-03	0.28538E+04	0.11435E+04	0.30812E+06	0.65247E+03
0.35012E+10	0.35828E-03	0.27911E+04	0.12309E+04	0.27765E+06	0.56504E+03
0.25279E+10	0.36886E-03	0.27111E+04	0.13323E+04	0.24685E+06	0.46363E+03

HP 1 B = 4.05, 1, 1, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.32520E+10	0.43234E-03	0.23130E+04	0.51826E+03	0.13430E+06	0.51826E+03
0.32435E+10	0.43258E-03	0.23117E+04	0.51968E+03	0.13353E+06	0.51684E+03
0.27850E+10	0.43881E-03	0.22789E+04	0.57310E+03	0.11496E+06	0.46342E+03
0.23265E+10	0.44583E-03	0.22430E+04	0.62981E+03	0.97753E+05	0.40671E+03
0.18680E+10	0.45358E-03	0.22047E+04	0.68944E+03	0.82439E+05	0.34708E+03
0.14094E+10	0.46201E-03	0.21645E+04	0.75161E+03	0.69754E+05	0.28491E+03
0.95092E+09	0.47110E-03	0.21227E+04	0.81615E+03	0.60101E+05	0.22037E+03
0.49240E+09	0.48093E-03	0.20793E+04	0.88328E+03	0.53852E+05	0.15325E+03

HP 2 B = 6.0, 1.7, 1.3, 0.25

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.36704E+10	0.42251E-03	0.23668E+04	0.58493E+03	0.17107E+06	0.58493E+03
0.37930E+10	0.42088E-03	0.23760E+04	0.59910E+03	0.17739E+06	0.57077E+03
0.32662E+10	0.42652E-03	0.23445E+04	0.65328E+03	0.15767E+06	0.51659E+03
0.27394E+10	0.43297E-03	0.23097E+04	0.71151E+03	0.13881E+06	0.45836E+03
0.22126E+10	0.44108E-03	0.22672E+04	0.77685E+03	0.11933E+06	0.39302E+03
0.16858E+10	0.45105E-03	0.22171E+04	0.84930E+03	0.10064E+06	0.32057E+03
0.11590E+10	0.46277E-03	0.21609E+04	0.92785E+03	0.85021E+05	0.24202E+03
0.63226E+09	0.47569E-03	0.21022E+04	0.10104E+04	0.74539E+05	0.15951E+03

HP 3 B = 7.40, 1.9, 1.65, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.56110E+10	0.40161E-03	0.24900E+04	0.80255E+03	0.32204E+06	0.80255E+03
0.55002E+10	0.40249E-03	0.24845E+04	0.81246E+03	0.31721E+06	0.79263E+03
0.47543E+10	0.40862E-03	0.24472E+04	0.87979E+03	0.28637E+06	0.72530E+03
0.40084E+10	0.41652E-03	0.24009E+04	0.95647E+03	0.25264E+06	0.64862E+03
0.32624E+10	0.42662E-03	0.23440E+04	0.10432E+04	0.21699E+06	0.56189E+03
0.25165E+10	0.43928E-03	0.22765E+04	0.11404E+04	0.18165E+06	0.46473E+03
0.17706E+10	0.45461E-03	0.21997E+04	0.12473E+04	0.15046E+06	0.35783E+03
0.10247E+10	0.47237E-03	0.21170E+04	0.13623E+04	0.12725E+06	0.24275E+03

HP 4 B = 10.5, 1.75, 1.6, 0.7

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.98500E+10	0.37051E-03	0.26990E+04	0.12042E+04	0.72508E+06	0.12042E+04
0.96953E+10	0.37136E-03	0.26928E+04	0.12157E+04	0.71689E+06	0.11928E+04
0.84274E+10	0.37854E-03	0.26417E+04	0.13107E+04	0.65327E+06	0.10977E+04
0.71595E+10	0.38747E-03	0.25808E+04	0.14171E+04	0.58582E+06	0.99134E+03
0.58916E+10	0.39861E-03	0.25088E+04	0.15359E+04	0.51567E+06	0.87261E+03
0.46237E+10	0.41246E-03	0.24245E+04	0.16683E+04	0.44563E+06	0.74016E+03
0.33558E+10	0.43000E-03	0.23256E+04	0.18174E+04	0.37854E+06	0.59111E+03
0.20879E+10	0.45347E-03	0.22052E+04	0.19896E+04	0.31743E+06	0.41882E+03

HP 5 B = 12.0, 1.3, 1.0, 0.75

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.13016E+11	0.35907E-03	0.27850E+04	0.14317E+04	0.10249E+07	0.14317E+04
0.12823E+11	0.35977E-03	0.27796E+04	0.14434E+04	0.10160E+07	0.14201E+04
0.11437E+11	0.36624E-03	0.27304E+04	0.15380E+04	0.93968E+06	0.13255E+04
0.10050E+11	0.37368E-03	0.26762E+04	0.16395E+04	0.86311E+06	0.12240E+04
0.86640E+10	0.38221E-03	0.26164E+04	0.17483E+04	0.78672E+06	0.11152E+04
0.72777E+10	0.39208E-03	0.25505E+04	0.18652E+04	0.71147E+06	0.99827E+03
0.58913E+10	0.40374E-03	0.24768E+04	0.19923E+04	0.63796E+06	0.87115E+03
0.45050E+10	0.41806E-03	0.23920E+04	0.21332E+04	0.56615E+06	0.73032E+03

PFP1 B = 13.0, 0.65, 1.1, 0.8

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.13270E+10	0.35753E-03	0.27970E+04	0.10100E+03	0.51117E+04	0.10100E+03
0.12694E+10	0.35756E-03	0.27967E+04	0.10238E+03	0.50705E+04	0.99617E+02
0.11163E+10	0.35801E-03	0.27932E+04	0.11072E+03	0.45383E+04	0.91275E+02
0.96321E+09	0.35849E-03	0.27895E+04	0.11924E+03	0.40581E+04	0.82760E+02
0.81012E+09	0.35898E-03	0.27857E+04	0.12788E+03	0.36327E+04	0.74125E+02
0.65703E+09	0.35947E-03	0.27819E+04	0.13654E+03	0.32856E+04	0.65461E+02
0.50393E+09	0.35996E-03	0.27781E+04	0.14522E+03	0.30178E+04	0.56784E+02
0.35084E+09	0.36045E-03	0.27743E+04	0.15387E+03	0.28200E+04	0.48128E+02

PFP2 B = 10.2, 0.3, 0.5, 0.6

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.25420E+10	0.35162E-03	0.28440E+04	0.17600E+03	0.15444E+05	0.17600E+03
0.24942E+10	0.35169E-03	0.28434E+04	0.17780E+03	0.15276E+05	0.17420E+03
0.21949E+10	0.35277E-03	0.28347E+04	0.19585E+03	0.12750E+05	0.15615E+03
0.18955E+10	0.35389E-03	0.28257E+04	0.21413E+03	0.10491E+05	0.13787E+03
0.15962E+10	0.35503E-03	0.28167E+04	0.23259E+03	0.85438E+04	0.11941E+03
0.12969E+10	0.35620E-03	0.28074E+04	0.25127E+03	0.68785E+04	0.10073E+03
0.99757E+09	0.35740E-03	0.27980E+04	0.27025E+03	0.55428E+04	0.81748E+02
0.69825E+09	0.35866E-03	0.27881E+04	0.28970E+03	0.45054E+04	0.62299E+02

PFP3 B = 14.5, 0.6, 0, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.35370E+10	0.34542E-03	0.28950E+04	0.25700E+03	0.33217E+05	0.25700E+03
0.34598E+10	0.34549E-03	0.28945E+04	0.25919E+03	0.33005E+05	0.25481E+03
0.30052E+10	0.34668E-03	0.28844E+04	0.28257E+03	0.29144E+05	0.23143E+03
0.25506E+10	0.34800E-03	0.28736E+04	0.30698E+03	0.25538E+05	0.20702E+03
0.20960E+10	0.34943E-03	0.28618E+04	0.33252E+03	0.22265E+05	0.18148E+03
0.16414E+10	0.35102E-03	0.28488E+04	0.35940E+03	0.19366E+05	0.15460E+03
0.11868E+10	0.35281E-03	0.28344E+04	0.38786E+03	0.16920E+05	0.12614E+03
0.73217E+09	0.35483E-03	0.28182E+04	0.41822E+03	0.15042E+05	0.95784E+02

PFP4 B = 13.0, 0.2, 0.5, 0.6

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.49470E+10	0.33557E-03	0.29800E+04	0.37100E+03	0.68767E+05	0.37100E+03
0.48544E+10	0.33564E-03	0.29794E+04	0.37354E+03	0.68432E+05	0.36846E+03
0.42970E+10	0.33722E-03	0.29655E+04	0.40319E+03	0.61261E+05	0.33881E+03
0.37396E+10	0.33881E-03	0.29515E+04	0.43301E+03	0.54963E+05	0.30899E+03
0.31822E+10	0.34042E-03	0.29375E+04	0.46294E+03	0.49526E+05	0.27906E+03
0.26248E+10	0.34204E-03	0.29236E+04	0.49302E+03	0.44945E+05	0.24898E+03
0.20674E+10	0.34369E-03	0.29096E+04	0.52332E+03	0.41208E+05	0.21868E+03
0.15100E+10	0.34538E-03	0.28953E+04	0.55403E+03	0.38279E+05	0.18797E+03

PFP5 B = 14, 0.85, 0, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.81860E+10	0.32712E-03	0.30570E+04	0.55500E+03	0.15381E+06	0.55500E+03
0.80876E+10	0.32721E-03	0.30561E+04	0.55803E+03	0.15306E+06	0.55197E+03
0.73440E+10	0.32924E-03	0.30372E+04	0.59693E+03	0.13744E+06	0.51307E+03
0.66004E+10	0.33146E-03	0.30169E+04	0.63750E+03	0.12217E+06	0.47250E+03
0.58568E+10	0.33389E-03	0.29950E+04	0.67997E+03	0.10724E+06	0.43003E+03
0.51133E+10	0.33658E-03	0.29711E+04	0.72468E+03	0.92695E+05	0.38532E+03
0.43697E+10	0.33959E-03	0.29447E+04	0.77200E+03	0.78618E+05	0.33800E+03
0.36261E+10	0.34301E-03	0.29153E+04	0.82245E+03	0.65107E+05	0.28755E+03

PFR1 B = 9.6, 0.0, 0.4, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.23850E+10	0.35149E-03	0.28450E+04	0.17800E+03	0.15904E+05	0.17800E+03
0.23680E+10	0.35152E-03	0.28448E+04	0.17861E+03	0.15851E+05	0.17739E+03
0.21000E+10	0.35254E-03	0.28366E+04	0.19513E+03	0.13601E+05	0.16087E+03
0.18319E+10	0.35355E-03	0.28285E+04	0.21157E+03	0.11645E+05	0.14443E+03
0.15639E+10	0.35454E-03	0.28206E+04	0.22792E+03	0.99817E+04	0.12808E+03
0.12958E+10	0.35553E-03	0.28127E+04	0.24420E+03	0.85939E+04	0.11180E+03
0.10278E+10	0.35651E-03	0.28050E+04	0.26042E+03	0.74998E+04	0.95586E+02
0.75972E+09	0.35750E-03	0.27972E+04	0.27667E+03	0.66504E+04	0.79327E+02

PFR2 B = 16, 0, 0, 0.9

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.48320E+10	0.34025E-03	0.29390E+04	0.34800E+03	0.60670E+05	0.34800E+03
0.47321E+10	0.34030E-03	0.29386E+04	0.35010E+03	0.60464E+05	0.34590E+03
0.41403E+10	0.34165E-03	0.29270E+04	0.37839E+03	0.54492E+05	0.31761E+03
0.35485E+10	0.34301E-03	0.29154E+04	0.40678E+03	0.49336E+05	0.28922E+03
0.29567E+10	0.34441E-03	0.29036E+04	0.43551E+03	0.44900E+05	0.26049E+03
0.23649E+10	0.34588E-03	0.28912E+04	0.46503E+03	0.41085E+05	0.23097E+03
0.17731E+10	0.34751E-03	0.28776E+04	0.49604E+03	0.37813E+05	0.19996E+03
0.11813E+10	0.34945E-03	0.28617E+04	0.52993E+03	0.35030E+05	0.16607E+03

PFT1 B = 8.8, 0.2, 0.5, 1.1

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.10930E+10	0.36206E-03	0.27620E+04	0.76000E+02	0.28781E+04	0.76000E+02
0.10650E+10	0.36208E-03	0.27618E+04	0.76767E+02	0.28561E+04	0.75233E+02
0.94183E+09	0.36260E-03	0.27579E+04	0.84772E+02	0.23441E+04	0.67228E+02
0.81865E+09	0.36313E-03	0.27539E+04	0.92844E+02	0.18901E+04	0.59156E+02
0.69548E+09	0.36367E-03	0.27497E+04	0.10099E+03	0.14886E+04	0.51013E+02
0.57230E+09	0.36422E-03	0.27455E+04	0.10927E+03	0.11436E+04	0.42729E+02
0.44912E+09	0.36482E-03	0.27411E+04	0.11780E+03	0.85034E+03	0.34201E+02
0.32595E+09	0.36547E-03	0.27362E+04	0.12679E+03	0.60212E+03	0.25208E+02

PFT2 B = 7.7, 0, 0, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.23600E+10	0.35211E-03	0.28400E+04	0.18100E+03	0.16457E+05	0.18100E+03
0.23382E+10	0.35221E-03	0.28392E+04	0.18248E+03	0.16223E+05	0.17952E+03
0.20128E+10	0.35376E-03	0.28268E+04	0.20492E+03	0.12892E+05	0.15708E+03
0.16873E+10	0.35530E-03	0.28144E+04	0.22736E+03	0.10064E+05	0.13464E+03
0.13619E+10	0.35685E-03	0.28023E+04	0.25002E+03	0.77477E+04	0.11198E+03
0.10365E+10	0.35840E-03	0.27902E+04	0.27246E+03	0.59673E+04	0.89539E+02
0.71105E+09	0.35995E-03	0.27781E+04	0.29489E+03	0.46874E+04	0.67102E+02
0.38562E+09	0.36150E-03	0.27663E+04	0.31734E+03	0.38858E+04	0.44657E+02

PFT3 B = 8.8, 0.2, 0.5, 0.6

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.35300E+10	0.34868E-03	0.28680E+04	0.25000E+03	0.31203E+05	0.25000E+03
0.35120E+10	0.34874E-03	0.28674E+04	0.25110E+03	0.30969E+05	0.24890E+03
0.30855E+10	0.35053E-03	0.28528E+04	0.27875E+03	0.25091E+05	0.22125E+03
0.26590E+10	0.35235E-03	0.28380E+04	0.30661E+03	0.19914E+05	0.19339E+03
0.22326E+10	0.35418E-03	0.28233E+04	0.33456E+03	0.15512E+05	0.16544E+03
0.18061E+10	0.35604E-03	0.28087E+04	0.36266E+03	0.11875E+05	0.13734E+03
0.13796E+10	0.35792E-03	0.27939E+04	0.39102E+03	0.89735E+04	0.10898E+03
0.95314E+09	0.35987E-03	0.27788E+04	0.41986E+03	0.67696E+04	0.80144E+02

PFT4 B = 11.5, 0.7, 0, 0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.50790E+10	0.34211E-03	0.29230E+04	0.35600E+03	0.63538E+05	0.35600E+03
0.50520E+10	0.34215E-03	0.29227E+04	0.35692E+03	0.63379E+05	0.35508E+03
0.44852E+10	0.34403E-03	0.29067E+04	0.38964E+03	0.54420E+05	0.32236E+03
0.39185E+10	0.34609E-03	0.28894E+04	0.42379E+03	0.45851E+05	0.28821E+03
0.33517E+10	0.34835E-03	0.28707E+04	0.45953E+03	0.37777E+05	0.25247E+03
0.27849E+10	0.35085E-03	0.28502E+04	0.49717E+03	0.30234E+05	0.21483E+03
0.22182E+10	0.35365E-03	0.28276E+04	0.53702E+03	0.23364E+05	0.17498E+03
0.16514E+10	0.35684E-03	0.28024E+04	0.57954E+03	0.17316E+05	0.13246E+03

PFT5 B = 18.0, 1.2, 0.3, -0.2

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.86500E+10	0.32626E-03	0.30650E+04	0.57400E+03	0.16450E+06	0.57400E+03
0.85402E+10	0.32628E-03	0.30649E+04	0.57523E+03	0.16438E+06	0.57277E+03
0.76465E+10	0.32823E-03	0.30466E+04	0.61704E+03	0.14864E+06	0.53096E+03
0.67528E+10	0.33047E-03	0.30260E+04	0.66173E+03	0.13272E+06	0.48627E+03
0.58591E+10	0.33304E-03	0.30026E+04	0.70970E+03	0.11668E+06	0.43830E+03
0.49654E+10	0.33604E-03	0.29759E+04	0.76142E+03	0.10071E+06	0.38658E+03
0.40717E+10	0.33953E-03	0.29452E+04	0.81726E+03	0.85182E+05	0.33074E+03
0.31780E+10	0.34361E-03	0.29103E+04	0.87759E+03	0.70651E+05	0.27041E+03

PFT 6 B = 5.0, 0.2, 0, 0 Gap=0.07 mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.25700E+10	0.35511E-03	0.28160E+04	0.17600E+03	0.15412E+05	0.17600E+03
0.25270E+10	0.35512E-03	0.28160E+04	0.17633E+03	0.15405E+05	0.17567E+03
0.21278E+10	0.35624E-03	0.28071E+04	0.19749E+03	0.12899E+05	0.15451E+03
0.17286E+10	0.35751E-03	0.27971E+04	0.21999E+03	0.10586E+05	0.13201E+03
0.13293E+10	0.35897E-03	0.27857E+04	0.24420E+03	0.84755E+04	0.10780E+03
0.93012E+09	0.36071E-03	0.27723E+04	0.27055E+03	0.66441E+04	0.81450E+02
0.53090E+09	0.36286E-03	0.27559E+04	0.29976E+03	0.52176E+04	0.52232E+02
0.13168E+09	0.36564E-03	0.27349E+04	0.33305E+03	0.44210E+04	0.18947E+02

PFT 7 B = 7.5, 0.1, 0, 0 Gap=0.0500 mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.36340E+10	0.34868E-03	0.28680E+04	0.25300E+03	0.31782E+05	0.25300E+03
0.35688E+10	0.34870E-03	0.28678E+04	0.25416E+03	0.31708E+05	0.25184E+03
0.30037E+10	0.35023E-03	0.28553E+04	0.28353E+03	0.26951E+05	0.22247E+03
0.24387E+10	0.35189E-03	0.28418E+04	0.31419E+03	0.22779E+05	0.19181E+03
0.18736E+10	0.35373E-03	0.28270E+04	0.34644E+03	0.19184E+05	0.15956E+03
0.13085E+10	0.35578E-03	0.28107E+04	0.38050E+03	0.16291E+05	0.12550E+03
0.74346E+09	0.35811E-03	0.27925E+04	0.41673E+03	0.14248E+05	0.89264E+02
0.17839E+09	0.36079E-03	0.27717E+04	0.45565E+03	0.13277E+05	0.50349E+02

RY 2 B = 16.00, 1.25, 0.57, 0.28 (0.100mm gap) QVC = 4.0 required extra viscosity)

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.38520E+10	0.37411E-03	0.26730E+04	0.47900E+03	0.11467E+06	0.47900E+03
0.38484E+10	0.37520E-03	0.26652E+04	0.48099E+03	0.11048E+06	0.47701E+03
0.33122E+10	0.37682E-03	0.26538E+04	0.51043E+03	0.10489E+06	0.44757E+03
0.27760E+10	0.37876E-03	0.26402E+04	0.54265E+03	0.99259E+05	0.41535E+03
0.22397E+10	0.38113E-03	0.26238E+04	0.57828E+03	0.93597E+05	0.37972E+03
0.17035E+10	0.38412E-03	0.26034E+04	0.61829E+03	0.88007E+05	0.33971E+03
0.11673E+10	0.38811E-03	0.25767E+04	0.66449E+03	0.82575E+05	0.29351E+03
0.63108E+09	0.39408E-03	0.25376E+04	0.72095E+03	0.77519E+05	0.23705E+03

RY 4 B = 23, 1.65, 0.7, -0.2

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.14486E+11	0.30855E-03	0.32410E+04	0.13820E+04	0.95594E+06	0.13820E+04
0.14323E+11	0.30952E-03	0.32308E+04	0.13946E+04	0.94211E+06	0.13694E+04
0.12584E+11	0.31327E-03	0.31922E+04	0.14753E+04	0.89342E+06	0.12887E+04
0.10845E+11	0.31796E-03	0.31450E+04	0.15656E+04	0.84068E+06	0.11984E+04
0.91060E+10	0.32393E-03	0.30871E+04	0.16673E+04	0.78372E+06	0.10967E+04
0.73670E+10	0.33161E-03	0.30156E+04	0.17829E+04	0.72335E+06	0.98113E+03
0.56280E+10	0.34151E-03	0.29281E+04	0.19140E+04	0.66230E+06	0.85001E+03
0.38890E+10	0.35389E-03	0.28258E+04	0.20606E+04	0.60700E+06	0.70336E+03

RY 5 B = 24.0, 2.2, 2.1, 0.7

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.11603E+11	0.32712E-03	0.30570E+04	0.11406E+04	0.65043E+06	0.11406E+04
0.11374E+11	0.32813E-03	0.30476E+04	0.11558E+04	0.63901E+06	0.11253E+04
0.99836E+10	0.33117E-03	0.30197E+04	0.12207E+04	0.60758E+06	0.10604E+04
0.85931E+10	0.33514E-03	0.29838E+04	0.12948E+04	0.57210E+06	0.98623E+03
0.72027E+10	0.34032E-03	0.29384E+04	0.13798E+04	0.53280E+06	0.90136E+03
0.58123E+10	0.34701E-03	0.28818E+04	0.14760E+04	0.49142E+06	0.80502E+03
0.44218E+10	0.35534E-03	0.28142E+04	0.15837E+04	0.45149E+06	0.69740E+03
0.30314E+10	0.36526E-03	0.27378E+04	0.17011E+04	0.41751E+06	0.58001E+03

TFA 1 B = 3.90, 1.4, 0.7, 0.1 G=.163

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.22966E+10	0.47444E-03	0.21078E+04	0.39393E+03	0.77591E+05	0.39393E+03
0.22810E+10	0.47464E-03	0.21068E+04	0.39573E+03	0.77120E+05	0.39213E+03
0.19643E+10	0.47935E-03	0.20861E+04	0.43411E+03	0.67237E+05	0.35376E+03
0.16476E+10	0.48517E-03	0.20611E+04	0.47697E+03	0.56973E+05	0.31089E+03
0.13309E+10	0.49245E-03	0.20307E+04	0.52496E+03	0.46414E+05	0.26290E+03
0.10143E+10	0.50161E-03	0.19936E+04	0.57880E+03	0.35986E+05	0.20907E+03
0.69757E+09	0.51325E-03	0.19484E+04	0.63947E+03	0.26379E+05	0.14839E+03
0.38088E+09	0.52809E-03	0.18936E+04	0.70799E+03	0.18747E+05	0.79877E+02

TFA 2 B = 14.00, 2.3, 2.0, 0.2 G=.251

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.11475E+11	0.36319E-03	0.27534E+04	0.14407E+04	0.10378E+07	0.14407E+04
0.11455E+11	0.36326E-03	0.27529E+04	0.14419E+04	0.10370E+07	0.14395E+04
0.10424E+11	0.36758E-03	0.27205E+04	0.15082E+04	0.99138E+06	0.13731E+04
0.93934E+10	0.37292E-03	0.26815E+04	0.15824E+04	0.93981E+06	0.12990E+04
0.83626E+10	0.37964E-03	0.26341E+04	0.16656E+04	0.88170E+06	0.12158E+04
0.73319E+10	0.38800E-03	0.25773E+04	0.17583E+04	0.81779E+06	0.11231E+04
0.63011E+10	0.39825E-03	0.25110E+04	0.18611E+04	0.74996E+06	0.10203E+04
0.52703E+10	0.41032E-03	0.24372E+04	0.19726E+04	0.68258E+06	0.90878E+03

TFA 3 B = 36.50, 3.3, 3.3, 1.05

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.27505E+11	0.29542E-03	0.33850E+04	0.26058E+04	0.33952E+07	0.26058E+04
0.27184E+11	0.29591E-03	0.33794E+04	0.26183E+04	0.33820E+07	0.25933E+04
0.25651E+11	0.29826E-03	0.33528E+04	0.26772E+04	0.33212E+07	0.25345E+04
0.24118E+11	0.30145E-03	0.33173E+04	0.27470E+04	0.32444E+07	0.24646E+04
0.22585E+11	0.30541E-03	0.32743E+04	0.28249E+04	0.31548E+07	0.23868E+04
0.21052E+11	0.31049E-03	0.32208E+04	0.29130E+04	0.30469E+07	0.22987E+04
0.19519E+11	0.31715E-03	0.31532E+04	0.30140E+04	0.29147E+07	0.21977E+04
0.17986E+11	0.32627E-03	0.30649E+04	0.31484E+04	0.27462E+07	0.20632E+04

TFA 4 B = 55.00, 2.0, 1.6, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.46888E+11	0.25920E-03	0.38580E+04	0.35759E+04	0.63935E+07	0.35759E+04
0.45928E+11	0.25950E-03	0.38536E+04	0.35928E+04	0.63799E+07	0.35589E+04
0.42591E+11	0.26313E-03	0.38006E+04	0.37026E+04	0.62285E+07	0.34492E+04
0.39253E+11	0.26729E-03	0.37414E+04	0.38204E+04	0.60697E+07	0.33314E+04
0.35916E+11	0.27212E-03	0.36748E+04	0.39474E+04	0.59014E+07	0.32044E+04
0.32578E+11	0.27785E-03	0.35993E+04	0.40856E+04	0.57198E+07	0.30662E+04
0.29241E+11	0.28447E-03	0.35155E+04	0.42341E+04	0.55297E+07	0.29177E+04
0.25903E+11	0.29226E-03	0.34216E+04	0.43954E+04	0.53247E+07	0.27564E+04

TFA 5 B = 55.0, 2, 1.4, 0.35 (0.04 mm gap)

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.41033E+11	0.26116E-03	0.38290E+04	0.33611E+04	0.56485E+07	0.33611E+04
0.40462E+11	0.26206E-03	0.38159E+04	0.33838E+04	0.56124E+07	0.33385E+04
0.37523E+11	0.26493E-03	0.37746E+04	0.34753E+04	0.55057E+07	0.32470E+04
0.34585E+11	0.26836E-03	0.37264E+04	0.35756E+04	0.53894E+07	0.31466E+04
0.31646E+11	0.27255E-03	0.36690E+04	0.36866E+04	0.52596E+07	0.30356E+04
0.28707E+11	0.27767E-03	0.36014E+04	0.38092E+04	0.51135E+07	0.29130E+04
0.25769E+11	0.28409E-03	0.35200E+04	0.39464E+04	0.49472E+07	0.27758E+04
0.22830E+11	0.29241E-03	0.34198E+04	0.41026E+04	0.47515E+07	0.26196E+04

TFA 6 B = 95.0, 2.0, 1.6, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.10058E+12	0.23886E-03	0.41865E+04	0.55782E+04	0.15558E+08	0.55782E+04
0.10641E+12	0.23896E-03	0.41848E+04	0.55821E+04	0.15549E+08	0.55743E+04
0.93708E+11	0.24321E-03	0.41119E+04	0.57509E+04	0.15169E+08	0.54055E+04
0.87005E+11	0.24808E-03	0.40315E+04	0.59315E+04	0.14773E+08	0.52248E+04
0.80303E+11	0.25362E-03	0.39437E+04	0.61239E+04	0.14356E+08	0.50324E+04
0.73601E+11	0.25995E-03	0.38475E+04	0.63298E+04	0.13913E+08	0.48265E+04
0.66898E+11	0.26731E-03	0.37415E+04	0.65518E+04	0.13439E+08	0.46045E+04
0.60196E+11	0.27577E-03	0.36263E+04	0.67898E+04	0.12923E+08	0.43665E+04

TFA 7 B = 16.00, 3.4, 3.5, 0.9 0.1 mm=G

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.17504E+11	0.32175E-03	0.31080E+04	0.19180E+04	0.18394E+07	0.19180E+04
0.17417E+11	0.32176E-03	0.31079E+04	0.19188E+04	0.18392E+07	0.19172E+04
0.16710E+11	0.32431E-03	0.30835E+04	0.19612E+04	0.17967E+07	0.18748E+04
0.16003E+11	0.32727E-03	0.30556E+04	0.20069E+04	0.17493E+07	0.18291E+04
0.15296E+11	0.33072E-03	0.30237E+04	0.20564E+04	0.16963E+07	0.17796E+04
0.14589E+11	0.33482E-03	0.29867E+04	0.21101E+04	0.16364E+07	0.17259E+04
0.13882E+11	0.33968E-03	0.29439E+04	0.21688E+04	0.15683E+07	0.16672E+04
0.13175E+11	0.34558E-03	0.28937E+04	0.22333E+04	0.14897E+07	0.16027E+04

TFA 10 B = 4.50, 1.65, 1.65, 0.7

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.50270E+10	0.44444E-03	0.22500E+04	0.71922E+03	0.25864E+06	0.71922E+03
0.49924E+10	0.44478E-03	0.22483E+04	0.72262E+03	0.25698E+06	0.71583E+03
0.44741E+10	0.45170E-03	0.22139E+04	0.78248E+03	0.22484E+06	0.65597E+03
0.39559E+10	0.45980E-03	0.21749E+04	0.84727E+03	0.19184E+06	0.59118E+03
0.34376E+10	0.46923E-03	0.21312E+04	0.91714E+03	0.15841E+06	0.52130E+03
0.29194E+10	0.48001E-03	0.20833E+04	0.99191E+03	0.12579E+06	0.44654E+03
0.24011E+10	0.49219E-03	0.20318E+04	0.10713E+04	0.95378E+05	0.36712E+03
0.18829E+10	0.50570E-03	0.19775E+04	0.11550E+04	0.68528E+05	0.28345E+03

TFB 1 B = 9.0, 2.45, 2.5, 0.9

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.77850E+10	0.39494E-03	0.25320E+04	0.90435E+03	0.40893E+06	0.90435E+03
0.77520E+10	0.39516E-03	0.25306E+04	0.90705E+03	0.40723E+06	0.90166E+03
0.70082E+10	0.39986E-03	0.25009E+04	0.96610E+03	0.37306E+06	0.84261E+03
0.62643E+10	0.40583E-03	0.24640E+04	0.10327E+04	0.33414E+06	0.77597E+03
0.55205E+10	0.41348E-03	0.24185E+04	0.11081E+04	0.28991E+06	0.70058E+03
0.47766E+10	0.42326E-03	0.23627E+04	0.11933E+04	0.24059E+06	0.61538E+03
0.40328E+10	0.43561E-03	0.22956E+04	0.12891E+04	0.18737E+06	0.51958E+03
0.32889E+10	0.45088E-03	0.22179E+04	0.13957E+04	0.13271E+06	0.41303E+03

TFB 2 B = 15.50, 2.2, 2.0, 0.6

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.13637E+11	0.34412E-03	0.29060E+04	0.14463E+04	0.10459E+07	0.14463E+04
0.13468E+11	0.34450E-03	0.29028E+04	0.14544E+04	0.10408E+07	0.14383E+04
0.11945E+11	0.35016E-03	0.28558E+04	0.15472E+04	0.97038E+06	0.13455E+04
0.10423E+11	0.35750E-03	0.27972E+04	0.16527E+04	0.89058E+06	0.12399E+04
0.89002E+10	0.36700E-03	0.27248E+04	0.17730E+04	0.80135E+06	0.11197E+04
0.73777E+10	0.37923E-03	0.26369E+04	0.19093E+04	0.70495E+06	0.98335E+03
0.58551E+10	0.39468E-03	0.25338E+04	0.20626E+04	0.60652E+06	0.83006E+03
0.43325E+10	0.41346E-03	0.24186E+04	0.22317E+04	0.51506E+06	0.66098E+03

TFB 3 B = 19.00, 2.3, 2.0, 0.2 s=1.3029

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.22995E+11	0.29633E-03	0.33746E+04	0.21641E+04	0.23416E+07	0.21641E+04
0.22854E+11	0.29650E-03	0.33727E+04	0.21689E+04	0.23379E+07	0.21593E+04
0.19744E+11	0.30271E-03	0.33034E+04	0.23077E+04	0.22082E+07	0.20204E+04
0.16634E+11	0.31172E-03	0.32080E+04	0.24748E+04	0.20478E+07	0.18533E+04
0.13523E+11	0.32512E-03	0.30757E+04	0.26787E+04	0.18522E+07	0.16495E+04
0.10413E+11	0.34484E-03	0.29000E+04	0.29259E+04	0.16254E+07	0.14023E+04
0.73031E+10	0.37074E-03	0.26978E+04	0.32096E+04	0.14164E+07	0.11185E+04
0.41929E+10	0.39787E-03	0.25134E+04	0.35001E+04	0.13150E+07	0.82807E+03

TFB 4 B = 45, 2, 1.5, 0.4 Gap = 0.1 mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.44848E+11	0.26042E-03	0.38400E+04	0.32865E+04	0.54005E+07	0.32865E+04
0.44165E+11	0.26094E-03	0.38322E+04	0.33055E+04	0.53774E+07	0.32675E+04
0.41704E+11	0.26389E-03	0.37894E+04	0.33906E+04	0.52554E+07	0.31824E+04
0.39243E+11	0.26723E-03	0.37421E+04	0.34812E+04	0.51283E+07	0.30917E+04
0.36783E+11	0.27098E-03	0.36903E+04	0.35773E+04	0.49948E+07	0.29957E+04
0.34322E+11	0.27522E-03	0.36335E+04	0.36793E+04	0.48533E+07	0.28937E+04
0.31861E+11	0.28003E-03	0.35712E+04	0.37881E+04	0.47029E+07	0.27849E+04
0.29400E+11	0.28542E-03	0.35036E+04	0.39032E+04	0.45425E+07	0.26697E+04

TFB 5 B = 5.50, 1.41, 0.67, 0.15

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.29320E+10	0.43592E-03	0.22940E+04	0.41205E+03	0.84892E+05	0.41205E+03
0.28990E+10	0.43647E-03	0.22911E+04	0.41631E+03	0.83307E+05	0.40779E+03
0.24935E+10	0.44055E-03	0.22699E+04	0.45673E+03	0.72503E+05	0.36737E+03
0.20880E+10	0.44559E-03	0.22442E+04	0.50189E+03	0.61272E+05	0.32221E+03
0.16825E+10	0.45192E-03	0.22128E+04	0.55253E+03	0.49664E+05	0.27157E+03
0.12770E+10	0.46006E-03	0.21736E+04	0.60994E+03	0.37973E+05	0.21415E+03
0.87147E+09	0.47089E-03	0.21237E+04	0.67615E+03	0.26736E+05	0.14795E+03
0.46595E+09	0.48605E-03	0.20574E+04	0.75445E+03	0.17041E+05	0.69645E+02

TFC 1 B = 5.3, 2.3, 2, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.47630E+10	0.43630E-03	0.22920E+04	0.68083E+03	0.23176E+06	0.68083E+03
0.46717E+10	0.43754E-03	0.22855E+04	0.69149E+03	0.22600E+06	0.67017E+03
0.43390E+10	0.44134E-03	0.22658E+04	0.72690E+03	0.20904E+06	0.63476E+03
0.40063E+10	0.44583E-03	0.22430E+04	0.76552E+03	0.19057E+06	0.59613E+03
0.36736E+10	0.45118E-03	0.22164E+04	0.80770E+03	0.17032E+06	0.55396E+03
0.33410E+10	0.45758E-03	0.21854E+04	0.85380E+03	0.14821E+06	0.50785E+03
0.30083E+10	0.46523E-03	0.21495E+04	0.90426E+03	0.12424E+06	0.45739E+03
0.26756E+10	0.47441E-03	0.21079E+04	0.95948E+03	0.98487E+05	0.40217E+03

TFC 2 B = 14.5, 2.3, 2, 0.65

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.12492E+11	0.35894E-03	0.27860E+04	0.14767E+04	0.10903E+07	0.14767E+04
0.12243E+11	0.36062E-03	0.27730E+04	0.14972E+04	0.10700E+07	0.14563E+04
0.11202E+11	0.36501E-03	0.27396E+04	0.15647E+04	0.10195E+07	0.13887E+04
0.10161E+11	0.37042E-03	0.26997E+04	0.16397E+04	0.96303E+06	0.13137E+04
0.91203E+10	0.37711E-03	0.26517E+04	0.17231E+04	0.89994E+06	0.12303E+04
0.80794E+10	0.38547E-03	0.25942E+04	0.18163E+04	0.82965E+06	0.11371E+04
0.70385E+10	0.39599E-03	0.25253E+04	0.19210E+04	0.75183E+06	0.10325E+04
0.59976E+10	0.40937E-03	0.24428E+04	0.20389E+04	0.66632E+06	0.91453E+03

TFC 3 B = 23, 3, 3, 0.9 (Average Hugoniot; C0=3,S=1.05158)

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.31478E+11	0.28106E-03	0.35580E+04	0.28132E+04	0.39572E+07	0.28132E+04
0.31047E+11	0.28226E-03	0.35428E+04	0.28360E+04	0.39200E+07	0.27905E+04
0.30096E+11	0.28462E-03	0.35135E+04	0.28834E+04	0.38488E+07	0.27431E+04
0.29146E+11	0.28725E-03	0.34813E+04	0.29334E+04	0.37726E+07	0.26931E+04
0.28195E+11	0.29017E-03	0.34463E+04	0.29861E+04	0.36913E+07	0.26404E+04
0.27244E+11	0.29339E-03	0.34085E+04	0.30414E+04	0.36045E+07	0.25851E+04
0.26294E+11	0.29695E-03	0.33676E+04	0.30995E+04	0.35114E+07	0.25270E+04
0.25343E+11	0.30092E-03	0.33232E+04	0.31609E+04	0.34109E+07	0.24656E+04

TFC 4 B = 35, 2.1, 2, 0.8

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.38657E+11	0.26961E-03	0.37090E+04	0.31689E+04	0.50209E+07	0.31689E+04
0.38204E+11	0.27046E-03	0.36975E+04	0.31884E+04	0.49889E+07	0.31494E+04
0.31854E+11	0.28216E-03	0.35443E+04	0.34604E+04	0.45998E+07	0.28773E+04
0.25505E+11	0.29877E-03	0.33473E+04	0.37848E+04	0.41562E+07	0.25530E+04
0.19155E+11	0.32215E-03	0.31041E+04	0.41697E+04	0.36725E+07	0.21681E+04
0.12805E+11	0.35478E-03	0.28190E+04	0.46243E+04	0.32029E+07	0.17135E+04
0.64554E+10	0.40024E-03	0.24987E+04	0.51609E+04	0.28210E+07	0.11769E+04
0.10563E+09	0.47050E-03	0.21254E+04	0.58267E+04	0.26483E+07	0.51108E+03

TFC 5 B = 75, 2.3, 2, 0.45

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.54939E+11	0.26015E-03	0.38440E+04	0.38600E+04	0.74498E+07	0.38600E+04
0.54572E+11	0.26061E-03	0.38372E+04	0.38730E+04	0.74248E+07	0.38470E+04
0.51369E+11	0.26297E-03	0.38028E+04	0.39583E+04	0.73034E+07	0.37618E+04
0.48165E+11	0.26577E-03	0.37627E+04	0.40529E+04	0.71722E+07	0.36671E+04
0.44962E+11	0.26906E-03	0.37168E+04	0.41554E+04	0.70307E+07	0.35646E+04
0.41759E+11	0.27279E-03	0.36659E+04	0.42647E+04	0.68783E+07	0.34553E+04
0.38555E+11	0.27717E-03	0.36080E+04	0.43831E+04	0.67128E+07	0.33369E+04
0.35352E+11	0.28223E-03	0.35432E+04	0.45157E+04	0.65322E+07	0.32044E+04

TFD 4 "New" B = 6.6, 1.7, 1.5, 0.5 Gap=0.200mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.41870E+10	0.42265E-03	0.23660E+04	0.57300E+03	0.16455E+06	0.57300E+03
0.41849E+10	0.42279E-03	0.23652E+04	0.57354E+03	0.16398E+06	0.57246E+03
0.37144E+10	0.42671E-03	0.23435E+04	0.62296E+03	0.14877E+06	0.52304E+03
0.32439E+10	0.43143E-03	0.23179E+04	0.67004E+03	0.13276E+06	0.47596E+03
0.27734E+10	0.43707E-03	0.22879E+04	0.72158E+03	0.11627E+06	0.42442E+03
0.23029E+10	0.44374E-03	0.22535E+04	0.77759E+03	0.99906E+05	0.36841E+03
0.18324E+10	0.45150E-03	0.22148E+04	0.83797E+03	0.84526E+05	0.30803E+03
0.13619E+10	0.46030E-03	0.21725E+04	0.90233E+03	0.71083E+05	0.24367E+03

TFD 5 "New" B = 9.6, 2.2, 2, 0.5 No Gap

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.85140E+10	0.38895E-03	0.25710E+04	0.99800E+03	0.49749E+06	0.99800E+03
0.84942E+10	0.38898E-03	0.25708E+04	0.99869E+03	0.49728E+06	0.99731E+03
0.76413E+10	0.39399E-03	0.25381E+04	0.10648E+04	0.45738E+06	0.93118E+03
0.67884E+10	0.40031E-03	0.24981E+04	0.11382E+04	0.41286E+06	0.85787E+03
0.59355E+10	0.40824E-03	0.24495E+04	0.12204E+04	0.36352E+06	0.77565E+03
0.50826E+10	0.41818E-03	0.23914E+04	0.13124E+04	0.31014E+06	0.68364E+03
0.42297E+10	0.43035E-03	0.23237E+04	0.14142E+04	0.25511E+06	0.58179E+03
0.33768E+10	0.44476E-03	0.22484E+04	0.15251E+04	0.20191E+06	0.47095E+03

TFD 6 "New" B = 11.5, 2.3, 2, 0.5 Gap = 0.070mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.10680E+11	0.37411E-03	0.26730E+04	0.11810E+04	0.69785E+06	0.11810E+04
0.10649E+11	0.37416E-03	0.26726E+04	0.11822E+04	0.69732E+06	0.11798E+04
0.95783E+10	0.37945E-03	0.26354E+04	0.12574E+04	0.64477E+06	0.11046E+04
0.85075E+10	0.38621E-03	0.25893E+04	0.13424E+04	0.58491E+06	0.10196E+04
0.74367E+10	0.39493E-03	0.25321E+04	0.14390E+04	0.51690E+06	0.92296E+03
0.63660E+10	0.40624E-03	0.24615E+04	0.15490E+04	0.44052E+06	0.81298E+03
0.52952E+10	0.42084E-03	0.23762E+04	0.16739E+04	0.35743E+06	0.68808E+03
0.42245E+10	0.43925E-03	0.22766E+04	0.18143E+04	0.27196E+06	0.54773E+03

TFD 7 "New" B = 12.8, 1.93, 1.62, 0.83 Gap=0.05mm (QVC = 2)

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.13974E+11	0.35211E-03	0.28400E+04	0.14420E+04	0.10403E+07	0.14420E+04
0.13786E+11	0.35282E-03	0.28343E+04	0.14536E+04	0.10306E+07	0.14304E+04
0.12367E+11	0.35909E-03	0.27849E+04	0.15478E+04	0.95038E+06	0.13362E+04
0.10947E+11	0.36677E-03	0.27265E+04	0.16522E+04	0.86333E+06	0.12318E+04
0.95278E+10	0.37625E-03	0.26578E+04	0.17682E+04	0.76885E+06	0.11158E+04
0.81085E+10	0.38814E-03	0.25764E+04	0.18980E+04	0.66691E+06	0.98602E+03
0.66891E+10	0.40341E-03	0.24789E+04	0.20451E+04	0.55693E+06	0.83892E+03
0.52697E+10	0.42405E-03	0.23582E+04	0.22150E+04	0.43640E+06	0.66798E+03

TFD 8 "New" B = 50, 2.7, 2.25, 0.5 Gap=0.075mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.35040E+11	0.27739E-03	0.36050E+04	0.27180E+04	0.36948E+07	0.27180E+04
0.34009E+11	0.27763E-03	0.36019E+04	0.27338E+04	0.36867E+07	0.27022E+04
0.31036E+11	0.28103E-03	0.35584E+04	0.28330E+04	0.35808E+07	0.26030E+04
0.28062E+11	0.28561E-03	0.35013E+04	0.29496E+04	0.34519E+07	0.24864E+04
0.25088E+11	0.29174E-03	0.34278E+04	0.30845E+04	0.32958E+07	0.23515E+04
0.22115E+11	0.30023E-03	0.33308E+04	0.32431E+04	0.31025E+07	0.21929E+04
0.19141E+11	0.31259E-03	0.31990E+04	0.34345E+04	0.28549E+07	0.20015E+04
0.16168E+11	0.33168E-03	0.30150E+04	0.36722E+04	0.25264E+07	0.17638E+04

TFD 9 "New" B = 52.5, 2.1, 1.85, 0.95 Gap=0.035mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.53431E+11	0.25681E-03	0.38940E+04	0.35460E+04	0.62867E+07	0.35460E+04
0.53104E+11	0.25685E-03	0.38933E+04	0.35499E+04	0.62843E+07	0.35421E+04
0.49062E+11	0.26097E-03	0.38319E+04	0.36781E+04	0.60808E+07	0.34139E+04
0.45020E+11	0.26588E-03	0.37614E+04	0.38188E+04	0.58649E+07	0.32732E+04
0.40979E+11	0.27159E-03	0.36820E+04	0.39708E+04	0.56327E+07	0.31212E+04
0.36937E+11	0.27852E-03	0.35906E+04	0.41381E+04	0.53811E+07	0.29539E+04
0.32895E+11	0.28679E-03	0.34870E+04	0.43207E+04	0.51099E+07	0.27713E+04
0.28853E+11	0.29693E-03	0.33678E+04	0.45231E+04	0.48080E+07	0.25689E+04

TFD 10 "New" B = 30, 2, 1.7, 0.6 Gap=0.050mm QVC = 2.0

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.57171E+11	0.25747E-03	0.38840E+04	0.40230E+04	0.80918E+07	0.40230E+04
0.57050E+11	0.25881E-03	0.38639E+04	0.40357E+04	0.80155E+07	0.40103E+04
0.53395E+11	0.26585E-03	0.37617E+04	0.41961E+04	0.76376E+07	0.38499E+04
0.49740E+11	0.27385E-03	0.36519E+04	0.43672E+04	0.72453E+07	0.36788E+04
0.46086E+11	0.28294E-03	0.35346E+04	0.45493E+04	0.68319E+07	0.34967E+04
0.42431E+11	0.29338E-03	0.34089E+04	0.47446E+04	0.63938E+07	0.33014E+04
0.38776E+11	0.30529E-03	0.32758E+04	0.49532E+04	0.59351E+07	0.30928E+04
0.35121E+11	0.31895E-03	0.31353E+04	0.51766E+04	0.54496E+07	0.28694E+04

TFD 11 "New" B = 35, 3.2, 2.4, 0.1 Gap=0.091mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.25817E+11	0.29568E-03	0.33820E+04	0.22939E+04	0.26310E+07	0.22939E+04
0.25122E+11	0.29585E-03	0.33801E+04	0.23048E+04	0.26268E+07	0.22830E+04
0.23644E+11	0.29841E-03	0.33512E+04	0.23662E+04	0.25663E+07	0.22216E+04
0.22167E+11	0.30153E-03	0.33164E+04	0.24341E+04	0.24965E+07	0.21537E+04
0.20690E+11	0.30556E-03	0.32727E+04	0.25111E+04	0.24127E+07	0.20767E+04
0.19212E+11	0.31088E-03	0.32167E+04	0.25997E+04	0.23088E+07	0.19881E+04
0.17735E+11	0.31834E-03	0.31414E+04	0.27045E+04	0.21733E+07	0.18833E+04
0.16257E+11	0.32976E-03	0.30325E+04	0.28341E+04	0.19816E+07	0.17537E+04

TFD 12 "New" B = 22, 2.9, 2.34, 0.4 Gap=0.085mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.20502E+11	0.32510E-03	0.30760E+04	0.18586E+04	0.17271E+07	0.18586E+04
0.20244E+11	0.32518E-03	0.30752E+04	0.18631E+04	0.17255E+07	0.18540E+04
0.18955E+11	0.32834E-03	0.30456E+04	0.19267E+04	0.16652E+07	0.17905E+04
0.17665E+11	0.33238E-03	0.30086E+04	0.19988E+04	0.15933E+07	0.17184E+04
0.16376E+11	0.33742E-03	0.29636E+04	0.20793E+04	0.15097E+07	0.16378E+04
0.15087E+11	0.34389E-03	0.29078E+04	0.21706E+04	0.14102E+07	0.15466E+04
0.13797E+11	0.35249E-03	0.28370E+04	0.22758E+04	0.12884E+07	0.14414E+04
0.12508E+11	0.36446E-03	0.27438E+04	0.24027E+04	0.11334E+07	0.13144E+04

TFE 1 "Old" B = 7.6, 2.3, 2, 0.5 Gap = 0.070mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.16060E+10	0.49603E-03	0.20160E+04	0.30000E+03	0.45088E+05	0.30000E+03
0.15992E+10	0.49530E-03	0.20149E+04	0.30135E+03	0.44660E+05	0.29865E+03
0.13727E+10	0.49826E-03	0.20070E+04	0.32239E+03	0.41793E+05	0.27761E+03
0.11461E+10	0.50104E-03	0.19958E+04	0.34746E+03	0.38350E+05	0.25254E+03
0.91959E+09	0.50505E-03	0.19800E+04	0.37754E+03	0.34291E+05	0.22246E+03
0.69305E+09	0.51074E-03	0.19580E+04	0.41339E+03	0.29809E+05	0.18661E+03
0.46651E+09	0.51829E-03	0.19294E+04	0.45473E+03	0.25571E+05	0.14527E+03
0.23997E+09	0.52708E-03	0.18972E+04	0.49937E+03	0.22646E+05	0.10063E+03

TFE 2 "Old" B = 12.0, 2.3, 2, 0.5 Gap=0.25mm

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.35660E+10	0.46232E-03	0.21630E+04	0.60200E+03	0.18132E+06	0.60200E+03
0.35578E+10	0.46313E-03	0.21592E+04	0.60457E+03	0.17845E+06	0.59943E+03
0.30640E+10	0.46587E-03	0.21465E+04	0.64263E+03	0.16955E+06	0.56137E+03
0.25701E+10	0.46973E-03	0.21289E+04	0.68623E+03	0.15891E+06	0.51777E+03
0.20763E+10	0.47524E-03	0.21042E+04	0.73837E+03	0.14637E+06	0.46563E+03
0.15824E+10	0.48306E-03	0.20701E+04	0.80041E+03	0.13245E+06	0.40359E+03
0.10886E+10	0.49347E-03	0.20265E+04	0.87206E+03	0.11908E+06	0.33194E+03
0.59475E+09	0.50575E-03	0.19772E+04	0.94995E+03	0.10942E+06	0.25405E+03

TFE 3 "Old" B = 10.7, 2.3, 2, 0.5

Pressure	Volume	Density	Up (+)	Energy	Up(-)
0.76990E+10	0.41408E-03	0.24150E+04	0.10180E+04	0.51763E+06	0.10180E+04
0.76140E+10	0.41524E-03	0.24083E+04	0.10279E+04	0.50887E+06	0.10081E+04
0.68302E+10	0.41987E-03	0.23817E+04	0.10881E+04	0.47587E+06	0.94785E+03
0.60463E+10	0.42581E-03	0.23485E+04	0.11563E+04	0.43831E+06	0.87968E+03
0.52625E+10	0.43351E-03	0.23068E+04	0.12340E+04	0.39551E+06	0.80203E+03
0.44787E+10	0.44353E-03	0.22546E+04	0.13225E+04	0.34759E+06	0.71347E+03
0.36948E+10	0.45649E-03	0.21906E+04	0.14233E+04	0.29572E+06	0.61276E+03
0.29110E+10	0.47279E-03	0.21151E+04	0.15362E+04	0.24304E+06	0.49978E+03

Appendix B

Discussion of Density Measurements

At one point during the course of this study, it was noticed that Sandia density measurements for a suite of tuffs were falling 2 -3% below density measurements made at the DNA Impact Facility of what should have been similar materials. The decision was made to perform a cross-comparison exercise. This Appendix summarizes the results of that exercise.

Experiments conducted:

Two teams (one at the Sandia STAR Facility and a second at the DNA Impact Facility) performed density measurements by immersion and geometry methods, exchanging samples to afford comparisons. Several “ideal” samples were measured, including three fused silica windows and three carefully machined disks of 6061-T6 aluminum. Rock samples measured included three disks of phyllite, three disks of Salem limestone, three disks of DM grout and two disks of HT Tuff. All samples were in a condition appropriate for gas-gun experimentation during these measurements. In addition, parallel measurements by Waterways Experimental Station and Terra Tek were compared where available. Results are summarized in Table B.1.

“Mass/Volume” density measurements were made by measuring the thickness and diameter of the samples (taken to be perfect cylinders), then measuring the weight and dividing to obtain the density. Where samples had flats ground into the side for gauge access, the volume correction for these was calculated as well. As these measurements have been performed, the density of air is not taken into account. “Immersion” density measurements were made by measuring the in-air weight of the sample and of a fine wire basket, then the in-water weight of the basket with and without the sample, then calculating the sample density using appropriate values for the density of water and air.

Through the remainder of this Appendix, the two principal sets of measurements will be referred to as the Impact Facility measurements and the STAR measurements.

Objects of Concern:

The primary questions driving this study were how characteristics such as porosity, water saturation and mechanical irregularities of the sample would affect the accuracy of density measurements. In keeping with the overall goal of producing gas-gun physical properties data usable in modeling groundshock, “density” must be an intensive quantity (same value whatever the shape or size of the sample).

Pitfalls in the laboratory measurements include making a correct volume determination and maintaining the correct saturation state. For nonporous, well-machined materials such as aluminum and fused silica, these are not serious problems. If water-saturated porosity is added, as with the Salem Limestone, the weight must be measured with attention being given to neither drying the sample too much nor leaving excess water on it. If a porous material is not fully water-saturated, oversaturation is a danger (this often pre-

Table B.1
Density Comparisons Among Laboratories

Sample	STAR		Impact Facility		Other	
	Mass/ Volume	Imm.	Mass/ Volume	Imm.	Mass/ Volume	Imm.
<i>Fused Silica</i>						
SiO ₂ #1	2.197	2.198	2.198	2.204		
SiO ₂ #1	2.197	2.199	2.198	2.205		
SiO ₂ #3	2.197	2.201	2.198	2.205		
<i>6061-T6 Aluminum</i>						
Aluminum #1	2.702		2.703	2.711		
Aluminum #2	2.702		2.703	2.712		
Aluminum #3	2.701		2.702	2.711		
<i>Phyllite (SNL vs. Ktech vs. Terra Tek)</i>						
Phyllite P-1-A	2.785		2.796		2.814	
Phyllite P-1-B	2.790		2.789		2.800	
Phyllite P-2-B	2.806		2.808		2.835	
<i>Salem Limestone (STAR vs. Impact Facility vs. Waterways Expt. Station)</i>						
SL-D3-17	2.425	2.439	2.424		2.45	
SL-D8-06	2.425	2.430	2.424		2.44	
SL-D3-24	2.438	2.437	2.409	2.432	2.45	
<i>BEX GC-1(R) Grout</i>						
Grout #1	2.286	2.326		2.3075	STAR Mass/Volume, reducing diameter 0.2 mm for plucking
Grout #5	2.273	2.322		2.359		
Grout #8	2.288	2.347		2.222		
<i>HP-3 Tuff (D, E)</i>						
Tuff #3-17	2.010	2.041	1.995	2.048	2.023	
Tuff #3-10	1.993	2.020	1.979	2.046	2.007	
<i>Thawed Quartzite (STAR vs. Terra Tek)</i>						
Quartzite #2	2.7179				2.7316	
Quartzite #4	2.7239				2.7326	
Quartzite #6	2.7238				2.7424	
<i>Preserved Frozen Quartzite (STAR vs. Terra Tek)</i>						
Quartzite #1	2.746				2.750	2.749
Quartzite #2	2.749				2.754	2.751
Quartzite #3	2.742				2.737	2.742

cludes immersion density measurements). With this in mind, the teams refrained from immersing phyllite samples which may not have been fully saturated. Finally, if the material deviates from a simple geometry (e.g. by damage), measuring the density by measuring the linear dimensions and the weight may give misleading results. Two examples of this are the BEX GC-1(R) grout (Grout B) and the Tuffs D and E. The finished grout surface contains projecting crystals of a hard mineral of the bauxite family (diaspore?) projecting from the softer matrix, along with some plucking sites where crystals were dislodged from the matrix during grinding. Such irregularities will cause an overestimate of sample thickness, leading to a low final calculated density.

Figure B.1. BEX GC-1(R) Grout - Grinding Behavior

The tuff provides another difficulty. It is a very friable material, so the edges of finished samples are generally somewhat plucked. Unless corrections are made for these gaps in the volume estimate, the calculated density will again be too low. On the other hand, an immersion technique may give an erroneously small volume for such a material by excluding open pores from the volume measurement, giving a calculated density higher than the true (large-sample) density. This is also important for certain grouts which have large bubbles.

Discussion of Specific Trials

For the aluminum and fused silica samples, mass/volume measurements by the two laboratories yielded comparable results (deviations less than 0.05%). The STAR mass/volume and immersion measurements for fused silica differed by 0 to 0.18%, while the corresponding Impact Facility measurements by the two methods gave approximately 0.3% deviations (immersion density higher). For the aluminum, a value of 2.703 is expected, suggesting that the mass/density technique is better than the immersion technique. The fused silica used (Dynasil 100) had a nominal density of $2.200 \pm 0.001 \text{ gm/cm}^3$.

The phyllite samples were not immersed due to fears that such treatment might alter their properties for gas gun experiments to follow. STAR and Impact Facility density measurements agreed closely, and were up to 1% below the corresponding Terra Tek measurements (I do not know what contributing measurements caused the STAR/Impact Facility vs. Terra Tek disagreement).

In the Salem limestone (16% porosity), the effect of porosity on the accuracy of density measurements becomes apparent. STAR mass/volume measurements gave density values ranging from 0% to 0.6% below those from immersion, while an Impact Facility mass/volume measurement gave a density value 1% below the corresponding immersion value. Mass/volume measurements at Waterways Experiment Station could not be compared

with STAR or Impact Facility measurements at this level of detail because of rounding.

The BEX GC-1(R) grout showed the effect predicted above: mass/volume density calculations gave significantly (2 - 2.5%) lower density values than did immersion. If we suppose that the thickness is overestimated by 0.12 mm (individual surfaces eroded about 1.5 mils below bauxite grain tops), the two methods will give the same value for the density. In fact, the immersion method will probably give a greater density than would be found for a large sample because an unrepresentatively large amount of dense bauxite is left by the grinding process.

The Tuff D, E samples were not only porous, but also imperfectly machined due to their friability. As with the BEX GC-1(R) grout, the actual volume must be calculated with care for a mass/volume estimate of the density. STAR measurements of the volume and mass gave densities about 1.4% lower than those calculated from immersion; for the Impact Facility measurements, the difference is about 2.5%. Reducing the radius by about 0.2 mm to allow for plucking removed this discrepancy.

In comparing density measurements of the samples of preserved frozen quartzite, it became apparent that the main source of the small (0.2%) discrepancy was a difference in measured diameters of the samples. It is not surprising that such a disagreement could occur because of the need to perform these measurements in a cold room. These samples were quite competent and cleanly cut.

Other Comments About These Tests:

Where possible, densities were calculated in various ways from the data. For example, immersion density values may be calculated using various combinations of the sample weight in air, the wire basket weights in air and water, and the sample weights in wire basket in air and in water. These have given very consistent values (within 0.15%).

Another manipulation of the data acquired from immersion techniques can give the in-air mass of the sample. This requires measuring the geometric volume of the sample, the density of the water, and the weights of the sample+basket and basket in water. This calculation gives a mass value obtained without having to guess how much water to leave on the sample for a weighing. Applying this method to the Salem limestone, it is apparent that most of the STAR Facility weighings of this material in air probably underestimated the best weight by a tiny amount (~0.1%, or 20 - 50 mg). A similar experiment on the fused silica gave very good agreement (better than 0.04%). However (see below), correcting the scale weights for the density of air will give very close agreement between the in-air weights (measured and calculated as here) of the Salem limestone.

Finally, as a check of algorithms for immersion calculations, I recalculated several densities from the Impact Facility immersion data. Values from my routine were about 0.1%

below those from the Impact Facility calculations. The Impact Facility calculation is:

$$\rho = \frac{W \times 0.998}{W_1 - W_2 - WB}$$

W = weight of sample in air

W_1 = weight of sample + wire basket in air

W_2 = weight of sample + wire basket in water

WB = wire basket(air) - wire basket (water)

The STAR calculation includes a calculation of the densities of air and water:

$$\rho_{\text{Air}} = (1.2929 \cdot (273.13 / (T_{\text{Air}} + 273.13)) \cdot (\text{barom} - 0.3783 \cdot e) / 760.0) \cdot 0.001 \text{ gm/cm}^3$$

$$\rho_{\text{Water}} = 1.0006 - 0.69632 \cdot 10^{-4} \cdot T_{\text{Water}} - 0.35887 \cdot 10^{-5} \cdot T_{\text{Water}}^2 \text{ gm/cm}^3$$

(where e = vapor pressure of water in air (mm Hg), barom is air pressure (mm Hg) and temperatures are in $^{\circ}\text{C}$), but is otherwise quite similar to the Impact Facility calculation. Since this calculation gives densities around $\rho_{\text{Air}} = 0.995 \cdot 10^{-3}$ and $\rho_{\text{Water}} = 0.9973$, a small amount of figuring suggests that the Impact Facility calculations should use an air-compensating factor of 0.997 instead of 0.998. This would explain the 0.1% disagreement. For the overall purposes of this exercise, though, this particular disagreement can be ignored.

All of the mass/volume measurements are slightly low because they do not account for the density of air (about 0.001 gm/cm^3). We can make a first approximation correction to these measurements by simply adding this density to the observed densities. In fact, typical scales are calibrated to compensate for this for samples of densities around 8.00, so the correction is actually about 0.00075 gm/cm^3 for samples of densities around 2.00 gm/cm^3 .

Implications for Older Gas-Gun Data Interpretation:

At issue here is whether correct initial densities were assigned for specimens and ancillary materials in gas gun tests. By "correct," I mean to better than about 0.5%. The above data suggest the following:

- 1) Densities for nonporous, well-machined materials (all of the ancillary materials except for foams, as well as granites, quartzites and similar sample materials) are reliable as measured (whether by immersion or mass/volume).
- 2) Densities for porous, well-machined materials are reliable as measured. This category includes limestones, rhyolites (densely welded, relatively lightly altered) and competent grouts such as MJ-2.
- 3) The BEX GC-1(R) grout is a special case because of the nature of the surface created by grinding the soft matrix/hard barite nodule mixture. Initial densities of these samples were probably underestimated by about 2.5% in the STAR tests (although by less relative to the *in situ* grout).
- 4) Heavily altered tuffs probably require immersion measurements to accurately characterize density UNLESS the machining process left a clean geometry. For samples to be tested dry or in an incompletely saturated condition, of course, immersion methods are not feasible. The Tuffs D and E group is an example of a material which is difficult to machine cleanly (i.e. without plucking or crumbling). STAR density measurements for this material were probably about 1.5 - 2% low for this reason.

Reverse-ballistic experiments give stress (P) and particle velocity (U_p) information directly from the impedance match, so these quantities would not be affected by any correction. Shock velocity (single-shock case, as applies to most of the materials here) depends on initial density according to $U_s = P/(\rho_0 U_p)$, i.e. will decrease by the same percentage as ρ_0 increases. Shocked density will also change; it is calculated as $\rho = \rho_0 U_s / (U_s - U_p)$.

Forward-ballistic experiments use shock velocity as primary data. Pressure and particle velocity are determined by performing an impedance match in pressure-particle velocity space, finding the intercept of the line $P = \rho_0 U_s U_p$ with a Hugoniot curve of an ancillary material, reflected and shifted according to projectile velocity.

Release curves (extracted by wavecode modeling of the experiment) would (to good approximation) translate in P/ρ or P/V space, tending to increase hysteresis (and attenuation) slightly.

Reviewing representative STAR test series from recent years on tuffs and grouts (i.e. excluding granites, limestones and rhyolites):

- MJ-2: Samples machined well. Density of samples (allowed to dry, then resaturated) was 2.5% *above* as-poured densities provided by WES (later corroborated at Sandia)
- RT/PT: (MC-2 and MC-3 units of Paintbrush Tuff): Machined well. Density 7% below large sample density (large-sample data from F&S Geology and from our own measurements of large sections of core); attributed to difficulty resaturating. This is analyzed in the Sandia report, SAND90-1307.
- NT (Tunnelbed Tuff): Machined well. Density 3% below large sample density (large-sample data from F&S Geology and from our own measurements of large sections of core); attributed to difficulty resaturating (see same reference as above). Saturated samples subsequent to this were not allowed to dry at any point in preparation or testing.
- Tuff A (U20bd#1 2198'): I don't have enough information to evaluate likely density errors for this tuff.
- Tuff B (U20bb SH-1): I don't have enough information to evaluate likely density errors for this tuff.
- HPNS-12 Grout: Machined well; densities probably valid as measured earlier. This material had open bubbles, and the mass/volume methods used were probably more appropriate than immersion methods would have been. Unable to locate independent measurements of grout density.
- Tuffs D and E (U12n 24 HP#3 36' and U12n 24 GI#1): As discussed above, the STAR density measurements for this material are likely to be about 1.5 - 2% low.
- Tuff C (U12p.04 IH20 145'): Machined well; densities probably quite close to "correct" values. Field data for this formation gives densities 0 - 1.0% above ours as dominant near WP, although an exact core ID for the samples tested in gas-gun experiments to make a closer comparison was never provided.

- BEX GC-1(R) Grout: As noted above, densities may have been underestimated by up to 2.5% in the STAR tests. However, it is unclear what density to use for the best relationship of lab tests to larger-scale tests.

Hugoniot corrections are relatively easy to perform, and we can do so for Tuffs D and E and for the BEX GC-1(R) grout if appropriate. A reinterpretation of the Hugoniot states for the BEX GC-1(R) grout is presented in Table B.2. Changes in interpretation of Tuffs D and E would be about 60% of the changes for the BEX GC-1(R) grout.

**Table B.2. Hugoniot Conditions for Grout B (BEX GC-1(R))
(Reverse-Ballistic Tests)
Effect of Changed Initial Densities**

Hugoniot Conditions									
Shot #	Proj. Velocity km/sec	Observed Vel. km/sec	ρ_0 gm/cm ³	Particle Vel km/sec	Pressure GPa	ρ gm/cm ³	Shock Vel. km/sec	ρ/ρ_0	Specific Vol cm ³ /gm
With as-used densities:									
GTB 3	0.877(3)	0.297(8)	2.296(11)	0.584(9)	4.4(1)	2.79(4)	3.29(15)	1.215(16)	0.358(5)
GTB 4	0.876(9)	0.310(5)	2.292(11)	0.57(1)	4.6(1)	2.73(3)	3.53(12)	1.193(11)	0.366(4)
GTB 5	1.095(11)	0.384(4)	2.291(11)	0.72(1)	5.8(1)	2.87(3)	3.55(8)	1.253(12)	0.348(4)
GTB 6	1.423(21)	0.535(12)	2.326(12)	0.90(2)	8.4(2)	2.99(6)	4.03(18)	1.286(25)	0.334(7)
With densities increased by 2.2%:									
GTB 3	0.877	0.297	2.346	0.584	4.4	2.86	3.22	1.221	0.349
GTB 4	0.876	0.310	2.342	0.57	4.6	2.81	3.45	1.198	0.356
GTB 5	1.095	0.384	2.341	0.72	5.8	2.95	3.47	1.260	0.339
GTB 6	1.423	0.535	2.377	0.90	8.4	3.08	3.95	1.294	0.325

Rigorous release corrections are time-consuming and it may not be practical to perform these for whole suites. To a good approximation, release curves may be translated in P/ ρ or P/V space to originate from recalculated Hugoniot points.

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