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PUFF TOO: A Residual Stress Experiment

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Carl W. Smith

Sandia National Laboratories

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PUFF TOO: A RESIDUAL STRESS EXPERIMENT

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ABSTRACT

Following the passage of the dynamic effects in a contained explosive detonation, there remains a strong compressive stress field in the material about the cavity. In this experiment, a 454-kg (1000 lb) sphere of high explosive was detonated in saturated ashfall tuff. Instrumentation measured peak stresses over the range of 0.1 to 6.0 GPa (1 to 6 kbar) and the complete stress-time waveform, including the so-called residual stress, at the 0.1 GPa (1 kbar) peak stress range. Mineback revealed detonation-induced fractures and fractures induced by postevent work.

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SUMMARY

PUFF TOO was a nuclear containment-related experiment in which a 454-kg (1000-lb) high explosive was detonated in saturated tuff in G Tunnel at NTS. Currently available prototype stress gages were fielded to assess their ability to measure the complete stress-time profile; particular emphasis was placed on measuring the late-time residual stress. Mineback was performed to examine gages, cavity details, and fractures which were detonation-related or induced after the event.

In tuff at the 1-kbar peak dynamic range, three stress gages with two types of sensors (lithium niobate and ytterbium) measured the full stress-time profile and showed an average residual stress of 0.25 kbar. In the grout stemming plug at the same range, seven sensing elements with three types of sensors (lithium niobate, ytterbium, and a fluid-coupled plate) measured residual stress; these values cluster about 0.19 kbar. With increasing peak stress levels, proportionally shorter recording times were obtained; at the 60-kbar level only the peak values are credible. We believe that the ability to measure residual stress is currently limited by survival of the gage package and cable.

Although we measured a residual stress at the 1-kbar level, it is not clear which stress component--mean, radial, or some intermediate value--was measured. Calibration data are available only for the one-dimension strain and hydrostatic loadings; at the 1-kbar level we must take into account the triaxial state of stress which loads these gages. The triaxial stress development gage and its background work is a start on this problem.

Work performed 2.5 hr after the detonation showed the presence of cavity gas 3.5 cavity radii (387 cm) from the original charge center. Specific locations in the residual stress field were pressurized and

fractured with nitrogen; fracture pressures indicate the approximate dependence of the residual stress field with range.

Mineback on the PUFF T00 event revealed a slickenside (sheared) surface in the tuff approximately radial to the charge and parallel to the stemming plug. The surface started 1.5 cavity radii (165 cm) from the charge center and extended to 4.3 cavity radii (463 cm). We believe that this sheared surface was the path for the cavity gas observed at 387 cm. We suggest that the slickenside surface is related to stress relief around the installation drift.

Examination of gages recovered during mineback allowed us to verify proper gage operation and helped us to explain anomalous gage records. The directions of the postevent fractures were obtained and provided information related to the components of the residual stress field. The cavity was elongated in the approximate direction of the stemming plug and showed maximum and minimum horizontal radii of 125 cm (4 ft) and 100 cm (3.5 ft). The averaged radius was 108.4 cm (3.56 ft).

A pre-event computer code calculation had been made for design purposes. We see reasonable agreement with field measurements in the peak dynamic and residual time frames and disagreement at intermediate times. Predicted cavity radius was 80 cm, which may be compared with the averaged observed value of 108.4 cm. Predicted cavity pressure of 0.55 kbar is close to the larger (0.52 kbar) of the two cavity pressure measurements.

PUFF TOO: A RESIDUAL STRESS EXPERIMENT

Introduction

A major role in the containment of underground nuclear detonations is credited to a late-time detonation effect called the residual stress field. If a calculation of the nuclear event is continued to late times, it shows an elastic rebound of material in the far-field which loads the plastically-deformed material closer to the cavity. Loaded by the cavity pressure on one side and by the inward converging material on the other side, this near-field region experiences strong compressive stresses which persist as long as the calculation is continued. This residual stress field is able to contain cavity pressures.

Calculations show a residual hoop (or tangential) stress whose peak is physically close to the cavity and has a maximum amplitude of about 1 kbar. This stress decays with distance, sometimes shows negative values, and then approaches in-situ value about five cavity radii from the charge center. The radial residual stress, on the other hand, rises to a peak at about 1.5 cavity radii, shows an amplitude slightly lower than the maximum hoop stress, and decays to the in-situ value. (Some calculations show detail in the decaying part of these fields.) Calculations of high-explosive events show that these residual fields are able to contain the approximately 0.5-kbar pressure found in the cavity.

Interest in this effect is not confined to nuclear containment because the residual stress field is a general geomechanical effect resulting when confined explosions interact with the solid. An old practice in oil fields was to detonate explosives in a well in an attempt to enhance production. Current knowledge of the residual stress effect, however, shows that flow of oil into the well may actually be inhibited, at least

until the residual field decays. Therefore, any energy recovery that involves explosives must take into account this residual stress effect.

Gage measurements of residual stress fields are difficult since the instrumentation must survive the passage of the dynamic effects. Typically the dynamic amplitudes are 5 to 10 times larger than the residual stress amplitude. For example, to measure 1 kbar of residual stress, a gage must survive the 10 kbars of dynamic stress and still retain a linear, or recoverable, calibration.

Active gage measurements of the complete stress vs time history are valuable for comparison with a calculation of the event. Agreement between data and calculation would suggest that one has accounted for the major processes involved and has modeled the phenomenon correctly.

We had several objectives in this 454-kg (1000-lb) high-explosive experiment (PUFF T00).^{*} The primary one was to measure, with currently available gages, the complete stress-time waveforms, with particular emphasis on the late time or residual stress regime. Another objective was to measure and examine some of the phenomenology of a high explosive detonation. The third objective was to provide test bed for gage development work.

The next section presents the general details of the experiment. Subsequently we display the measured waveforms. Finally, we discuss postevent and the mineback work. Appendices discuss current gage measurement problems, detail a pre-event design calculation of the detonation process, and describe a waveform correction technique.

^{*}This experiment is also known as RS3

The Experiment

Location and Environment

We fielded PUFF TOO in G Tunnel, Rainier Mesa, Nevada Test Site (NTS) in saturated ashfall tuff. The experiment drift was an extension of another drift, designated HFS20; these drifts are located at construction station 25+00 in the main G Tunnel drift (U12g.10M.D.B.P.). Here the vertical distance to the mesa surface is 420 m. Before PUFF TOO, hydraulic fracture measurements were made in the area and analysis yielded the following values for the in-situ stress:

- Maximum horizontal stress: 6.41 MPa (930 lb/in²), oriented N 42° E
- Minimum horizontal stress: 5.34 MPa (775 lb/in²)
- Vertical stress 8.76 MPa (1270 lb/in²)

Material Properties

The geologic host for PUFF TOO was zeolitized ashfall tuff in Bed 4 of the bedded sequence encountered in G Tunnel. Seven samples from the mined emplacement drift were sent to Holmes and Narver (H&N) Material Testing Laboratory at NTS, and two samples were sent to Terra Tec, Inc, at Salt Lake City. The H&N values and standard deviations (SD) are listed in Table 1.

Along with uniaxial strain tests, Terra Tec also measured material properties on one sample taken at 22.25 m (73 ft) from the start of the drift and on one sample from 36.88 m (121 ft). Table 2 lists their values.

Figure 1 shows the results of Terra Tec's uniaxial strain tests on these two samples.

Table 1
Material Properties (Holmes and Narver)

Properties	Average Values	Standard Deviation
Unconfined crushing strength	9.24 MPa (1340 lb/in ²)	3.3 MPa
Sonic pulse compressive velocity	2.16 km/s	0.17 km/s
Shear velocity	1.08 km/s	0.19 km/s
Density		
Natural state	1.92 Mg/m ³	0.308 Mg/m ³
Dry	1.57 Mg/m ³	0.054 Mg/m ³
Grain	2.50 Mg/m ³	0.024 Mg/m ³
Moisture content, natural basis	17.8%	1.3%
Porosity	36.8%	2.1%
Saturation	92.7%	1.9%

Table 2
Material Properties (Terra Tec, Inc)

Properties	Values at Stated Distance	
	22.25 m	36.88 m
Density (Mg/m ³)		
As received	1.90	1.76
Dry	1.53	2.48
Grain	2.48	2.43
Water by weight (%)	19.70	25.20
Porosity (%)	38.50	45.60
Saturation	97.30	97.40
Measured permanent compaction (%)	1.50	1.90
Ultrasonic velocity (km/s)		
Longitudinal	2.81	2.73
Shear	1.27	1.16

Figure 1. Uniaxial Strain Tests on Tuff Samples Measured by Terra Tec, Inc

Containment of PUFF TOO was required if we were to obtain meaningful measurements of residual stress and cavity pressure. We stemmed the first 16 m of the 41-m emplacement drift with a high-strength grout (HAHSGC); the rest of the drift, including the volume around the high-explosive sphere, was stemmed with a grout (GTMG7) designed to match the shear strength of the tuff. Originally designed for the MIGHTY EPIC structures experiment, this ME8-11 grout recipe was modified to be used in small volumes and to achieve about an 8.3-MPa (1200-lb/in²) unconfined crush strength in 12 days of curing. Samples of this stemming grout, cured for 14 days, showed a density of 2 Mg/m³, a sonic velocity of about 3 km/s (10,000 ft/s), and an unconfined crush strength of 6.2 to 8.75 MPa (1190 to 1270 lb/in²).

Experiment Details

We emplaced the PUFF TOO experiment in a mined drift that was 41 m long, 1.8 m high, and 1.2 m wide (135 x 6 x 4 ft); the initial design called for a 36-m (120-ft) emplacement drift but natural fractures were encountered at this distance. As shown in Figure 2, the 1.2- x 1.8-m drift tapers down to slightly larger than the size of the high explosive sphere, thereby minimizing the amount of grout around the sphere and allowing the cavity to grow mostly in tuff. The explosive was a cast TNT sphere with a diameter of 81.92 cm (32.25 in) and a mass of 453.6 kg (1000 lb). Inside the TNT was a 25.4-cm (10-in) diameter pentolite booster which was center-detonated with an exploding bridgewire device. The so-called tuff gages were inserted and grouted in 10.2-cm-(4-in) diameter drilled holes. Aluminum fixtures, bolted to the floor of the drift, supported the gages in the grout stemming plug. Four high-strength steel pipes terminated in the tuff at varying distances from the charge center. After the shot, we pumped nitrogen into these pipes to measure the pressure needed to overcome the residual stress. We fielded numerous gages for this event, mainly stress gages, with emphasis on those that offered the possibility of measuring residual stress. We fielded other gages which were in various stages of development because the event offered a point source explosion which was essentially free of reflecting boundaries.

Figure 2. Plan View Showing TNT Sphere, Gage Locations, Stemming Plug, and Fracture Pipes

The principal gages fielded to measure stress-time waveforms were paddle-shaped, about 7 cm wide and 15 cm long. Piezoresistive, and piezoelectric transducers (ytterbium and lithium niobate) were used in the paddles. Some of the gages used a thin fluid bath for coupling around the sensor. For ytterbium this fluid coupling provided a hydrostatic loading, eliminating a hysteresis problem; for lithium niobate the fluid coupling minimizes shear-stress loading on the crystal, probably enhancing the survival of this brittle material.

When gages are used at stresses that are large when compared with material strengths of the transducer, the material deforms in one-dimensional strain; appropriate calibration data are available for this case. When used below ~2 kbar, the effects of material strength become important. We must then account for triaxial stresses experienced by the gage and one-dimensional calibrations may not be appropriate. This problem and the specific calibrations used to reduce the data are discussed in Appendix A. Table 3 gives gage locations, gage type, and host material.

Table 3
Gage Types and Locations

Gage Type	Distance From Working Point		Host Material	Notes
	(cm)	(ft)		
60MK	51.1	1.68	Grout	End-loaded manganin element
60CK	51.1	1.68	Grout	End-loaded constantan element
60MP	51.1	1.68	Grout	Manganin element in C7 epoxy
60MR	51.1	1.68	Grout	Manganin element in REN epoxy
6BLFC	140.3	4.60	Tuff	Fluid-coupled lithium niobate
6BLH	132.8	4.36	Tuff	Solid-coupled lithium niobate
6AYFC	132.3	4.34	Tuff	Fluid-coupled ytterbium
6LH	120.3	3.95	Grout	Solid-coupled lithium niobate
6YFC	121.9	4.00	Grout	Fluid-coupled ytterbium
2CYFC	286.7	9.41	Tuff	Fluid-coupled ytterbium
2CLH	284.1	9.32	Tuff	Solid-coupled lithium niobate
3FCP	184.2	6.04	Grout	Steel-housed fluid-coupled plate
2FCP	287.3	9.43	Grout	Aluminum-housed fluid-coupled plate
1FCP	418.5	13.73	Grout	Aluminum-housed fluid-coupled plate
2T1S }	269.6	8.84	Grout	TOA detector, PZT rings 1-in diameter
2T1B }				
2T3B }				
2T3S }	264.8	8.70	Grout	TOA detector, PZT rings 3-in diameter
1AR1 }				
1AT1 }				
1AV1 }	395.3	12.97	Grout	Triaxial accelerometer package, epoxy housing
1AR2 }				
1AT2 }				
1AV2 }	395.9	12.99	Grout	Triaxial accelerometer package, aluminum housing
1YFC				
1LH				
1LD1 }	421.8	13.84	Grout	Fluid-coupled ytterbium
1LD2 }				
1YFC				
1LH	421.8	13.84	Grout	Solid-coupled lithium niobate
1LD1 }	407.8	13.38	Grout	Triaxial stress gage package with lithium niobate sensors
1LD2 }				
1YFC				
1YFC	407.5	13.37	Grout	Triaxial stress gage package with ytterbium sensors
1YFC				
1YFC				
1DLH	417.3	13.69	Tuff	Solid-coupled lithium niobate

Table 3 (cont)

Gage Type	Distance From Working Point		Host Material	Notes
	(cm)	(ft)		
1DYFC	417.0	13.68	Tuff	Fluid-coupled ytterbium
1DLFC	418.8	13.74	Tuff	Fluid-coupled lithium niobate
1EYG1				
1EYG2	405.4	13.30	Tuff	Triaxial stress gage package with ytterbium sensors
1EYG3				
CP1	--	--	Grout	Radial cavity pressure gage
CP2	--	--	Grout	Tangential cavity pressure gage

Cage power supplies and signal conditioning equipment were located underground about 46 m (150 ft) from the working point. Coaxial and twisted shielded pair (TSP) cables carried the signals to a recording trailer at the tunnel portal. Data are recorded on two Bell and Howell VR3700 tape machines; output from fast rise-time gages was recorded with wide-band electronics and from slower rise-time gages with multiplex electronics.

Analog data on the magnetic tape were digitized and filtered at various rates. These ranged from the sampling interval of 0.2 μ s and a low-pass filter of 400 kHz for the 60-kbar gages to a 5.0- μ s interval and 20 kHz low-pass filtering for the 1-kbar gages.

Cage Data and Discussion

General

Data recovery on this experiment was good. Of the 44 gage elements, a hook-up error caused the loss of one and improper signal conditioning distorted records from two gage elements slightly and from three moderately. Gage waveforms are discussed later; here we will show time of arrival (TOA) and peak-stress values as an overview of the data.

Table 4 presents gage locations, TOA of the first energy, peak stresses, and residual stresses. Over the stress range of 1 to 60 kbar, most arrival times cluster near a line (Figure 3). The main energy observed on the fluid-coupled plate (FCP) gages seems to have arrived late. Accelerometer arrivals are early when compared to stress-gage arrivals; Accelerometers on other field experiments have encountered this effect. The TOA gages also show early arrivals. Excluding the 60-kbar, TOA, and FCP gages, and accelerometers a least-squares fit of the TOA data gives

and the observed velocity is 2.45 km/s (8.03 ft/ms). If we consider only the gages in tuff, we observe a mean velocity of 2.43 km/s; for gages in the grout stemming plug, we see a mean velocity of 2.46 km/s.

Figure 3. Time of Arrival (First Energy) vs Range

Table 4

Data Recovery

Gage Stress	Range		Time of Arrival	Peak Stress*	Residual Stress*	Peak Acceleration
	(cm)	(ft)	(ms)	(kbar)	(kbar)	(kilo-gravities)
60MK	51.1	1.68	0.0855	--	--	--
60CK	51.1	1.68	0.080	--	--	--
60MP	51.1	1.68	0.080	52.00	--	--
60MR	51.1	1.68	0.082	63.00	--	--
6BLFC	140.3	4.60	0.390+0.003	--	--	--
6BLH	132.8	4.36	0.348+0.002	--	--	--
6AYFC	132.3	4.34	0.348+0.002	7.80	--	--
6LH	120.3	3.95	0.357+0.003	--	--	--
6YFC	121.9	4.00	0.357+0.003	9.70	--	--
2CYFC	286.7	9.41	1.025+0.005	2.10	0.220	--
2CLH	284.1	9.32	1.025+0.005	--	--	--
3FCP	184.2	6.04	0.6900	--	--	--
2FCP	287.3	9.43	1.27	2.80	--	--
1FCP	418.5	13.73	~1.69	0.80	0.200	--
2T1S	269.6	8.84	0.82	--	--	--
2T1B						
2T3B	264.8	8.70	0.81	--	--	--
2T3S						
1YFC	421.8	13.84	1.550+0.50	0.60	0.200	--
1LH	421.8	13.84	1.480+0.30	0.93	0.230	--
1LD1	407.8	13.38	1.650+0.20	0.52	0.185	--
1LD2				0.57	0.150	--
1YG1			1.550+0.05	1.24	--	--
1YG2	407.5	13.37	1.550+0.10	1.24	0.16	--
1YG3			1.500+0.10	1.29	0.23	--
1DLH	417.3	13.69	1.550+0.05	1.60	0.320	--
1DYFC	417.0	13.68	1.520+0.02	0.83	0.240	--
1DLFC	418.8	13.74	1.560+0.02	1.02	0.260	--
1EYG1				1.02	--	--
1EYG2	405.4	13.30	1.42+0.020	1.14	--	--
1EYG3				1.17	--	--
<u>Acceleration</u>						
1AR1				--	--	11.00
1AT1	195.3	12.97	~1.27	--	--	2.00
1AV1				--	--	1.65
1AR2				--	--	12.50
1AT2	395.9	12.99	~1.27	--	--	1.35
1AV2				--	--	1.70

*Indicated stresses, using calibrations discussed in Appendix A.

In a similar way, we can examine the peak stress data vs the range data on a log-log plot (Figure 4). Including another cycle on the ordinate would show that the 60-kbar data fall slightly above the fitted line. Stress values were obtained with currently available gage calibrations which, however, may be erroneous because of a possible under-registration effect for the fluid-coupled gages and because the one-dimension strain, or hydrostatic loading, experienced in calibration experiments may not be appropriate to the triaxial loading in the field experiment. These effects are briefly discussed in Appendix A. With all the data points shown in Figure 4, a least-squares power fit gives

$$\sigma(\text{kbar}) = 14.0 R^{-1.88}, \quad (2)$$

where R is the range in m. This peak-stress decay is very close to the fit of $R^{-1.882}$ obtained by Bass¹ for nuclear events in wet tuff in Rainier Mesa. The fit also compares favorably with data collected from previous (454-kg) 1000-lb HE detonations in wet tuff, which yield

$$\sigma = 15.6 R^{-1.87}. \quad (3)$$

Thus peak stress data from this event are consistent with data from previous work in wet tuff.

60-Kilobar Gages

Besides the work on residual stress, this experiment provided an opportunity to test other gages. Four gages were located 9 cm from the surface of the TNT sphere, the nominal 60-kbar level. Because of the high stresses and severe accelerations, we did not expect these gages to survive the peak stress and measure residual stress.

Figure 4. Measured Peak Stress vs Range

Gages 60CK and 60MK were the same type that had been used in the nuclear event HYBLA GOLD. During that event, we had obtained credible waveforms except that polarities appeared to have been reversed. Extensive investigation convinced us that it was a problem in the gage, and not a simple polarity charge. The probable cause was the epoxy around the grid becoming conductive under the 50- to 100-kbar shock loading. The output signal, then, was the result of the stress-induced resistance change in the piezoresistive grid being shunted by the stress-induced conductivity in the grid host. The resulting negative trace showed that the conductivity was the stronger of the two. PUFF TOO offered an opportunity to test this hypothesis and possibly to obtain a correction factor.

The gage packages for HYBLA GOLD had consisted of a sensing grid epoxied between two hemi-cylinders of lucite and potted in an aluminum can. This package was 7.6-cm (3 in) in diameter and 91.4 cm (36 in) in length and its axis was radial to the charge, thus loading the sensing grid end on. The disadvantage of this scheme is that there is a slight smearing of the rise time, about 7 μ s, because of the time needed by the stress wave to cross the grid. A potential advantage is that survival should be significantly longer than that of the normal grid configuration in which the grid is loaded perpendicularly to a radial line from the charge, or parallel to the wave front. Gage 60MK was the spare for the HYBLA GOLD and contained a 44-ohm manganin grid. Figure 5 shows its recorded output. After the arrival time of 85.5 μ s, the trace goes negative, reaches a magnitude of -0.3 V at 87.5 μ s, then rises to the positive band edge. The latter rise is probably caused by gage breakage. Using calibration data, the -0.3 V is equivalent to a decrease in gage resistance of 2.94 ohms. Gage 60CK was identical to 60MK except that the grid was a 95-ohm constantan element. Rosenberg² has shown that, unlike manganin, constantan has a negligible piezoresistive coefficient, thus the gage should respond only to the conductivity effect. Following stress-wave arrival at 80 μ s, the constantan grid also shows negative signal with one peak of -2V at 83 μ s, followed by a -4 V spike at 87 μ s. Again the rise to positive band is probably caused by breakage and occurs about 10 μ s after TOA. The two voltage levels represent resistance decreases of 19.1 ohms and 38.3 ohms respectively.

Figure 5. Constantan and Manganic Gages 60CK and 60MK

In PUFF TOO these gages broke earlier than expected and we did not obtain a correction for the HYBLA GOLD gages. The polarity of the traces and the relative signal magnitudes are consistent with the stress-induced conductivity hypothesis. We can, however, examine the constantan (CK) and manganin (MK) wave forms in detail and extract some bits of data. From the TOA to breakage, 60CK lasts 7 μ s and 60 MK 2 μ s (Figure 5). Since we know the grid dimensions and the shock velocity in lucite, we can calculate that the transit time along the length of the grid is 7 μ s. Therefore, it appears that the constantan broke when the shock-wave front reached the leads at the end of the grid and the manganin broke when 2/7 of the grid had been engulfed. About 2 μ s after TOA on 60CK, we see a negative 2-V signal. This resistance change is probably due solely to a conductivity, that is, a shunting effect in the host material. The shunt necessary to generate the -2 V is 377.5 ohms. This shunt may be added in an equivalent circuit for the manganin gage and a value extracted for the stress-induced ΔR change in that portion of the manganin grid that had been engulfed at breakage. We obtain a stress-induced resistance (ΔR) change of 2.07 ohms. Since only 2/7 of the grid had been pressured, the $\Delta R/R_0$ is

$$\frac{2.07}{(2/7)44}.$$

Using the usual calibration for manganin,

$$P(\text{kbar}) = 350 \frac{\Delta R}{R_0} \quad (4)$$

we obtain a pressure of 57.6 kbar. The other gages (60MP and 60MR) at this location show this to be a reasonable value.

If we review the HYBLA GOLD waveforms, we notice that the shunting effect varies with input pressure and that the analysis--as performed above--yields data on only one point along the curve. One redeeming feature is that assumed values of pressure for HYBLA GOLD give reasonable

values of shunt resistance, suggesting the plausibility of the assumed conductivity mechanism.

In addition to the two cylindrical gages near the explosive, we fielded two traditional-style manganin gages; these consist of short cylindrical slugs with the plane of the piezoresistive grid parallel to the wave front. Gage 60MR consist of a 50-ohm grid embedded in a mass-curable epoxy (REN RP-3269-1) with two RG213 coaxial cables leading out the back. We used only the center conductor of the coax in order to enhance survival of the lead lines. Gage 60MP had a 50-ohm manganin grid embedded in an epoxy cylinder and a sheet metal can around the cylinder. The can plus the shield of a single lead of RG215 coaxial cable, acted as an electrostatic shield around the gage. Figure 6 shows an initial pressure peak of 52 kbar, followed by a rising trace. There is some detail at 122 μ s and electrical breakage at 128 μ s. The waveform for gage 60MR shows pickup before the stress wave arrives, an initial peak stress of 63 kbar, a positive and negative spike starting at 126 μ s, and an electrical short at 288 μ s. The difference in peak-stress amplitude is probably caused by the difference in shock impedance of the two epoxies. The rising trace after the first peak on 60MP is probably associated with lateral strain caused by the spherically diverging wave--manganin acts like a strain gage when pulled laterally and exhibits a positive resistance strain coefficient. From known shock velocities and thicknesses of the epoxy cylinders, the 126- to 128- μ s detail is about what the expected TOA of the stress wave would be at the back of the gages. The 60MP opened electrically at this time and the 60MR with its double coax, continued to record until the leads shorted out at 288 μ s. At 288 μ s, the wave front is 1.13 m (3.6 ft) from the charge center; we do not know why the leads shorted at this time. Usually, this gage configuration at the 50- to 60-kbar level produces arrival information and stress peaks but other phenomena affect pressure unloading. The electrical shield helped minimize electrical pickup.

Figure 6. Manganin Gages 60MP and 60MR

Close to the 60-kbar gages we placed a "dummy gage," that is, a noise-study cable (60NS1) to observe the interaction of the stress wave and a signal cable. This was an RG22 cable whose end was located 139.3 cm from the charge center. At the signal conditioner end of the cable, we attached a fixed capacitor. The total capacitance of the cable and capacitor was $0.15\ \mu\text{F}$. This configuration was electrically similar to a lithium niobate gage. It was calibrated at 2 V and the band edges were set at ± 2.2 and ± 10 V. Figure 7 shows the output of 60NS1.

Figure 7. "Dummy Gage" 60NS1

In the 0- to 200- μ s portion of the record, we see oscillations that suggest "detonation" noise. At 350 μ s, there was a sharp negative spike. The time of this spike coincide within 5 μ s, with the arrival of the stress wave at Gage 6BLH which produced a negative 15-V signal, indicating that the spike on 60NS1 may have been crosstalk. We would expect the stress wave to arrive at the end of the 60NS at 370 μ s, yet we see no evidence of the arrival. Perhaps it was buried in the 6BLH pickup. At 1.02 ms we see a positive arrival. This TOA coincided with that of Gage 2CLH which produced a 10.8-V positive signal. After this arrival the voltage oscillated about 0.5 V, representing a charge on the cable of about 100 nanocoulombs (nC).

This experiment showed that RG22 cable terminating in a capacitor can readily sense overvoltage signals from other gages and shows an output which is probably stress-induced.

6-Kilobar Gages

At the nominal 6-kbar level about 1.2 m from the charge center, we located five paddle gages. Our interest at this stress level was threefold:

- To compare the stress and the TOA arrival in the grout backfill with those of the tuff
- To determine the ability of fluid-coupled gages to survive and to measure residual stress
- To examine the survivability of lithium niobate gages

After the event, we discovered that some channels of the signal conditioning unit contained inappropriate resistors, producing RC decay of the input voltage level. With a time constant of 1.7 ms, a 50- μ s phenomenon will show negligible distortion while a 1-ms phenomenon will produce about a 50% error. Traces from these channels were corrected.

Gage 6AYFC was a fluid-coupled ytterbium gage which we installed in tuff; its signal conditioning unit contained an inappropriate resistor. Figure 8 shows the corrected waveform, with an observed peak of

7.75 kbar.* Appendix C gives details of the corrections. During corrections the time scale was shifted; zero time in the figure is when the stress wave arrived at the gage (0.348 ms). We believe the oscillation at the 4-to-5-kbar level is real since we see it on other records from gages in tuff. We see another small oscillation near the 1-kbar level. At gage breakage time, 2.3 ms after the time-of-arrival, the observed amplitude is 0.5 kbar.

Figure 8. Corrected Fluid-Coupled Ytterbium Gage 6AYFC

*We have reduced the data for this and other fluid-coupled ytterbium gages by using the hydrostatic calibration data (Appendix A).

We placed Gage 6YFC, a fluid-coupled ytterbium paddle in the grout plug. Figure 9 shows the output. Following the rapid rise to 9.5 kbar, the waveform decays and shows electrical breaks at 490 and 620 μ s. Of the lithium niobate paddles one (6LH) was imbedded in the grout backfill and two (6BLH and 6BLFC) were in drill holes. The two solid-coupled paddles (6LH and 6BLH) produced spurious waveforms (Figure 10). The negative voltage, starting about 1.1 ms, is common to both and appears to be cross talk. The fluid-coupled gage (6BLFC)* produced a more reasonable shape (Figure 9) but the amplitude was too great for that range. The negative spikes at 0.348 ms and at 1.1 ms appear to be pickup from 6BLH.

The ytterbium fluid-coupled gages at this nominal 6-kbar level produced reasonable waveforms although they did not survive long enough to measure residual stress; cable breakage is suspected. The lithium niobate gages did not survive the 6- to 10-kbar level, although the fluid coupling seemed to give a more reasonable shape. We believe that the solid coupled crystals are fracturing; we have no plausible explanation for the enhanced output of the fluid coupled crystal.

2-Kilobar Gages

At the nominal 2-kbar stress level, we grouted two stress gages in a drill hole. Figure 11 shows the output from one gage, the fluid-coupled ytterbium paddle (2CYFC). The peak amplitude is band-edge limited, for the backup channel shows the peak to be 2.1 kbar (The backup channel has a poor signal-to-noise ratio which obscures unloading oscillations.) The waveform rises rapidly to a peak stress and its unloading portion contains oscillations similar to those obtained from the 6AYFC. The trace then settles to 0.22 kbar and shows electrical failure at 9.2 ms.

*We have reduced the data from the fluid- and solid-coupled lithium niobate gages by using the lithium niobate hydrostatic coefficient (Appendix A)

The other gage (2CLH) in the drill hole was a solid-coupled lithium niobate paddle. Figure 12 shows a TOA of 1.03 ms, a slope change at 2.7-kbar amplitude, an oscillation, and then a rise to the 10-kbar band edge.

Figure 9. Fluid-Coupled Ytterbium Gage 6YFC and Fluid-Coupled Lithium Niobate Gage 6BLFC

Figure 10. Solid-Coupled Lithium Niobate Gages 6LH and 6BLH

Figure 11. Fluid-Coupled Ytterbium Gage 2CYFC

Figure 12. Solid-Coupled Lithium Niobate Gage 2CLH

The fluid-coupled ytterbium gage at the nominal 2-kbar level produced a credible record. Although the trace ends at about 9 ms, the 0.22-kbar amplitude at this time is probably from residual stress (Appendix B compares 2CYFC to a computer calculation of the event). The solid-coupled lithium niobate gage broke, perhaps at the 2.7-kbar level, suggesting that dynamic effects at this distance are still too great for the lithium niobate crystals to survive.

Time-of-Arrival Detectors

We installed four stock TOA detectors at the nominal 2-kbar level in the grout stemming plug. We were interested in the prolonged response generated by these detectors when used in the open circuit, long time constant mode to sense multiple wave arrivals. Usually the short circuit, current mode is used with these detectors to eliminate all but the sharp initial stress-wave arrival. In experiments with a single-point source of energy, these detectors work well. However, current experiments involve multiple sources and require that successive TOAs be observed. How well the TOA detector could be adapted to this requirement had to be examined.

These TOA detectors consist of 25-mm (1-in) and 75-mm (3-in) lead zirconite titanate (PZT) rings potted in epoxy. Two TOA detectors, one of each diameter, were installed such that the incident wave impinged on the detector parallel to the ring axis. Two others, also of both diameters, were load side-on. Previous laboratory work had established the sensitivity and output polarity of these devices. Figure 13 shows the output from the smaller rings. The 2T1S was loaded side-on and shows positive output, as expected; similarly the 2T1B was loaded end-on and shows a negative signal, again as expected. These simultaneous arrivals, however, were followed by additional output.

Figure 14 shows the output from the larger rings. The 2T3S was side-loaded and shows a large output whose polarity is opposite of that expected. The 2T3B shows the expected polarity as well as significant subsequent energy. Polarity reversal on the 2T3S could be caused by lead reversal at an electrical connection. Details of signals that arrived after the initial arrival may have been caused by ring failure.

This work has shown that when used in point-source detonations, stock TOA detectors produce useful first-energy arrival data which is followed by additional output. This additional output will obscure subsequent energy arrivals if the detector is used in a multiple energy source experiment. For this reason, we conclude that the stock TOA detectors cannot be used for the reliable detection of closely spaced arrivals.

Figure 13. Time-of-Arrival Detectors 2T1S and 2T1B

Figure 14. Time-of-Arrival Detectors 2T3S and 2T3B

Fluid-Coupled Plate Gages

Fluid-coupled plate (FCP) gages have been fielded on numerous nuclear events. A massive steel version has been used to measure plasma flow in line-of-sight pipes with fast rise times ($<100 \mu s$) and peak pressures of up to 1 kbar. A smaller aluminum version has been used to make free-field measurements with rise-times longer than 1 ms and peak pressures up to 1 kbar. The gage consists of a force plate in front of a fluid chamber in

which transducers measure the pressure in the fluid. In PUFF TOO we installed three FPCs: one was a steel version, two were aluminum. We suspected that massiveness of the steel gage (3FCP) might affect its response to the dynamic effects in a 454-kg event; however, it might respond correctly to the residual stress.

Figure 15 shows the wave shapes obtained from gages 3FCP, 2FCP, and 1FCP. The 3FCP was located 184.2 cm from the charge center; other data show this to be the 5-kbar level. The signal rose rapidly to 12 kbar, oscillated about 6 kbar, and then an electrical lead broke. Because of an impedance mismatch between the steel case and the grout, we expected an overshoot phenomenon. A finite element code calculation, HONDO, was performed to see if the observed response of this FCP gage in rock-matching grout was reasonable. With an input waveshape extrapolated from a closer-in gage, the calculation showed that the output of the steel FCP should be a pulse with a peak of about 12 kbar and a duration of about 100 μ s. This is similar to the shape actually observed.

Gage 2FCP, an aluminum unit, was turned 90° in the stress field to measure residual hoop stress. Data show minor wave arrivals at 1.085 and 1.268 ms and a main arrival at 1.38 ms. The earlier arrivals are consistent with arrival data from other gages and may represent a low-amplitude wave propagating through the housing to the sensing element well before the stress wave induced motion in the force place occurs. The trace rose to about 2.8 kbar and indicated electrical failure about 300 μ s after the main arrival.

Data from 1FCP, also an aluminum unit, show a main peak of about 0.5-ms duration and 0.8-kbar amplitude and a long-term offset of 0.2 kbar. Its duration is short compared to that of other gages at this location (0.5 ms vs 2 ms) but the long term offset is credible for residual stress.

Figure 15. Fluid-Coupled Plate Gages 3FCP, 2FCP, and 1FCP

The FCP gages respond to stress-wave input. With short rise times, we see strong overshoot but for a rise time on the order of 0.5 ms we see none; however, the pulse length was shorter than that observed on other gages at this range. The data from the FCP gages helped us understand gage response better and measured residual stress at one location.

Accelerometers

One triaxial accelerometer package was placed in the grout stemming at the nominal 1-kbar level. This so-called "rectangular" package

contained three 50-kg piezoresistive accelerometers (Endevco 2264A-50K-R) mounted on an aluminum base and covered by a thick aluminum cover. This configuration was designed to prevent the stress wave from crushing the accelerometers. The accelerometers were oriented orthogonally, 1AR2 is the radial element (positive acceleration is outward), 1AV2 is the vertical element (positive acceleration is up), and 1AT2 is the transverse element (positive acceleration is clockwise, looking down on the arrangement). Figure 16 is data from 1AR2, the radial accelerometer, and shows an arrival at 1.27 ms, a rise-to-a-peak acceleration of 12.5 kg,* an abrupt drop to a negative 7 kg, and a return to approximately zero acceleration at 2.5 ms. The record is clean and credible.

Figure 16. Radial Accelerometer 1AR2

*When used with acceleration, kg designates 1000 times g, the acceleration due to gravity.

Figure 17 shows data from the vertical (1AV2) and transverse (1AT2) accelerometers. We processed the records normally, but they are quite noisy because the amplitudes were well below the 24-kg band edge. The traces in Figure 17 have been filtered with a 25-kHz low-pass digital filter; 1AV2 shows a positive (up) peak of 1.7 kg and a shape similar to that of the radial gage, and 1AT2 shows a positive acceleration of about 1.35 kg. These traces suggest some asymmetry to the sphericity of the explosion. The gage package was placed in the grout plug about 40% of the way up from the floor and about 25% of the way across the plug.

Figure 17. Vertical and Transverse Accelerometers
1AV2 and 1AT2

Close to the rectangular gage we placed a triaxial bottle-shaped accelerometer package with the elements encapsulated in epoxy and so orientated that the radial accelerometer is aligned with the axis of the bottle. Data from this accelerometer, IAR1 (Figure 18), shows a shape similar to the radial accelerometer in the rectangular package. Between 1.9 and 2.0 ms, there is a high-frequency high-amplitude "event." When we expand this interval, we find a damped sinusoid with a sharp onset. The oscillation period is about $15\ \mu\text{s}$ (66 kHz), about twice the natural frequency of the accelerometer. This "event" is probably spurious gage response and not material acceleration. After a peak outward acceleration of 11 kg, the trace drops rapidly to negative 6 kg and then returns to zero.

Figure 18. Radial Accelerometer IAR1

Figure 19 shows data from the other two components. The filtered vertical accelerometer (IAR1) shows a 1.65-kg peak and a shape similar to

that of the radial gage. The transverse gage, 1AT1, shows a sign convention that is the reverse of the other transverse component, 1AT2. We see a clockwise acceleration with a peak of 2 kg at 2.1 ms, at which time there appears to be large noise pickup. Again, when we spread out the waveform, we see damped sinusoid with a duration that increases from 20 to 40 μ s as the amplitude decays. The trace shows a negative 3-kg offset indicating that the gage was damaged.

Figure 19. Accelerometers 1AV1 and 1AT1

The accelerometer packages, which we placed in the grout backfill 395 cm from the charge center show a peak radial acceleration of 11 to 12 kg. Vertical and transverse components show peaks of up to 2 kg. When we compare data from the epoxy bottle with those from aluminum rectangular packages, we see similar wave shapes and fewer noise spikes from the rectangular package.

To show the relationship between acceleration, particle velocity, and stress, we have shown IAR2, the integral of IAR2 and ILH on a common time base in Figure 20. It is often observed that accelerometers usually show earlier TOAs than stress gages (0.1 ms of difference) due to the difference in distance. Here the first portion of the particle velocity waveform (integrated acceleration) is similar in shape to that of the stress waveform. This is to be expected: the stress wave induces particle motion and the theory of plane shock-wave propagation relates peak stress to peak particle velocity. The relation, $\sigma = \rho c u$, is not strictly applicable here because we do not have a shock wave. Using the relation, however, the peak particle velocity of (26.6 m/s) 87.5 ft/s gives a very reasonable value of 1.1 kbar. In subsequent work, we will examine at these records in more detail. For example, a power density spectrum will be studied to look for resonances that may affect the output.

Figure 20. Accelerometer IAR2, Particle Velocity (from IAR2), and Lithium Niobate Stress Gage ILH

Triaxial accelerometer packages are sometimes used in explosive events because their outputs and time integrals (velocity) provide useful diagnostics of wavefront direction and particle velocity data. One problem with their use, however, has been in predicting amplitudes; computer calculations, with their artificial viscosity, often give erroneous predictions. The PUFF 100 event provided useful acceleration data for use in other work, and data to use in comparing the two gage packages.

1-Kilobar Gages In Tuff

At the nominal 1-kbar range, we inserted gages into 10.2-cm (4-in)-diameter holes drilled in the tuff and we coupled them to the tuff with a rock-matching grout (Figure 1). They were loaded "face on," the usual loading for paddle style gages. The D and E holes contained two lithium niobate gages, a ytterbium gage, and a ytterbium triaxial bottle gage.

Gage 1DLFC (Figure 21) was a fluid-coupled lithium niobate paddle. After a rapid rise to a 1.02-kbar peak, we see one distinct dip in the unloading, at 4 ms, before the trace settles to a long-term residual stress of 0.26 kbar. Close to 1DLFC, we placed a fluid-coupled ytterbium paddle, 1DYFC. From this we see a waveform (Figure 22) similar in shape to that of the lithium niobate record, with a 0.83-kbar peak, a dip at about 4 ms, and residual stress of 0.24 kbar. The trace has some rapid detail on the peak. This is not a tape recorder band edge problem because the low sensitivity back-up channel shows the same amplitude. The oscillations beyond 20 ms show a period of about 15 ms which, most likely, is ac pickup. Also shown in Figure 22 is data from a solid-coupled (PHA) lithium niobate paddle gage, 1DLH; the shape is similar to that of 1DLFC and 1DYFC. The notable difference is in the peak amplitude (1.6 kbar) and residual stress (0.32 kbar). The differences in peak amplitudes probably reflect two effects: first, a potential underregistration* of fluid-coupled gages and second, we suspect the fluid-coupled gages are measuring mean stress and the solid-coupled lithium niobate gage is measuring radial stress.

*The fluid is more compressable than the gage package, thus a bridging, or underregistration effect may occur.

Figure 21. Fluid-Coupled Lithium Niobate Gage 1DLFC

Figure 22. Fluid-Coupled Ytterbium Gage 1DYFC and Solid-Coupled Lithium Niobate Gage 1DLH

The last gage in a drill hole was a triaxial ytterbium bottle with three sensing elements: 1EYG1, 1EYG2, and 1EYG3; Figure 23 shows the records. The peaks on G1, G2, and G3 are believable (1.02, 1.14, and 1.17 kbar);* on 1EYG3, the peak unloads similarly to the other gages in tuff and shows the start of a dip at 3.5 ms. The trace then flattens out and subsequently shows two jumps that look like breaks in the electrical leads. Elements G1 and G2 were recorded with signal conditioning channels that, through an error, had a too short an RC decay constant. These records were later corrected (see Appendix C for discussion of the correction technique). Figures 24 and 25 show the corrected versions of elements G1 and G2. Note that this bottle gage was loaded side on, thus the elements are orientated obliquely to a radial from the charge center. The residual amplitude on G1 and G2 contains two effects: residual stress and gage hysteresis.

Ytterbium and lithium niobate gage records at the nominal 1-kbar level show a shape which is characterized by a rapid rise to a peak stress, a gradual unloading with a distinct dip at 4 ms, and a settling to a residual stress of about 0.27 kbar.

1-Kilobar Gages in Grout Stemming

We placed four stress gages in the grout stemming at the 1-kbar nominal amplitude. Two, 1YFC and 1LH, were paddle gages and the others were prototypes of a triaxial stress gage. The long-range application of the triaxial gages is to measure principal stress components (Appendix A). They consist of three sensing elements on the orthogonal faces of an epoxy cube which, in turn, is encapsulated in an approximately cylindrical epoxy bottle. We aligned the axis of the bottle along a radial from the charge center.

* The one-dimension strain coefficient has been used to reduce these nonfluid-coupled ytterbium gages (Appendix A).

Figure 23. Triaxial Ytterbium Gage With Elements 1EYG1, 1EYG2, and 1EYG3

Figure 24. Corrected Version of LEYG1 Gage Element With Time Measured From TOA

Figure 25. Corrected Version of LEYG2 Gage Element With Time Measured From TOA

The orthogonal faces in the gage are orientated such that the plane of each sensing element is about 35° from the axis of the gage; the elements are symmetrically spaced with respect to the boundaries of the epoxy host. With the radial orientation of the gage package, we expected similar signals from each sensor - if the explosion produced an axially symmetric stress field. The accelerometers (see above) showed that there was, in fact, some asymmetry of the stress field.

The ytterbium fluid-coupled gage 1YFC (Figure 26) produced a rapid rise to a 0.6-kbar peak, the unloading showed oscillations at the 0.2- to 0.3-kbar level, and settled to 0.2 kbar at 22 ms. The waveform is quite believable and indicates a late residual stress of 0.2 kbar.

The companion lithium niobate gage (1LH) was a solid-coupled paddle (PHA). Figure 26 shows a rapid rise to a 0.93-kbar peak, some oscillation in the unloading, and finally a settling to 0.23 kbars at 22 ms. Again, it appears we measured residual stress. Except for the minor difference between 3 to 8 ms, 1YFC and 1LH are in remarkable agreement on waveform shape. The correct gage calibrations are unknown; however, if we assume that 1LH is correct, then the difference between 1LH and 1YFC suggests that the fluid-coupled package causes an under-registration effect of approximately 60% (Appendix A).^{*} This is about the difference noted for the 1DLH and 1DYFC in tuff. The data from the solid-coupled lithium niobate triaxial gage with sensing elements 1LD1, 1LD2, and 1LD3 is shown in Figure 27. Element 1LD1 shows a peak of 0.52 kbar and an oscillation in its unloading before it settles to a 0.185-kbar offset. Element 1LD2 differs from 1LD1 in some of the unloading oscillations; its peak is 0.57 kbar and its long-term amplitude is 0.15 kbar. The difference in the unloading oscillations of 1LD1 and 1LD2 may be due to some asymmetry of the stress field; 1LD3 was not recorded because of a field hookup error. These records are credible and the shapes are similar to paddle gages 1LH and 1YFC.

^{*}Subsequent work suggests that solid-coupled lithium niobate gages respond principally to the stress (which loads the face of the element). This implies that 1LH responded to the dynamic radial stress. Gage 1YFC is most likely trying to respond to the mean stress.

Figure 26. Fluid-Coupled Ytterbium Gage 1YFC and Solid-Coupled Lithium Niobate Gage 1LH

Figure 27. Lithium Niobate Triaxial Gage With Elements 1LD1 and 1LD2

The second bottle gage at the 1-kbar level contained three ytterbium grids. Figure 28 shows the traces produced by elements 1YG1, 1YG2, and 1YG3. Gage element G1 suffered from the incorrect resistor described previously. Figure 29 shows the corrected version.

Figure 28. Triaxial Ytterbium Gage With Elements 1YG1, 1YG2, and 1YG3

Figure 29. Corrected Version of Element 1YG1 With Time Measured From TOA

Elements 1YG2 and 1YG3 produced similarly shaped waveforms, showing some oscillation in the unloading before settling to a constant offset. If we use the one-dimensional strain coefficient, we see that the measured peaks and late time offsets are:

Element	Peak (kb)	Offset	
		(Kb)	$\Delta R/R_o$
1YG1	1.24	-	-
1YG2	1.24	0.3	0.0105
1YG3	1.29	0.36	0.0127

The peaks are believable; the late offsets contain the sum of the residual stress and the so-called hysteresis effect observed in ytterbium when it is not hydrostatically loaded.

If we carefully review Ginsberg's calibration work on ytterbium,³ we find that, below 1 kbar, ytterbium, loaded in uniaxial strain, shows no

hysteresis; above 1 kbar, it shows increasing hysteresis. Ginsberg's calibration shot that is appropriate to LYG2 and LYG3 is S7, showing a peak stress of 1.27 kbar and a zero stress offset ($\Delta R/R_0$) of 0.0052. Confidence in this calibration shot is enhanced by the presence of two gage elements which show peak $\Delta R/R_0$ and residual values agreeing to within a few percent. Subtracting the hysteresis effect from LYG2 and LYG3 and converting to stress, we obtain residual stresses of 0.23 and 0.16 kbar.

The solid-coupled lithium niobate crystals and the fluid-coupled ytterbium elements in the grout stemming show surprisingly similar wave-shapes. Peak amplitudes vary by a factor of about two; we must, however, examine the element, its host, orientation, and, in general, the gages' response to the triaxial state of stress. The rise in stress after the 3.3-ms dip may be associated with the rebound of the far field material. Late residual stress tends to cluster about 0.19 kbar and, in spite of differences in peak stress, they agree well.* Also, the 0.19-kbar value closely agrees with the calculational results described in Appendix B.

Comparing the 1-kbar gages in grout with those in tuff, we see that, typically, the gages in grout show a major oscillation between 3 to 20 ms which is not seen on the tuff gages. This difference in unloading behavior is probably due to a difference in the elastic-plastic behavior between the tuff and the grout. Also, gages in tuff show an average residual stress of 0.25 kbar and those in grout, 0.19 kbar.

Cavity Pressure Measurements

We attempted two cavity pressure measurements in the PUFF TOO experiment. Such measurements are of interest because it is the pressure that the residual stress field must withstand in order to contain the event. Also, cavity pressure and the final size of the cavity may be compared with computer calculations; agreement indicates that the explosion phenomenon has been modeled correctly.

*One can argue that in the late time regime the gages are all measuring mean stress.

To measure cavity pressure, we used a "blowdown" technique previously used on smaller charges. The equipment consisted of a quarter-litre volume pressure chamber, high-pressure tubing,* and an explosive valve. The pressure chamber, containing a pressure transducer, was located outside the grout stemming, and charged, before the shot, with nitrogen to about 69 MPa (10 000 lb/in²). The tubing extended from the chamber through the grout stemming plug and ended close enough to the high explosive so that the pipe tip was at the edge of or just inside the final cavity. An explosive valve was located 3 to 7 m from the tip of the pipe. We fired the explosive valve 10 ms before the main charge, starting the flow of gas. As the cavity grows and engulfs the tip of the pipe, the pressure in the chamber "blows down" into the cavity.

Data from our previous experience with this technique are shown in Figures 30 and 31. The former shows measurements on three 3.63-kg (8-lb) events, the latter on a 29-kg (64-lb) event.

The time record is characterized by a rapid drop of pressure that terminates in an abrupt change of slope, which, in turn, is followed by a slow decay of pressure. Calculations involving turbulent flow through a long thin tube duplicate the rapid decay and slope change and show that the pressure at the slope change is the cavity pressure. The slow decay is due to cavity cooling and porous flow out of the cavity.

In PUFF TOO, we installed the CPI gage like we did the gages used on the smaller events; the tip of the tubing was 525 mm (21 in) from the surface of the explosive and the tubing extended radially outward. On the CPI gage we used a variation of the same technique--a capped piece of tubing tangential to the explosive sphere. Circumferential grooves had been cut in the tube and the dynamic effects from the explosion were expected to break the pipe and allow the gas to flow, thus no explosive valve is used.

*The 4130 steel tubing has a 3.43-mm (0.135-in) ID, a 9.52-mm (0.375-in) OD, and is rated at 6.7-kbar tensile strength and 4.4-kbar yield stress.

Figure 30. Cavity Pressure From Events RS-5, RS-6, and RS-9

Figure 31. Cavity Pressure From Event RS-4 (64 1b)

Figures 32 and 33 show the pressure time records obtained. The CPI (radial) chamber bleeds from 62.1 MPa (9000 lb/in²) initial pressure down to 51.0 MPa (7400 lb/in²) and shows some oscillations. The 60-s record (Figure 33) shows a slight rise in pressure and then a slow decay. The tangential gage starts at 72.4 MPa (10 500 lb/in²) and decays to about 21.4 MPa (3100 lb/in²) at which point we see an inflection. The long term trace shows a slight rise, a slow decay, and a 2.1 MPa (300 lb/in²) jump at 48 s.

Figure 32. Cavity Pressure CPI and CP2 from Event RS-3 (0 to 5 s)

Figure 33. Cavity Pressure from RS-3 Event (0 to 70 s)

Mineback showed 15.2 cm (0.5 ft) of the CP1 pipe inside the cavity. This pipe, originally radial, had been bent to one side and the tip was jammed closed. In the grout, 183 cm (6 ft) from the charge center, there was a 4-mm gap in the pipe. The CP2 line was broken at the cavity wall; the break appears to have been at one of the circumferential grooves. At 310.9 cm (10.2 ft) from the charge center was a kink in this pipe with a small axial split.

If the tip of CP1 was jammed closed before pressure equilibrium was achieved, it signifies that the chamber pressure was higher than that in the cavity. The 29-kg (64-lb) event also had a jammed tube and a cavity

pressure of 49 MPa (7100 lb/in²). On the other hand, the CP1 pressure record is similar in shape to the records from the 3.6-kg (8-lb) events which are credible because mineback showed open pipes.

We encounter two problems when trying to interpret CP2 data. First, we have no previous experience with this tangential pipe arrangement. Second is the split at 310.9 cm. Two interpretations are possible. On the basis of past experience, CP1 is credible and the cavity pressure was 51.0 MPa (7400 psi). One, however, would like to be able to offer an explanation for the significantly lower cavity pressure measured by CP2. The alternate interpretation has CP2 measuring the cavity pressure and CP1 bent and jammed closed during cavity growth and thus the chamber pressure was not in equilibrium with the cavity. The cavity pressure is probably bracketed by these two values. In future work we will examine the operation of the blowdown technique.

Postevent

Fracture Pressure Experiment

Four steel pipes, identical to those we used to measure cavity pressure, were grouted in tuff near the charge center. After the event we had planned to pressurize these pipes with nitrogen to measure the pressure required to break out of the small cavity around the end of the pipes. Breakdown pressures should be related to the existence and strength of the residual stress field. After the nitrogen had fractured the material, we planned to pump dyed water into the fractures so that mineback would reveal their direction. This is of interest because orientation of the fractures should reflect the strengths of the hoop in relation to the radial residual stress field; fractures tend to open perpendicularly to the minimum component of the residual stress.

At 2.5 hr after detonation, and before pressurizing them with nitrogen we checked the contents of these fracture pipes (FP) by opening the valves at the bulkhead. FP1 and FP2 showed no pressure or carbon monoxide

(CO). FP3 "spitted" clean, followed by gray water, but contained no CO. FP4 showed a small volume of an explosive gas mixture, with 20 000 PPM of CO, i.e. cavity gas, under about 0.350 MPa (50 lb/in²) pressure.

We pressurized FP4 with nitrogen at a moderate pumping rate. The pressure rose to 14.1 MPa (2040 lb/in²) at which point it dropped rapidly. Subsequent steady pumping showed a pressure of 9.66 MPa (1400 lb/in²). FP3 was similarly pressurized, showed a peak of 19.3 MPa (2800 lb/in²). FP2 and FP1 were pumped at a slower rate: FP2 showed a break at 15.0 MPa (2180 lb/in²) and settled to 12.4 MPa (1800 lb/in²); FP1 broke at 30.3 MPa (4390 lb/in²) and settled to 10.3 MPa (1500 lb/in²). Ten days after this pressurization, we pumped about 6.7 L (2 gal) of dyed water into each pipe to mark the fractures.

Mineback showed that three of these 6.7-kbar tensile strength pipes had broken and that pressurization had occurred at either the breaks or at loosened pipe couplings (apparently caused by the detonation) at the grout-tuff interface. Figure 34 shows the cavities at the ends of the pipes (the designed fracture points), the actual fracture locations, the charge center, and the dyed fracture pattern observed on mineback. Most likely the fractures close to the pressurization points were caused by the nitrogen pumping 2.5 to 3 hr after the event. The fractures extending into the grout stemming were probably caused by the pressure of the dyed water. Most of the fractures were vertical. FP1 showed a fracture in tuff at an angle of 60° to a line running radially from the charge center to the pressurization point. When the fracture reaches the grout stemming, it turns and crosses the stemming at 90° to the axis of the drift. FP2 was pressurized at a break in the pipe at the grout-tuff interface.

A 30-cm (1-ft) fracture extends into the tuff at an angle of 56°; several fractures extend into the grout and proceed at 90° to the axis of the stemmed drift. The pressurization point for FP3 was also at the tuff-grout interface. The fracture extending into the tuff shows an angle of 132°; the fracture into the grout shows the same azimuth but eventually turns and becomes parallel with the other fractures in the grout. Two directions of fractures are noted at the pressurization point for FP4.

A short 15-cm (0.5-ft) fracture is aligned with a radial to the charge center. The second fracture is at 124° to the radial line and extends about 30 cm (1 ft) into the tuff. This fracture extends in the other direction, enters the grout, and turns parallel to the other grout fractures. Table 5 summarizes the data on these fractures.

Figure 34. Locations of Postshot Nitrogen and Water Fractures

Table 5

Fracture Pipe Data

Pipe	Radial Distance(cm)	Breakdown Pressure		Location	Fracture Angle(°)
		MPa	lb/in ²		
FP1	189	30.3	4390	Tuff	60
FP2	250	15.0	2180	Interface	56
FP3	305	19.3	2800	Interface	132
FP4	387	14.1	2040	Grout	0/124

We have observed:

- Breakdown pressures that decrease approximately with distance from the charge center (the exception is FP3)
- Nearly vertical fractures
- Fractures in grout that differ in orientation from fractures in tuff
- One fracture (FP4) that is aligned with a radial leading from the charge center

We believe that the pressure breakdown values show the existence and approximate dependence of the residual stress field on distance for hydraulic fracturing work, about 50 metres away, showed breakdown values in the range of 7.6 to 10.3 MPa (1100 to 1500 lb/in²). A 0° fracture at FP4 implies that the radial residual stress was larger than the hoop residual stress at 387 cm from the charge center. The 60° fracture in tuff at FP1 (189 cm) suggests that the residual hoop stress at this location is larger than the residual radial stress. The parallel dyed fractures crossing the grout column were interpreted by the geologist conducting the mineback as "staining along a series of pre-existing, i.e., detonation-related, fractures."

Although this fracture pipe experiment did not provide quantitative residual stress values, it did show the existence of the residual stress field, a rough idea of the decay of the field with distance, and an indication of the amplitude, of the hoop compared to that of the radial stress at two locations.

Mineback

Mineback in PUFF TOO proceeded in the tuff on the right (south) side of the grout stemming plug. We excavated a drift with a continuous miner to about 3 m (10 ft) beyond the charge center. Hand excavation exposed gages and pipes in the grout plug. Carbon monoxide was encountered along the grout-tuff interface. About 6 m (20 ft) from the cavity we stopped mining and drilled two holes into the cavity to flush out the CO. All notable details were carefully mapped and photographed; only highlights are included below.

At 42.43 m (135 ft) in the mineback drift, we encountered the cavity which was filled with rubble except for a 60- to 90-cm (2- to 3-ft) open zone at the top; the roof of the cavity had collapsed and exposed fresh tuff. When we cleaned out the rubble, we encountered the usual black detonation residue around the sides and on the bottom. Using the residue as boundary, we obtained the cavity shape shown in Figure 35. The cavity is elongated in a N 45° E direction,* has a maximum and a minimum horizontal dimension of about 250 cm (8 ft) and 200 cm (7 ft) respectively. Cavity radii toward the grout plug are about 20% larger than those to the tuff. To extract a radius of this cavity, the area of the horizontal plane through the charge center and bounded by the cavity edge was integrated and set equal to πR^2 , resulting in an extracted radius of 108.4 cm (3.56 ft). An average radius was obtained by measuring radii at 20° increments, arriving at 107.4 cm (3.52 ft).

Examination of the stemming plug grout at the cavity wall showed a notable difference from the tuff at the cavity wall. Although a sample of the tuff could be broken by hand, the grout appeared quite solid. To quantify the difference, we cored and tested samples at various distances from the charge center. There was poor recovery when the soft tuff was cored close to the cavity; apparently a hard inclusion would break up the core. Samples of this soft tuff have been submitted for petrographic examination. Tuff cores at a distance of 354 and 448 cm (11.6 and 14.7 ft) from the charge center showed unconfined crush strengths of 6.83 and 10.1 MPa (990 and 1460 lb/in²) respectively. A grout sample from the cavity wall, 128 cm (4.2 ft) from the charge center, showed an unconfined crushing strength of 15.8 MPa (2290 lb/in²) and one taken at 402 cm (13.2 ft), showed a value of 25.3 MPa (3670 lb/in²).

*This is about the direction of the maximum horizontal component of the in-situ stress. If in-situ stresses dominated the direction of maximum cavity growth, we would see a cavity turned 90° from the observed orientation.

Figure 35. Vertical and Plan Views of Cavity

The tuff next to the cavity had a zone of concentric (onion skin) fractures that was about 60 cm (2 ft) thick. At the cavity wall, black residue filled or coated about 3 cm of the concentric fractures. Beyond this onion skin zone, there was another zone of "softer than normal tuff" 100 cm (3.4 ft) thick. No radial fractures with black residue extended from the cavity walls. Samples of this soft tuff have been submitted for petrographic examination.

Black residue was observed at several locations well away from the cavity. An approximately radial fracture about 45 cm (1.33 ft) long was found at 210 cm (6.85 ft) from the charge center, near the end of FP3. No connection of this black fracture with the cavity was found. On the side away from the stemming plug, about 300 cm (10.2 ft) from the charge center, black residue was found on a core sample. No excavation was

performed to determine the source of the black residue. Near the collar of gage hole E, about 600 cm (20.4 ft) from the charge center, there was a patch, about 90 cm (2.9 ft) long x 60 cm (1.9 ft) high, of thin black residue in horizontal streaks at the grout-tuff interface.

We also encountered two slickenside surfaces, the main one (Figure 36) in tuff, approximately parallel to the grout-tuff interface. This surface started at 165 cm from the charge center (5.4 ft or 1.5 cavity radii) and extended to 463 cm (15.2 ft or 4.3 cavity radii). The observed vertical extent was 90 cm (2.9 ft) at FP1 and 30 cm (1 ft) at FP3. The approximately vertical surface had sheared three of the FPs when it moved. The time of this movement is suggested by the records from gage LEYG in hole E, whose three gage elements showed an abrupt electrical failure at 5.5 ms. If we were to extend this fracture vertically, we would find that it would, indeed, encounter hole E.

Figure 36. Plan View of Mineback Showing Zones of Shear Surface, Onion Skin Fractures, and Soft Tuff

Near the end of the FP1, there was another slickenside passing through broken and offset pipe. This surface was about 60 cm (2 ft) long and approximately parallel to the grout-tuff interface.

These two shear surfaces show that the grout plug and some adjoining tuff moved differentially to the rest of the tuff. The emplacement drift

had been open for about 8 months before grouting and some destressing had undoubtedly occurred in the tuff. This destressing is common in the tunnel complex and often causes open fractures parallel to the tunnel surface. (The walls of the drift had been sprayed with a sealant to minimize water loss.)

Mineback on PUFF TOO was useful because it enabled us to do the following:

- Examine the cavity
- Obtain details on the post-event fracture pressure experiment
- Obtain details on the cavity pressure pipes
- Recover gages to examine them for failure
- Sample the stressed tuff and grout
- Examine some evidence of differential motion in the tuff parallel to the emplacement drift

APPENDIX A

Gage Calibration

To measure residual stress, we need gages that survive the dynamic effects of the detonation and retain a linear, or recoverable, calibration. This requirement eliminates gages that show a variable hysteresis effect or those whose sensing element breaks under nonhydrostatic loading. Survivability of electrical leads in the divergent flow field is probably the main concern. In designing the PUFF TOO experiment, we chose state-of-the-art gages that offered the possibility of measuring residual stress.

Previous, small-scale, work at Sandia's Coyote Test Field had shown that fluid coupled lithium niobate crystal gages survived to about 6 kbar. Several of these were installed in PUFF TOO to explore their survivability at high stresses under field conditions. We also installed ytterbium gages which have been popular during the last 10 yr, principally because of their large piezoresistive coefficient (100% resistance change at 10 kbar) and survivability at high stresses. Calibration experiments using gas gun techniques to produce one-dimension strain on this material, however, show a hysteresis effect.³ Hydrostatic loading of ytterbium shows no hysteresis; therefore, by coupling ytterbium to the geologic host with fluid offers the possibility of measuring residual stress. This fluid-coupled ytterbium gage has also been tested at the Coyote Test Field. On PUFF TOO we used several of these fluid-coupled gages, along with several conventional ytterbium and lithium niobate gages. We also installed three examples of prototype triaxial stress gages.

Work with piezoelectric lithium niobate crystalline material is relatively new because satisfactory single crystals have been available only for the past 15 yr. An early application of these crystals was in high-temperature ultrasonics; their curie temperature is significantly higher than other piezoelectric materials. Graham showed that lithium

niobate was suitable for time-resolution measurements of impact loads, for example, in gas gun experiments.⁴ He also subjected the material to hydrostatic loading of up to 20 kbar and found excellent reproducibility, a piezoelectric constant of 6.31 pC/N, and minor nonlinearity.⁵ Reed adapted this transducer material to a variety of charge-mode gages for measuring free-field stress. In one design, a z-cut crystal is embedded between two thin pieces of epoxy-FiberglasTM (circuit) board; solid epoxy couples the crystal to the glass board. This solid-coupled (PHA) gage is shaped like a paddle with a width of about 7 cm and a length of about 15 cm. This package has been hydrostatically loaded and shows the same coefficient observed for the bare crystal but has one limitation: failure at high stress levels. This is believed to be caused by nonhydrostatic loading of the relatively brittle crystal material. Once fractured, lithium niobate shows enhanced output.

In the fluid-coupled adaptation (PFA)⁶ of the lithium niobate paddle, the crystal is held lightly between the pieces of circuit board by a porous foam. The coupling fluid, silicon oil DC710, was chosen for its low compressibility property and its high electrical resistivity. The difference in compressibility between the circuit board, the fluid, and the host material causes fluid-coupled gages to register a stress that is different from free-field stress when they are subjected to stress levels below the yields of the materials involved.

An examination of the cross-axis piezoelectric strain coefficients (d_{ij}) for lithium niobate^{4,6} shows that several are quite large, and the z-cut crystal may show significant cross-axis sensitivity when subjected to a triaxial stress field. Using the fluid-coupled crystal does not totally resolve the matter because the response of the gage package which contains the fluid-coupled crystal has not been fully explored in a triaxial stress field. Work on this problem is in progress.⁷

The data from lithium niobate gages in the PUFF TOO experiment were reduced by using $d_h = 6.31$ pC/N as the piezoelectric strain coefficient.

The other principal gages which we fielded in PUFF TOO used ytterbium foil grids. One-dimension strain calibration has been performed on these gages by Ginsberg with gas gun experiments.³ This calibration, appropriate to fast risetime loading, is

$$\sigma(kb) = 1.082 \left[1 - \exp -20.8 \frac{\Delta R}{R_0} \right] + 9.168 \frac{\Delta R}{R_0} . \quad (A1)$$

Under multidimensional strain loading and below yielding of host materials, one must account for the triaxial state of stress.

When used in one-dimensional stress compression, an ytterbium grid shows a hysteresis effect which may obscure a measurement of residual stress. Again we have used a fluid-coupling scheme to eliminate this effect. Lilly and Stephens showed that, under hydrostatic loading, ytterbium unloads along its loading path.⁸ The coefficient is:

$$\sigma(kb) = 2.15 \left[\sqrt{38 + 93.2(\Delta R/R_0)} - 6.16 \right] , \quad (A2)$$

where $\Delta R/R_0$ is stress-induced resistance change divided by the original gage resistance. As with any fluid-coupled gage, we have the potential effects of under-registration of the gage because of the mismatch of compressibility properties between the fluid, the package, and the host. This effect is a specific case of the gage package responding to the triaxial state of stress. Data from fluid-coupled ytterbium gages in PUFF TOO were reduced by using the Lilly and Stephens hydrostatic calibrations, but without correction for registration effect. Data from the solid-coupled ytterbium grids were reduced with Ginsberg's one-dimension strain calibration.

In the early days of stress measurements, amplitudes of interest produced hydrostatic pressure because stresses were well above yielding of host and gage package materials; therefore, the triaxial stress state problems were minimal. In loading materials at and below the 1-kbar peak amplitude, significant nonhydrostatic stresses are generated. Therefore,

one-dimension strain and hydrostatic gage calibrations may not be appropriate. We must examine the response of the gages to this triaxial state of stress; perhaps even new gage configurations may be required. Current application for these triaxial state-of-stress measurements is to determine the stress wave loading, unloading, and subsequent fracturing of geologic materials containing fossil fuel. To understand the phenomenology of rock fracture and to evaluate computer code modeling of the processes, triaxial state-of-stress measurements must be rigorously pursued.

APPENDIX B

Computer Code Calculation

Before we fielded PUFF TOO, R. C. Bass performed a computer code calculation of the detonation of 454 kg (1000 lb) of high explosive in wet tuff. Of interest were details useful for planning the experiment, for example, the radial dependence of the residual stress field. For this purpose, coarse edits (100- μ s intervals) were obtained through the 10-ms duration of the calculation. Zone sizes were large and associated "smearing" over zones were not optimized for postevent comparison with experimental results. A one-dimension Lagrangian code called CHART D, written by Sam Thompson, was used.⁹ In this calculation an elastic-perfect plastic model was used with an elastic limit of 1.0 kbar and a Poisson ratio of 0.31. These values were chosen on the basis of previous experience and parameter studies and are generally representative of wet tuff.

Figure B-1 shows stress vs distance at 10.0 ms. The small amplitude humps near the right edge (1400 to 2000 cm) are the outward propagating dynamic effects. The sharp rise at 79.4 cm is the edge of the cavity and the constant amplitude preceding the rise is the cavity pressure (0.55 kbar). From the cavity edge, we see that the hoop stress rises sharply to about 1.2 kbar, decays to near zero at 155 cm, shows a second rise, decreases to below the zero level and rises to the tail of the dynamic effect. Two comments are appropriate here: a hydrostatic pressure of 50-kbar preload was used, and no fracture was allowed in the calculation. Beginning at the cavity edge, the radial stress shows a rise to a rounded peak of 0.75 kbar and a decay to 0.1 kbar before we see the tail of the dynamic effects. The third curve shows mean stress, $\bar{\sigma} = (1/3)(\bar{\sigma}_r + 2\bar{\sigma}_\theta)$. Through the time regime of 6 to 10 ms the range-amplitude "snapshots," such as shown in Figure B-1, show little change in the stress

fields near the cavity; we believe that the curves are the residual stress field.

Figure B-1. CHART D Calculation - Stress vs Distance at 10 ms

Field measurements showed a distorted cavity; a cavity radius extracted from the cross-sectional area of a horizontal plane passing through the charge center and intersecting the cavity wall yields a value of 108 cm (compare with the calculated value of 79.4 cm). Field measurements of cavity pressures are still in their infancy; this is a difficult quantity to measure and only two values, 0.52 kbar and 0.21 kbar were obtained. Current experience does not allow us to give more weight to one or the other; however, the larger value is close to the calculated value of 0.55 kbar.

Figure B-2 shows the waveform measured in the experiment by gage 6AYFC. The figure also plots 100- μ s interval data (mean stress and radial stress) obtained from the edits of the calculation at the appropriate distance. Closer spaced edits would have shown a faster rise time and a higher peak stress.

Figure B-2. Calculated Radial and Mean Stress and Measured Stress at 133 cm

Figure B-3 shows similar data for the 2-kbar nominal level. Beyond 5 ms, we see close agreement between the measured residual stress and the calculated mean and radial stress. Figure B-4 shows field data from gage 1DLFC compared with the calculation. Again we see a notable difference in the 2 to 4-ms unloading behavior. The average of the residual stress for all the 1-kbar gages is 0.22 kbar, which agrees fairly well with the calculated 0.16-kbar radial stress.

Figure B-3. Calculated and Measured Stresses vs Time at 290 cm

Figure B-4. Calculated and Measured Stresses vs Time at 419 cm

Except for a major dip in the unloading portion of the waveform, the calculated waveforms show reasonable agreement with experimental measurements. However, measured and calculated cavity sizes disagree. This disagreement probably reflects the use of a material strength value in the calculation that was too high.*

*Postevent calculational work with a material model in which the strength value decreases following stress wave loading shows a larger cavity radius and an elimination of the tensile phase.

APPENDIX C

Correction of Data Distorted by the Measuring System (R. P. Reed)

The special constant-current power supply used for signal conditioning the ytterbium gages is designed to respond to the rapidly-changing stresses in explosive experiments. The measurement requires that we observe a relatively small transient signal superimposed on a relatively large dc level. Special signal conditioning eliminates the dc level and thus improves the resolution of the recording. The intended step-response of the power supply approximates a decaying exponential function of greater than a 20- μ s time constant. The transient signal distortion caused by this normal, long-time constant on pulses of less than 10 ms is much less than 0.1%.

After the PUFF TOO test, we found several channels of signal conditioning that had resistors with a value that was too low. These values resulted in a decay-time constant of less than 2 ms. As a result the corresponding transfer function grossly distorted the signals recorded on those channels. Fortunately, after the shot, we could measure the actual transfer function to a good approximation and make data corrections. The data we corrected had been recorded on gages 1YG1, 1EYG1, 1EYG2, and 6AYFC.

Figure C-1 illustrates that data recorded for gage 6AYFC, a fluid-coupled ytterbium gage. The record indicates, that stress returned to zero at 1.2 ms after the pulse arrived and then became tensile at 1.62 ms. Both indications are incorrect. The undershoot is a consequence of the response by the signal conditioning system. The measured unit step response of the system is shown in Figure C-2. The actual response was analytically represented by the exponential function

$$U(t) = 1781 \left(e^{-\frac{t}{1.7746}} \right) \left(1 - 0.1512 e^{-\frac{t}{0.2857}} \right).$$

This characteristic was used to calculate the system input (forcing function) from the distorted recorded output. The corrected result is shown in Figure C-3.

Correcting the data distortion affected the peak amplitude by only 0.04% (0.003 kbar) but the late-time residual stress was corrected significantly to 0.58±0.03 kbar compressive instead of 0.30 kbar tensile. The correction is crucial because a major objective of PUFF TOO was to measure residual stress.

The unfold algorithm used for correction is the same simple time-domain deconvolution long used for correcting data from quartz shock-stress gages with a shorted guard-ring. The entire unfolding algorithm, as implemented in the GENFOLD signal analysis code (R. P. Reed), is as follows:

```

PERFORM UNFOLDING BY DIRECT INVERSION
OF DUHAMEL SUMMATION.

RESULT(1)=SUBJ(1)/U(1)

DO 1070 N=2,NSTEPS

  RESULT(N)=S'BJ(N)

  NM1=N-1

  DO 1060 M=1,NM1

1060   RESULT(N)=RESULT(N)-(U(N-M+1)-U(N-M))*RESULT(M)

1070   RESULT(N)=RESULT(N)/U(1)

```

Figure C-1. Data from Gage 6AYFC as Recorded
(Distorted by Short Time Constant)

Figure C-2. Unit Step Response of Signal Conditioning

Figure C-3. Data from Gage 6AYFC Corrected for Transient Distortion

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