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RIO BLANCO:

NUCLEAR OPERATIONS AND CHIMNEY REENTRY

W. R. Woodruff

R. S. Guido

May 15, 1974

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

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Foreword

This report has been prepared to document the project Rio Blanco nuclear operations and chimney reentry activities. It is our intent to give an overview rather than a detailed description. For more detailed information, the references for the particular subject should be consulted. We have attempted to give a description of

the activities of the Laboratory from the beginning of preparation for the project through completion of reentry activities. We hope these descriptions will provide a better understanding of what transpires between the Laboratory and an industrial sponsor in preparing and executing an experiment utilizing a nuclear explosive.

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RIO BLANCO: NUCLEAR OPERATIONS AND CHIMNEY REENTRY

Abstract

Rio Blanco was the third experiment in the AEC's Plowshare Program to develop technology to stimulate gas production from geologic formations not conducive to production by conventional means. The project was sponsored by CER Geonuclear Corp with the Lawrence Livermore Laboratory providing the explosives and several technical programs, such as spall measurement.

Three nuclear explosives, specifically designed for this application, were detonated simultaneously in a minimum-diameter emplacement well using many commercially available, but established-

reliability components. The explosive system performed properly under extreme temperature and pressure conditions. Emplacement and stemming operations were designed with the aim of simplifying both the emplacement and reentry and fully containing the detonation products. An integrated command and control system was used with communication to all three explosives through a single coaxial cable. Reentry and the initial production testing have been completed. To date 98 million standard ft³ of chimney gas have been produced.

Introduction and Summary

Project Rio Blanco was the third, joint industry-government sponsored experiment in the USAEC Plowshare program to develop the technology for the nuclear stimulation of low permeability gas reservoirs, and the first to utilize nuclear explosives specifically designed for this application. Figure 1 shows the sites of the Plowshare experiments. Rio Blanco was also the first US experiment where three nuclear explosives were simultane-

ously detonated in the same emplacement well.

The general objective of Rio Blanco was to produce natural gas from geologic formations not conducive to production by conventional means. The following specific objectives were considered in designing the experiment:

1. Stimulation of a thick gas-bearing interval by the utilization of multiple explosives, and subsequent

* Parts of this report were initially prepared for presentation at the ANS 1973 Winter Meeting held in San Francisco, November 11-16, 1973.

Fig. 1. Low-permeability basins of the Rocky Mountain States.

evaluation of its production capacity.

2. Determination of postdetonation environment characteristics, such as interchimney communication, effective height and volume of the chimneys, and the effective fracture zone radius.
3. Determination of the chemical and radiochemical composition of the gas resulting from the detonation.
4. Development of an emplacement and stemming technique allowing rapid reentry to the stimulated interval.
5. Reduction of tritium production to levels below those experienced on previous gas stimulation projects.

Project Rio Blanco was sponsored by the CER Geonuclear Corporation of Las Vegas, Nevada, under a joint venture agreement with the Equity Oil Company of Salt Lake City, Utah. The AEC Nevada Operations Office discharged the government's field responsibility and the University of California's Lawrence Livermore Laboratory provided for the detonation service, the nuclear explosives, and several technical programs. There were a variety of public and private organizations responsible for many other technical and safety programs and still others with an operational responsibility.

A project definition contract was signed by the industrial sponsor and the government on December 18, 1970. Subsequently, the project definition plans and environmental impact statement were developed and issued. The project execution contract was signed on April 12, 1973¹ and the nuclear operations started immediately thereafter.

At LLL we first tested a complete explosive and cooling system prototype at expected conditions to provide lifetime and performance data. This was followed by a partial system assembly at the Livermore Laboratory, and then final assembly at the USAEC facilities at the Nevada Test Site.

An Integrated Control System (ICS) provided command, control, and monitoring for the explosive and safety program sensors. The ICS facilities were installed in the field before explosive delivery. When the ICS was ready, and other field facilities were accepted, the explosives were delivered to the emplacement well by a special USAEC shipping van equipped to provide the appropriate safety and security for fully assembled nuclear explosives.

After an initial electrical interrogation, the first phase of explosive emplacement consisted of sequentially mating each of the three explosives to its cooling system and lowering the assembly into the emplacement well. The second phase of the emplacement was an around-the-clock lowering on 7-in.-o.d. drill casing. The emplacement and stemming of the sub-surface measurements equipment and preparation for data recording, installation of equipment for the gas sampling experiment, and installation and calibration of the safety program sensors and recorders were done before and during the explosive emplacement. After the explosives were lowered, and after verification of cooling system operation, the emplacement well was stemmed with cement slurry, and a pressure-tight seal made between the emplacement-well casing and the lowering casing with standard wellhead hardware.

Fig. 2. Site of the Rio Blanco experiment.

The three 30-kt-yield nuclear explosives were simultaneously detonated at 1000:00.12 h $\pm$ 0.01 s, Mountain Daylight Time, or 1600:00.12 h $\pm$ 0.01 s, Greenwich Mean Time, on May 17, 1973. The three explosives were at depths of 5838, 6230, and 6689 ft. The emplacement well location (Fig. 2) was at geodetic coordinates of 108°21'59" west longitude and 39°47'35" north latitude.

A few hours before detonation, the residents in the immediate area had been evacuated. The commands to the explosives originated from the ICS control trailer some 12 miles from the emplacement well. Subsurface instrumentation indicated that all three explosives detonated, while the safety program radiation monitors never registered above background. The principal surface manifestation of the detonation were some rock falls on nearby roads and bank sluffing on Fawn Creek immediately adjacent to the well.

Preparation for reentry drilling into the detonation region was started in mid-August 1973. Actual drilling started on September 23, 1973. The drilling was completed, after having to sidetrack outside of the lowering and emplacement casings to the chimney top, on October 19, 1973. A satisfactory two-hour production test flaring was completed on October 25, 1973 and the drill rig subsequently removed. Surface equipment and plumbing was installed for routine production which was started on November 14, 1973. The first test was completed by November 20 and the well shut in for pressure build up. At this writing the Rio Blanco site is inactive while requisite equipment for a second production test is being procured. It is expected that the equipment will be installed so that a return to production testing will be possible early in calendar year 1974.

LLL Objectives and Goals

GOALS

The Lawrence Livermore Laboratory was responsible for providing the detonation service, the nuclear explosives, related technical direction in the field, and a measurement of the depth and extent of any spall. The general Laboratory goals on Rio Blanco were:

- Advancement of the technology for the nuclear stimulation of low permeability gas reservoirs by fielding and detonating the nuclear explosives so there would be negligible environmental impact.

- Achievement of a good approximation of a commercial development mode of fielding operations that would enable a meaningful engineering evaluation and economic analyses.
- A product gas that would be significantly lower in tritium concentrations than previously achieved.

OBJECTIVES

To achieve these general goals the Laboratory had a number of specific objectives and development requirements.

Explosive

The Diamond explosives that were employed on Rio Blanco were designed and developed specifically for the gas stimulation application. Explosive design objectives were:

- A minimum diameter consistent with expected hole diameters. Emplacement hole drilling costs are a strong function of hole diameter.
- A minimum quantity of tritium in the product gas, with a target approaching zero.
- A yield range (20 to 100 kt in the Rio Blanco geometry) suitable for the formation thickness in Rio Blanco and similar gas-stimulation applications.
- A minimum cost for hardware components with no loss of reliability. For Rio Blanco most all parts that could be, were fabricated by private industry rather than AEC-integrated contractors.
- An explosive that could be handled with minimal training and would be safe and suitable for drill rig handling and emplacement.

Explosive System

The explosive system (canister, cable, connectors, etc.) was designed and tested to withstand the downhole temperature, pressure, and the presence of sour gas (H_2S). The system was designed for a maximum temperature of 250°F and a maximum pressure of 7000 psi. The expected maximums on Rio Blanco were 215°F and 5400 psi, respectively, and no sour gas. A cooling system was designed and tested that was simple (only one moving part), reliable, completely self contained,

and had a lifetime consistent with the emplacement and stemming time and an appropriate contingency period. The explosive system when fully assembled at the AEC's facility at the NTS was to be ready for emplacement so that there would be no explosive assembly work required in the field.

Integrated Control System (ICS)

The command and control system was designed, tested, and used on NTS events before Rio Blanco. The ICS was to be simple and reliable with a minimum of set-up and check-out time required in the field. All explosives were to be controlled and powered through a single coaxial cable. All the commands originating at the control point (Trailer 95) were to be sent unaltered informat to the command decoders (interface units) in the explosive canisters at the bottom of the hole where the commands were carried out. Signals from monitors in the explosives were decoded, displayed, and recorded in Trailer 95. The system had to be capable of handling nonexplosive functions such as communications, technical and safety program data transmission, display, and recording. The system compatibility and its proper operation of the explosive electronics was assured with Laboratory checks prior to fielding. These checks included all subsystems such as the command and control cable and the microwave link that were to be taken to the field.

Emplacement and Stemming

The explosive-emplacement technique was to be simple to minimize field support requirements, yet be compatible with and simplify the eventual reentry and gas

production. The most important consideration in stemming was that there be adequate containment; but, when consistent with this aim, we also considered the ultimate reentry and gas production. Both the emplacement and stemming were to use standard drilling hardware, equipment, and techniques.

General

All field operations associated with Laboratory responsibilities were to be done in a way to minimize the environmental impact, the amount of field support, and costs to the industrial sponsor.

The Laboratory people and equipment were to be as self-sufficient as possible, and the entire operation was to approximate a commercial development so more meaningful engineering and fiscal assessment could be made for the future applications of this technique. A maximum creditable accident model was developed consistent with emplacement, stemming, explosive yields, and past experience on Gasbuggy, Rulison, and other applicable underground detonations. This model was used along with the predicted ground motion, avenues of access, and location of residences to formulate an area control plan.²

Livermore Activities

The design and development of an explosive specifically for the gas-stimulation application has been underway for some years at the Laboratory. The development of computer codes for a predictive capability of explosive detonation phenomenology has been going on for even longer. Developments such as these have been provided for by the Plowshare research and development program and were underway long before the Laboratory was selected in January of 1971 to provide the nuclear explosive service for project Rio Blanco.

EXPLOSIVE

The Diamond explosive^{3,4} was designed by the Laboratory physics group specifically for gas stimulation. It was designed for temperatures and pressures more severe than those expected on Rio Blanco. Its features allowed a minimum overall

diameter (7.8 in.) and minimum tritium in the product gas, while maintaining a suitable yield range (20 to 100 kt) to be useful in various gas-stimulation applications.

Early designs for the Diamond explosive underwent tests at the AEC's Nevada Test Site (NTS) to confirm the overall physics design. On the Miniata Event^{5,6} a complete explosive assembly was tested, although downhole gas-well environment conditions requiring full temperature and pressure protection were not present. The Miniata test used as complete an explosive system (physics package, command and control system, etc.) as was possible consistent with the test requirements and was fully diagnosed to give the physics and engineering designers information on explosive performance.

Each explosive system used on Rio Blanco was completely inspected at LLL and partially assembled to insure proper

mechanical fits. This gave the assembly personnel explosive system assembly experience and insured a more straightforward and routine complete explosive assembly. One canister system was completely assembled for the "System Tests" described later.

The nature of the event required that the explosive be instrumented. Pressure and temperature information from each explosive was recorded at the Control Point trailer at given intervals to monitor the environmental conditions, the performance of the cooling system of each explosive (the condition of the explosive depended on proper cooling system performance), and gave some assurance of the proper system functioning at detonation.

EXPLOSIVE SYSTEM

The canister vessel,⁷⁻¹⁰ which provided the pressure isolation and housed each explosive, was fabricated from a specially developed steel (cesalloy "80")^{11,12} that provided sufficient material strength, fracture toughness, and stress corrosion resistance without being prohibitively expensive. Special heats of this material were made for our application. These were rough machined, heat treated, and final machined to our requirements. Extensive tests (composition, tensile strength, tear tests, etc.) were run on the basic material from each heat, from the forged material prior to heat treatment, and from the rough-machined and heat-treated pieces to insure proper material properties. Canister test sections were manufactured to allow assembly and testing under expected downhole loads

to insure that safe stress levels were not exceeded at critical areas. A full canister was assembled and tested at the downhole pressure and temperature expected on Rio Blanco in a specially provided test facility ("System Tests").

The explosive arming and firing system design required investigations beyond those normally required because of the unique environmental concerns¹³ and space restrictions owing to the small diameter of the canister. In most applications, system performance is the salient feature (space not being a consideration), but with Rio Blanco and Miniata earlier, the space available for these systems was also a major concern. After extensive review, the appropriate arming and firing components were selected. Some of the components have functions normal to most test operations (neutron generators, firesets, CDUs). The coded switch was one of the unique components employed. The coded switch provided separation between the arming and firing components and the other downhole canister electronics (timing, control, and monitors). It insured against an unplanned detonation even while we applied system downhole power and interrogated monitors for data from each explosive system during the periodic explosive condition checks.

The electronic system employed for Rio Blanco was an integrated timing, control, and monitor system planned to have the capability of operating up to five explosives in a single well and using a single coaxial cable to service all explosives. In Rio Blanco, three explosive systems were used. The downhole canister electronic system for each included a power

supply (400-Hz 208-V input, various dc levels out), a command decoder, and a monitor system that included verification and/or information pertaining to:

- Functioning of the command decoder;
- Voltage levels coming out of the power supply;
- Explosive system canister integrity;
- Explosive system temperatures;
- Cooling system performance and expected longevity;
- Nuclear explosive performance.

These electronics systems were tested as components and electronic subassemblies at expected downhole temperatures and were subjected to shock and vibration testing commensurate with expected levels during transportation and emplacement. They were subsequently used on complete system tests like the "System Test" (described later) and on the System Compatibility and Certification.

The system used to cool the Rio Blanco explosive was a single-pass absorption system designed for reliability and simplicity of operation.¹⁴⁻¹⁷ It required neither downhole power nor external control as it was completely self-contained. It consisted of a temperature controlled expansion valve (evaporator), a downhole water supply tank, and downhole calcium oxide absorber tanks. Cooling resulted from the vacuum vaporization of water. The water vapor was then absorbed by the calcium oxide. Such a system has a limited life based on amounts of either water or calcium oxide. The evaporator valve was the only moving part in the cooling system. It sensed evaporator temperature with an isopentane-filled bellows; the movement of the bel-

lows regulated the flow of water through the valve. This valve was assembled and tested as a component prior to full evaporator assembly. Then each evaporator was tested as a unit under simulated downhole loading. After each was committed to an explosive system a final simplified check of valve operation only was performed prior to final nuclear assembly.

Part of the electronic system monitor capability was used for cooling system information. The monitors gave us cooling system performance data in the form of explosive system temperatures so we knew the cooling system was controlling and a measure of the water remaining via a pressure reading (in Rio Blanco, the lifetime indicator). Computer modeling was used in the basic design of the explosive/cooling system, prediction of system performance, and data reduction from the event records.

The electronic system and the arming and firing system were run through a series of combined tests (Compatibility and Certification Tests) to insure the highest probability of correct performance. The compatibility tests verify that all interface requirements are within specified tolerance limits and proper isolation exists before and after marrying of the two systems. The system certification test enabled a complete functional check-out of the married systems at the expected environment (temperature) into loads simulating as best possible those to be encountered at detonation time.

Our plan to use a single coaxial cable for all requisite electrical functions for up to five explosives caused concern over performance and capability requirements of the cable. The initial specifications

for this cable¹⁸⁻²⁰ called for an armored, fully gas-blocked (for explosion containment reasons) coaxial cable capable of proper operation at 400°F and 10000 psi. This was a difficult goal. The environmental temperature requirements were later loosened, but the electrical requirements were tightened from an impedance range of 30 to 50 Ω with 10% tolerance to 50 Ω with 4% tolerance. These changes were required to conform to operations of the timing and control system and to obtain a real cable that could be manufactured and tested in our time and dollar frame. The final cable specification called for an armored, gas-blocked coaxial cable capable of proper operation at 300°F and 10,000 psi having a characteristic impedance of $50 \pm 2 \Omega$.

We had great difficulty in procuring a cable. Out of four potential cable suppliers, only one cable was ever successfully manufactured and it did not provide complete gas-blocking. At one point, a review of the Rio Blanco emplacement hole temperature and stemming information led us to seriously consider using RF-1, HT, and HP cables (rated at 250°F). These possibilities were discarded because of concern for proper termination with the requisite special pressure-tight downhole connectors and concern about the gas-blocking fluid in the RF-1 center conductor. The cable that was finally adopted was manufactured by the Rochester Cable Company* and although it was not fully

gas-blocked it was chosen because it would be terminated inside the pressure-tight wellhead. Sample pieces of this cable and its special connectors were tested as components²¹⁻²³ and then also used for the "System Tests" at full expected temperatures and pressures.

The coaxial, high pressure connectors were of a special LLL-developed "pressure balanced" design. They included features that allowed verification tests, as each was made up, for good seals and mechanical integrity.

The cable was placed on a Pengo-Reel Winder Machine which was to be used during emplacement and could rewind the cable in the event of its having to come back out of the hole. This kept the critical cable in a small area and on a relatively well-protected reel all during the explosive emplacement operation.

A test at expected environmental conditions of an explosive package and cooling system prototype modules was performed using facilities at LLL. This was called the "Full System Test" or "System Test."²⁴⁻²⁶ This test provided performance data and some lifetime projections for the overall system.

The test started on October 30, 1972 and proceeded for 12 days before it was terminated due to problems with the cooling system. The hardware was removed from the test facility, a revised cooling system evaporator and cooling water module were installed, the hardware reassembled and replaced in the test facility, and a new test commenced on December 28, 1972. This test ran for approximately 30 days at the expected downhole temperatures and pressures. The results indicated

*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.

satisfactory performance could be expected on Rio Blanco.

INTEGRATED CONTROL SYSTEM

The LLL-built command, control, and monitor system (Fig. 3)²⁷ was employed on the Rio Blanco Event. It incorporates a command generator located in Command Trailer 95 (Fig. 4) that provides the signal format that is transmitted via microwave to the ICE Box and then over the coaxial cable to the downhole command decoders. Monitor information which originated from each downhole package traveled the same path and was recorded

and/or displayed at the command trailer. The command frequency was common to all explosives, but individual frequencies were assigned to each monitor.

The basic units of the ICS are a command headquarters (control room), a microwave system from the control room to a receiver/transmitter station (RTS) (Fig. 5), a cable link to the remote well-head station (ICE Box) (Fig. 6), and a downhole coaxial cable link to potentially as many as five explosive systems.

This system was previously used on two experiments at the Nevada Test Site. An ICS using separate trigger (fire) cables, was successfully employed on the Flask

Fig. 3. Layout of the integrated control system (ICS) used on Rio Blanco.

Fig. 4. The firing point control point with Trailer 95 (command and control trailer).

Fig. 5. Remote telemetry station used to relay microwave signals from the ICE Box to the command point.

Fig. 6. ICE Box Compound.

Event. On the Miniata Event, the ICS we planned to use on Rio Blanco was successfully tested.

For the Rio Blanco Event, one half of Trailer 95 served as the control room (Fig. 7) and housed command generation systems, monitor display and recording systems, microwave transmitter and receivers, and special control units for operating unique elements like the coded switches in each explosive system. The other half of Trailer 95 was used by the safety program for display and recording of data from RAMS, weather monitors, and geophones (see Fig. 8). Part of the system capability included communication between the various stations via the microwave system. This allowed voice links

between the control room, ICE Box, and RTS during setup and tests.

The ICE Box housed the 400-Hz power supply that provided the power for all downhole systems and all necessary interface equipment and explosive verification instrumentation. A separate monitor system was used to transmit data from the ICE Box internal status monitors back to the CP.

The ICS design incorporated the concepts of complete system checkout at a lab facility, transportation to a test site and subsequent rapid setup, system checkout, verification, and readiness for an event. This ICS system was fully tested at LLL with the actual units used on Rio Blanco both as system components and as

Fig. 7. Trailer 95 — command and control console.

functional subsystems on the full system test. The Miniata system had been done (certified) similarly in Livermore.

FIELD ENGINEERING

The LLL field engineers were responsible for the emplacement²⁸ and stemming of the explosives and specification of all the construction support²⁹ provided by the industrial sponsor. For Rio Blanco, the

industrial sponsor desired to have all construction support delineated in advance in the project definition plan.³⁰⁻³² Thus, it was the field engineers who had a major responsibility for review of the draft, project definition plan. This meant that the emplacement and stemming had to be designed and specified well in advance of the experiment (~1-1/2 year). Because we wanted a simple reentry and the re-entry plan was intimately connected with

Fig. 8. Detectors and control room (Trailer 95) used to monitor radioactivity and weather conditions.

the emplacement and stemming, it was also necessary to have the operation well-thought-out and planned at an early time. Of particular importance was the metallurgical specification of the 7-in. casing on which the explosive was to be lowered.^{33,34} Centralization and the method by which the arming and firing cable would be attached were also important.^{35,36} The detonation verification cable and the stainless steel sampling hose were also to be attached to the 7-in. lowering casing. We engaged in considerable discussion and negotiation with the industrial sponsor over the specification, inspection, and testing of the 7-in. lowering casing, to insure rigid quality control.

A mandrel (simulating the explosive system) was designed and constructed. Its free passage to the bottom of the emplacement well would be one of the conditions for shipping the explosive to the site. Calculations on the elongation of the emplacement pipe^{37,38} were required because of the competing temperature, load, and buoyant effects on total length that would be encountered during emplacement. This kind of refinement in the ultimate explosive position was required because we wanted to place the explosives in well-defined, but narrow geological horizons; the middle sandstone bed was but 8-ft thick. Horizons low in lithium content were chosen to minimize the soil activation by neutrons. The emplacement drill rig specifications^{39,40} were discussed with the industrial sponsor, as were the inspections we would be making of the rig and the inspection and testing we would want "outside experts" to make.

The stemming of the emplacement hole (see Fig. 9) was designed to be consistent

Fig. 9. Downhole emplacement and stemming plan for Rio Blanco explosive. The figure is not to scale and all depths are ground level measurements.

with satisfactory containment⁴¹⁻⁴³ and minimization of the temperature and pressures the cables were required to survive. Working with the other LLL engineers a considerable amount of environmental testing at emplacement temperatures and pressures was done on the electrical cables to not only assure that they would survive and operate properly, but that any gas leakage to the surface would be minimized even though any such gas leakage would be contained within the confines of the high pressure wellhead.

The site layout (Fig. 10) power and communications were developed in cooperation with the industrial sponsor. Shock mitigation systems and tie downs were designed for the ICE Box and power box on the emplacement-well pad, the RTS on the hill above, and the technical program recording and power trailer some 2600 ft southwest of the emplacement well. An instrumentation program⁴⁴ for acceleration and velocity was designed for the wellhead. Figure 11 shows the wellhead in detail. This program will aid future high pressure wellhead evaluations and specifications where the wellhead is to be subjected to detonation produced ground motions. The results would be compared to the predetonation calculational results⁴⁵⁻⁴⁸ made in evaluating the wellhead with special interest in any enhancement of motion on the arms cantilevered off the main wellhead body. A passive pressure transducer was connected at the end of the detonation verification cable to monitor the pressure history of the stemming. One aim was to provide better cable pressure specifications where the cable would be subjected to the stemming material and its pressures.

TECHNICAL MEASUREMENTS

Spall (Oil Shale)

The spall measurements program was fielded to determine the depth and radial extent of any spall resulting from the detonation of the explosives. Both industrial and government people involved with the recovery of kerogen from the oil shale were worried that spall might deleteriously fracture the oil shale at the planned recovery depth. Figure 12 is a geological section of the Rio Blanco site. The concern was that any spall would fracture the shale sufficiently to make the room and pillar mining technique impossible, or require considerable rock bolting, or that mining would be made impossible or significantly more difficult by the influx of added water from either one of the aquifers above or below the shale zone owing to their being further fractured. Calculations had been made previously at the Laboratory on the maximum depth at which spall would occur, and it was concluded that spall would not affect the minability or water transmissibility of the oil shale. Consultants to the prospective oil-shale-recovery industry calculated otherwise, and the result was the spall measurement program.

In order to properly design an instrumentation array, a more refined theoretical prediction of the depth and extent of spall was required.⁴⁹⁻⁵¹ A refined prediction in turn required specific geological and geophysical data rather than data which had been averaged over a wide area. The geologic and geophysical data had already been assembled for the material close to the detonation points as part of the input used to predict chimney size and

Fig. 10. Map showing the site layout (predetonation).

Fig. 11. The wellhead.

Fig. 12. Generalized stratigraphic section through the experiment site.

fracture extent. Most of the specific information required was developed from the geophysical logs which had been run on the emplacement well before casing. Other data was developed from equation-of-state measurements on core samples that had been taken. With the refined predictions available, an instrumentation program was designed^{52,53} which comprised instrumentation at five different ranges from the emplacement well (see Fig. 13). The instrumentation consisted of accelerometers, velocity gages, and CLIPERS. Only the CLIPER would determine the precise depth of spall, as the

accelerometers and velocity gages are discrete instruments that can only be expected to bracket the maximum depth of spall. The velocity and accelerometer gages placed below any spall would thus measure the free field motion, while those buried above any spall would experience the characteristic -1 g in attendant acceleration that is associated with the spall zone. The CLIPER gage would measure the maximum depth of spall only if the cable was actually broken by the spall gap, as the measurement technique depends on continuous electrical length measurement of the cable. Sometimes

Fig. 13. Hole locations, depths, and instruments for the spall measurement program.

the spall gap is not large enough to break the CLIPER cable.

Three instrumentation wells were planned on the emplacement pad ranging in depth from 150 to 900 ft deep. There were two instrument wells planned for a range of 2600 ft at depths of 150 and 500 ft, and one at 7000 ft at a depth of 500 ft. There were to be two surface stations at ranges of 12,000 and 24,000 ft.

The mechanical parts of the instrumentation package were designed at the Laboratory and then sent for outside fabrication. When ready, the gages and electronics were installed in the mechanical housing. The entire instrument package was then checked electrically and mechanically for its pressure integrity. A five conductor cable was required for monitors and control and an RF-1 was used for the signal cable. Both of these cables employed pressure tight connectors previously developed. The adequacy of the connectors was also checked at the time of the environmental testing.

At both ends of the gage there was an explosive operated release section, whose function was to disconnect the instrument packages from the steel cable on which they were lowered after the instruments had been grouted in place. This was to assure that the instrument would measure the motion at the gage horizon and not be influenced by being mechanically connected to other parts of the instrument well through the lowering cable. These release sections were actuated through the five-conductor control cable. We encountered difficulty with these units (see Detonation Time - Emplacement Well Area Activities).

Concurrent with the design, fabrication, assembly, and testing of the instrument

package was the outfitting and dry running of the recording trailer (No. 68). The primary and backup recording was done on two Ampex tape recorders. This trailer also served as an interface with the command and control system receiving commands from the ICE Box over hard wire and feeding monitor information into the command and control system at the ICE Box for display in Trailer 95. Trailer 68 housed requisite power supplies for the various gages and the electronics necessary to interface the output of the gage VCOs with the Ampex tape recorders. Before the trailer left Livermore, its wiring was completed and dry runs were done to ensure proper operation. Trailer 68 arrived at the site in late January, as it was required during the emplacement and cementing of the gages in the instrument holes.

Gas Sampling

The objective of the gas sampling program was to obtain chimney gas samples, from very early time (detonation time + 1 h) up to the beginning of the reentry, for both chemical and radiochemical analysis.⁵⁴ To do this the techniques currently employed at NTS for obtaining cavity gas samples were modified in order to obtain chimney gas samples. Computer calculations were used to predict various properties of the chimney gas such as the chemical composition, radioactivity concentration, and temperature and pressure, all as a function of time. To make this calculation it was necessary to know the chemical and physical properties of the material that would be vaporized and melted in the cavity in addition to the appropriate information about the explosives.

Fig. 14. Surface schematic of gas-sampling and pressure-measurement system.

With the predictions of temperature and pressure available, the mechanical hardware for the program was designed (Fig. 14). The major downhole mechanical component was a 0.5-in.-diam stainless steel tube running from the surface to near the top of the upper explosive assembly⁵⁵ (Fig. 15). A bottom portion of the tube was filled with a wire rope to prevent the tube from being crushed closed by ground shock; the rope had sufficient interstitial space to allow withdrawal of gas samples. Above the wire rope and at depths of 3000 and 4000 ft below ground were rupture diaphragms. These diaphragms could be opened from the surface by applying 1500 psi above any pressure which existed on the downhole (bottom) side of the diaphragm. The burst pressure of the stainless steel would have to be exceeded to rupture the diaphragms backwards from the bottom side.

The surface end of the stainless steel tube terminated at a sampling skid⁵⁶ which contained the necessary radiation and pressure instrumentation, high pressure tubing, lead shielding, and remote controls to fill the sample bottles. A storage tank⁵⁷ into which residual contents of the gas sampling tube from previous samplings could be flushed was designed and fabricated. This flushing assured a fresh chimney gas sample each time. A high pressure, booster pump system⁵⁸ was designed and assembled so the requisite 4000-psi pressure could be achieved to burst the diaphragms should the downhole pressure be at formation pressure. The sampling skid, high pressure skid, storage tanks, sampling tube, and burst diaphragms were all assembled and tested in Livermore.⁵⁹

Because the industrial sponsor was concerned about the handling of the

Fig. 15. Downhole layout of gas-sampling and pressure-measurement system (not to scale).

sampling tube, a simulated emplacement was carried out in Livermore⁶⁰ so they could observe the handling properties of the sampling tube and how it might affect the emplacement operation. The Laboratory required that detailed working procedures be developed for operation of the high pressure sampling equipment. As early-time gas samples could have high levels of radioactivity, an assessment was made of the radiation fields attending the sampling apparatus and of the sample bottles. This analysis resulted in the burying of the sampling line from the wellhead to the sampling skid (some 300 ft from the wellhead) and the storage tank.

The spacing between the top and middle explosive (392 ft) was less than that between the middle and bottom explosive (459 ft). Different rare gases were placed immediately below each explosive so that we could determine whether the fracture systems from the three detonations were interconnected. Since these rare gases did not occur naturally in the formation, we would be able to determine whether the three chimneys were interconnected by determining the presence of the rare-gas tracer in any gas sample. The Laboratory prepared containers of the three rare gases which were each placed inside separate sections of 7-in. emplacement casing; thus, the tracer gas was integrated into the emplacement hardware and did not engender any special handling.

Phenomenology Prediction

The largest single predictive effort made by the Laboratory was of the close-in phenomenology resulting from the detonations.⁴⁹ Computer calculations were

made of such things as cavity diameter, chimney height, and the vertical and radial extent of fractures. The phenomenological predictions were then used in conjunction with a gas-reservoir radial-flow computer code to predict gas production for a 20-year well lifetime. There were also predictions made of chemical composition and the radionuclide concentrations in the chimneys as a function of time after the detonation.

To make these predictions required information about the physical and chemical properties of the material surrounding the detonation points. This information was obtained from the geophysical logs that were run on the emplacement well before casing and from core taken during drilling. The in-situ permeability information needed for the reservoir calculation was inferred from the geophysical logs. The permeability was also measured on core samples in the Laboratory both under ambient and in-situ conditions. Samples of core were tested in the Laboratory to obtain their equation of state and analyzed for their chemical composition and mineralogy.

Miscellaneous Technical Measurements

The Rio Blanco emplacement-hole wellhead was theoretically analyzed for its response to the transient motion resulting from the detonation so that we could assure ourselves that the wellhead would survive the motion in a satisfactory condition and maintain the desired pressure seals. The theoretical analysis was made difficult because of the various side arms cantilevered off the main wellhead structure. There was an instrumentation

program designed to measure the motions so they could be compared with the calculation. The sensors consisted of three accelerometers; two on the main body of the wellhead, and one on a side arm. The data from the accelerometers was recorded in Trailer 68.

To assist in developing the most appropriate specifications for both the emplacement casing and the cable to be used downhole on any future project, we desired to know the pressure/temperature history during and after stemming. For cable designs one must know whether the maximum hydrostatic pressure that results at the time the column of stemming cement is fluid persists or whether the pressure drops when the cement sets to the pre-cementing hydrostatic, or still some other pressure. We wanted to know this bottom hole pressure behavior as a function of time after stemming. To obtain the information an aluminum housing was fabricated that would contain a pressure transducer and attach to the bottom of the 7-in. emplacement casing. The transducer signal was carried back to the surface on the explosive detonation verification cable and recorded in the ICE Box. This measurement was completed and disconnected before the detonation so there was no interference with the detonation verification measurement.

For technical and safety reasons it was desired to know whether or not the three explosives were detonated, and two measurements were prepared to determine this. The primary measurement was based on the fact that ionizing radiation from the explosive which struck the cable would cause a current to flow; thus an electrical pulse would be recorded as each

explosive was detonated. The explosives were detonated at 10- μ s intervals to insure that the signals that resulted from each detonation could pass the next higher explosive undisturbed. An unarmored RF-1 coaxial cable was used for the measurement; it was capable of withstanding the emplacement temperature and pressure and was strapped to the outside of the 7-in. emplacement casing from the extreme bottom to the surface. The data were recorded on film from oscilloscope traces in the ICE Box.

A high-band-pass filter was fabricated and installed on the geophone signal line. This filter, passing only frequencies above 10 Hz, was designed so it would be possible to see an initial individual seismic wave from each explosive detonation which would not be confused by reflections. This data was recorded on tape in Trailer 68.

A technical documentary photography program was designed to photograph the emplacement well pad area with fair resolution using normal framing rates for a period of up to 5 min after detonation time and a time sequence rate for a period of a half-hour after detonation time. The photography enabled observation of the motion of the wellhead and other facilities left on the emplacement well pad that was not possible with instrumentation. Of special interest was the effectiveness of the shock mitigation system used on the ICE Box and attendant power van.

SAFETY PROGRAM

The responsibility for radiological and industrial safety on and about the emplacement well pad area was assigned to the

Laboratory by the AEC. Laboratory programs and procedures for implementing this responsibility were set forth in a number of operational safety procedures⁶¹ (OSPs) pertaining to explosive emplacement, detonation day reentry operations, gas sampling, and drillback. During the months prior to project site mobilization, meetings were conducted with the AEC, CER, and CER's radiological safety contractor, the Eberline Instrument Corporation, to work out details for executing the safety functions described in the OSPs.

Early in 1972 the LLL safety equipment to be used on project Rio Blanco had been checked out, modified as necessary, bench tested by the LLL Hazards Control electronic engineers, and installed in the Hazards Control section of Trailer 95. This equipment consisted of remote area monitors (RAMs), weather instrument recording for any effluent documentation, and geophone recording for chimney collapse data (see Fig. 8). In conjunction with the systems tests of the explosive system and ICS in September, Hazards Control tested their equipment to verify the proper operation of all sensors, microwave links, meters, and recorders. The test was performed under conditions closely approximating field conditions. As a result additional changes were made, primarily to improve the interface compatibility of the RAMs to the ICS transmission mode. Also participating in this test were engineers from Eberline Instrument Corporation. This provided them with an opportunity for familiarization with equipment they would be responsible for installing and maintaining at the Rio Blanco site.

ADMINISTRATIVE

In the evolution of a Flowshare project, an industrial sponsor first submits a feasibility study to the government. If the study is accepted, a Laboratory is assigned to the project and a Project Definition Contract is drawn up. LLL provided technical advice to the AEC where it was needed in the preparation of the Project Definition Contract for project Rio Blanco. After the Project Definition Contract was executed, there followed a phase of preparation of detailed Project Definition Plans³⁰⁻³² for the experiment. For project Rio Blanco the Project Definition Plans contained a description of all work and support the industrial sponsor was to provide. The preparation of this document necessitated close coordination between the Laboratory and the industrial sponsor since the sponsor and the Laboratory would need to function together on-site. These plans covered the technical, engineering, support, security, and safety areas.

Since the Project Definition Plans would ultimately become part of any Project Execution Contract if the experiment went forward, and the industrial sponsor was not committed to providing any support not specified in those plans, it was necessary to give these plans very careful scrutiny to see that the requisite construction and support would be provided for the Laboratory's activities in the field. The Project Definition Plan for Rio Blanco consisted of the following three volumes:

- Summary of the project plan;
- Activities and support up to and including the explosive detonation;

- Post-detonation reentry and production testing.

The Laboratory also gave technical advice to the AEC during their negotiations of the Project Execution Contract.

A further part of the AEC program is to technically review all underground nuclear detonations to insure that the project will not result in any unplanned releases of radiation into the atmosphere; Project Rio Blanco was subjected to such a review. The Laboratory as well as the industrial sponsor were heavily involved in these studies and calculations, the preparation of a containment prospectus,⁶² and its ultimate presentation before the AEC's Nevada Operations Office Containment Evaluation Panel. It was the responsibility of the Panel to rule on the adequacy of plans for the complete containment of the Rio Blanco detonations.⁶³ The unique feature regarding containment in this experiment was that after a successful detonation there would be a chimney volume several thousand feet below the surface which would be filled with high pressure gas (see Fig. 16). This meant that special attention had to be paid to the long-term containment of this high pressure gas until the short-lived radioactivities could decay away. Thus, containment evaluation involved not only the usual things like thorough studies and understanding of the drilling and cementing of the emplacement casing, but other things such as scrutiny of the wellhead fixtures and evaluation of the potential for leakage through the firing cable. Special attention was also given the emplacement hole stemming design, which was unique due to our desire to

have a simple and rapid reentry into the chimney.

One of the largest and most important single efforts was the Laboratory's assistance in the preparation of the environmental statement,⁶⁴⁻⁶⁶ which is now required by the National Environmental Policy Act, under guidelines issued by the Council on Environmental Quality, for all Federal projects potentially having significant impact on the environment. The initial draft of the environmental statement was prepared from information and surveys gathered by the industrial sponsor and his contractors. Further information was taken from various federal and state publications and sources, many county and local publications, and books and articles published on the area. In addition to recording the baseline environmental information about the area, and in view of the Laboratory's past experience in making effects evaluations, we were able to make predictions not only of the environmental consequences of the detonation itself, but also of the consequences of any postshot production testing and related planned release of radioactive effluent to the atmosphere.

After the draft of the environmental statement was forwarded to the AEC, the Laboratory worked with the AEC in the preparation of the Project Rio Blanco Draft Environmental Statement that was subsequently issued. We also prepared responses to the letters of comment that were received in reply to the draft; these comments and responses were incorporated into the Final Environmental Statement that was issued. The considerable delay between the issue of the final statement

Fig. 16. Projected postdetonation well configuration before reentry drilling (not to scale) (wellhead not shown).

and the actual project execution date allowed an addendum to the statement to be issued, and the Laboratory also assisted in the preparation of the information that was contained in this addendum.

A model was developed to evaluate in real time the consequences of an unplanned release of radioactivity to the atmosphere at detonation time, unlikely though it was, and the consequences of the presence of radioactive gas and water during the production testing.⁶⁷⁻⁶⁹

The model resulted from a combined effort of the industrial sponsor and his radiological support contractor, the AEC, and the Laboratory. The model could accommodate all reasonable sources, site and regional meteorology and calculate the consequences to nearby ranches and population centers. The model could then be used during production testing, if necessary, to insure that any radioactive release to the atmosphere would be within the AEC stipulated limits.

In order that the project and its goals would be understood by both the people in the area and their local governmental officials, a number of briefings were held in which Laboratory representatives participated. Governor Love of Colorado appointed a special committee to advise him on the experiment, and Laboratory representatives helped brief this committee. In addition, personnel from the state geologist's office, and the water pollution control board were briefed on the experiment, as were personnel from the state oil and gas conservation commission. There were public informational meetings in the local communities, and official meetings as provided for under the Council on Environmental Quality (CEQ)

guidelines for the preparation of environmental statements were held in order to receive comments on those statements. Briefings were also prepared for the various county commissions and city governments in the areas that could be affected by the experiment.

Security protection for the explosive was required. The arrangements for physical security were worked out between the engineers handling the explosives, the LLL Field Operation representative to the Livermore Operation Director, and the security people at the Nevada Operations Office. The arrangements required that security be established on the ICE Box, at the wellhead where access could be gained to the firing and control cable, and on the explosive delivery van when it was at the emplacement well area. Also a security man was placed outside Trailer 95 at the firing point control point to assist in area control during the time the explosive cable was connected via the wellhead and the ICE Box into the command and control system.

In order to preclude and minimize concerns for the unintentional detonation of nuclear explosives, the AEC holds what are called 0560 (Nuclear Safety) reviews.⁷⁰ The 0560 refers to the AEC manual chapter that specifies these reviews. The reviews cover the explosive assembly, its transportation, its handling once it reaches the emplacement area, and its ultimate functioning. The review has to be held early with respect to the detonation so all tasks can be completed on a timely basis, but late enough that sufficient detailed knowledge about the explosive is available to make a meaningful review.

Fig. 17. Predicted horizontal ground motion accelerations and distribution of dwellings and industrial plants within 14.5 miles of the EW.

Laboratory personnel also assisted the AEC and the industrial sponsor in doing the effects evaluation of the detonation in respect to the ground motion consequences on private, public, and industrial structures. The distribution of these structures is shown in Fig. 17. Our assistance was primarily in the form of critiquing the predictions and plans of the industrial sponsor's subcontractor on ground motion and bracing. In addition to the industrial sponsor's effort in this area, we developed our own ground motion predictions. The Laboratory personnel also assisted the AEC and the industrial sponsor in ascertaining the effect of ground motion on the Tosco/Colony oil shale retort tower. The

owners were concerned that the ground motion might seriously endanger the tower. This tower is located some 29 km south of the detonation point and is some 180 ft high and 20 ft on a side. Because some of the tower footings were on fill, the tower was already leaning, and required additional support in the form of guy wires to the nearby canyon wall. We assisted the AEC in looking at the evaluation of the ground motion at the location, and the industrial sponsor's structural engineers attendant design recommendation for still further bracing of the tower.

An operations plan⁷¹ was prepared which discussed all Laboratory field activities and requirements.

Nevada Test Site Activities

EXPLOSIVE ASSEMBLY

The three Rio Blanco explosives were fully assembled at the USAEC facilities at the Nevada Test Site. Prior to complete nuclear assembly the electronic systems which would go downhole inside an explosive assembly were fully tested with simulated arming and firing components utilizing the "Dry Run Rack"—an equivalent of the electronic systems in the CP trailer, ICE Box, etc. This verified, as late in time as possible, the proper performance of all the downhole command and monitor systems. The

cooling system evaporators also received a late "as possible" checkout for valve functioning only.

The explosives were then assembled one-at-a-time into their final configuration and readied for emplacement with all mechanical joints pressure tested. The explosives were stored at local facilities (NTS) until all three explosives were assembled and work at the Rio Blanco site had progressed to a point of readiness for the explosives. The three explosives were loaded into a special USAEC shipping van and prepared for shipment to the Rio Blanco site.

Detonation Time-Emplacement Well Area Activities

TECHNICAL PROGRAM INSTRUMENTATION

Emplacement of instrumentation⁷² for the Spall Measurements Program was the first major technical activity involving LBL personnel at the Rio Blanco site. This occurred in late January and early February of 1973. The location of the instrument holes is shown in Fig. 18. All the holes were uncased except for the requisite surface casing; this necessitated that the instrumentation be done soon after drilling because of the possibility of losing the hole due to caving if it had to stand open and fluid filled for a prolonged time.

The general sequence of instrumenting the holes consisted of first lowering a 3-1/2-in.-diam, slotted, fiberglass guide pipe to accommodate the cementing tubing. The instrument packages were then lowered alongside the fiberglass pipe on wire rope pendants with the electrical cables being secured to the pendants with Kellem grips. In addition to the discrete instrument packages, several holes also included a CLIPER cable. The instrument package consisted of a top and bottom unit containing an explosive disconnect to mechanically isolate the instrument package from the lowering cable, a center unit containing velocity and accelerometer gages, and the attendant voltage controlled oscillator (VCO) electronics. Once at their planned depth, the instruments were cemented in the hole with medium-matching grout. Figure 19 shows a typical cementing operation. For those holes where the instruments were located below the calculated spall depth, the grout was placed to only just above the top instrument package.

Had the associated signal cables above the top instrument package been grouted all the way to the surface, they would likely have been parted by the spall; this grouting technique precluded that eventuality.

After the grout had hardened, electrical signals were sent to actuate the explosive operated lowering cable disconnect. Several failures were encountered in the operation of the explosive disconnect; however, the failure pattern was such that just two of the gages (in RB-S-01) remained mechanically connected through the lowering cable. In the other cases disconnect failed, the cable was connected either above or below the instrument, thus, just partially providing a potential for invalidating the measurement.

Signal cable was run between the collar of each instrument hole to the recording trailer located adjacent to the instrument hole at 2600 ft southwest of the emplacement well. The two surface stations at 12 000 ft and 23 000 ft were not instrumented until shortly before detonation time and were recorded locally. Figure 20 shows a recording unit at one of the remote surface stations.

INTEGRATED CONTROL SYSTEM

As discussed earlier, the command and control system (ICS) had been developed and tested for use on Rio Blanco and other similar projects and had been shown to provide good electrical communications without extensive surface cables, shorten field occupancy prior to explosive delivery, minimize field manpower and

Fig. 18. Locations of the sensors used in the spill measurements program.

Fig. 19. Spall instrumentation being grouted.

support, and to be compatible with the explosive.

By April 17, 1973 (D-33 days) all major components of the ICS were installed. For Rio Blanco there was no microwave repeater required. The command and control trailer (Fig. 4) and its power van (No. 11) were located at the firing point control point (FPCP) 12 miles east-northeast of the EW and just a short distance from the EPNG compressor station (No. 24). The receiver/transmitter station (RTS) (Fig. 5) was on a hill above the EW area with a line of sight to Trailer 95. The power for the RTS was supplied via cable from the power box at the EW area. The integrated control element (ICE Box) and the power box were positioned about 200 ft northwest of the

EW collar, and shock mounted (Fig. 21) for uninterrupted operation during and after detonation.

The installation of Trailer 95 and Power Van 11 had been delayed until the above date due to administrative procedures attendant to the Bureau of Land Management issuing a Land Use Permit. This issuance was on the critical path and therefore determined the earliest possible detonation day.

One of the prerequisites to explosive delivery was routine satisfactory on-site operation of the ICS. It took 10 working days to achieve this status. The checkout typically included such things as installation and alignment of the microwave antennas for the transmitting of commands, their receipt, and proper interpretation

Fig. 20. Remote surface station used to record spill data.

and action. The command timing and encoding was done in Trailer 95 (Fig. 7). The commands were then transmitted via the microwave link to the RTS. From the RTS the commands were carried on coaxial cable to the ICE Box and from the ICE Box via the armored downhole command and control cable to an explosive package simulator. Dry-run

explosive monitor information was carried in the reverse direction back to Trailer 95 where it was displayed and recorded.

The ICS carried data for the safety program in addition to explosive commands and monitors; the proper operation of the ICS therefore included satisfactory performance of these safety program data

Fig. 21. Shock mounting for the ICE Box.

channels. The safety sensors were located in and about the EW area. The signals were carried on field wire to the ICE Box where they were interfaced with the ICS. Half of Trailer 95 was devoted to the recording and display of the safety data (Fig. 8). This was another novel feature of the ICS concept eliminating the necessity of a second parallel system to accommodate safety data and display.

In addition to verifying the ICE Box readiness as a junction in the command, monitor, and safety data link, the ICE Box checkout included verification of proper operation of the 400-Hz power supply that was the source of the downhole electrical power, and the oscilloscope/camera recording system for the explosive detonation verification measurement.

There were two coaxial electrical cables going downhole to the explosives. One cable, the armored command and control cable, accommodated the commands, monitors, and power for all three explosives. The other cable was used for the explosive detonation verification and a bottom hole stemming pressure measurement. Both cables terminated in the ICE Box via the wellhead (high pressure feed through bulkhead connectors).

The culmination of the checkout of the ICS was a complete electronic systems check (CESC), where all subsystems with an electrical connection to the ICS were put in their detonation-time configuration along with the electrical power, and the entire system was verified to operate compatibly and correctly.

Fig. 22. Geophone (schematic and photo of the emplacement).

with a complete system check and countdown dry run.

SAFETY PROGRAM

Installation of instrumentation for detonation time radiological effluent documentation and personnel protection was established with the emplacement of a remote area monitoring (RAM) system, an air sampling array, and a weather station. Nine RAMS were installed; three at the emplacement well, and six roughly spaced in an arc approximately 300 ft from the EW. The battery powered particulate air samplers, which had an iodine collecting filter media, were started when seismically activated switches were closed by detonation-induced ground motion.

An air sampler was mounted near each RAMS location. The weather sensors which provided local surface wind speed and direction were located within several hundred ft of the EW. The RAMS and weather sensors data were fed into the ICS at the ICE Box and displayed in Trailer 95.

A geophone system (Fig. 22) consisting of three stations located at 1000, 4000, and 7000 ft from the EW was installed to provide information relating to cavity collapse and chimney formation. Seismic surveillance of the area after the detonation was also necessary in determining the appropriate time when reentry parties could safely return to the EW area. Geophone data was also transmitted on the ICS to Trailer 95 for recording and display.

The radiological safety contractor provided engineering support to assist in the emplacement, calibration, and maintenance of instruments used by LLL Hazards Control. This contractor also provided routine dosimetry for all site personnel, radiological monitoring personnel to accompany reentry parties, and technical personnel to man their mobile laboratory located at the Entry Control Center. LLL personnel provided the radiological monitoring for the explosive handling.

ENGINEERING, CONSTRUCTION, AND LOGISTIC SUPPORT

Another prerequisite to explosive delivery was the inspection and acceptance of the industrial sponsor's (CER/CONOCO) engineering, construction, and logistical preparations at the Rio Blanco site. There was a detailed inspection and testing of the drill rig (especially the running gear) that was to be used for explosive emplacement and the running to the depth of the lower explosive (6690 ft) of a dummy explosive package including short lengths of the command and control and verification cables to assure that the total explosive package would pass freely to bottom. There was additional practice by the drill rig crews in picking up the dummy explosive package from the pipe rack and getting it to hang from the hook on the rig's traveling block. There had been previous inspections and tests of the casing on which the explosive would be lowered. Other areas receiving scrutiny were electrical power, the total communications system, and industrial safety.

SECURITY

A small security force was required to provide physical security for the explosives while above ground, and to protect the uphole end of the command and control cable during emplacement and stemming. The same security personnel were used in assuring that personnel were signed-out of the closed area at detonation. The security force arrived 7 to 10 days before the explosive arrived in order to establish the necessary controls and become familiar with the site. As it evolved at the EW area, only the ICE Box required a fence around it to control access; the cable and explosive delivery van were simply roped off and direct surveillance maintained. At the FPCP, Trailer 95 was in a fenced enclosure; however, security was required only when the command and control cable was attached to the system.

EXPLOSIVE EMPLACEMENT

When all preparation of the industrial sponsor, the Laboratory, and the AEC were verified complete, a request was made for the explosives to be shipped from their final assembly point at the Nevada Test Site. This verification was considered an important prerequisite to requesting the explosives, in that it avoided having the explosives and attendant resources on-site until we were actually ready for them. Failing to do this verification on a previous experiment resulted in the explosive and resources being on-site much longer than expected or desired, and caused additional costs to be incurred for the maintenance and protection of the

explosive. Final site acceptance and a satisfactory CESC was achieved on April 28, 1973 (D-19 days), and the explosives arrived at the Rio Blanco site in the early evening of May 1, 1973 (D-16 days).

The transportation of the explosive from the Nevada Test Site to the Rio Blanco site was under the control of the USAEC field office at Albuquerque, New Mexico. They provided the prime mover for the special shipping van, couriers, and a security group to accompany the shipment. LLL provided a four-man team to act as technical advisors to the convoy personnel and to make periodic measurements on these fully assembled explosives⁷³ to insure that they would be in good condition when they arrived at the Rio Blanco site.

The expected overall time in transit was projected at 18 to 20 hours. The convoy followed a fairly direct route from NTS through the states of Nevada, Utah, and into Colorado, but inclement weather (snow) caused an overnight stop in Utah and the explosives arrived one day later than planned.

All three explosives were shipped in a single explosive delivery van, which was positioned so the rear double doors opened onto the northern end of the drill rig catwalk. Another van containing the cooling-system water tanks was positioned just west of the drill rig; the lime tanks had been previously placed on the pipe rack. The water tanks were in a van with environmental control as they had to be kept from freezing as the weather was still cold at that time of year. Both the water and lime tanks had arrived at the EW area in advance of the explosive delivery. The explosives arrived at the site completely ready for emplacement.

After arrival, the engineers gave the explosive an external physical inspection and then connected the armored command and control cable to the top explosive, the two jumper cables between the top and middle, and the middle and bottom explosives, and conducted a complete electrical interrogation of all explosive monitors. The physical inspection and electrical interrogation disclosed that all explosives had arrived in satisfactory condition. If any explosive had been found defective, it would have been returned to the NTS for repairs as there was intentionally no field capability for explosive repair.

Before the first explosive was removed from the delivery van, a length of 7-in. casing, housing a cylinder of rare gas (krypton), had been positioned in the drill rig. This casing would be directly below the first (bottom) explosive so the krypton gas could serve as a tag for later determination of chimney interconnection. Below the casing containing the krypton gas tracer bottle was a short aluminum cover providing protection for a pressure transducer being emplaced to obtain data on the pressure history of the stemming.

Early on the morning of May 2, the first explosive was removed from the explosive delivery van and positioned²⁷ on the rig catwalk using a winch within the van, a sheave, and wire rope (see Fig. 23). While resting in a wooden blockcradle on the catwalk, all joints in the explosive canister were checked for their pressure integrity. The canister was required to pressure isolate the explosive and attendant systems from the pressure to which it would be subjected while being emplaced in the fluid-filled EW and the still higher pressures it would have to sustain at

Fig. 23. Explosive delivery van and the first explosive at the emplacement rig.

stemming. After pressure testing, each joint was pinned to insure its integrity.

The explosive was raised into the drill rig by utilizing a cable attached between the rig traveling gear and one end of the explosive while the other end of the explosive was attached to a cable from a winch truck (Fig. 24). With both the rig and truck working simultaneously, the explo-

sive was first picked straight up to the horizontal, and then gradually maneuvered to a vertical position in a manner that precluded the explosive from ever bumping any part of the drill rig structure.

Once the explosive was in the vertical position and hanging freely from the rig traveling block (Fig. 25), it was attached to the casing containing the gas tracer.

Fig. 24. Explosive being lifted to stand in the emplacement rig.

The assembly was then lowered and fastened at a point where the top of the explosive canister was at a convenient working level above the drill rig floor (Fig. 26). A temporary cable connection was then made between the explosive and the command and control cables. The water canister was removed from its van, picked up, and positioned directly above

the explosive can in much the same manner as the explosive was handled. The water tank was then lowered to a position where the requisite connections (see Fig. 26) for the cooling system could be made up between the top of the explosive can and the bottom of the water tank. This connection entailed the evacuation of the vapor line in the makeup section and the

connection of monitor cables and water supply and pressure transducer tubing. With the ICS operational, a manual valve was opened in the makeup section which allowed the water to flow from the tank into the explosive section; the correct water pressure was then verified by the monitor readout in Trailer 95. The temporary cable was then disconnected and

removed from the rig floor. The makeup joint between the explosive and the water tank was then completed and pressure checked. The total assembly was lowered and fastened so that the top of the water can was at the working level. The first of three water-vapor-absorption lime tanks was then positioned above the water tank, lowered to a point where the vapor

Fig. 25. Explosive hanging in the emplacement rig.

Fig. 26. Explosive being lowered; the top is at the rig floor and the hydraulic tongs, slips, and water can can all be seen.

line connection between the water tank and the lime tank could be made up, and the makeup section evacuated. The joint was then made up and pressure checked between the water tank and the first lime tank. This last sequence was repeated twice more for the other two lime tanks in each total explosive assembly.

While the water tank was being attached and the assembly being lowered below the rig floor in the "cellar," the explosive detonation verification cable was being strapped with steel bands at regular intervals to the completed explosive assembly. At the top of the explosive module, the jumper section of the command and control

Fig. 27. Strapping the verification and command and control cables to the assembly.

cable between the second (middle) and first explosive was attached, and then the cable and connector checked for electrical and pressure integrity. As the lowering continued, both the command and control and detonation verification cables were strapped to the assembly at regular intervals (Fig. 27).

Casing centralizers to keep the 7-in. lowering casing centered in the 10-3/4-in.

hole casing were also installed near each coupling in the explosive assembly, and at regular intervals on the spacer casing between the explosives at coupling locations (Fig. 28).

The spacer casing between explosives was the special, quality-controlled 7-in. casing, with the top and bottom section slotted so as to permit the bore of the casing to fill with fluid as lowering

Fig. 28. Attaching the firing cable; notice the centralizers on the lowering casing.

progressed. The slot allowed for relief of hydrostatic pressure which would have been great enough at the emplacement depth to collapse the casing. The two electrical cables were strapped to this spacer casing at regular intervals.

All casing/coupling joints were made up with hydraulic tongs (see Fig. 26),

with the makeup being monitored by a small on-line computer, to achieve maximum strength and a gas tight joint. After the appropriate amount of spacer casing was used, the casing containing the rare-gas tracer bottle for the middle explosive was attached.

It took about 17 hours to complete the work sequence of taking the first explosive out of the transport van and attaching it to the gas tracer canister for the second explosive. As the work with the explosives was being done only during daylight hours, the second explosive was not removed until the following morning. After the second explosive was attached, it was lowered to a position that permitted connection of the command and control jumper cable to the bottom of the second explosive package. This connection was then pressure checked. The preceding explosive emplacement sequence was then repeated for the second and third (top) explosive. The sequence went faster for the second and third explosives, taking 10 and 8 hours respectively.

Since the explosive cooling system was totally self-contained and would have no outside controls, confirmation of proper cooling system performance and operation⁷⁴ was required before any stemming. To check system performance and operation, and starting after the first explosive system was complete, there were regular pauses in the lowering to allow system connection and utilization of the ICS for monitoring of the explosive system temperature, pressure, and water use rate⁷⁵; all these data were necessary to determine if the cooling system was operating properly.⁷⁶

Beginning at the bottom of the second lime tank in the top (third) explosive assembly, the downhole end of a 1/2-in. o.d. stainless steel gas sampling tube was strapped to the outside of the lime tank in addition to the two cables. Both cables, and the stainless steel tube were on reels adjacent to and outside the rig

substructure feeding through a hole onto a rounded trough of sufficient radius to preclude any damage to the cables and tubing when changing direction from the horizontal to the vertical required for emplacement (Fig. 29). The trough was so positioned that the cables and tube came off tangent to the lowering casing at a level convenient for attaching the steel securing bands at regular intervals along the entire length of the emplacement string.

Above the third lime tank of the top explosive assembly, a slotted piece of casing to be utilized during stemming was put in the string of lowering casing; two float collars (check valves) were installed above the slotted casing. Above the float collars there was 7-in. casing sufficient to lower the explosives to the planned emplacement depth. Centralizers were placed on the casing at regular intervals; the cables and stainless steel tubing were strapped to the casing.

A careful measurement was made on the pipe rack of all the 7-in. casing to be used in the emplacement. This included not only the pipe used between the top explosive assembly and the surface, but also that which was used as spacer between the first, second, and third explosives. In addition to the standard lengths of casing, there were short sections that were to be used to adjust the spacing between the explosives and to give the desired total emplacement depth. Calculations were made of the elongation the pipe would undergo due to the increasing temperature with depth in the emplacement hole, the stretch due to the weight, and the buoyant effect resulting from some of the emplacement casing above the top explosive not being filled with water. Careful attention to

Fig. 29. Cable winding machine with cables.

these second order length effects was necessary as it was required that all three explosives be in a sandstone layer and the middle sandstone layer was quite thin (approximately 8 ft). The final emplacement depths⁷⁷ measured from the ground surface were: the bottom explosive, 6689.5 ft; the middle explosive, 6229.7 ft; and the top explosive, 5838.5 ft (see Figs. 30 and 31).

Perhaps one of the most unique things about this project as compared to the Laboratory's experiences on previous off-site Plowshare and Detection program experiments was the interest that the local residents exhibited; they came by the tens to observe the emplacement activities.

The public information people had made arrangements for press and TV coverage of the emplacement, but the thing most pleasing was having the local ranchers and their families visit the site. There were also classes of students from the local Rock School, from Meeker High School, and Mesa College in Grand Junction. While the average number of such observers at a time might not have been more than ten, there were times when there were a hundred. We made an effort to encourage their interest and accommodate them; the only restriction was that dictated by normal industrial safety for activities in and about the drill rig and security (i.e. no access to the

Fig. 30. Downhole assembly plan of the complete three-explosive system as built. (See Appendix A for the complete assembly.)

Fig. 31. Downhole assembly plan—the bottom explosive package as built. (See Appendix A for the complete assembly.)

ICE Box, explosive delivery van, and cable reel enclosure).

Once the third explosive had been put in the emplacement string, the lowering continued on a 24-hour basis with each coupling still being made up with the hydraulic tongs. The lowering was completed when a "landing donut" (Fig. 32) attached to a section of 7-in. casing was lowered to seat on the casing hanger inside the Y-Spool at the top of the hole. The two cable exited through one arm of the Y-Spool, by means of pressure-tight feed-through connectors. The gas-sampling tube exited through the opposite arm of the Y-Spool with pressure-tight fittings including an in-line valve on the sampling line (see Fig. 33). After all joints between the lowering casing, Y-Spool, and emplacement hole casing connectors and fittings had been assembled, they were checked for pressure integrity to the working pressure rating of the wellhead hardware (~3000 psi).

STEMMING

Once the explosives were emplaced and the wellhead pressure checked, the stemming plan was to lower tubing down the bore of the 7-in. lowering casing and latch it into the float collar placed above the third explosive assembly. Cement was then pumped down the tubing through the float collars and out into the annular space between the 10-3/4-in. emplacement hole casing and the 7-in. lowering casing. Figure 34 shows an overall view of this cementing. The annular space was about 1-1/2 in. thick. The entire annular space from the perforated casing (~5641 ft below ground) to the surface

was completely filled with cement. The armored command and control cable, the detonation verification cable and the sampling tube were thus cemented in this annulus. Some cement probably got below the level of the perforated casing due to the turbulence at the interface between fluid in the hole and the cement; however, it is unlikely this mixing was more than a few feet deep. The explosives were in the lower portion of the hole where there was only water in the annular space between the explosives and the emplacement hole casing. Cement returns were observed at the surface so the entire annular space from the slotted casing to the surface was filled.

The maximum hydraulic pressure on the cables in the hole occurred at the time the cementing was nearing completion. The cables at the bottom of the hole had to sustain the pressure of about 1000 ft of water, 5600 ft of fluid cement, and the pulsating pump pressure. This combined pressure determined the specification for the cables at the bottom hole temperature of about 215°F. The maximum temperature the cables had to withstand occurred during the cement curing process, as the curing of cement is exothermal. The cables just above the top explosive assembly experienced the maximum temperature (~250°F) excursion when the exotherm from the concrete curing combined with the downhole temperature.

The pressure transducer below the first explosive measured the stemming pressure history.⁷⁸ The maximum hydrostatic pressure (5400 psi) was achieved when the cement was still fluid. After the cement hardened, the pressure was decreasing toward the

Fig. 32. Landing the emplacement string.

initial hydrostatic pressure in the hole (3000 psi).

The next thing to be stemmed was the bore of the 7-in. lowering casing. The plan was to leave the bottom 500 ft of the 7-in. casing filled with fluid, have a cement plug above that sufficient for containment (~2400 ft), and leave the remainder of the 7-in. bore to the surface filled

with fluid. The idea behind this plan was that the chimney formed by the detonation would be high enough that the emplacement hardware above the top explosive would break off in the water filled section of the 7-in. casing with the water then draining into the chimney. Since we felt that the water-filled section would extend well above the level where any casing might

Fig. 33. Wellhead and cellar set up for detonation.

get damaged or pinched by the detonation, on reentry we would not have to drill through bent or pinched casing and would have only (and hopefully easily) to drill out the containment plug to have access to the chimney (Fig. 16). We believed that even where there was damage in the water-filled section there still would be a sufficient opening for the desired gas flow.

To execute the stemming plan and avoid having the 500 ft of water immediately

above the third explosive displaced by the denser cement plug, material was added to the water that caused it to gel. The cement was placed when the gelled water was sufficiently "stiff" and would not turn over. After ~10 days the water was supposed to lose its gelled property (we found on reentry that this did not occur and the water had remained gelled).

The cement plug placed in the bore of the 7-in. casing was 2400 ft high and it was placed in two stages of 1200 ft

each. Cement was first pumped down the tubing such that the bottom 1200 ft was placed; then the tubing was raised 1200 ft and the remainder cemented. The total

cementing operation (annulus and bore) took several days as is shown on the "as-built" schedule (Fig. 35). The material balance between cement placed and

Fig. 34. Cement stemming operations.

Rio Blanco "as built" field schedule

	April													May																									
	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Received land use permits (1)				1																																			
Complete electronic system check (2)																2																							
Stem farm creek government no.1 well(3)																	3																						
Explosive arrive? (4)																			4																				
1st explosive downhole assembly (5)																						5																	
2nd explosive downhole assembly (6)																							6																
3rd explosive downhole assembly (7)																									7														
Downhole operation (8)																										8													
Landing operation (9)																											9												
Cooling system verification (10)																												10											
Stemming operation (11)																														11									
Rig demobilization (12)																																12							
Detonation day (13)																																					13		

Fig. 35. Actual field activities schedule.

the calculated volumes required agreed quite well as would be expected when cementing between two right circular cylinders or filling a cylinder.⁷⁹ As with the explosive emplacement, there was considerable interest in the stemming on the part of the local residents and many came to watch.

An important administrative and technical point should be made about the stemming. The emplacement hole stemming was an irrevocable commitment of the explosives. Based on our knowledge of drilling techniques, there would have been no way to recover the explosives before the cooling system was exhausted and the explosives were rendered nonoperational from exposure to the elevated temperature.

When the stemming of the emplacement hole was completed, there was no longer any requirement for the drill rig and it was removed. The drill rig removal activity took about two days. While it is not particularly germane to a nuclear operation, other than for scheduling purposes, we could not help but be mesmerized and fascinated by the skill with which the rig crew and the oil field hauling company employees skillfully and rapidly disassembled and trucked away these very large pieces of machinery.

When access could be gained to the immediate wellhead and cellar, we made another check of the wellhead for pressure integrity.

TECHNICAL MEASUREMENTS

Concomitant with the emplacement and stemming of the explosives were the final preparations of the technical measurements program; the principal activities were:

recording for the spall measurements program, installing testing of the gas sampling system, and the installation of motion sensors on the wellhead.

Spall

As already discussed, the instruments for the spall measurements program had been installed. In the interim, before the final preparations for the detonation started, the surface cable between the instrument hole collars and the recording location had been laid. Trailer 68 had remained on-site since the time of instrumentation. While its proper operation was not requisite for explosive delivery, it had to be sufficiently ready so it could meaningfully participate on the CESC. In addition to recording the spall measurements program data, Trailer 68 was used to record wellhead acceleration, dynamic water levels measurements, and geophone sounds. Figure 36 shows the tiedown and inside of Trailer 68.

The recording trailer and its attendant power trailer had been shock mounted to prevent damage from ground motion at detonation time. All recording was on tape recorders, primarily on two Ampex tape recorders. Command signals for start and a manual stop of the tape recorders came over hard wire from the ICE Box and originated in the command and control Trailer 95 at the FPCF. Monitors to indicate the status in the recording trailer were sent back and displayed in Trailer 95. The predetonation activities were concerned primarily with getting the trailer to operate and record remotely as it would be unattended at detonation time, adjusting signal levels for the proper recording, and peaking up

Fig. 36. Trailer 68, the control center for the spall measurements program.

the performance of all ancillary equipment. The two spall measurement sensors at 12 000 and 23 000 ft northeast of the EW had their data recorded locally in a self-contained station adjacent to the sensor (see Fig. 19). These stations consisted of battery-powered tape recorders suspended on Bungy cords to all eight corners of 3-ft padded boxes. These recorders had a 30-min running time and were started by mechanical timers set by the recording engineers immediately prior to the arming party completing their EW checks and exiting the closed EW area.

Gas Sampling

The gas sampling tube was strapped to the outside of the 7-in. lowering casing along with the two electrical cables.⁸⁰ Its handling properties were essentially the same as that of the electrical cables. To prevent undue abrasion owing to bowing in passing over the couplings in the 7-in. casing, a special tool was used which formed upsets into the gas sampling line so it could accommodate and remain tight against the casing at the coupling. The sampling tube was a 1/2-in. o.d. stainless steel tube with a 0.049-in. wall. The bottom 1300 ft (5751 to 4451 ft deep) contained a steel cable which had sufficient interstitial space such that a gas sample could be withdrawn even though the tube might be completely collapsed around the cable. At 3000 and 4000 ft below the ground surface were two rupture diaphragms incorporated in the sample line. From the chimney side it took 16 000 psi to burst these diaphragms. From the surface side it took a 1500 psi pressure differential above any pressure being

exerted from the chimney side to break the diaphragms.

The tube terminated near the bottom of the wellhead and a flex hose made the tube connection to a wellhead flange on the Y-spool. This flange provided for the transition of the sampling hose to outside the Y-spool; it also included a manual valve. There were pressure transducers built into the flange which permitted measurement of the pressure in the annulus and in the sampling tube. The readout for these transducers was at the sampling skid. From the cellar location where the sampling tube exited the wellhead, a section of stainless steel tube led to the sampling skid about 300 ft northwest. This tube was buried in a trench to provide the requisite shielding, as the earlier (D-Day to D+1 week) gas samples were expected to be sufficiently radioactive that some shielding would be required. Burying the tube was the best answer and it also prevented it from being damaged during the emplacement activities.

There was a possibility of condensate freeze-out and plugging in the sampling tube in the area of the cellar where the sampling tube was not otherwise covered. We dealt with this problem by placing electrical heaters on the wall of the cellar and covering the cellar with an insulated blanket. The buried tube could also be heated.

The sampling line terminated at the sampling skid where all the requisite instrumentation and plumbing for the sampling and the sample bottles in their shielding pigs were located (Fig. 37). In the immediate area there was a truck-trailer mounted bank of nitrogen cylinders, a compressed air driven pressure booster

Fig. 37. Overview of the gas-sampling compound.

pump, and very high pressure nitrogen bottles (Fig. 38); These were necessary to burst the diaphragms and allow sampling after detonation. A bank of storage bottles was buried nearby in order to provide a reservoir into which the sampling line could be purged. Thus, any gas samples collected would be fresh gas from the area of the chimney.

High pressure tests were made of the surface portion of the system because of the possibility of needing 5000 to 6000 psi to burst the diaphragms. This high pressure testing required, for reasons of safety,⁸¹ that the area be clear of personnel and that it be done after most emplace-

ment operations and EW area cleanup had been completed. It was decided early there would be no remote capability for operating the sampling system from the FPCP; thus sampling could only be done after the EW area had been reentered after the detonation.

Wellhead Dynamic-Motion Measurements

We wished to measure the motion of the wellhead at detonation time so that it could be correlated with the motions that were measured in the ground nearby and also to assist in developing suitable criteria for any future wellheads. Three

Fig. 38. Gas-sampling system—sampling skid, booster pump, and high pressure nitrogen supply.

accelerometer gages were mounted on the wellhead; two on the main wellhead body, and one on an arm of the Y-spool. The latter was used to determine if there was any amplification due to being at the end of an equivalent lever arm of the wellhead assembly. The gages on the wellhead were installed after all the wellhead testing had been completed subsequent to the emplacement and stemming operation. The data from the three accelerometers was sent over hard wire and recorded in Trailer 68.

Documentary Photography

A fixed photo station (Fig. 39) was located around 300 ft north and about 100 ft above the EW collar to document the ground motion effect on equipment

and structures. The station incorporated two motion picture cameras; one ran at the normal framing rate of 24 frames/s, while the other was a time-lapse camera and had a framing rate of four frames/s. The first camera was programmed to start at -15 s in the countdown and run till +11 min; the second could run for about an hour and was started at -30 s. The field of view for the two cameras was different, but both covered the EW pad environs. Both cameras got their start commands via the ICS over hard wire coming from the ICE Box. The sequence camera could be stopped and started from the command and control trailer if it was desired.

There was a hand-held motion picture camera operated from a helicopter circling

the emplacement well at detonation time. The color film from this camera, besides providing the technical information desired, was also loaned to the press so that it could be duplicated and shown on TV as part of the news coverage for the event.

Non-LLL Technical Programs

Other organizations also fielded Rio Blanco technical programs. The field

installation of the instrumentation for these other programs occurred for the most part during emplacement and stemming of the explosives. While the Laboratory was not directly involved in the field installation of these experiments, there were varying degrees of coordination and participation. For example we attempted to assure that there would be no interference between the ICS microwave

Fig. 39. Fixed photo station for documentary photography.

and UHF transmission being utilized by one of the programs. Their readiness, considering the investment in time and equipment to make the measurement, was a consideration in determining a detonation day.

Although the programs will not be discussed in any detail they will be mentioned here for the sake of completeness.

- Sandia Laboratories, Albuquerque, New Mexico — measurement of the dynamic pore pressure in the Fawn Creek Valley alluvium while also making some attendant ground motion measurements.
- The USGS Hydrology Branch, Denver, Colorado — dynamic water level measurements in the several hydrologic investigation wells around the EW area. The Laboratory provided detonation time recording for this program.
- USGS National Center for Earthquake Research, Menlo Park, California — location of after shock hypocenters.
- USGS and CER Geonuclear — jointly fielded a program in strong motion documentation.
- El Paso Natural Gas Company — instrumented for the dynamic responses of nearby engineered and unengineered bridges and in another measurement for any permanent earth strain that developed.
- Kenneth Medearis & Associates, funded by the National Science Foundation — measurements to enable correlation of the structural response and the input ground motion resulting from the detonation.
- John A. Blume and AEC-NV — observations on any responses at

the earth filled dams at Rifle Gap and Harvey Gap Reservoirs.

- Colorado State University, funded by CER — pre- and post-detonation radioecology surveys of the area around the EW.

ADMINISTRATIVE

On D-3 days, a complete rehearsal of D-Day activities took place. As a general rule, most of the activities were rehearsed on a simulated basis by a single representative rather than by complete reentry teams and actual activity. The valuable lessons learned by this rehearsal enabled a smooth D-Day reentry for the 22 teams totaling more than 50 persons and representing approximately 11 different organizations.

The AEC delegated to the Livermore Operations Director (LOD) the technical, radiological, and criticality safety responsibility for the area around the EW and along the approximate 6.0 miles of Fawn Creek access road leading to the EW from the Black Sulphur Creek Road. This area was controlled before nightfall on D-1 day, and a record was kept of all persons subsequently entering or departing the designated area. At H-3 hours on D-Day, the delegated area was cleared of all personnel except those required to maintain security controls at the ICE Box, complete setup of spall measurement recording equipment, and conduct the final checkout and setup at the ICE Box and RT for detonation. From this time through detonation, the area was maintained under visual surveillance from helicopters to assure no unauthorized entry. By H-1 hour, the area was completely clear of all personnel,

and the final procedures for detonation commenced in Trailer 95 at H-15 minutes.

The AEC Project Director (APD) convened an Advisory Panel meeting on D-5 days at the Grand Junction Control Point for the first formal readiness briefing by representatives of each participating organization. The Advisory Panel was chaired by Dr. James E. Carothers, LLL Scientific Advisor to the APD. This first meeting preceded the rehearsal session referred to earlier. A second meeting was held in the late afternoon of D-1 day at which time the final decision was made to go ahead with the detonation on May 17, 1973. On D-Day, the Advisory Panel was convened in the APD control trailer adjacent to Trailer 95 at the FPCP. The AEC Project Director had been delegated the authority by the AEC for detonation of the Rio Blanco explosives. Several hours before the planned detonation time he in turn gave permission to the Laboratory Operations Director to detonate the explosives. The engineers at the EW were then permitted to connect the downhole run of the command and control cable at the ICE Box interface for the last time and begin to make other final checks of the command and controls system. When checks were completed, the engineers left the EW area and proceeded to the FPCP for more checks of the command and control system in Trailer 95. After these checks had been completed, the coded switch contained in each one of the explosives packages was closed. The coded switch required a particular set of signals to close and thereby provided a great measure of the nuclear safety for it was impossible to gain electrical

access to any of the firing circuitry until this switch was closed.

At an appropriate time after closing the coded switch, the countdown sequencer which automatically sends all the commands at the appropriate time was started. All monitors from the three explosives and recording stations gave the proper readings and the countdown proceeded without incident. After the detonation, the safety program data display in the opposite end of Trailer 95 was observed. Everything here was also normal and it was clear that if the microwave link alignment had been disturbed by the ground motion it had not been sufficiently disturbed to degrade reception of the signal. The RAMS units never showed a radiation intensity above their internal check source. The meteorological data from both sensors on wind speed and direction were routinely being recorded. The geophones, which sensed the ground motion attendant to the chimneying process, were showing the expected ground motion.

The Entry Control Center (ECC) (Fig. 40) was the staging point for the initial EW area reentry operations. Figure 41 shows the staging of the reentry party. The ECC was located about 6 miles northeast of the EW and generally situated at the confluence of Black Sulphur Creek and Fawn Creek. When the geophones indicated the ground motion had subsided at about H+30 min, permission was received to move the data recovery teams from the ECC to a location closer to the emplacement well.⁸² This preliminary move was engendered by the desire to reduce the time required to ultimately get the emplacement well reentry activities

Fig. 40. Entry-control center (ECC).

started. It was especially important to start the gas sampling activity because of the prospect of seeing very short-lived gaseous isotopes. Because the geophones indicated continued ground motion, the reentry teams were held 1-1/2 miles from the emplacement well. It was almost 2 hours after the detonation before reentry teams reached the EW area.

Of the 22 teams, the first four were two initial radiological survey teams and the structural survey and EW inspection

teams. It had been planned that of the first four teams, only the first would move directly to EW from ECC for the initial radiological survey; the other three teams were to remain at the 1.0 mile marker until advised. Unfortunately, and as mentioned above, all teams were held further back and delayed from reaching the EW as planned. When the initial radiological survey teams reported the EW area safe to reenter, the remaining teams were dispatched periodically. The

Fig. 41. Reentry party staging at the ECC.

remaining reentry teams were constituted by agencies having a primary data recovery mission, plus support and advisory personnel. Data recovery missions included gas sampling, fixed photo, ICE Box film, spall and pore pressure measurements, shock-induced crack photography, aftershock recording, radiological surveys by the Colorado Department of Health, wildlife surveys by the Colorado Division of Wildlife, and fault monitoring resurveys.

At detonation time, ~350 members of the public and press were at an observer point in the vicinity of the FPCP. Upon conclusion of the technical program data recovery and after the radiological safety contractor established control of the EW area, those observers who desired were escorted to the EW for final briefings and interviews. During this time at the EW, the observers were initially allowed to step directly to the

edge of the emplacement well cellar for photographs and interviews and were asked to move back only at such time as high pressure operations began for the gas sampling system. The observers remained in the area for approximately 1 hour then departed on assigned buses.

Security services for protection of classified materials were provided by a contract security force administered by the Nevada Operations Office of the USAEC. Guard control service for classified interests became operational with explosive arrival on May 1, 1973, and terminated all activities on May 19, 1973. The classified areas under continuous control consisted of the explosive delivery van, the explosives themselves, the command and control cable reel and the ICE Box compound. The explosives were electrically interrogated at regular intervals to assess their condition. During

each of these interrogations the command and control Trailer 95 was also placed under security controls. Commencing with the final dry run on D-1, Trailer 95 was continuously controlled through detonation time. A minimal amount of attendant classified work papers and drawings were maintained at the EW area. These were in the custody of the security force. A small amount of classified film was generated at detonation time in the ICE Box. After reentering the EW area post-detonation, this film and all other classified documents were returned to the Laboratory.

The Laboratory provided assistance to the Project Rio Blanco Public Affairs Program by assigning one person to help in the Joint Office of Information in Grand Junction for a period of approximately three weeks, and to attend public meetings to describe the Laboratory's part in the Rio Blanco program. In addition, other Laboratory personnel made themselves available periodically to the news media.

LOGISTIC SUPPORT

CER provided for local surface transportation of personnel and materials. The vehicles for personnel transportation were contracted from a local car rental agency. Special use vehicles, vehicles for personnel on site for only a short time, and all commercial air and long-haul trucking between the Laboratory and the site were provided for by the Laboratory.

Radio communication equipment, both fixed and mobile, was provided in the

general locality of the Project. The industrial sponsor installed and maintained the equipment. Though there were a large number of mobile radios on loan from the Government, the sponsor provided the balance of the equipment. Telephone communication was provided by CER. Although the Project site was situated some 50 miles from Grand Junction, the telephone system was connected to the Grand Junction exchange by virtue of a microwave system with repeater sites. All organizations at the EW area shared two radio nets at the FPCP. The Grand Junction Control Point had four telephone lines, of which one was assigned to the Laboratory.

Many project personnel lodged in the nearby communities of Rifle and Glenwood Springs, Colorado, where there were sufficient living accommodations. The industrial participant provided general office space at both the EW area and the Grand Junction Control Point.

Clerical support was not available at the EW area and was provided at the FPCP only by special arrangement. Paper work generated at the EW was taken to the Grand Junction Control Point for final preparation and copying. This situation did not handicap the technical effort but an inordinate amount of time was spent at the EW in answering telephones and finding the persons being requested.

All participating programs had assigned an operations coordinator for their respective organizations. Administrative support and interfacing for overlapping activities were handled through these coordinators.

Programmed Delay

EMPLACEMENT-WELL AREA ACTIVITIES

It was planned to delay the reentry drilling into the chimney for a minimum of three months following the detonation to allow the short-lived radioactivities to decay so they would not be a potential problem to the reentry drilling operations. The isotope of principal concern was Iodine-131. Because of the unavailability of drill rigs on the desired schedule, the reentry drilling did not start until late in September; over 4 months after the detonation.

It was planned to follow the history of radioactive composition of the chimney gas through samples taken with the gas sampling system. However, the gas sampling system did not function as expected, and it was not possible to determine if earlier drilling would have been possible. Laboratory personnel made numerous but unsuccessful attempts to get the sampling tube to function.⁸³⁻⁸⁵

During the delay period the radiological safety equipment and laboratory trailer vans which had been at the Entry Control Center (ECC) for the reentry were moved to the emplacement-well pad area and were manned on a routine basis during the day shift. There was no plan to exclude any visitors from the site during the delay period and, in fact, many did come. The radiological safety contractor's presence then permitted not only a capability for routine radiological surveillance of the EW area and the nearby Fawn Creek Well, but also provided for a modicum of physical security. Construction by the industrial sponsor in preparation for the

reentry drilling started about a month in advance of the actual arrival of the drill rig.

LIVERMORE ACTIVITIES

The Laboratory activities during the programmed delay period were primarily concerned with data reduction^{75, 78, 86-89} of the information gathered at detonation time, refining plans for the reentry drilling in conjunction with the industrial sponsor and his radiological safety contractor, demobilizing and returning Laboratory equipment, and activity in support of the remedial action to get the gas sampling system to function properly. Personnel involved in the technical measurements made very preliminary data reduction and interpretation available that was included in the AEC Project Director's D+30 Day Report.⁹⁰ This information was also verbally reported at a briefing meeting in Grand Junction that coincided with the issuance of the Project Director's report.

SAFETY ACTIVITIES

Trips to the site during the attempt to remedy the gas sampling system provided the LLL Hazards Control personnel an opportunity to monitor the radiological coverage being provided.

Hazards Control and Radiochemistry personnel assisted the radiological safety contractor during the programmed delay period with the calibration of their on-line radiological monitoring system to be used for documentation of any radioactive

effluent (tritium and krypton-85*) encountered during the reentry drilling and subsequent production testing.

*The reader is cautioned that krypton-85 is a radioactive gaseous fission product, and to differentiate between it and the rare gas tracer krypton emplaced below the first (bottom) explosive for the chimney interconnection determination.

In conjunction with the radiological safety contractor and AEC radiological operations people, Hazards Control personnel developed procedures⁹¹ that would be followed for the on-site radiological and safety program during the reentry drilling and production testing period.

Chimney Reentry

REENTRY DRILLING

Site preparations for the reentry drilling started in mid-August, and the drill rig was moved on location September 10, 1973. Preceding the arrival of the drill rig, Laboratory engineers inspected and witnessed the testing of the blow-out preventor (Figs. 42 and 43) that would be utilized for the reentry drilling. When the drill rig and all the ancillary equipment was completely assembled, there was a test to verify the pressure integrity of those joints that were made up in the field. The test pressure was about 3000 psi.

After the erection of the drill rig, the radiological monitoring and control equipment was installed. There were two systems fielded for the detection and quantification of krypton and tritium in the product gas. These systems were cross calibrated against standards supplied by both the Laboratory and the Environmental Protection Agency. A sampling port was provided on both the high and low pressure side of the Drilling Well Control (DWC) unit (Fig. 44) so that if it proved necessary to utilize the DWC any radioactive effluent in the separated gas stream going to the flare stack could be documented. Explo-

sive gas detectors were installed on the rig and over the mud-system tanks.

All equipment requisite to drilling was installed and checked such that drilling actually commenced on September 23, 1973. The drill rig layout is shown in Figs. 45 and 46. A Dyna-drill fitted with a 6-1/8-in.-diam flat bottom mill was used to drill out the 2400-ft cement containment plug inside the 7-in. casing. The actual drilling started when the top of the cement plug was tagged at 2775 ft below ground level. The drilling circulating medium first used was water, but at 4700 ft below ground a change was made to mud. At 5172 ft below ground, on September 27, the drill broke through the bottom of the cement plug.

Drilling out the plug had been quite routine. There had been no radioactivity detected around the rig or in the circulating medium, nor had there been any explosive gas mixtures. When the drill broke through, it was expected there would be communication with the chimney as the stemming plan incorporated a water-filled length of casing from the plug bottom to where the chimney top was expected (see Stemming). The stemming plan called for the water to be temporarily gelled, and after about 10 days the gell was to break down and the mixture return to a

Fig. 42. Blowout preventor snubbing stack.

Fig. 43. Photograph of the blowout preventor.

fluid. On drilling through the cement plug, it was found that this had not happened and the mixture had remained gelled. Further, there was no loss of any of the gelled water mixture and there was complete drilling fluid circulation indicating that either the emplacement hardware had not broken off into the chimney or the casing was completely collapsed making it impossible for the gelled water to drain out.

Considering the consistency of the gelled water mixture, it is unlikely that it would have drained had the casing been open to the chimney. As the drill was lowered through the gelled-water-filled section of the casing, the mixture clogged the mud circulating system. The drill was lowered 157 ft below the bottom of the

Fig. 44. Drilling well control unit (DWC), used to remove gas from the drilling mud.

Fig. 45. Schematic drawing of drill rig layout for reentry drilling (not to scale).

Fig. 46. Overview of the layout for reentry drilling.

cement plug to the 5329-ft level where it took weight indicating collapsed casing at that level. For the next several days, progress was slow because the casing had to be milled in several tight spots; the interval between tight spots though was not damaged. On a couple of the tight spots, the drilling returns indicated that the mill was outside the 7-in. casing as we were finding pieces of copper from the command and control cable. On one of these there was evidence the mill was outside both casings as shale particles were found in the returns. A total depth of 5534 ft was finally achieved. After nearly getting the milling tool stuck in the hole, it was decided to abandon this reentry plan and to follow an alternative plan of a side-track hole outside the casing in the formation

to the chimney top. Up to this time there had been no loss of drilling fluid circulation, no radioactivity, and no explosive gases.

A whipstock tool was set at 5300 ft to enable the side track. After milling through the casing, a hole was drilled to a total depth of 5684 ft below ground level [155 ft above the third (top) explosive] on October 11. There was some circulation loss at 5575 ft and all circulation was lost at 5592 ft below ground level. There were no problems with either radioactivity or explosive gases. A production packer and screened joint (Fig. 47) were set in the 7-in. casing just above the point of the side track and 2-7/8-in. instrument tubing was lowered to just above the packer/screen joint. During this time

Fig. 47. Schematic drawing of the packer assembly and screened joint that serve as a downhole valve (not to scale).

the hole was filled with mud to keep the well "killed" to avoid having high pressure gas reach the surface. The plugs in the tubing and in the packer were removed and an attempt was made to displace the mud in the hole through the screen joint into the chimney by applying nitrogen pressure from the surface. This displacement was only partially successful; while waiting overnight for the remaining mud to drain in the chimney, pressure did rise inside the 7-in. casing. The pressure rise was so slow however, it was concluded that a satisfactory connection to the chimney system had not yet been achieved. Since some bridging and fillup had occurred during drilling in the open hole section outside the 7-in. casing, it was presumed that this had reoccurred and was preventing chimney gas from entering the 7-in. casing. It was decided to bleed down the pressure in the 7-in. casing, drill the hole deeper, and line the open hole portion with casing. During the bleed down, gas samples were taken and the preliminary chemical and radiochemical analyses of the gas were reported at the ANS 1973 Winter Meeting held in San Francisco,⁹² November 11-17, 1973.

The tubing, packer, and screen joint were removed. The screened joint was found clogged with shale. The hole was drilled to a new total depth of 5723 ft below ground level on October 19 and a 5-in. extreme line casing run in the hole to a total depth of 5712 ft with the top of the 5-in. casing inside the 7-in. casing at 5202 ft (see Fig. 48). Mud was again being pumped into the hole continuously to keep the well "killed" after reaching total depth and during the placement of the 5-in casing. Instrument tubing was

then run to 5200 ft and a perforating gun lowered on a wire line through the 2-7/8-in. tubing was used to perforate the liner casing in 150 different places between 5605 and 5705 ft. The perforating was done on October 22 and 24.

Tritium was detected in the mud system during the second drilling pass through the open hole section below the side track. Circulation had been regained for a while and tritiated water became incorporated into the mud. Field measurements gave a maximum concentration of HTO in the water separated from the mud as 80 pCi/cm³. The contaminated mud was ultimately pumped back into the chimney. After the 5-in. casing was perforated, gas pressure began to build at the surface. The two on-site radiological monitoring systems both indicated the presence of radioactivity in the gas. The field measurements on a dry gas sample showed that there were between 400 and 500 pCi/cm³ of krypton-85 and about 26 pCi/cm³ of tritium, primarily as CH₃T.

A short duration production flare test through the DWC was run on October 25 to confirm communication with the chimney. The average flow rate was just under 6 000 000 standard ft³ per day, the total chimney gas released was about 400 000 standard ft³, and the surface pressure when the test started was about 1525 psig. Field measurements of the radioactivity content of the gas when dried were 413 to 439 pCi/cm³ of krypton-85, about 25 pCi/cm³ of tritium, and xenon-131m was detected. There were about 47 barrels (42 gallons/barrel) of water separated from the gas stream during the test with a concentration of HTO ranging from 9000 to 11 000 pCi/cm³. The tritiated

Fig. 48. Reentry well.

water is being stored until it can be disposed of in the Fawn Creek Government No. 1 well during the long production test.

SAFETY

Simultaneous with the rig-up operations the radiological safety contractor installed instrumentation which permitted the detection, analysis, and quantification of radioactive effluent which we expected to encounter under various circumstances

during reentry drilling and production flaring. Radiation detectors were installed above and below the rig floor, on the mud return line, and the gas flare line. The meter readouts and recorders for these detectors were located in the site laboratory trailer. We considered it essential to record and document all evidence of any radiation above normal background which might be detected. Air monitoring devices (i.e. charcoal filters and a molsieve tube) were set up at prescribed work locations. These devices were analyzed routinely

each day. While we could have used the information provided by these devices to quantify the extent of any radioactive release, it was not necessary since at no time during the reentry drilling did our rig detectors record any radiation levels above natural background.

Perhaps the most ambitious array of instrumentation was designed and fabricated to permit the real-time evaluation and quantification of krypton-85 and tritium released under various circumstances—such as when pressure was released from the blow-out preventers through the drilling well control (DWC) unit, or during test flaring through the DWC, or production flaring. While the rig was in operation the gas sampling system was plumbed into the DWC. This system was continuously purged using the Fawn Creek well gas, until such time as the Rio Blanco well gas was released through the system. From the DWC unit a small (1/4 in.) pipe carried a continuous stream of the gas to the gas cleanup skid located adjacent to the site laboratory. At the skid, the gas was processed through a series of water drop out points and finally a molysieve tower and a charcoal filter. After this processing the gas was considered to be clean, fairly dry, and ready for analysis. The gas was then distributed to instruments which comprised primary and backup analytical gear. The primary system was the CER Try-Kry instrument developed especially for Rio Blanco and had the capability of analyzing simultaneously for krypton and tritium. The backup system used an Eberline krypton chamber which permitted a real-time meter readout and recording of the activity levels of krypton. The backup analysis for tritium was made

by burning the gas in an oxidizer and then analyzing the water collected by liquid scintillation methods.

All of the instruments which comprised this on-site gas analysis system were calibrated and tested using EPA furnished standard gases of known composition. A thorough series of qualifying tests and evaluation were made on these instruments by the Hazards Control Health Physics personnel. The close correlation of test data provided by these field instruments, each of which differed from the other in the methods of deriving data, provided not only considerable versatility, but also the comfort of redundancy.

During the production flaring the same instrument array is being used. The only difference is that the DWC is no longer with us, and the gas cleanup skid is plumbed directly into the gas flare line downstream from the separator. The same laboratory counting techniques employed previously are still being used. The radiation levels in the gas stream are evaluated each day and using the gas flow information provided by CONOCO we are able to assign total curies of krypton-85 and tritium released to the environment through the flare stack each 24-h period.

The water and hydrocarbon products that are dropped out of the gas stream as it is processed through the separator are another stream of contamination which must be evaluated. These products are pumped into storage tanks located on-site. Periodically, water in the 400 barrel holding tanks is analyzed by liquid scintillation counting for total tritium curie content and then injected into the Fawn Creek well. The hydrocarbons are

analyzed similarly, but are injected into the flare stack and burned. Documentation of the total curie content of each of these contamination streams is prepared by CER, verified by our Laboratory personnel and then submitted to the AEC for release to interested parties.

Periodically, during the test flaring and production flaring, gas samples were taken and shipped to our Laboratory for analysis of the chemical constituents as well as the radioactivity. The results of the Laboratory analyses were communicated to the site as soon as completed. This gave us another check on the accuracy of our on-line gas analysis instruments.

A great number of words have been spoken in various circles about containment of radioactivity in the mud stream during reentry drilling. In previous off-site operations containment efforts led to the development of what have come to be called "drip pans" — large metal pans which, on some projects, encompassed the entire ground area on which the rig was located. At Rio Blanco, the size of these drip pans was reduced to include just the "sloppy" areas, i.e. the rig cellar, the

DWC, the shaker table and the pipe stands on the rig floor. A combination of good drilling techniques and good equipment well maintained, kept all of the contamination contained during reentry drilling. The highest level of tritium contamination encountered in the mud stream was 80 pCi/cm^3 in mud water. Since circulation was lost while drilling continued we were able to continually dilute the 80 pCi/cm^3 until the tritium was non-detectable. Nevertheless when the drill rig and ancillary equipment was demobilized, all items were cleaned, and "wipe" checks made to document the radioactive cleanliness of this equipment before it was released from the site.

While we stressed radiation safety on-site and practiced standard health physics techniques for personnel protection, and containment controls to protect the environment, we also developed and implemented a general, site-safety program. Laboratory and OSHA standards were used as guidelines. These included the areas of explosive gas control, high pressure gas containment, fire protection, first aid, as well as general rig safety.

Production Testing

There have been two periods of production testing (flaring) to obtain data on the detonation effects on the gas reservoir and the chemical and radiochemical composition of the chimney gas. The first production test started on November 15, 1973 and ended on November 21, 1973 with five continuous and uninterrupted days of testing from November 17 to November 21. The second production

test started on January 28, 1974 and ended on February 15, 1974. During the first production test 35+ million standard ft^3 of dry gas was produced; during the second test 62+ million standard ft^3 of dry gas was produced for a total production of just under 98 million standard ft^3 . The principal constituents of the dry chimney gas were as predicted being primarily CH_4 , H_2 , CO_2 . The first test

Fig. 49. Production test system.

was terminated when the surface flowing gas temperature got over 300°F and there was concern that if it were to go higher the temperature specifications on the plumbing, separator, and test equipment would be exceeded.

The second test⁹³ was initiated after gas cooling equipment (fin fan coolers) had been obtained and installed (Figs. 49 and 50 show the test systems). The second test was terminated when the chimney pressure had been drawn down (~440 psig) to a point where the majority of chimney gas was steam with a dry gas component rate of only ~1.4 million standard ft³ per day. The bottom hole flowing pressures and temperatures

for both tests were recorded on self-contained instruments lowered on a wire line through a lubricator attached to the wellhead (Fig. 51). The water vapor was knocked out of the chimney-gas steam at the separator. As the separated water contained some tritium, it was first stored in holding tanks to enable radioactivity concentration measurements and then disposed of by injection into the sandstone/shale horizons about a mile below ground in the Fawn Creek Government No. 1 well. Another reason for terminating the second production test was that we were approaching the maximum quantity of water which could be injected in the Fawn Creek well within

Fig. 50. Liquid storage and disposal systems.

the existing State of Colorado permit for that purpose. After the gas was dried by the separator it went through the gas sampling apparatus,

the meter run for determining flow rates and then to the flare stack (Fig. 52) on a nearby hill where it was burned.

Fig. 51. Wellhead with wireline lubricator.

Fig. 52. Flare stack.

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Appendix A:

Engineering Drawing of the Complete Rio Blanco Downhole Assembly

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