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**PROJECT RIO BLANCO SPALL MEASUREMENTS
DATA REPORT**

Clyde Sisemore

John Toman

November 14, 1973

MASTER

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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PROJECT RIO BLANCO SPALL MEASUREMENTS DATA REPORT

Abstract

A major instrumentation program was undertaken for the Rio Blanco experiment using accelerometers and velocity gages buried at various depths below the ground surface and at various horizontal ranges from the emplacement well. The objective

was to physically measure the depth and aerial extent of spall (tensile failure of the earth material). Data from each of the instrument stations is given, along with the appropriate integrated data for particle velocity and displacement or just displacement.

Introduction

RIO BLANCO EXPERIMENT

Project Rio Blanco was a joint Government-Industry experiment to stimulate a natural gas reservoir using three 30-kiloton nuclear explosives in a single well bore (emplacement depths were 5840, 6230, and 6690 ft). The three explosives were detonated nearly simultaneously at $1000:00.12 \pm 0.01$ sec MDT, May 17, 1973. The emplacement well (EW), at an elevation of 6629.9 ft above mean sea level, is located 1080.5 ft south of the north line and 1188.5 ft east of the west line in Section 14, Township 3 South, Range 98 West of 6th Prime Meridian (P. M.), Rio Blanco County, Colorado. The geodetic coordinates are $108^{\circ} 21' 59''$ west longitude and $39^{\circ} 47' 35''$ north latitude. The site as shown in Fig. 1 is 52 miles north of Grand Junction, 31 miles south-

east of Rangely, 30 miles southwest of Meeker, and 37 miles northwest of Rifle, all in Colorado.

PURPOSE AND SCOPE

This report presents data obtained from the spall measurements program which was undertaken as part of Project Rio Blanco to determine the depth below the ground surface of failures (spall) in the rock caused by excessive tensile stress. Spall occurs whenever, at some subsurface point, the ascending compression wave and the surface reflected tension wave interact to give a tensile stress larger than the failure strength of the rock at that point.

The spall measurement program was designed and fielded to verify theoretical calculations which led to the conclusion

Fig. 1. Rio Blanco site location.

that spalling would not extend down into a rich oil shale zone located at a depth of about 750 to 900 ft below the ground surface. An oil shale company projected that any new fractures would increase the room and pillar mining costs enough to make oil shale development uneconomic. The primary purpose of these measurements then was to experimentally locate

the deepest spall zone. Since theoretical calculations had been made to predict spall depths, a secondary goal was to establish the validity of these predetonation calculated values. A list of the predetonation predictions, a description of the experimental methods to be employed in the field, and a summary of past experience with this method have been reported.¹

Description of Spall Measurements Program

In brief, the method employed to detect the occurrence of spall utilized accelerometers and velocity gages at various depths below the ground surface to record earth motion histories at several subsurface locations. Material which has been spalled (placed in free flight) exhibits characteristic acceleration and velocity histories which can be used to define spall zones. This is accomplished by assigning all the material above an instrument displaying spall characteristics to a spalled region and all the material below an instrument displaying only free field characteristics to a region free of spall. Since the maximum depth of spall would be at some unknown depth between two instruments, the precision with which this method can establish the maximum depth of spall depends on the number of instruments used and their spacing. This uncertainty for Project Rio Blanco was a maximum of 150 ft.

A total of 36 gages (20 accelerometers and 16 velocity gages) were used at 20

different locations. Most of these instruments were installed in six instrument holes located within 7300 ft of the EW, at emplacement depths ranging from 600 to 821 ft (Fig. 2). Two additional surface accelerometers were placed at distances of 12,000 and 23,000 ft from the EW.

In addition to the above instruments, clipper cables were installed in five of the six instrument holes to provide an independent check on the spall depth (Fig. 2). This clipper transducer system, using time domain reflectrometry, can continuously measure the length of a cable during a specified length of time. Therefore, any cable break caused by spall during this specified time can be identified accurately with respect to time and location (depth).

1. J. Toman, R. Terhune and C. Sismore, Spall Measurements Program for Rio Blanco, Lawrence Livermore Laboratory, Rept. UCID-16078 (1972).

Fig. 2. Instrument hole locations.

Instrumentation

DESCRIPTION AND SPECIFICATIONS OF INSTRUMENTS

A total of 16 canisters, each containing an accelerometer and velocity gage, were installed at locations which are shown in Fig. 2 and Table 1. The canister as shown in Fig. 3 also contained a thermistor, two explosive cable cutting devices and two release monitoring systems. The thermistor was used to measure the shot time

temperature at each canister. These data were used later to correct the velocity gage outputs for the variations generated by temperature-induced changes in the oil viscosity. The cable cutting devices were used to sever the emplacement wire rope at each end of the canister. Their purpose was to free the canister from any part of the emplacement paraphernalia so motion of the unit would be similar to that of the surrounding rock. The release monitoring

Table 1. Summary of instrumentation.

Gage designation	Hole designation	Horizontal range (ft)	Depth (ft)	Slant range ^a (ft)	Depth top of cement (ft)	Release operation upper-lower
00AC00	Surface	138.23	15	6216	Surface	NA
01AC80V	RBS-01	148.26	61	6170	10	Yes-No
01AC150V	RBS-01	148.26	149	6082	10	No-Yes
02AC350V	RBS-02	128.43	352	5879	272	No-Yes
02AC450V	RBS-02	128.43	452	5779	272	No-Yes
02AC600V	RBS-02	128.43	604	5627	272	Yes-Yes
03AC720V	RBS-03	130.48	723	5508	633	No-Yes
03AC820V	RBS-03	130.48	821	5410	633	Yes-Yes
04AC30V	Surface	2420	35	6683	Surface	NA
04AC120V	RBS-04	2435	120	6610	5	No-Yes
05AC280V	RBS-05	2413	285	6449	200	Yes-Yes
05AC380V	RBS-05	2413	398	6344	200	No-Yes
7300AC00V	Surface	7200	15	9516	Surface	NA
06AC90V	RBS-06	7248	107	9560	3	No-Yes
06AC190V	RBS-06	7248	190	9506	3	No-Yes
06AC290V	RBS-06	7248	288	9443	3	No-Yes
06AC550V	RBS-06	7248	532	9288	3	No-Yes
06AC630V	RBS-06	7248	630	9227	3	Yes-Yes
12000AC00V	Surface	12034	15	13450	Surface	NA
23000AC00V	Surface	~23000	15	~23828	Surface	NA

^aThe slant range is measured from the center explosive at a depth of 6230 ft.

system determined whether both cutting devices functioned properly.

Spall can be readily identified in records of surface motion, and therefore only acceleration was measured at the surface stations. However, subsurface detection of spall was expected to be more difficult, and both velocity and acceleration were measured at each subsurface station. In addition, at each of these stations, only single vertical component transducers were used for each parameter. This restriction in data was possible because in the stated experimental method only the vertical component of motion is needed to determine free fall and thus the

"spall" or "no-spall" condition of the surrounding material.

All accelerometers were "force balance" servo units (Kistler model 305A).^{*} As shown in Fig. 4, the working components of these units are a mass, a permanent magnet, a forcer coil, a displacement sensor, and an amplifier. In operation, the displacement unit senses movement of the seismic mass relative to the case. The amplifier feedback system then converts

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Fig. 3. Canister drawing.

Fig. 4. Servo accelerometer schematic (Kistler Model 305A).

this displacement signal into the specific amount of electrical current needed by the forcer coil to bring the separation between the seismic mass and the displacement sensor back to its original value.

In this manner, the spatial separation between the seismic mass and the displacement sensor is held constant by the mechanism of balancing the input force created by an acceleration imparted to the case against an equal and opposite electronically generated restoring force. Since the restoring force is proportional to the acceleration of the transducer case, the current needed to generate this force must be proportional to the acceleration. The transducer design is complete if this current can be sampled and recorded. The accelerometer's specifications are as follows:

Range	0 to ± 50 g
Sensitivity	0.200 mA/g

Frequency Response	DC - 500 Hz
Natural Frequency	1000 Hz
Damping	0.6
Weight	3.4 oz
Case diameter	1.125 in.
Suspension of seismic element	Translational flexure

The particle velocity transducer (Spartan model 603V) used for these measurements was a highly damped mass-spring mechanical system. The gage as shown in Fig. 5 was developed at Stanford Research Institute, with later improvements by the Albuquerque Sandia Laboratory.^{2,3} The gage proved to be useful in many areas,

2. L. M. Swift, Development of an Earth Velocity Gage, DASA-T191 (Oct. 31, 1960).

3. W. P. Perret, J. W. Wistor, G. J. Hansen and D. G. Palmer, Four Papers Concerning Recent Work on Ground Motion Measurements, Sandia Laboratories, Albuquerque, Rept. Sc-R-65-904 (1965).

Fig. 5. Particle velocity gage (Spartan Model 603V).

and it has been used extensively over the past ten years by several laboratories, including LLL.

This system is made up of a pendulum (mass) and a volume of viscous liquid — silicone oil. The pendulum (actually a paddle) is placed in the liquid such that its motion is constrained only by its pivots and the viscosity of the liquid. If the frequency content of the input signal is limited to a frequency span centered around the resonance frequency of the paddle system, the angle of the paddle in the viscous fluid is proportional to the

magnitude of the velocity imparted to the transducer case. Given these operational conditions, this system will measure the particle velocity of the surrounding rock if the unit is well coupled to the rock. Sensing and recording the angular position of the paddle provides a velocity history at the location of the instrument.

A variable reluctance system senses the angular position of the paddle. Two coils are rigidly mounted to the case so that the ends of the coils are in close proximity to two blades attached to the free moving paddle. As the paddle moves, the spatial separation between coil and blade changes, and since the inductances of the two coils are directly dependent on the separation between coils and blades, any change in paddle position is reflected by a change in inductances of the two coils. Now, if these two inductances are used to control the frequencies of two local oscillators, the paddle position can be determined from the relationship between the frequencies of the two oscillators.

The outputs of the two oscillators are then mixed to reduce the number of signal channels and to reduce the dependence of the paddle position measurement to just one frequency. Obviously, this transducer system would function properly with just one oscillator coil arrangement, but using two improves linearity and doubles the sensitivity. Since sensitivity and linearity are important parameters in this measurement, two oscillator-coil arrangements were used. Using the appropriate calibrations, this output frequency can be made directly proportional to the velocity experienced by the transducer case.

Specifications of the velocity gage are as follows:

Range	± 10 ft/sec to ± 500 ft/sec
Sensitivity	4 ft/sec/kHz
Frequency response	150 Hz
Natural frequency	3 Hz
Damping	5%
Weight	507 g
Case diameter	1.62 in.
Case length	3.14 in.
Suspension of seismic element	Jeweled pivot

ELECTRONICS AND RECORDING

The electronics recording scheme was designed to provide two levels of accelera-

tion data and one level of velocity data. The two levels of acceleration were obtained by taking the accelerometer output and applying it to the inputs of two voltage control oscillators (VCO); each operating with a different gain. The VCO center carriers were arranged to have a 300-kHz unit with a low gain and a 1200-kHz unit with a high gain. The high gain unit was designed to maximize the system for recording a -1 g acceleration signal with a very high resolution. The low gain unit was set to the proper levels for recording the expected peak values of the initial signals; typical recording levels were ± 5 g to ± 20 g. Figure 6 is a block diagram of the electronics contained in each canister and the recording trailer.

Fig. 6. Electronics block diagram for canister and recording trailer.

Fig. 7. Velocity gage electronics schematic.

Fig. 8. Remote station recording schematic.

The dual oscillator-modulator system in the velocity gage operated with a center carrier at a nominal frequency of 125 kHz. The gain of this system was fixed by the characteristics of the particular velocity gage feeding the oscillator system, i. e., the oil viscosity. The two VCO outputs and the dual oscillator output were combined into a single signal through a "summer multiplexer" for transmission

to the recording trailer. A block diagram of the velocity gage electronics is shown in Fig. 7. The RG-213U coaxial cable transmission line accommodated the multiplexed signal carriers as well as the d. c. power for the canister electronics. At the recording trailer, the multiplexed signals were removed from the d. c. power line and the signals were then recorded directly on magnetic tape.

A different recording scheme was used for the data from the remote stations at 12,000 and 23,000 ft. As shown in Fig. 8, the analog signals were fed directly to the FM module of a cassette tape recorder. In this module, the signals were converted to FM signals and then recorded on magnetic tape.

The analog data presented in this report were extracted from the high-frequency data stored on the magnetic tape by using bandpass filters to isolate each carrier. Finally, each carrier was then demodulated

with an FM discriminator. Data from the remote stations on the cassette tapes were similarly retrieved except that band-pass filters were not required.

INSTRUMENT EMPLACEMENT

The spall measurements instrumentation was installed during the period of 10 January 1973 to 10 February 1973. Before their shipment to the Rio Blanco site, each canister was subjected to a series of tests to certify its performance. First, each "gage module" was tested statically (-1 g, 0, and $+1$ g) to verify gage response. Then it was tested on the Hygee machine to test dynamic response

Fig. 9. Canister being placed by hand.

of the gage and electronic circuit. Finally, each gage module was hydrostatically tested to 1000 psi for a 30-min period as a proof test of its watertight integrity. Before being lowered in the appropriate instrument hole at the experiment site, each canister was subjected to a final checkout. An emplacement string containing the proper number of canisters tied together by 5/16-in.-diam wire rope was lowered into each instrument hole using a drill rig. The lowering operation was systematic. First, a single canister with a 30 ft section of wire rope was lowered and tied off at the top of the hole. Another 30-ft section of wire rope (pendant) was then added and the lowering continued. When enough pendants had been added to give the proper spacing, the next canister was attached, and so forth. Periodically during this downhole operation, all systems were checked for electronic performance and spatial consistency in emplacement lengths. Single canisters which were placed at shallow depths were lowered into position by hand. Figure 9 is a photograph of a canister being lowered into position by two technicians.

The cliper, a continuous RG-81/U cable, was added to the emplacement string during this downhole operation. As with the canisters, the cliper system was tested before field installation. For the systems test at LLL, a length of cable was cemented into two sections of pipe butted together so that the cable was the only continuous structural member from end to end. The pipes were then pulled apart. The cliper performed as designed and experimentally confirmed that a minimum separation of 4.5 in.

between the pipes was required to break the cable.

After the emplacement was completed and the systems were determined to be operational, the instruments were cemented in place. The top of the cement was established at a fairly large depth below the surface of the ground in three of the holes. This length of open hole was used to isolate the instrument cables from the near surface formation so they would not be damaged at an early time by spalling of these near-surface layers. Location of the top of the cement in each instrument hole is included in Table 1.

After several days of curing for the cement, the cable cutting devices were actuated and the canisters were released from their cable supports. Several of these cutters did not function properly, and at the time of the detonation a number of canisters were still partially connected by at least one end to the downhole string. A listing of the released and unreleased canisters is given in Table 1. Only in hole, RBS-01, however, was there a link tying two adjacent canisters together.

SYSTEM PERFORMANCE

With two exceptions, the originally installed instruments were functioning properly at the time of the detonation. One exception was a failure of the signal cable attached to the canister installed at 60 ft in hole RBS-04; it had become shorted soon after the cementing was completed. Since it was impractical to retrieve this unit, another was placed at a depth of 35 ft in a nearby well. This unit, identified as 04Ac30, was functioning properly at detonation time. The second

exception was intermittent operation of canister 02Ac450 in hole RBS-02; it had also developed problems after the grouting was completed. Apparently, a voltage regulator in the downhole electronics had failed. When the supply voltage was increased, the poor performance of this regulator could be overridden and the unit appeared to be usable. This was not a perfect correction, however, since the amplitudes of the carriers were appreciably decreased and they were also slightly shifted in frequency. Data were obtained from the 20 accelerometers and 16 velocity gages installed to measure spall depth; however, all records were terminated after a time slightly longer than 1 sec. This termination of data was a result of a failure in the recording trailer when a power control circuit relay was mechanically tripped by the larger than expected accelerations experienced by the trailer. The peak incident acceleration was 2.5 g's and the slapdown acceleration was 3.7 g's. The relay tripped immediately after slapdown occurred. A photograph of the recording trailer and its shock mounting is shown as Fig. 10.

The time period over which dynamic motions were recorded, however, were generally longer than required to measure the peak incident acceleration to record free fall signals (spall) if any occurred, and to record the peak acceleration due to spall closure ("slapdown"). Only at the 7200-ft station where power failure occurs at about the same time as spall closure is there some loss of data. Therefore, the loss of power and the subsequent loss of data beyond 1 sec did not compromise the major objective of this measurements program.

Fig. 10. Recording trailer and shock mounting.

Recorded Data

All the data recorded in this measurements program are included in Figs. 11 to 29. All data, both measured and derived, pertaining to a specific instrument package and location are grouped under a single major figure number. The computer printouts identify each acceleration plot with either a "HI" or "LO" which means "high range" or "low range." Peak accelerations may be read directly from the high-range plots. The low-range plots provide more detail in the -1 g range, and should not be used for determining peak accelerations.

The boundaries of good data in these plots are delineated by the horizontal lines at the top and bottom of the plot; data beyond these lines are not ranged properly.

The analog data obtained from the accelerometers and velocity gages, except for the accelerometers at 12,000 and 23,000 ft, were digitized so that additional operations could be performed effortlessly by a computer. A first integration of the accelerometer plot provides a velocity plot which can then be compared to the original data from the velocity gages. Displacement as a function of time can be obtained independently from two different sources: (1) a second integration of the accelerometer data; and (2) a first integration of the velocity data. A comparison of derived and actual velocity data as well as a comparison between the two independently derived displacement plots show rather remarkable agreement.

Table 2. Summary of recorded data.

Gage designation	Depth/slant range (ft)	Time of arrival (msec)	Peak incident acceleration (g's)	Spall closure (g's)	Peak incident velocity (fps)	Peak displacement (ft)
00AC00	15/6216	542	3.0	12.5	3.0	0.25
01AC80	61/6170	527.5	9.5	8.8	3.7	0.18
01AC150	149/6082	516.8	7.9	8.7	2.5	0.16
02AC350	352/5879	492.7	8.8	—	2.2	0.10
02AC450	452/5779	482.9	10.0	—	2.0	0.12
02AC600	604/5627	470.4	8.5	—	1.6	0.092
03AC720	723/5508	459.7	11.0	—	2.2	0.09
03AC820	821/5410	448.5	13.0	—	3.25	0.09
04AC30	35/6683	570	3.8	4.1	1.9	0.14
04AC120	120/6610	554	4.2	3.8	2.1	0.10
05AC280	285/6449	537	4.0	5.5	1.4	0.08
05AC380	398/6344	526	3.3	—	1.3	0.07
7300AC00	15/9516	806	2.0	Data lost	2.2	0.14
06AC90	177/9560	778	1.8	>7	1.4	0.08
06AC190	190/9506	767	1.4	1.2	1.2	0.06
06AC290	288/9443	760	1.35	—	0.9	0.05
06AC550	532/9288	741	1.9	—	0.8	0.03
06AC630	630/9227	732	2.2	—	0.9	0.036
12000AC00	15/13450	Unknown	1.8	>4.0	Unknown	Unknown
23000AC00	15/23828	Unknown	0.6	—	Unknown	Unknown

Typically, the acceleration data are superior to the velocity data. The reason is that the low-amplitude signals generated by the Rio Blanco detonation were generally below the operating range of the velocity gages. Since these were the only gages available, they were used and operated at their lowest range. As a result, the signal-to-noise ratio for these signals is very poor as seen in the velocity data prior to the arrival of the first pulse. Some of this noise can still be eliminated to significantly improve the quality of the velocity data. This would also bring the derived values into even closer agreement.

Table 2 provides a summary of the key information contained in Figs. 11 to 29.

Included data are the time of arrival of the first pulse (TOA), the incident peak acceleration, the peak velocity, the peak displacement, and the peak acceleration due to spall closure where it exists. The velocity and displacement values are derived from the acceleration data.

No information is presented on the clipper systems because no spall separation was large enough to break a cable, i. e., all the cables are still continuous over their entire length. Again since evidence based on laboratory tests indicate a separation of 4.5 in. is required to break the clipper cable, either there were no spall separations or the spall separations must be less than 4.5 in. Supporting

Fig. 11. Data from surface zero station.

evidence can be gotten from Table 2 and Fig. 9d by observing that the maximum temporary displacement at

the EW was only 0.25 ft or 3 in.; again, this is not enough to break a cliper cable.

Fig. 12. Data from 61-ft depth in RBS-01 instrument hole.

Fig. 13. Data from 149-ft depth in RBS-01 instrument hole.

Fig. 14. Data from 352-ft depth in RBS-02 instrument hole.

Fig. 15. Data from 452-depth in RBS-02 instrument hole.

Fig. 16. Data from 604-ft depth in RBS-02 instrument hole.

Fig. 17. Data from 723-ft depth in RBS-03 instrument hole.

Fig. 18. Data from 821-ft depth in RBS-03 instrument hole.

Fig. 19. Data from 35-ft depth in a shallow hole near the 2400-ft recording station.

Fig. 20. Data from 120-ft depth in RBS-04 instrument hole.

Fig. 21. Data from 285-ft depth in RBS-05 instrument hole.

Fig. 22. Data from 398-ft depth in RBS-05 instrument hole.

Fig. 23. Data from the 7200-ft surface station.

Fig. 24. Data from 107-ft depth in RBS-06 instrument hole.

Fig. 25. Data from 190-ft depth in RBS-06 instrument hole.

Fig. 26. Data from 288-ft depth in RBS-06 instrument hole.

Fig. 27. Data from 532-ft depth in RBS-06 instrument hole.

Fig. 28. Data from 630-ft depth in RBS-06 instrument hole.

Fig. 29. Data from (a) the 12,000-ft station, and (b) the 23,000-ft station.

Conclusions

The instrumentation, recording systems and data retrieval methods used for the spall measurements program in Project

Rio Blanco have provided the basic information needed to analyze the depth and extent of spall within reasonable limits.

Acknowledgments

There is no way to adequately describe the total effort required to obtain the data presented in this report or to single out each of the many people who were involved. However, the success of this measurement program was due largely to the work of Thomas Barlow, Project Mechanical

Engineer, Sam Spataro, Project Electronics Engineer; and Norman Stewart, the senior technician in charge of the assembly and emplacement of canisters. Our thanks and appreciation are extended to all of the active participants in the spall measurements program for its successful completion.