RIO BLANCO ELECTRONICS

O. H. Krause, J. B. Carson, M. F. Jaroska,
S. J. Spataro, and G. E. Russell

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RIO BLANCO ELECTRONICS

Abstract

The Electronics Engineering Department was responsible for the Integrated Control System (ICS) and the spall measurements program on the Rio Blanco Event.

The ICS, consisting of a Control Point, Integrated Control Element, and the downhole system in each canister, was a modified version of the one used in the Miniata Event. After testing, assembly, and fielding, it performed successfully. The arming and firing cable was able to

withstand severe environmental conditions and was novel in that it went through the explosive canisters rather than along the side of them.

Spall was measured with CLIPER cables and 20 instrument canisters placed at a variety of locations both above and below the surface. The canisters contained various combinations of accelerometers and velocity gages. Spall was detected at all surface stations except one and at depths to 107 m.

Introduction

The Rio Blanco Event (May 17, 1973) was an underground experiment in which three nuclear explosives were detonated simultaneously in the same emplacement well in order to increase the permeability of gas-bearing rock (see Fig. 1). The purpose of the project, carried out in Rio Blanco County in western Colorado, was to stimulate natural gas production. Three Diamond explosives, each with a nominal yield

of 30 kt were detonated at depths of 1780, 1900, and 2030 m.

This report describes the role of the Electronics Engineering Department in the Rio Blanco Event. The department was responsible for the Integrated Control System, safety program, spall measurements program, arming and firing cable, and explosive performance verification. The geographical layout of the electronics systems is shown in Fig. 2.

Fig. 1. Geological section of the Rio Blanco site. The holes that were drilled for the experiment (i. e. RB-S-01) and the original exploratory well (Equity) are shown.

Fig. 2. Map showing the locations of the various electronics installations.

Integrated Control System

The Integrated Control System (ICS) was used to conduct all remote control and monitoring functions on the Rio Blanco Event. This section summarizes the ICS concept, design, evaluation, assembly, and fielding for Rio Blanco.

DESCRIPTION

Three major elements make up the ICS (see Fig. 3): the Control Point (CP)

located in Trailer 95, the Integrated Control Element (ICE Box), and the down-hole system contained in each explosive canister.

The CP (see Fig. 4) contained the following equipment:

- Control console from which commands were manually or automatically transmitted to the emplacement well (EW) area and on which ICS monitor information was displayed to indicate the condition

Fig. 3. The Integrated Control System.

of each explosive, the ICE Box, and related EW-area equipment.

- Safety program data displays for weather, remote area radiation monitoring, seismic, and other related information.

- Microwave equipment for data transmission and communications.

The ICE Box was the emplacement well terminal of the ICS. It distributed the commands from the CP downhole to the explosives and to close-in surface installations, provided power to the explosives, and transmitted monitor information from the explosives, ICE Box, and safety program equipment to the CP. Also, the ICE Box contained oscilloscopes to record explosive performance data. The ac power to the ICE Box was supplied from two, redundant, diesel-electric

generator sets with automatic switchover (the Power Box in Fig. 3). In the event of failure of either generator set, the remaining set could handle the entire ICE Box load. The complete installation is shown in Fig. 5.

Communications and command and monitor information were transmitted between the CP and the ICE Box by microwave radio. The microwave links were dual redundant with automatic switchover in the event of failure of either link. A single coaxial cable transmitted all power and command and monitor information between the ICE Box and the explosive canisters. On the Rio Blanco Site, the closest line-of-sight path between the CP and the EW area passed approximately 244 m from the ICE Box location (see Fig. 2). Because of this, the microwave

Fig. 4. Trailer 95, the Control Point.

Fig. 5. The ICE Box installation.

equipment normally contained in the ICE Box was placed in a small transportainer (the Remote Telemetry Station or RTS) which was located on the EW/CP line-of-sight path (see Fig. 6). Communications and data were transmitted between the ICE Box and the RTS by coaxial cables. The ac power was supplied to the RTS from the Power Box. The RTS is normally operated as a microwave relay station when there is no line-of-sight path between the CP and ICE Box (Fig. 3).

The downhole system in each explosive canister contained a command decoder, a monitor system, and a power supply (see Fig. 7). In addition, each explosive con-

tained a coded switch which interrupted the arming and firing signals between the command decoder and the arming and firing components. The coded switches were closed, from the CP, just prior to the final countdown.

DESIGN CHANGES FROM MINIATA

The ICS design for Rio Blanco was similar to the design used in the Miniata Event, which occurred in July 1971 at the Nevada Test Site (NTS). The Miniata Event was the proof test of the Diamond explosive that was specifically designed for Plowshare gas stimulation applications.

Fig. 6. The Remote Telemetry Station used to relay microwave signals from the ICE Box to the Command Point.

The ICS design changes for Rio Blanco were as follows:

- The single explosive design used on Miniata was adapted to a system capable of handling multiple explosives. This adaptation included:

- a. Provision for the multiplexing of the monitor data from the three explosives onto the single cable and the de-multiplexing of this data in the ICE Box and CP.
- b. Provision for pulse firing of the explosives to permit the explosives to be fired at nominal 10- μ s intervals starting with the bottom explosive. This delay between detonations was needed to allow

the recording of explosive performance data from each explosive in sequence in the ICE Box and does not significantly alter the simultaneous nature of the explosions. Pulse firing was needed because the normal ICS command system has a jitter in the decoding of commands of plus or minus one cycle of the command subcarrier (165 kHz) which is equivalent to plus or minus 6.06 μ s. Under normal circumstances this jitter is of no consequence.

The downhole monitor system for each explosive was changed from a 20 channel digital (go-no-go) system to a 27 channel analog system. The system has an accuracy and resolution of better than 1% of full scale.

- The reliability of the downhole systems was significantly improved by:

- a. Reducing the number of components through simplified circuit design. Since each component has a finite failure probability, a reduction in component count improves reliability as long as performance requirements are not compromised.
- b. The use of integrated circuits. The use of integrated circuits improves reliability because their failure probability is much lower than an equivalent circuit made with discrete components.

- The command output board circuit design was changed so that the circuit would fail safe (turn off) if the ground connection to the board became open circuited. In addition, the circuit design was changed to eliminate the need for the

Fig. 7. Schematic of the explosive canister.

plus and minus 15-V power supplies that were required in the previous design.

- The immunity of the command decoder to noise was improved by putting more stringent requirements on the acceptance of the command word format.

- The power supply circuit changes were as follows:

- a. The plus and minus 15-V outputs were deleted.
- b. The 3-V output was replaced with a 5-A constant current output for the purpose of charging the X-unit. This change was made because the X-unit charging requirements are specified in terms of current rather than voltage.
- c. Separate 28-V outputs were provided for the command and monitor systems. This prevents a failure that draws excessive power supply current in either system from affecting the other because all of the power supply outputs are individually current limited.
- d. The 16-V, 9-A output was replaced by a capacitor discharge unit for the purpose of firing squib valves and fuse-actuated switches. This was needed to reduce the input power surges drawn by the power supply, and thereby reduce the voltage regulation range required due to input voltage fluctuations. The input voltage fluctuations are caused by the changing input power requirements of the power supply and the loop resistance of the firing cable to the explosives from the ICE Box. Reducing the range of input voltage over which regulation is required reduces the internal

heat losses in the power supply and therefore improves efficiency.

SYSTEM TEST

A complete prototype of the Rio Blanco explosive was tested in a 100-ft-deep well in Livermore to evaluate its performance under the environmental conditions in the emplacement well. The well was equipped with a pressure vessel capable of simulating the expected temperature and pressure environment (210°F and 5000 lb/in.² peak pressure during the grouting period and 4000 lb/in.² formation pressure thereafter). The ICS was used to measure temperatures, pressures, and ICS functions in the explosive canister. The temperature and pressure inputs to the pressure vessel were separately recorded.

The first test started on October 30, 1972, and ended 12 days later due to a malfunction in the cooling system. The necessary repairs and modifications were made and the second test started on December 16, 1972. Although there was a one-week interruption because of a faulty electrical connector on the pressure vessel, this test was satisfactorily concluded on February 1, 1973, with a simulated countdown to verify the performance of the ICS and the arming and firing components after 41 days of operating time. The mechanical engineering aspects of this test have been described.

J. Harri, Lawrence Livermore Laboratory, Internal Document COMN-73-69 (1973) (SRD). Readers outside the Laboratory who desire further information on LLL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore Laboratory, Livermore, California 94550.

The systems test was conducted using the complete ICS in the Rio Blanco configuration so that it could serve as a checkout and dry run for the actual experiment. During this test, there was an occasional malfunction of the microwave receivers in the ICE Box during the warmup period of the receivers. This was caused by the failure of the local oscillator to synchronize through its phase-lock loop to the reference crystal oscillator in the receiver. After a warmup period of about 1 h, the oscillators would synchronize and the receivers would function normally. The symptom during the period of malfunction was that the command subcarrier output of the receiver would be strongly modulated by and summed with the search frequency of the phase-lock loop of the local oscillator (approximately 60-80 cycles per second).

The defective signal from the receivers caused the command decoders to decode false commands with an address related to valid commands existing in the system at that same time. With no valid commands in the system, no false commands were decoded. In addition, the receiver select chassis, which checks the command subcarrier to decide if either redundant command link is functioning properly, failed to prevent the defective signal from being transmitted to the command decoder. The false command problem was carefully analyzed and a three part solution was implemented. The solutions were:

- The logic of the data-validity board in the command decoder was changed to prevent the decoding of false commands due to noise-modulated signals.
- The receiver select chassis was redesigned to reject noise-modulated

signals; thereby, preventing such signals from being transmitted to the command decoders.

- New local oscillators that do not have this characteristic failure mode were purchased for the microwave receivers.

COMPATIBILITY AND CERTIFICATION TESTING

The compatibility and certification tests for the ICS and the Arming and Firing (A&F) system were conducted at the Sandia Livermore Laboratory. J. P. Johnson and W. L. Lemmon of Organization 9132 (A&F Systems Division) Sandia Albuquerque Laboratory were responsible for the A&F system and represented Sandia at these tests.

During initial testing, which started in October 1972, no incompatibilities were found between the ICS and the A&F system. Although the overall performance of the ICS and A&F system was satisfactory some apparent problems in the ICS were noted. These problems and their solutions were:

- The delay-output board, which was responsible for the pulse firing of the explosives, was putting out a double trigger to the Sandia Fire Pulse Capacitor Discharge Unit (FPCDU). The delay-output board is triggered by the fire pulse from the ICE Box which in turn triggers the FPCDU. Since the first pulse from the delay-output board triggered the FPCDU at the proper time and the second pulse had no effect, this situation did not constitute an operational problem. This situation was traced to transient feedback within the delay-output board from output to input. The feedback was caused by a

combination of the fast switching time of the output transistor on this board and the large capacitive load presented by the input trigger circuits to the FPCDU. This combination produced large peak transient currents which fed back to the input of the board causing it to trigger a second time. The situation was corrected by slowing the switching time of the output transistor with negative capacitive feedback.

- On the first dry run at the expected downhole operating temperature (140°F), one ICS downhole system failed to produce an arming current into the fire set. This problem was traced to a failure of the command-output board which controls this function. A diode was found to have failed open-circuit. This diode is an established-reliability component and is operated at well below rated stress levels and its failure can only be attributed to either mechanical stresses caused by handling and soldering or random failure. This board was replaced with an identical board, which operated satisfactorily through the detonation.

- After the ICS downhole systems had been soaked at temperature for approximately 48-h and 20 dry runs, one ICS downhole system began to trigger the FPCDU prematurely.

This problem was traced to an intermittent switching action of the 28-V delay board that was caused by induced voltage from an adjacent board (frequency separator I). The 28-V delay board delays the application of 28 V to the command-output boards until the 5-V logic circuits have stabilized after the application of downhole power. The command output boards, when addressed by

the appropriate command, gate the 28-V power through to perform the command functions. By its intermittent switching action, the 28-V delay board was gating on and off the active commands. This problem was eliminated by bypassing high source impedance voltage reference points with capacitors to shunt the induced voltage to ground. This provided the stable dc reference voltages necessary for the proper functioning of the circuit.

- One ICS downhole system occasionally produced spurious ratchet pulses to the coded switch when all commands were dropped at the end of a dry run (+2 s). This problem was traced to an inductive voltage transient reflected from one of the Sandia, fire-set simulators back into the ICS downhole system. The defective transformer in the fire set simulator was replaced. In addition, capacitors to ground were placed on the output of each of the arm current power supplies to minimize the effect of reflected transients on the ICS system from the fire sets.

- Later, a delay-output board was found to be producing a spurious output at the end of dry runs when all commands were dropped. This was traced to a cause similar to the previous item. The arm-enable relay was opening before the reflected, inductive-voltage transient from the fire-set simulator could be bypassed to ground by the capacitor on the output of the arm-current power supply. The solution to this problem was to delay the dropping of the arm-enable command until one second after all other commands were dropped, thereby leaving the bypass capacitor to ground in the circuit until the inductive transient was dissipated.

After the previously mentioned problems were resolved, testing was resumed. A full-scale certification test with live A&F components was conducted in December 1972. Due to a malfunction of the camera shutter actuation system, no oscilloscope data was recorded. Streaking camera data showed that all the A&F components performed satisfactorily; however, no analog output data was obtained from the neutron generators. A second certification was run in January 1973 in which all data was successfully recorded.

During this test series, the ICS downhole systems were operated from the dry-run rack and through the Rochester²⁰ (see Arming and Firing Cable) cable, which included jumpers of the appropriate length to interconnect the three systems. The downhole systems were maintained at 140°F, the maximum expected temperature. The dry-run rack contained, in a portable double width relay rack, equipment identical to that which was used in the CP trailer and the ICE Box.

FINAL CHECKOUT AND ASSEMBLY

The final checkout and assembly of the Rio Blanco explosives took place in two parts. The downhole ICS system, auxiliary system, A&F system, and the evaporator for cooling system were assembled in Livermore. The ICS and the A&F systems were checked for proper operation during several dry runs. Also, the pressure and temperature channels

for each of the downhole monitor systems were calibrated at that time. The check-out and calibration was performed through the entire ICS including CP trailer, microwave link, and ICE Box. This phase was completed in January 1973.

The final assembly took place in the 410 area at the NTS. The ICS dry-run rack was used to complete this part. The downhole systems were checked out through both the Rochester and RF-1 (see Arming and Firing Cable) firing cables so that either cable could be used for the actual detonation. The last electrical system checks were then completed and the final code set into the coded switches.

FIELD OPERATIONS

We started work at the Rio Blanco site on Monday, April 16, 1973. By the following Saturday, April 21, the ICS was set up, checked out, and ready for the delivery of the explosives. There were three dry-run ICS downhole systems and three A&F system simulators in the ICE Box to simulate the actual downhole systems. These were used to check out the ICS. The dry-run ICS downhole systems were identical to the actual systems except that they did not contain high reliability parts. In addition to checking the A&F signals from the ICS downhole systems, the A&F system simulators fed simulated pressure and temperature data into the ICS to check out the monitor systems.

Before the explosives were unloaded from the shipping van, an explosive system check was performed on all three systems. The explosives were then removed from the shipping van, the external

²⁰ 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.

cooling system components attached, and the downhole operation started. Figure 8 shows the emplacement rig and shipping van. At various times during the downhole and stemming operations and up to the final detonation, explosives systems checks were performed. The purpose of the systems check was to verify the performance of the power supplies, command decoders, monitor systems, and the integrity of the explosives. The status of the coded switches and other downhole monitors was verified and pressure and temperature data were recorded. These checks were made two to four times a day depending on the circumstances.

The explosive systems check procedure was as follows:

- ICS performance was verified through the dry-run systems and A&F simulators.
- Power was applied to the explosives.
- The downhole monitor status was verified.
- The test command was transmitted and receipt was confirmed through the monitor systems. The test command served to verify the performance of the downhole command decoders. It performed no other functions; therefore, safety requirements were not compromised.

Fig. 8. Photograph of the site showing the emplacement well and the van used to transport the explosives.

• Pressure and temperature data from the explosives were recorded.

After the explosives were at the bottom of the emplacement well, but before stemming operations were initiated, it was noticed that the test command was intermittently decoded in the top explosive during a systems check. The command system utilizes a digital format that is composed of a series of "ones" and "zeros" coded into pulses of different widths in time sequence to denote a particular command. The width or time duration of a "one" is double the width of a "zero." The logic of the command decoder is designed to prevent the decoding of false commands from either a noisy signal, an invalid command format, or a combination of both. This is very important for safety reasons. One of the checks performed on the command format by the decoder is the width of the "zero" bits. The "zero" bit width detector is set

to reject bits with widths less than 90% of the normal value.

The intermittent decoding of the test command was caused by a drift in the bit widths of the command generator in the CP combined with a probable change in the set range of the downhole bit width detector in the top explosive due to the downhole temperature. Adjusting the zero bit width in the command generator to the proper value solved the problem.

Mandatory dry runs for all technical program participants were held on the fifth and the fourth days preceding the detonation. The total time in the field for the ICS detonation service was five weeks from the initial set-up and check-out of the system through the securing of the system for shipment back to Livermore. The ICS field crew consisted of four electronics engineers, two electronics technicians, and one electronics coordinator.

Safety Program

The ICS contained a remote area monitoring system (RAMS) to detect and monitor radioactive gases that might escape from the emplacement well, an air analyzer to detect radioactive particulates, and geophones to record postshot seismic activity.

DESIGN

The safety equipment was first tested on the Miniata Event both as a backup for the NTS safety system and as a dry run for Rio Blanco. The compatibility of the safety program equipment with the

ICS monitor-telemetry system was studied after the Miniata Event and the system parameters were defined. Subsequently, the equipment was modified or redesigned to conform to a 0 to +5 V high-input impedance ($>1\text{ M}\Omega$), a low output impedance ($<100\text{ }\Omega$), and a 250 ms per channel sampling rate. The modified equipment for Rio Blanco was tested by Hazards Control and Eberline Instruments personnel during the system test.

Reservations were expressed about the interpretation of the geophone signals because of the sampling rate and the unipolar monitor system. The geophones

normally produce a bipolar output and operate above their resonance frequency, which was about 1.0 cycle per second for the chosen units.

The geophone system was expected to perform adequately while the RAMS and weather instruments were expected to perform well. Prior to fielding the equipment, current and voltage limiting for

electromagnetic pulse (EMP) protection was added, even though it was felt that EMP would not be a problem with the Rio Blanco configuration.

FIELDING

During the installation of the RAMS, the readout equipment gave a high background reading when the monitor inputs

Fig. 9. The detectors and control room used to monitor radioactivity and weather conditions.

were open. This situation was unacceptable. After installation and checkout of the geophone system it became necessary to amplify the signal level and provide voltage offset to properly transmit the bipolar output of the geophones over the unipolar monitor system. The wind speed sensing head required modi-

fication to function properly with the long cable between the sensor head and the translator. The Hazards Control sensors and control room are shown in Fig. 9. The safety program equipment required only minor field modifications to achieve the desired operating characteristics, and performed very successfully.

Arming and Firing Cable

With the development of the single cable ICS it became necessary to develop a coaxial cable and a flat cable of equal impedance to meet all anticipated conditions. The worst foreseeable environment for the coaxial cable was a mud-filled, uncased, 6100-m-deep hole with a temperature of 205°C and a pressure of 70 MPa. To meet these conditions the specifications called for a double-armored, fully gas blocked, 30- to 50- Ω impedance cable with a loop resistance of less than 3 Ω per 1000 ft, to operate at 205°C and 70 MPa. These specifications were sent to 34 cable manufacturers. Proposals were received from five. Orders for prototype production were given to the three lowest bidders, but the only prototypes received in time were from Rochester Cable and US Steel. The Rochester cable used Tefzel as a dielectric material to meet the temperature requirement and met all the electrical and impedance requirements. However, it failed the gas blocking tests and the 205°C, 70-MPa requirement. At that temperature and pressure the Tefzel started to crack. Succeeding tests showed that the cable was good up to 150°C and 49 MPa, which was well within the

requirements for Rio Blanco (120°C and 35 MPa).

The US steel cable met all specifications except those of the time-domain reflectometry (TDR) tests which showed a 1.5- Ω impedance variation every 10 ft. This was due to a cyclic variation in the dielectric thickness. United States Steel did not have any solution to this problem. Since time was a critical factor at this point and a 50- Ω impedance was needed, the cable order went to Rochester.

Rochester continued looking for an acceptable gas blocking compound, but all our tests indicated gas leakage. Most tests were performed at ambient temperature and pressure. Then it was decided to simulate the effect of pressure on the cable. A piece of cable was grouted at 21 MPa. After grout setup, the pressure was released and the gas-blocking test repeated. A 200-fold decrease in the leak rate was observed. It was thought that the effects of temperature and continued pressure on the cable might result in an even greater improvement.

When the event was suddenly delayed by six months, it was decided to test a standard RF-1 cable (gas blocked) at 120°C and 35 MPa. This test was

successful and a special order was placed to double armor a RF-1 cable for use on Río Blanco. In the meantime the Rochester cable was used for the certification tests at the Sandia Livermore Laboratory.

After receipt of the armored RF-1 cable, it too was tested at temperature and pressure, while terminated in the appropriate downhole Advanced Systems Engineering (ASE) connector. After a few days at temperature and pressure the electrical resistance between the center conductor and the shield of the cable showed a slow but steady decrease. The test was stopped and examination of the connector showed that some of the gas blocking compound from the stranded center conductor had been extruded into the connector. Chemical analysis showed the presence of titanium oxide which becomes conductive in the presence of even very small amounts of water.

At that time it was decided to make the final explosive assembly and checkout at Nevada with both the Rochester cable and the RF-1 and simultaneously initiate another test to see if the cable termination could be improved to eliminate the extrusion of the gas blocking compound into the connector.

Both cables were then sent into the field while the RF-1 test was repeated. When the results of the second test were essentially the same as before it was decided to use the Rochester cable for

Río Blanco. The Rochester cable was used successfully and showed no postshot gas leakage.

In the early planning stages it was assumed that the 20.3-cm-diameter explosive could and would be emplaced in a 24.5-cm casing. This left very marginal clearance for a double-armored cable. The better and safer solution was to bring the cable into the top of the canister and out at the bottom, and on the next explosive. The only problem with this solution was the very limited space (0.15-cm thickness by 1.65-cm in width) available inside the canister and the need to maintain the 50- Ω impedance. Therefore, it was necessary to develop another special cable to link the top and bottom of each canister.

The first prototype built to our specification for the Miniata Event was a triplate cable, 0.18 cm by 1.27 cm. This cable was electrically satisfactory, but the permissible bending radius was much too large to be useful for our application.

Following Miniata we looked for bids from various flat cable companies, but no one could meet the bending radius requirements for this particular design. Ansley East Company showed the greatest interest in the problem and eventually designed and built a 50- Ω , shielded, parallel-wire cable with overall dimensions of 0.15 $\times$ 0.64 cm that could meet all specifications. This cable was successfully used in the top two explosives.

Explosive Verification

Since Río Blanco was the first gas stimulation experiment to use three simultaneous detonations in the same emplace-

ment well, it was decided from the start that a positive verification of detonation of each explosive was essential. It was

also decided that the cost of any special explosive diagnostic system had to be kept to the minimum. Previous experience had shown that the easiest and simplest verification comes from the electromagnetic signal generated on coaxial cables during a nuclear explosion. Thus, the perfect solution was to look at the signal from each explosive on the arming and firing cable.

With only one cable providing all the power and command signals to the three explosives, the cable had to either run on the outside or the inside of the two top explosives. As previously mentioned in the Rio Blanco cable description, it was decided to run the firing cable on the inside of the explosive canisters to avoid any accidental cable damage during lowering of the explosives. Since there was no prior experience with the special 0.15 cm

Fig. 10. The diagnostic signal from the firing cable. The signal corresponds to the detonation of the upper explosive since the cable was severed in the top explosive before the arrival of signals from the lower explosives.

Fig. 11. The response from the RF-1 diagnostic cable. The three signals are from each of the three explosives and are shown with programmed time delay on a dual-trace oscilloscope. The upper trace sensitivity was set for 50 V/cm and the lower for 10 V/cm. The timing wave was 2 MHz.

X 0.64 cm, 50- Ω shielded parallel wire line on the inside of the explosive canister, it was too risky to rely on the firing cable as the only verification source. Therefore a standard, continuous, unarmored RF-1 cable was run all the way to the bottom of the well alongside of the explosives. This cable eventually served three functions: Detonation verification, chimney height information, and with the addition of a passive pressure transducer at the end of the cable, the downhole pressure history was recorded during and after the grouting operation.

To see all three explosive signals on the two cables it was necessary to detonate with some delay from the bottom up. A nominal 10- μ s delay was used between detonations to allow enough time for the signals to pass the other explosives before the cable was cut.

Fig. 12. A different presentation of the response from the RF-1 cable. The pulses were attenuated on a raster scope with 2.5- μ s sweeps and 0.5- μ s markers on each sweep line. The scope retriggered giving the double trace.

RESULTS

We obtained only the signal from the top explosive on the firing cable (Fig. 10).

This is because the cable was severed in the top explosive before the arrival of the signals from the detonation of the lower two explosives. Fortunately, signals from all three explosives were detected on the RF-1 cable that was alongside the explosives (see Figs. 11 and 12).

Figure 12 shows the pulses attenuated on a raster scope. The measured signal separation is approximately 8.7 μ s between detonations. The oscilloscopes were triggered from a delayed fire pulse.

The cable break measurement yielded the desired chimney height information, recording a break in the RF-1 approximately 335 ft above the top explosive and a break in the firing cable at 150 ft above the explosive. The pressure measurement confirmed the anticipated pressure increase during the grout pumping.

Spall Measurements Program

The objective of the spall measurement program was to measure the depth and extent of ground spall (tensile failure of the rock) caused by explosion-induced stress-field interactions as the ascending compressive wave is reflected at the ground surface.

To accomplish this objective, 10 instrument holes ranging in depth from about 4.6 m to 274 m were drilled and emplaced with 20 instrument canisters containing accelerometer and velocity gages (see Fig. 13). In addition, five of the holes were instrumented with special CLIPER (Collapse Location Indicator by Pulsed Electromagnetic Reflection) cables. The

experiments were all controlled from Trailer 68 (see Fig. 14).

Following is a description of the various instrumentation systems used in the spall program, discussion of the data and playback system, and recommendations for future fielding operations.

DOWNHOLE CANISTERS

All of the spall canisters were identical, with the exception of those at the four surface stations. Each canister contained one Kistler Model 305A accelerometer, one Spartan Model 602 V velocity gage,

Fig. 13. Locations of the sensors used in the spall measurements program.

Fig. 14. Trailer 68, the control center for the spall measurements program.

and appropriate electronics (see the block diagram, Fig. 15). Also included in the canisters were an explosive guillotine system used to sever the canisters from the downhole lowering cable after emplacement and prior to shot time, and a thermistor to monitor canister temperature.

Accelerometer System

The accelerometer was mounted in a vertical attitude on a central, removable core within the canister body. Its signal output was delivered in parallel to two, high-input impedance, voltage-controlled oscillators (VCOs), LEA 70-1128, center

tuned to nominal frequencies of 300 kHz and 1200 kHz. Precision, metal-film resistors at the VCO inputs determined the accelerometer sensitivity (volts per g). The 300-kHz VCO sensitivity was set so that we could measure the maximum expected acceleration pulses on initial ground acceleration and slapdown. We used a nominal $\pm 15\%$ deviation of center frequency for full-scale gage range, which was typically 12 to 20 g. System sensitivities for the 300-kHz VCOs were 3-4 kHz/g.

The 1200-kHz VCO sensitivities were established so that a $\pm 15\%$ deviation of center frequency was again equal to the full-scale gage range, which was ± 2.5 g. This resulted in sensitivities of 70-80 kHz/g for these VCOs. The idea was to establish greater resolution when looking at the -1 g spall levels.

This dual-ranged accelerometer system provided us with a system capable of measuring accelerations from a few tenths of a g to about 20 g or roughly a 40-db dynamic range. The +15 V and -15 V required for the accelerometer operation was taken from the +15 V and -15 V regulators on one of the VCOs.

Fig. 15. Block diagram of a typical downhole canister used in taking spall measurements.

Fig. 16. Block diagram of a remote surface station.

Fig. 17. Tape recorder used to record spill data at a remote surface station.

Velocity Gage System

The velocity gage was mounted just below the accelerometer. The gage output was used to frequency modulate a dual oscillator-modulator circuit, LEA 72-1186, which was center tuned to a nominal 125 kHz. System sensitivities for the

velocity gages were typically 650 to 1000 Hz/m/s.

Summer-Mixer

The VCO and dual oscillator outputs were then delivered to a summer-multiplexer, LEA 70-1137. The three summer inputs were low-pass filtered at the 3 carrier frequencies $\pm 15\%$ with a 6-pole LC filter. The signals were then combined and delivered through a buffer amplifier to the surface run RG-213 cable via RF-1. The dc power for the canister electronics was delivered from Trailer 68 down this same cable, through a high pass filter at the summer output, and then distributed to the VCOs and dual oscillator in the canisters.

The surface canisters at the well-head area and at the 2195-m station were identical to the downhole canister described above, except that they contained only the accelerometer and its electronics. No velocity gage was used.

REMOTE SURFACE STATIONS

The two remote surface stations, at approximately 3.6 km and 7.3 km from

the emplacement well, were arranged differently from the other spall canisters (see Fig. 16). Small 15-V mercury batteries were used to supply power to the Kistler 305A accelerometer. The accelerometer sensitivities for the 3.6- and 7.3-km stations were 0.5 V/g and 1 V/g, respectively.

The signal output was delivered to two channels of a cassette tape recorder, a TEAC Model R-70. FM mode recording was used. The signals were dual ranged at a 2:1 ratio so that our sensitivities were increased to 1 V/g and 2 V/g. The recorders were powered from an external battery pack (12 V at 350 mA). A mechanical clock timer was used for remote start capability. The tape recorder was suspended by bungee cord inside a 3-ft-cube plywood box to minimize shock due to ground motion (see Fig. 17). At approximately H-2 h, accelerometer and tape recorder power was applied, and the mechanical timer set. Recording started

at approximately T - 10 minutes. No zero-time signal was applied to the tape.

CLIPER SYSTEM

Five of the instrument holes contained a special CLIPER cable, which consisted of RG-81 cable (copper jacketed) installed in the grouted portion of the instrument hole and pulsed from its lower end (see Fig. 18). External upsets (circular knobs) were attached every 60 cm to increase its shear bond to the grout. RF-1 cable was used to carry pulses downhole to and from the lower end of the RG-81. A CLIPER pulser, LEA 72-1087, was used to send (and receive) a pulse train to the CLIPER cable system. The pulser acted as a triggerable multivibrator so that the pulse repetition frequency (PRF) was a function of total cable length. The system was capable of a resolution of a meter in several thousand, and would detect either a short or open in any part of the cable.

Fig. 18. Block diagram of a CLIPER system.

Fig. 19. Block diagram of a channel for recording data from a downhole canister.

The pulses were delivered to Trailer 68 via RG-213 surface-run cable.

TRAILER-68 INSTRUMENTATION

Downhole Canister Signals

All connections to the spall canisters entered Trailer 68 and terminated at a coaxial patch panel. From there, cables were run to modified Power Fanout and High Pass Filter-Amplifier units, LEA 69-1061, (see Fig. 19). The amplifiers in these units, which were normally high passed at 300 kHz, had to be modified to accept the 125-kHz velocity gage signal. This was done by removing the front-end filter and changing the size of the coupling capacitor. The amplifier gains were set so that the multiplexed signal to the tape recorder was approximately 3 V, peak to peak. The voltage delivered at the canister was 28 V, resulting in typical currents of 200 mA per canister. Voltage, current, and canister signals were monitored daily.

Individual VCO frequencies were monitored by routing the multiplexed signals through 3 bandpass filters in parallel, each tuned to the nominal center frequencies of 125 kHz, 300 kHz, and 1200 kHz. These carriers were then displayed on an oscilloscope and frequency counter.

The multiplexed signals from the Power Fanout and High Pass Filter-Amplifier units were delivered to wide-band tape recorders, one canister multiplexed signal per track.

Two wide-band direct-record tape units were used—one Ampex Model FR-1800 and one Ampex Model FR-1900. Track 14 of each recorder was reserved for a mixed time code (IRIG B) and zero time signal. Remote start, stop, and monitor light indication from Trailer 95 (CP) was used.

CLIPER Signals

The CLIPER pulser signal output was delivered to a 50- Ω terminated, wide band amplifier and then to the tape recorder. An external 100-V power supply was used for the output avalanche transistor collector supply. Before and during installation of the CLIPER system, the lengths of the 3 individual cables (RG-213 surface run, RF-1 downhole cable, and RG-81 cliper cable) for each hole were monitored by counting the pulse repetition frequency with a period counter. Daily measurements, before and after the shot, checked system stability and changes (if any) in cable lengths.

Fig. 20. Block diagram of the crystal accelerometer system that was placed on the wellhead.

Fig. 21. Block diagram of the accelerometer used to measure the response of Trailer 68 to ground shock.

ADDITIONAL INSTRUMENTATION

Wellhead Accelerometers

Three crystal accelerometers (Fig. 20) were mounted on the wellhead and were used to deviate 3 VCOs, center tuned to the same spall frequencies. The VCO outputs were summed and delivered to Trailer 68 via RG-213 surface cables. An isolation transformer was used in the trailer to prevent possible electromagnetic noise from crosstalking into the spall instrumentation system. The canister was placed above the wellhead on a wooden frame and was powered by a 28-V source from the ICE Box.

Trailer Response Accelerometer

A Kistler 305A servo accelerometer was mounted on one of the instrumentation racks in Trailer 68 to measure the trailer response to ground shock. This signal was to be compared with the surface accelerometer signal just outside the trailer to give us data on the effectiveness of the trailer shock mitigation system. The accelerometer was battery powered and deviated a 3.9-kHz VCO, LEA 70-1162. The VCO signal was delivered to the tape recorder (see Fig. 21).

Water Well Pressure Measurements

We used Trailer 68 to record pressures from 3 different wells in and near the

Fig. 22. Block diagram of a typical system used to record water-well pressures for the United States Geological Survey.

emplacement well for the United States Geological Survey. Figure 22 shows the instrumentation used in recording these measurements. The USGS supplied the strain gage pressure gages, strip chart recorders, and all equipment in the instrument box. LLL supplied the surface cable, VCOs, LEA 70-1162, and tape recorder. The object of this experiment was to measure dynamic water pressure at shot time and the quasistatic decay for several hours after the shot. This was part of a continuing study by the USGS, who have made these measurements on several nuclear events.

DISCUSSION AND RESULTS

Downhole Measurements

The overall results from the Rio Blanco spall measurements were very good. Data was received on every one of the 59 individual carrier and CLIPER signals. Figure 23 is a block diagram of the preliminary data playback system. Surface spall was clearly detected at all surface stations except the one at 7.3 km. In the emplacement-well area, ground spall was detected down to about 107 m below ground surface. This spall zone depth diminished to less than 91 m at a 800 m

Fig. 23. The data playback system.

Fig. 24. Accelerometer trace from surface station 3. The data shows clear evidence of spall.

radius and to less than 61 m at 2.4 km from the wellhead. Thus, the earth spall zone took the shape of a large, shallow bowl with a radius of 3.6 to 7.3 km and a maximum depth at the "center" of the bowl of about 107 m.

None of the five CLIPER cables broke during the shot. This was verified from preshot and postshot measurements. This indicated that ground layer separa-

tion did not exceed 7 to 10 cm anywhere in the spall zone.

Figures 24-26 show the differences in the data between areas where spall did

Fig. 25. Signals from canister 02-600.

Fig. 26. Signals from the 7.3-km surface station.

and did not occur. The Rio Blanco spall data has since been digitized and computer analyzed and put in its final form.*

Wellhead Accelerometers

The three crystal accelerometers which were mounted on the wellhead showed higher frequency acceleration components than did the spall accelerometers. All three units showed a rather large spike (up to 30 g's) at T + 560 ms

Trailer Response Accelerometer

The trailer response to the ground shock was monitored and revealed a longer duration -1 g free flight than did any of the surface canisters. An initial peak acceleration of 2 g at about 670 ms

was followed by about 330 ms of -1 g free flight. This -1 g free flight time was at least 50% longer than any other station response. The slapdown spike was in excess of 3 g. A comparison of this record to the accelerometer signal just outside the trailer showed a shock reduction of at least a factor of two. Although the trailer slapdown caused no introduction of noise on the tape recorded data, it was the cause of another problem which will be mentioned later.

USGS Instrumentation

The three water well pressures were recorded both on tape and strip chart. Dynamic pressure spikes of up to several hundred psi were recorded as the shock wave passed through the wells. Quasi-static long term data was recorded on the strip charts and showed a slow decrease in pressure asymptotically approaching the preshot level.

PROBLEM AREAS

Several problems occurred during the initial system design and procurement and preshot and postshot fielding. It is worthwhile mentioning some of the more critical ones and the solutions to them.

Crosstalk Between VCOs

We initially decided to use VCO frequencies of 125 kHz, 600 kHz, and 1200 kHz for the downhole canister signals. Consequently, the VCOs were all tuned accordingly. During the course of our preshot shock testing of the canisters on the Hyge machine, we discovered a serious crosstalk condition existing between the 600- and 1200-kHz signals.

*C. Sisemore and J. Toman, Project Rio Blanco Spall Measurements Data Report, Lawrence Livermore Laboratory, Rpt. UCRL-51484 (1974).

A spectral analysis of those two carriers showed the second harmonic of the 600-kHz carrier booming "loud and clear" into the 1200-kHz signal. The decision was made to retune all the 600-kHz VCOs to 300 kHz to alleviate this problem. When further shock testing showed no crosstalk conditions, the canisters were sealed and shipped to Colorado.

Canister Failures

The emplacement of the spall instrumentation took place during January and February. All systems were operating at the time we left. A three day return trip was made in late March to check on the status of all systems. It was found that one canister, 04-060, had failed completely, and one other, 02-450, showed intermittent operation.

Canister 04-060 was drawing about 10 times the nominal current and no carriers were present. This suggested possibly that water had gotten into the down-hole connector and created a partial short. It was decided to replace this canister with a spare. A new hole was drilled and the spare canister emplaced with no further problems.

Canister 02-450 was intermittently drawing no current and twice nominal current. Since the canister was at a depth of 450 ft, replacement was not feasible. It was decided to isolate that canister from the rest of our instrumentation system by powering it from a separate 30-V source and routing the carriers to a separate amplifier. The carriers were about 10% off of their nominal outer frequency and low in amplitude. Good quality data (in terms of the signal-

to-noise ratio and waveshape) was received from that canister at shot time. However, amplitudes may be questionable because of the erratic performance and shift of the center frequencies.

Each canister had a thermistor bead which was used to monitor temperature. This was required in order to properly adjust velocity gage sensitivities at shot time. Many of the thermistors failed between January and May. The mode of failure was the same in all cases—a drastic lowering of thermistor resistance. Presumably, the bead became shunted by water contamination in the canister connector. However, enough data was recorded before failure (temperatures were monitored several times a week) so that we were confident that the temperatures were stabilized and did not change at shot time.

Fire in Trailer 68

On D - 1 day, just a few hours before the final dry run, a fire broke out in the trailer. One of the oscilloscope blower motors overheated and ignited the oil-impregnated air-flow filter. Flames then melted the rubber insulation off of some of the cables behind the rack. The fire was put out quickly with a dry chemical extinguisher. The final dry run was delayed several hours while we replaced cables and cleaned open relay contacts (used to start the tape recorders) that had become contaminated with the residue from the extinguisher. A good final dry run was conducted later that day after several other tests were made to insure that the relays would consistently start the tape recorders.

Power Drop Out at Shot Time

The most heart-sinking event of the entire experiment occurred on reentry into Trailer 68, some two to three hours after shot time, when it was discovered that there was no power on the instrumentation equipment. Further observations showed the instrumentation main power line contactor to be open. After restoring power by resetting the contactor, it became evident what had happened. The ground shock at the trailer had caused a small control relay to open up, which in turn opened the large contactor. The small control relay is normally activated by an electrical timer which can be used to automatically shut down power at some preselected time after zero time. This feature was at one time used for shots at the NTS.

Further investigation revealed that the small control relay spring tension was so weak that a small rap of the hand on the box that housed the relay was sufficient

to open it, and hence the main power contactor.

Later tape playbacks showed that loss of signals caused by the power failure occurred at 1.065 s after zero time. Fortunately, this was enough time to capture all parts of the data from all canisters, so that there was no loss of data.

Future use of Trailer 68 on an event will require that this automatic shutdown feature be bypassed to prevent recurrence of this problem.

Velocity Gage Sensitivities

All velocity gage signals were much lower than predicted—by about a factor of 10 or so. Consequently, we were far overranged and had a poor signal-to-noise ratio on these gage signals. The noise was predominately high frequency while the data was in the range of 1 to 5 Hz. We overcame the problem without too much effort by low-pass filtering the data at 30 Hz.

Field Coordination

The field coordination effort involved the installation and maintenance of cables and equipment as well as the coordination of all Electronics Engineering Department activities with other groups and agencies. During the period from early January 1973 to late May 1973 three trips were made to the Rio Blanco Site in connection with spall measurement, gas sampling, ICS, USGS, diesel-generator power systems, prearming, arming, and reentry detonation activities.

SPALL MEASUREMENTS PROGRAM

Field effort on the Spall Program consisted of laying over 2150 m of cable and locating the instrumentation trailer (T-68) and power trailer (T-11). CER Geonuclear provided a crew of electricians to lay 18 runs of RG-213 from the instrument trailer (T-68), which was located at the 800-m station, to the emplacement well and to the 2225-m station (see Fig. 2). Two multiconductor cables for commands

and a fiducial cable were run between T-68 and the ice box location at the emplacement well.

Two runs of Sandia white wire were laid from T-68 to the emplacement well and the 370 m-well north of the EW for the USGS experiment. We assisted the USGS people and provided recording space in T-68 for them.

Electrical support was provided for the gas sampling system. The gas sampling tube had to be shielded due to the radiation hazard and protected from freezing temperatures. A thermistor controlled heat tape was taped to the gas sampling tube for heating. This was then insulated and buried underground for shielding. A power cable and ground wire were also buried from the wellhead to a backboard near the power box. This was to provide a common ground and power to the wellhead heater. An additional backboard was installed at the gas sampling skid to furnish power at that location. Both backboards were tied together and could be powered from either commercial or diesel sources.

INTEGRATED CONTROL SYSTEM

The ICE Box, power box, and RT box were spotted at the emplacement well location. As shown in Fig. 2, the ICE Box was located about 60 m NW of the emplacement well and the RT box about 250 m NW of the emplacement well on a

line-of-sight path for microwave communication with the CP. The CP (Trailer 95) and power trailer were spotted on a plateau overlooking the emplacement well at an elevation of 2300 m. Six RG-213 cables were laid between the ICE Box and the RT box. Two power cables were laid between the power box and RT box. The power cables were terminated by the CER electricians and the coaxial cable was terminated by LLL technicians. A 6-m antenna tower was installed by CER at the RT box.

The ICE Box, power box, and the RT box were shock mounted. The microwave antennas were carefully supported to ensure the proper functioning of the ICS during the ground motion after detonation (see Fig. 6). A grounding system was tied to the Ice Box through a knife switch so it could be ungrounded if desired. The ground from the wellhead also went through a knife switch on the backboard near the power box. All grounds were lifted during shot time.

Miscellaneous activities included the maintenance of the power-box diesels and provision of a flash bulb at the EW to provide a zero time marker on the motion picture film. All our trailers were prepared for shipment to LLL on D + 2 by Plowshare EE personnel. The surface run RG-213 cables were to be rereeled and returned to the NTS by CER personnel. The gas sampling system was left intact for postshot analysis.

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