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LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

PROJECT RIO BLANCO:

PHASE I

TECHNICAL STUDIES

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PROJECT RIO BLANCO: PHASE I TECHNICAL STUDIES

ABSTRACT

Project Rio Blanco is the third experiment in the application of contained underground nuclear explosions to stimulate natural gas production. To support the formulation of a project definition document for this experiment, Lawrence Livermore Laboratory has conducted technical studies in several pertinent areas. Among these are the elucidation of rock properties at the detonation site, a prediction of explosion effects, a treatment of expected gas production from the stimulated well, and a study of radioactivity production and gas quality. Proposals are made for meaningful technical measurements and possible add-on programs.

INTRODUCTION

To support the formulation by CER Geonuclear of a project definition document for Project Rio Blanco, Lawrence Livermore Laboratory (LLL) has conducted technical studies in several pertinent areas:

- Rock properties at the detonation site;
- Prediction of explosion effects;
- Anticipated gas production from the stimulated well;
- Radioactivity production and gas quality.

Proposals have been made for technical measurements and possible add-on technical programs considered to have special merit.

Those studies reported in this document which pertain to, or depend on, rock properties at the Rio Blanco site must be considered preliminary, since the only rock samples now available to LLL were obtained several miles from the projected emplacement well.

Equation-of-state studies on these rock samples are not yet complete. When these results become available they will be reported separately, with whatever changes result in the explosion effect calculations.

When samples are available from the emplacement well, several of the studies reported here will be repeated. A supplementary document then will be issued. However, it is felt that the studies summarized here are sufficiently accurate and detailed to permit the formulation of an adequate project definition plan.

Appended to the summaries comprising the first portion of this document are the actual memoranda reporting the work done at this Laboratory.

ROCK PROPERTIES

Core Density and Porosity

Table 1 compares the density and porosity of a sandstone core taken some distance from the Rio Blanco site with similar data from two other gas-bearing formations. The core in this instance is from Equity South Sulphur Creek #4, a well 7.5 mi WSW from the site. While the Rio Blanco sandstone appears to have a much greater pore volume than the other formations, the results should be considered only indicative until other tests can be made on a core from the Rio Blanco emplacement hole or a nearer well.

Table 1. Gas-bearing formation densities and porosities.

	Rio Blanco sandstone	Gasbuggy Pictured Cliffs sandstone	Wagon Wheel sandstone
Grain density	2.68	2.70	2.67
Bulk density (saturated)	2.47	2.5	2.49
Effective pore volume	12.4%	8.0%	9.7%
Pore water content (fully saturated)	5.0 wt%	3.2 wt%	3.9 wt%

Chemical Analyses and Rock Composition

Analytical results from cores and chips recovered from South Sulphur Creek #4 and Texaco Fawn Creek #3 (2.6 mi SSW from the Rio Blanco site) are compared in Table 2 with data from three other gas-bearing formations. The calcium, magnesium, carbon, and carbon dioxide analyses are used in estimating the quality of the gas expected from the Rio Blanco experiment; that is, the amount of CO₂ in the produced gas. The lithium and boron analyses are used in calculating the amount of tritium formed by interaction of neutrons from the nuclear detonation with materials outside the canister; the mercury-203 content of the produced natural gas may be estimated from the mercury analyses.

The Rio Blanco shale seems to contain significantly less dolomite than the shales from Gasbuggy and Wagon Wheel. Dolomite, of course, releases carbon dioxide when heated by the nuclear detonation; this carbon dioxide appears in the cavity gas. Again, these results should be treated with some caution until samples from the Rio Blanco emplacement hole have been analyzed.

Relative to tritium production, it would seem advisable to emplace the Rio Blanco explosives in sandstone rather than shale. Tritium is produced by the interaction of neutrons from the explosive with lithium in the soil. Boron also captures neutrons which otherwise would be available to react with the lithium and produce tritium. Since the ratio of lithium to boron in the Rio Blanco sandstone is about 0.27, compared to 0.66 for shale, fewer neutrons will be captured in the sandstone than the shale.

Other gas quality considerations probably do not depend so critically on the explosive placement.

Table 2. Gas-bearing formation analyses and mineral compositions.

Analysis	Rio Blanco		Gasbuggy	Wagon Wheel		Rulison	
	Sandstone	Shale	Shale	Sandstone	Shale	Sandstone	Shale
Content - wt%							
Ca	1.7	1.8	3.0	3.6	3.7	3.7	0.3
Mg	0.8	1.0	1.4	0.5	1.5	0.7	0.5
Acid CO ₂	3.1	2.1	4.6	4.2	5.3	4.6	0.3
C (total)	1.2	1.3	1.4	1.2	2.1	1.4	0.7
Content - wt (ppm)							
Li	6.7	46	22	10	35	14	43
B	25	70	10	15	100	20	50
Content - wt (ppb)							
Hg						10-100	30-130
Mineral composition - wt%							
Dolomite	6	1.5	9 (est)	2	4	—	—
Calcite	0.5	3	—(est)	9	5	—	—

In our judgment, the mercury content of the Rulison cores could be representative also of Rio Blanco. However, due to the wide variation in mercury content over relatively small distances in the Rulison cores, the final values for Rio Blanco should be determined from emplacement hole cores.

Mineralogy

As noted in Appendix F, the samples from South Sulphur Creek Well #4 (the "sandstone" Mesaverde II horizon) can be categorized as greywackes intermediate in mineralogical properties between samples from Gasbuggy and Wagon Wheel. The average grain size of the Rio Blanco samples (102-192 μ) also is intermediate between those from Gasbuggy (average < 100 μ) and Wagon Wheel (100-200 μ).

Equation-of-State

Work on the equation-of-state (EOS) of the South Sulphur Creek #4 cores is still in progress. Results from these samples should be considered only indicative of the possible range of properties at Rio Blanco. Comparisons with Gasbuggy, Wagon Wheel, and Rulison data will provide some forecast of the variability of the EOS from a number of similar horizons.

EXPLOSIVE CANISTER ASSEMBLY CONFIGURATION

Project Rio Blanco will use three explosives. Each explosive has two major parts: a nuclear explosive assembly which is housed within a pressure-tight

environmental canister, and an environmental cooling system which consists of water and absorber tankage. One armored coaxial cable connects all the explosive systems to the control equipment on the surface. Other items emplaced with the explosives are a tank of tracer gas for each chimney, a single coaxial cable for verifying the detonations, and a cable for early sampling of the cavity gas.

The explosive canister contains all the nuclear components and the electrical hardware for control and firing. It is approximately 30 ft long, has a maximum diameter of less than 8 in., and weighs about 2000 lb.

Storage tanks for the water and refrigerant absorber are estimated to have a total length of 80 ft for each explosive; each will be 7 in. in diam and weigh about 4000 lb. Tanks for each explosive will be delivered in two sections, to be assembled in the field prior to emplacement operations.

The tracer gas tanks below each explosive will be installed during emplacement. The storage tanks, directly above each explosive, will be installed later. The electrical and gas sampling cables will be attached to the casing used for lowering the explosives.

PREDICTION OF EXPLOSION EFFECTS

The cavity radii and other parameters from SDK 70-16¹ still appear appropriate for Rio Blanco planning. When the estimated Rulison cavity size is scaled to Rio Blanco conditions $[(\rho h)^{1/4}]$, a cavity radius of approximately 70 ft is forecast (for a 30-kt explosive yield). When Gasbuggy observations are similarly scaled, the Rio Blanco cavity radius is some 10 percent larger (~77 ft). The predicted cavity radius according to conservative Wagon Wheel assumptions—scaled to Rio Blanco depths—is ~63 ft, 10 percent smaller than that forecast from Rulison scaling.

Thus, the 70-ft cavity radius now estimated for Rio Blanco is probably within 10 percent of the radius finally calculated from more complete information. The combined shock wave from the three explosives can be expected to fracture the rock to a distance of ~400 ft above the top explosive, ~350 ft horizontally, and ~300 ft below the bottom explosive.

Ground Motion Effects on Oil Shale

Calculations in Appendix G indicate that the Green River oil shale layer will be essentially unaffected by the Rio Blanco shock wave. As noted below, only the zone extending about 5 cavity radii (R_c) above the top explosive—less than 400 ft—is expected to be fractured enough to display a significant increase in permeability. The oil shale, lying some 2500 ft above the top explosive, should not be affected.

Surface Spall Effects

Calculations have been carried out to predict the spall effects at or near the ground surface. The expected depth of spall is 170 ft, with a surface spall velocity

of 2.5 m/sec for a 100-kt total yield. The maximum predicted spall depth is 380 ft. These surface effects are relatively small as compared with Nevada Test Site (NTS) experience. Because of this, the integrity of the explosive lowering casing and the emplacement hole casing are not expected to be adversely affected.

Chimney Model

An appropriate chimney model can be developed from the data in SDK 70-16 (see Fig. 1). The best calculated values for the cavity radius will depend on the EOS measurements currently in process on rock similar to that anticipated at the Rio Blanco emplacement site.

Present theoretical models for nuclear explosives detonated simultaneously indicate with high probability that a continuous fracture or rubble zone will connect the detonation points if the spacing between the explosives is $7 R_c$ or less. As the spacing increases from $7 R_c$ to $10 R_c$, the probability of connecting the fracture systems progressively decreases until, at $10 R_c$, it is unlikely that new fracture permeability will be developed between the chimneys. The chimney of rubble is expected to have a radius of $1-1.2 R_c$. A highly fractured zone will extend $2.5 R_c$ around each shot point and, at an explosive spacing of $6.0 R_c$, would produce an effective well radius of approximately $2-2.5 R_c$. The permeability would be increased enough out to $5 R_c$ above the top explosive and $2 R_c$ below the bottom explosive to warrant the inclusion of these regions in the stimulated interval.

Chimney Pressure and Temperature Immediately After Detonation

During the first sec or so after detonation, the three Rio Blanco cavities (so far unconnected) will contain uncondensed "rock gas" at very high temperature and pressure. However, the configuration of these three simultaneous explosions is expected to produce a rapid collapse of rubble into the bottom cavity (in a few sec), with the concurrent destruction of the upper two cavities as separate entities. As noted in Appendix H, if certain assumptions are made concerning the amount of rock heated and its composition, the maximum temperature and pressure in the collapsed Rio Blanco chimney a few sec postshot may be inferred as follows:

Assumed rock composition:

CO₂: 5 wt% (10 percent by wt of carbonate minerals).

H₂O: 4 wt% (half of which is unbound or pore water).

Amount of rock from which CO₂ and H₂O are released:

CO₂: 1000 tons/kt.

H₂O: 1000 tons/kt will lose all water; 1000 tons/kt will lose only pore water.

Based on these assumptions and an assumed reservoir pressure of about 190 atm and temperature of approximately 100°C, the total amount of gas in the cavity from 20-60 sec is predicted as

Fig. 1. Artist's conception of the Rio Blanco chimney.

$$\text{CH}_4 = \sim 1 \times 10^8 \text{ mole}$$

$$\text{CO}_2 = \sim 1 \times 10^8 \text{ mole}$$

$$\text{H}_2\text{O} = \sim 3 \times 10^8 \text{ mole.}$$

The CH_4 component is all of this gas expected to be present in the chimney rubble. We recognize that only a small fraction of this would be rapidly released into the void space and that this figure—at least for the first few sec after detonation—probably represents an overestimate by a factor of 2 to 10.

The extremely high cavity temperature during the first 0.1 sec or so after detonation will be reduced to $\sim 2000^\circ\text{K}$ by "blowoff" of the cavity wall. The gas then will be further cooled by radiation transmission during the first sec or two to about 1000°K . Below this temperature, cooling will take place rather slowly by means of convection and conduction until, sometime between 10 and 100 sec, the gas temperature will reach about 650°K .

At this temperature, the cavity pressure will approximate the formation pressure. Thus, the chimney pressure will exceed the formation pressure for only a relatively brief time.

As the chimney gas cools below $\sim 600^\circ\text{K}$, the steam will condense and the cooling rate decrease still more. The final equilibrium gas temperature in the chimney (about 520°K) will be reached some 1000 sec (~ 1 hr) after chimney collapse. At this time, the chimney pressure will be about 110 atm: less than 60 percent of the formation pressure. As formation gas enters the chimney, the pressure will slowly build up again to formation pressure.

Possible Effect on Nearby Wells

Figure 2 shows pressure change as a function of time for different distances between nearby gas wells and the center of the Rio Blanco chimney. If a 70-ft cavity radius and gas production rate consistent with the following are assumed, an appreciable pressure drop would be experienced, in the first year after the start of production, as far as 1000 ft from the emplacement well.

EXPECTED GAS PRODUCTION

Fractional Recovery of Gas in Place

The calculations in SDK 70-16 have been reworked by means of a recent, more adequate computer code, TRUMP.² The results are plotted in Figs. 3 and 4; the recoverable fraction of the estimated gas in place is shown as a function of time after detonation for different cavity radii and formation permeabilities.

Fig. 2. Pressure vs time after start of production in four hypothetical satellite wells 360 to 1266 ft from the center of the Rio Blanco chimney. The cavity radius (R_c) is assumed to be 70 ft, the formation porosity (k) 20 μ d, and the formation hydrocarbon density (ϕ) 4.8%.

Fig. 3. Fractional recovery of gas in place for various cavity radii, for a formation porosity of $20 \mu d$.

Fig. 4. Fractional recovery of gas in place for various cavity radii, for a formation porosity of $40 \mu d$.

The gas production was calculated by a finite-difference solution to the nonlinear partial differential equation for radial darcy flow. The parameters for this calculation were:

Formation pressure	2750 psi
Formation temperature	220°F
Formation permeabilities	20 and 40 μ d
Formation hydrocarbon porosity	5%
Bottom-hole pressure	750 psi
Well spacing	1/sq mi.

The compressibility and viscosity were chosen for a 0.65-gravity gas. Note that the formation pressure and temperature in the calculation exceeded those presently assumed for Rio Blanco (2600 psi, 205°F).

The effect of the explosive fracturing was simulated by a thirty-three-fold increase in permeability from the chimney wall out to a distance of $2.75 R_c$, thence decreasing to formation permeability at $3 R_c$.

Gas Flow Calculations

A series of calculations were carried out to ascertain the effect of interchimney permeability on downhole pressure and on total gas production at high flow rates during testing. The results of the studies to date are given in Appendix I; as expected, the total production at high flow rates is enhanced by high permeability between chimneys. The TRUMP computer program was used to simulate gas flow in the schematic chimney system shown in Fig. 5; various conductances were then assumed for the connecting regions, to test the effect of conductance on gas flow up the re-entry hole. The parameters for this study are summarized in Table I-1 (Appendix I).

Figure 6 shows the effect of such a parametric variation on the calculated bottom-hole pressure; in this context, "bottom-hole pressure" means the pressure at the top of the uppermost chimney. It can be seen that where communication between the top chimney and the underlying chimney is poor, as in Case B, the rapid drawdown (3×10^7 SCF/d) will result in virtual emptying of the upper chimney in less than 10 d. Qualitative conclusions on the degree of chimney interconnection apparently can be drawn from the decline rate of the bottom-hole pressure if a high drawdown rate is used.

Rates of downhole pressure buildup during the shut-in period are shown in Figs. I-9 through I-15; actual data on this parameter from the Rio Blanco Phase I experiment will aid in the evaluation of chimney interconnection.

However, the most sensitive and quantitative measure of the conductance of the two connecting regions can be obtained from analyzing the stable gas tracer data acquired during drawdown. Further calculations are being carried out to determine the probable stable gas tracer concentrations in the produced gas, using the same assumptions reported in the present study. This work will facilitate the final interpretation of gas tracer data from the actual experiment. Results of these preliminary calculations will be reported as soon as available.

Fig. 5. Schematic diagram of the Rio Blanco chimney system.

Fig. 6. Bottom-hole pressure decline during the production period, for various conductances.

TECHNICAL MEASUREMENTS

This measurements program is proposed to supplement the basic objectives of Project Rio Blanco, Phase I. Experiments are intended to provide data for planning future field developments in the project area and implementing other nuclear gas stimulation projects.

Chimney Interconnection

Inert Gas Tracers

To assess the degree of chimney interconnection resulting from the detonation, we plan to emplace noble gas "tracers" in each of the three explosive canisters. The estimate will derive from measurements of the concentrations of the gas tracers in the natural gas as a function of the amount of natural gas produced. See "Gas Sampling and Analysis Schedule (Quality Determination)" for further particulars.

As noted in Appendix J, if it is assumed that the natural gas at the site contains no more than 100 ppm of helium (preliminary analyses indicate ~80 ppm), and if the other noble gases are present in the same ratios as observed in air, then the following tracer loadings and costs will be appropriate for this experiment:

Explosive	Tracer	Amount (SCF)	Estimated cost
Top	Ne	500	\$10,000
Middle	Kr	250	8,000
Bottom	Xe	25	4,000

Interpretation of Gas Tracer Data

As previously noted, a model has been developed to simulate gas flow between chimneys of similar configuration to that expected in the Rio Blanco Phase I experiment. The use of inert gas tracer data, together with the gas production history, should facilitate an understanding of the chimney interconnections.

Chimney Gas Sampling System

A small sampling cable will be emplaced in the annulus between the explosive lowering casing and the emplacement hole casing so that small samples of chimney gas may be withdrawn at appropriate time intervals after the detonation. See Appendix L for a more detailed description of the proposed system. Relatively early gas sampling is being proposed because we want the following information:

- Amount of iodine present in chimney gas shortly after detonation, to help in refining our radioactive gas seepage analyses for future gas stimulation experiments and applications;

- Speed at which interchimney mixing takes place (employing gas tracer data);
- Distribution of radioactivity (especially tritium and carbon-14) by chemical species as a function of time;
- Variation in the chemical composition of the chimney gas as a function of time;
- Cavity pressure history, for better understanding of the gas cavity system with respect to potential gas quality control and radioactive gas seepage analyses.

Note that the system will be pressurized with an inert gas at shot time to prevent the immediate appearance of radioactive gas in the upper portion of the cable; thus the proposed uphole radiation measurement system will not be compromised. Sample collection times will be adjusted so that the safety-related measurements of these radiation detectors can be adequately interpreted.

Detonation Verification

To verify that all three Rio Blanco explosives have detonated, an appropriate detector system will be deployed. The sensor will be a single RF-1 cable extending to the bottom explosive; the actual verification measurement will be performed by instruments located with other LLL instrumentation near the emplacement well.

The RF-1 cable will be continuously pulsed in the early postshot period to detect any change in its unbroken length as a function of time. This measurement may give information suggesting the upward extent of effective fracturing.

Acceleration Measurements

For future gas stimulation detonations, we would like to be able to estimate seismic accelerations to which equipment near the emplacement well is likely to be subjected. To get these data, three accelerometers will be emplaced near the emplacement well (one will be attached to the wellhead assembly). The recording unit for these sensors will be located with the other LLL instrumentation near the well.

RADIOACTIVITY PRODUCTION AND GAS QUALITY

This analysis of Rio Blanco gas quality assumes the detonation of three nominally 30-kt Plowshare gas stimulation explosives at approximately 60 ft in sandstone.

Radioactivity Production/Well Re-entry

Table 3 lists the predominant fission products expected to be remaining at various times after detonation of the three explosives. Of these, only krypton-85 continues to be produced with the cavity gas 6 mo postshot.

Table 4 lists the maximum amounts of significant gaseous radionuclides predicted for Rio Blanco, compared with the amounts produced by Gasbuggy and Rulison. Each of the Rio Blanco explosives will produce less than one-tenth as much tritium as Rulison.

Table 3. Fission product activity at various times after detonation of three 30-kt nuclear explosives.

Nuclide	Activity — Ci		
	D + 30 days	D + 90 days	D + 180 days
^{85}Kr	2.05×10^3	2.03×10^3	2.00×10^3
^{89}Sr	1.6×10^6	6.8×10^5	2.0×10^5
^{90}Sr	1.4×10^4	1.4×10^4	1.4×10^4
$^{90}\text{Y}^a$	1.4×10^4	1.4×10^4	1.4×10^4
^{91}Y	1.8×10^6	9.2×10^5	3.2×10^5
^{95}Zr	2.0×10^6	1.1×10^6	4.0×10^5
$^{95}\text{Nb}^a$	1.1×10^6	1.3×10^6	7.2×10^5
^{99}Mo	3.6×10^4	—	—
$^{99}\text{Tc}^a$	3.6×10^4	—	—
^{103}Ru	1.2×10^6	4.3×10^5	9.2×10^4
$^{103\text{m}}\text{Rh}^a$	1.2×10^6	4.3×10^5	9.2×10^4
^{106}Ru	4.5×10^4	4.0×10^4	3.4×10^4
$^{106}\text{Rh}^a$	4.5×10^4	4.0×10^4	3.4×10^4
^{111}Ag	1.7×10^4	6.7×10^1	—
$^{115\text{m}}\text{Cd}$	1.2×10^3	4.5×10^2	1.1×10^2
^{115}Cd	5.8×10^1	—	—
$^{115\text{m}}\text{In}^a$	6.1×10^1	—	—
$^{123\text{m}}\text{Sn}$	1.3×10^3	9.2×10^2	5.6×10^2
^{124}Sb	2.7×10^2	1.3×10^2	4.7×10^1
^{125}Sn	4.9×10^4	5.8×10^2	—
^{125}Sb	5.4×10^3	5.6×10^3	5.4×10^3
$^{125\text{m}}\text{Te}^a$	2.9×10^2	7.4×10^2	9.9×10^2
^{126}Sb	2.0×10^4	7.2×10^2	—
^{127}Sb	1.6×10^4	—	—
$^{127\text{m}}\text{Te}$	1.6×10^4	1.1×10^4	6.3×10^3
$^{127}\text{Te}^a$	3.4×10^4	1.1×10^4	6.3×10^3
$^{129\text{m}}\text{Te}$	3.2×10^4	9.4×10^3	1.5×10^3
$^{129}\text{Te}^a$	2.0×10^5	5.9×10^3	9.5×10^2
^{131}I	9.7×10^5	5.6×10^3	2.3
$^{131\text{m}}\text{Xe}$	1.6×10^4	1.1×10^3	—
$^{133\text{m}}\text{Xe}$	2.0×10^2	—	—
^{133}Xe	5.8×10^5	2.2×10^2	—
^{136}Cs	1.7×10^5	6.8×10^3	5.6×10^1
^{137}Cs	1.7×10^4	1.7×10^4	1.6×10^4
$^{137\text{m}}\text{Ba}^a$	1.6×10^4	1.6×10^4	1.5×10^4
^{140}Ba	2.5×10^6	1.0×10^5	7.7×10^2
$^{140}\text{La}^a$	3.1×10^6	1.2×10^5	8.8×10^2

Table 3 (Continued).

Nuclide	Activity — Ci		
	D + 30 days	D + 90 days	D + 180 days
¹⁴¹ Ce	2.7×10^6	7.6×10^5	1.2×10^5
¹⁴³ Pr	2.5×10^6	1.2×10^5	1.3×10^3
¹⁴⁴ Ce	4.7×10^5	4.1×10^5	3.2×10^5
¹⁴⁴ Pr ^a	4.7×10^5	4.1×10^5	3.2×10^5
¹⁴⁷ Nd	9.2×10^5	2.2×10^4	7.9×10^1
¹⁴⁷ Pm	5.6×10^4	6.5×10^4	6.1×10^4
¹⁴⁹ Pm	1.6×10^3	—	—
¹⁵¹ Sm	4.7×10^2	4.7×10^2	4.7×10^2
¹⁵³ Sm	7.6×10^1	—	—
¹⁵⁵ Eu	3.2×10^3	2.9×10^3	2.7×10^3
¹⁵⁶ Eu	1.2×10^4	7.4×10^2	—
Total	2.3×10^7	7.0×10^6	2.9×10^6

^aNuclides in transient or secular equilibrium with the isotope listed immediately preceding.

Table 4. Significant gaseous radionuclides remaining 180 d after detonation.

Nuclide	Total production — Ci		
	Gasbuggy ^a (29 kt)	Rulison ^b (48 kt) ^c	Rio Blanco (3-30 kt)
T	40,000 ^d	10,000 ^d	<3,000 ^d
¹⁴ C			
as ¹⁴ CO ₂	~6 ^e	~3 ^e	} ≤ 22.5 ^{d,e}
as ¹⁴ CH ₄	~1.5 ^e	—	
³⁷ Ar	370	1,200	≤ 2,600 ^{d,f}
³⁹ Ar	0.25	11	≤ 20 ^{d,f}
⁸⁵ Kr	350	1,112	2,000 ^d

^aC. F. Smith, "Behavior of Radionuclides in Nuclear Gas Stimulation Applications," from Symposium on Engineering with Nuclear Explosives (January 14-16, 1970), Conf-700101 (Vol. 1), pp. 818-830.

^bC. F. Smith, "Gas Analysis Results for Project Rulison: Calibration Flaring Results," Lawrence Livermore Laboratory Rept. UCRL-50986 (1971).

^cC. F. Smith, personal communication.

^dTotal production (calculated).

^eTotal present in gas.

^f¹⁴C, ³⁷Ar, and ³⁹Ar estimates are conservatively scaled (per kt of yield) from observed production; ¹⁴C is scaled from Gasbuggy and ³⁷Ar and ³⁹Ar from Rulison.

Obviously, the amounts of radioactivity which could be present in the gaseous state must be considered when one selects the optimum time for well re-entry. To assess the relative biological impact of the gaseous radionuclides as a function of time after detonation, we have divided the total inventories of these isotopes 2, 10, 30, 90 and 180 d postshot by the appropriate MPC values and normalized to the sum of the noble gases at D + 2 d. The MPC values are those for continuous occupational exposure.³ The results are given in Table 5.

It should be noted that the iodine radioisotopes are treated separately in this table. Since only a small fraction of the radioiodines will be present in the gaseous state, their inclusion with the noble gases would not be appropriate.

Table 5. Relative biological impact of gaseous radionuclides as a function of time after detonation: Rio Blanco.

Nuclide	Relative biological impact				
	D + 2 days	D + 10 days	D + 30 days	D + 90 days	D + 180 days
T ^a	<4.0 (-5)	<4.0 (-5)	<4.0 (-5)	<4.0 (-5)	<4.0 (-5)
¹⁴ C ^a	≤6.0 (-7)	≤6.0 (-7)	≤6.0 (-7)	≤6.0 (-7)	≤6.0 (-7)
³⁷ Ar	≤2.3 (-6)	≤2.0 (-6)	≤1.3 (-6)	≤4.2 (-7)	≤6.8 (-8)
³⁹ Ar	≤1.8 (-7)	≤1.8 (-7)	≤1.8 (-7)	≤1.8 (-7)	≤1.8 (-7)
^{85m} Kr	2.5 (-3)	—	—	—	—
⁸⁵ Kr	1.8 (-5)	1.8 (-5)	1.8 (-5)	1.8 (-5)	1.8 (-5)
⁸⁸ Kr- ⁸⁸ Rb	1.0 (-3)	—	—	—	—
^{131m} Xe	4.0 (-5)	1.8 (-4)	1.1 (-4)	7.4 (-6)	—
^{133m} Xe	7.7 (-3)	9.3 (-4)	1.8 (-6)	—	—
¹³³ Xe	1.6 (-1)	7.7 (-2)	5.1 (-3)	2.0 (-6)	—
^{135m} Xe	3.2 (-2)	—	—	—	—
¹³⁵ Xe	8.0 (-1)	—	—	—	—
Total except I	1.0 ^b	7.8 (-2)	5.3 (-3)	<6.8 (-5)	<5.9 (-5)
¹³¹ I ^c	3.2 (-3)	1.5 (-3)	2.7 (-4)	1.6 (-6)	6.7 (-10)
¹³³ I ^c	0.10	1.1 (-4)	—	—	—
¹³⁵ I ^c	0.01	—	—	—	—
Total I ^c	0.11	1.6 (-3)	2.7 (-4)	1.6 (-6)	6.7 (-10)

^aAll T and ¹⁴C are assumed to be gaseous.

^bNormalizing value.

^cOnly 1% of the direct fission yield of the iodines is assumed to be in a volatile form, as based on data from NTS experiments (R. Pastore, NVO-100). All iodine figures also are scaled to the total noble gases at D + 2 days.

Radioactivity Distribution

Tritium and carbon-14 distributions among the various molecular species in the cavity gas depend critically on the initial formation conditions, as well as on the effects of the detonation. Relative to the predicted post-detonation cavity temperature, if all the energy from the three explosives were deposited in the estimated 10^{12} g of chimney rubble, the temperature rise would be approximately 360°C. However, at Gasbuggy, only about one quarter of the explosive yield appeared as environmental heat 6 mo after the detonation; current data indicate that the fraction was somewhat larger for the Rulison experiment.

As discussed elsewhere, we assume that about 40 percent of the Rio Blanco explosive energy will be available to heat the cavity rubble, resulting in a final temperature of about 250°C (480°F). It's interesting to note that if data from single detonations (Gasbuggy and Rulison) were scaled to Rio Blanco conditions, the predicted rubble temperature would be somewhat less (about 190°C, 370°F).

Chemical Species in the Cavity Gas

Carbon Dioxide—Almost all the carbon dioxide in the post-detonation gas will be formed from the thermal decomposition of carbonate minerals in the vicinity of the explosion. In the Gasbuggy experiment, about 1350 metric tons of rock per kt were heated to decomposition temperature. For Rulison, about twice that much rock per kt had to be decomposed to yield the observed carbon dioxide content of the cavity gas.

For Rio Blanco, we assume the heating of 2000 metric tons of rock per kt of explosive yield to a temperature which will cause decomposition of the carbonate minerals. Thus, from the three 30-kt detonations, 4.5×10^9 g of carbon dioxide will be released into the estimated void volume of 1.3×10^{11} cm³. In addition to this, some 1.7×10^9 g of carbon dioxide will be formed when the ~0.5 wt% of free carbon in the gas sand reacts—"burns"—in the water vapor to yield hydrogen and carbon dioxide. Therefore, a total of about 6.2×10^9 g of carbon dioxide will be present in the cavity, leading to a carbon dioxide partial pressure of about 47 atm.

Water—Assuming saturated steam to be present in the cavity at 250°C (523°K), the partial pressure of water vapor will be about 38 atm. This represents approximately 2.1×10^9 g of water. Inasmuch as the 10^{12} g of chimney rubble are assumed to contain about 2.7 wt% water, this amounts to 2.7×10^{10} g of water, of which some 5 percent is consumed in the "burning" of the free carbon present in the gas sand. Of the remaining 2.6×10^{10} g of water, some 8 percent is present as steam in the cavity.

Hydrogen—For this treatment of gas quality, it has been assumed that all the free carbon in the rock that is heated above 1000°C will be "burned" in water vapor according to the reaction

This represents about 1000 metric tons of rock per kt of nuclear yield, in which all of the carbon is considered to undergo this reaction. Since the rock in this region contains ~0.5% free carbon by weight, some 4.5×10^8 g of carbon are assumed to undergo the reaction, yielding some 1.5×10^8 g of hydrogen and 1.7×10^9 g of carbon dioxide. This mass of hydrogen introduced into the assumed void volume of 1.3×10^{11} cm³ will result in a hydrogen partial pressure of about 25 atm.

Carbon Monoxide—Although large amounts of carbon monoxide probably will be produced in the cavity following the detonation, it is expected to react with water vapor as the cavity temperature declines. The principal reaction probably will be

Thus, at re-entry time, there should be relatively little carbon monoxide remaining in the cavity gas, and its presence should not markedly affect either chemical or radiological gas quality.

Formation Gas—The Rio Blanco formation pressure is about 190 atm; thus, as soon as the cavity rock cools to where the cavity pressure drops below this value, formation gas (mostly methane) will enter the cavity. When the assumed equilibrium temperature of 520°K is attained, the partial pressure of the formation gas in the cavity can rise to about 80 atm, representing some 3.9×10^9 g.

Radioactive Species in the Cavity Gas

Tritium—As noted in Table 4, less than 3000 Ci of tritium are expected to be present following the detonation of the three Rio Blanco explosives. Of this, some 40 percent is expected to be trapped in the "melt" (unavailable for exchange in the chimney). Hence, we should consider that the effective maximum amount of tritium will be 1800 Ci. At the relatively high temperature predicted for the chimney region in this experiment, it has been assumed that the available tritium will be distributed among the methane, hydrogen, and water such that the tritium-to-hydrogen ratio is the same in all molecular species. On this basis, we will find the 1800 Ci of tritium distributed among 2.6×10^{10} g of water (all the water in the chimney rubble), 3.9×10^9 g of formation gas (mostly methane), and 1.5×10^8 g of hydrogen present in the cavity at 520°K. This will result in maximum tritium concentrations of about 0.05 μCi/g in water, 0.12 μCi/g in methane, and 0.5 μCi/g in hydrogen. Note that the isotope effect at these temperatures should cause the specific activity of tritium in hydrogen gas to be more than a factor of 2 lower than assumed here; however, this will have relatively little effect (less than 3 percent) on the specific activities calculated for methane and water.

The estimated 6-mo postshot radioactivity concentrations are listed in Table 6.

Table 6. Chemical composition and radioactivity distribution in produced Rio Blanco gas 6 mo after detonation (cavity temperature 250°C).

Chemical composition		Radioactivity concentration ^a (wet gas)	
Molecular species ^a	Vol% ^b	Nuclide	pCi/ml ^b
CH ₄ ^c	42	T in CH ₄ ^c	<35
H ₂ O	20	T in H ₂ O	<8
CO ₂	25	T in H ₂	<5
H ₂	13	¹⁴ C in CH ₄ ^c	≤1.1
		¹⁴ C in CO ₂	≤0.6
		⁸⁵ Kr	160
		³⁷ Ar	≤200
		³⁹ Ar	≤1.6

Radioactivity concentration ^a (dry gas)		Radioactivity concentration ^a (dry gas, with CO ₂ removed)	
Nuclide	pCi/ml ^b	Nuclide	pCi/ml ^b
T in CH ₄ ^c	<45	T in CH ₄ ^c	<65
T in H ₂	<7	T in H ₂	<10
¹⁴ C in CH ₄ ^c	≤1.4	¹⁴ C in CH ₄ ^c	≤2.0
¹⁴ C in CO ₂	≤0.8	⁸⁵ Kr	300
⁸⁵ Kr	200	³⁷ Ar	≤400
³⁷ Ar	≤300	³⁹ Ar	≤3
³⁹ Ar	≤1.9		

^aOther molecular species will be present in smaller amounts probably mainly CO. Since some of the ¹⁴C will be present as ¹⁴CO, ¹⁴C concentrations in CH₄ and CO₂ probably will be slightly lower than shown here.

^bCalculated for produced gas at STP.

^cAll the formation gas is assumed to be CH₄. Presence of higher alkanes will not affect this treatment significantly.

Carbon-14—Current estimates place the amount of carbon-14 in the Rio Blanco gas for each 30-kt explosive at less than the 7.5 Ci measured in the Gasbuggy gas, or less than 22.5 Ci in all. As in the case of tritium, we assume that the elevated temperatures in the Rio Blanco chimney will induce chemical exchange of the carbon-14 with all the carbon-containing species present. As previously noted, we expect to find about 6.2×10^9 g of carbon dioxide in the cavity gas, together with 3.9×10^9 g of methane. If the ratio of carbon-14 to nonradioactive carbon in these compounds is the same, we may expect the maximum initial carbon-14 concentrations to be 1300 pCi/g in carbon dioxide and 3700 pCi/g in methane. Volume concentrations are indicated in Table 6.

Noble Gases—As observed in the Gasbuggy and Rulison experiments, all the krypton-85 and the argon radioisotopes are assumed to be mixed uniformly with the cavity gas (including the steam). The expected 6-mo postshot concentrations of these also are given in Table 6.

Other—Other gaseous radionuclides (principally isotopes of krypton and xenon) will be present in the cavity after the detonation. If re-entry and some gas production is contemplated earlier than 6 mo postshot, additional radioactive species (possibly including the radioiodines) should be considered.

GAS SAMPLING AND ANALYSIS SCHEDULE (QUALITY DETERMINATION)

The LLL Gas Analysis program is expected to provide data in two primary areas of interest:

- Gas quality and variation with time after the detonation;
- Degree of chimney interconnection.

Each of these objectives requires the collection of several gas samples. An appropriate sampling schedule proposed by LLL is as follows:

Gas sampling system:

1, 1-1/2, 3, 3-1/2, 8, 8-1/2 hr;
1, 3 d;
1, 2 w;
1, 2, 3, 4-1/2, 6 mo.

During production testing:

Initial re-entry (2);
Each calibration flaring (2);
Production test, 2/day.

The 4-1/2 and 6 mo gas sampling system samples will not be taken if flaring starts before the indicated times.

Each sample will be about 10 liters (STP) in volume. Analyses to be made on some or all of these samples include:

Chemical constituents:

CH₄, C₂H₆ (and higher alkanes), CO₂, CO, H₂, H₂O, He, Ne, Kr, Xe.

Radiochemical analyses:

Tritium (in all appropriate chemical constituents);
¹⁴C (in all appropriate chemical constituents);
⁸⁵Kr, ³⁷Ar, ³⁹Ar, ²²²Rn, ²⁰³Hg.

In early samples:

Inert gas fission products as appropriate;
Iodine fission products;
Other fission products of interest.

We anticipate that mercury-203 and "other fission products of interest" in the gas may be associated with particulate material. Hence, the prefilter (upstream from the gas sampling bottle) will be dissolved and radiochemically analyzed for these radioisotopes.

ADD-ON TECHNICAL PROGRAMS

These programs are intended to supplement the basic objectives of the Project Rio Blanco Phase I experiment. The proposed measurements are subject to the concurrence of the project's industrial sponsor and will be implemented only if adequately funded.

Biomedical Program

The environmental monitoring program conducted in conjunction with production testing at Rulison provided data which would permit reasonably realistic dose estimates for any future flaring operations in the same general geographic area. The biomedical program proposed for the Rio Blanco experiment would test the applicability of the Rulison model to an ecologically dissimilar area. Additional studies also are being proposed to ascertain the uptake and release rates of both tritium and carbon-14 in a number of different plant species.

While these studies are not intended to parallel the primary radiological surveillance program for Rio Blanco, the results should be complementary and especially useful in planning for future production testing activities.

Dynamic Detonation Effects Measurements

Existing rock mechanics computer codes can be used to estimate the cracking radii from nuclear gas stimulation experiments. The most sensitive test of the predictive capability of these codes, however, is the adequacy by which they reproduce local rock response to a nuclear detonation. Measurements of this sort have never been carried out for rock types and depths encountered in gas stimulation experiments and applications. Especially of interest would be a test of the capability of these calculations to predict the shock interaction (and any enhancement in cracking) when two or more explosives are detonated simultaneously.

Rock response measurements needed for code verification include time of shock wave arrival as a function of distance from the detonation point(s) and a stress history at given locations in the rock. To get such measurements, a partially cased instrument well (Well B) will be drilled about 550 ft from the emplacement well, directionally drilled so as to be radially oriented to the lowest Rio Blanco explosive (see Figs. 7 and 8). The instrumentation will include four packages incorporating nonoriented stress gages and four shock time-of-arrival (TOA) pins. Nonsanded cement will be employed in the well stemming; the overall stemming plan will be consistent with that of the emplacement well to ensure complete containment of the nuclear detonation.

Fig. 7. Instrumental well arrangement. Well A, $2\frac{1}{2}$ cavity radii from the chimney centerline, is intended for measuring the fracturing permeability. Well B, 8 cavity radii from the centerline, will contain instruments for measuring pressure during production testing.

Drilling plan:

Well A. Drill out of casing at 4000 ft; drill vertically to 7500 ft with 200-ft core logs, 10 drill stem tests. Sidetrack holes: 500 ft directional drilled hole toward chimney, attempt 10% core log with two drill stem tests.

Well B. Drill out of casing at 5200 ft; drill vertically to 7200 ft with 20% core log, four drill stem tests, set packer at casing point with tubing to bottom. Monitor pressure.

Fig. 8. Postshot drilling plan for the instrumental wells.

Uphole Radiation Measurements

The measurements described here will be aimed at optimizing the emplacement hole design and minimizing the field support required for future nuclear gas stimulation detonations. Such measurements in no way imply that seepage of radioactive gases is expected or probable. On the contrary, negative readings—that is, no gas seepage detected—are expected to form the body of information on which future emplacement hole designs will be based.

Current explosive emplacement practice at NTS includes the emplacement of radiation detectors at varying depths to provide information on the adequacy of stemming in the emplacement hole. The emplacement hole and stemming designs for NTS nuclear weapon tests are significantly different from those planned for deeply buried gas stimulation detonations. For Rio Blanco, an effort will be made to design and develop a system for detecting seepage of radioactive gases within the emplacement hole. This detection system would have to be compatible with the gas sampling system previously described, requiring that techniques be established for distinguishing between the residual radioactivity in the gas sampling cable and the seepage of radioactive gas in the stemming. Because we need to keep the interior of the explosive emplacement casing free for re-entry to the chimney, the radiation detectors and the gas sampling cable will both be located in the annulus between the explosive emplacement casing and the emplacement hole casing. This annulus is to be cemented entirely to the ground surface. Gas seepage within the emplacement hole casing reaching the wellhead would be indicated not only by the radiation detection but by increased pressure readings on pressure sensors at the wellhead. Although it is extremely unlikely that gas will appear prematurely at the wellhead, such an eventuality is not expected to pose containment problems because the wellhead is designed to contain gases at formation pressures.

From an operations viewpoint, it would be highly desirable to have an early warning system capable of detecting gas seepage outside the emplacement hole casing. This gas would not be contained at the wellhead if it reached the ground surface. An early warning system would lengthen the reaction time available to implement corrective or protective action. The reduction in operational support required at the time of detonation has not been evaluated with a functioning early warning system, but it could be significant.

A positive system for accomplishing this would require detectors to be placed outside the emplacement hole casing. Detectors and associated cables so located have not been considered seriously for the Rio Blanco experiment because of the possibility that systems of this sort might compromise the cementing of the emplacement hole casing and increase the possibility of gas seepage.

For the present experiment, apparently, there is no specific set of conditions under which information from the proposed detectors can be used uniquely as an early warning for seepage outside the emplacement hole casing.

The design and operation of the detection system planned for Rio Blanco may give us the data we need for the ultimate development of such an early warning system.

Postshot Investigations

It should be emphasized that no add-on technical programs are currently planned for the immediate postshot period at Rio Blanco. After production testing is underway and some analyses have been made of the effectiveness of the stimulation, the need for a postshot investigation program will be ascertained and, if required, a program formulated in detail. The suggested programs are only indicative of some studies which later may be deemed desirable.

Fracturing and Chimney Size Measurements

Another well (Well A, Figs. 7 and 8) will be drilled about 170 ft from the emplacement well for determining the amount of fracturing at this distance. The depth will be approximately 7500 ft. The measurements are expected to provide additional verification of calculations made by means of the present rock mechanics computer codes. In addition, sidetrack holes will be drilled toward the chimney(s) at selected points, to define the chimney dimensions. This program is intended to provide better delineation of the effects from a simultaneous multiple detonation, so that an informed decision can be made on the detonation method most appropriate for optimum field development.

Ancillary Production Test Measurements

Instrument well B will be re-entered and a vertical extension drilled to about 7200 ft. The downhole pressure history of well B will be recorded and analyzed and compared with that of the re-entered emplacement hole to aid in understanding the chimney/gas field interaction.

ACKNOWLEDGMENTS

The authors who have contributed to this document are listed below, with the topic(s) they elucidated. The authors wish to thank these individuals for their cooperation in the preparation of this technical studies summary.

Rock Properties: D. O. Emerson, P. L. Turner, J. H. Hill, R. L. Braun, R. W. Taylor, I. Borg;

Explosive Canister Assembly Configuration: G. A. Broadman, A. W. Lundberg;

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APPENDIX A
RIO BLANCO CORE DENSITY AND POROSITY

March 25, 1971

M E M O R A N D U M

UOPKL 71-26

TO: H. Tewes
FROM: D. Emerson
SUBJECT: Rio Blanco Core Density and Porosity.

Attached is a data sheet for sandstone from the So. Sulphur Creek #4 well (7.5 mi WSW from the site for Rio Blanco). This core is of an excellent gas sand from the Mesaverde II which is stratigraphically about 500 feet below the bottom Rio Blanco explosive. It should be similar to the better sands in the Mesaverde I. The range is small and the following average values are quite reasonable when compared to log values.

Grain Density	2.68
Bulk Density, Saturated	2.47
Effective Pore Volume	12.4%
Water Content, Fully Saturated	5.0 wt.%

DOE:mn

UOPKK 71-14

MEMORANDUM

February 25, 1971

TO: Don Emerson

FROM: Phil Turner

SUBJECT: RIO BLANCO (SULFUR CREEK) So. Sulphur Creek #4

Ref: P. 87, Log Book 1

DEPTH	WET WT.	SUSP. WT.	DRY WT.
6305 - 6306	82.014	48.649	77.573
6370 - 6371	494.2	298.0	472.2
6394	42.239	25.049	39.924
6399	267.1	157.9	253.0
6411 - 6412	425.9	253.6	406.4

DEPTH	ρ_{bd}	ρ_{bs}	ρ_{bg}	Y	Z	G.D.
6305 - 6306	2.325	2.458	2.682	.1331	.0542	2.66
6370 - 6371	2.407	2.519	2.711	.1121	.0445	2.67
6394	2.323	2.457	2.684	.1347	.0548	2.69
6399	2.317	2.446	2.660	.1291	.0527	X
6411 - 6412	2.359	2.472	2.659	.1132	.0458	2.66

Beckman Pycnometer starting pressure 1.50 psi Helium

Calibrate Quartz crystal 27.627 g 10.56 cc = 2.613 (2.654)

OFFICIAL USE ONLY

APPENDIX B
CHEMICAL ANALYSES OF RIO BLANCO SAMPLES

March 9, 1971

MEMORANDUM

TO: H. Tewes
FROM: J. Hill
SUBJECT: Chemical Analysis of Rio Blanco Samples

The attached sheet contains chemical assays for two sandstone and two shale samples from the Rio Blanco area. The geographical location of the sample sites is shown on the map attached.

The sandstone samples were inner slices taken from core. The shale samples were cuttings > 1mm in size. The shale samples contained wood chips which were removed by flotation before the samples were pulverized.

The sandstone should be virtually free of contamination for the elements assayed. The shale samples probably contain some drilling mud. However, contamination from the drilling mud probably did not cause significant errors in the assay of the major constituents. Contamination from the drilling mud can also cause errors in the trace element analysis. The extent of these errors is not known.

J. H. Hill

JHH:ob

ANALYTICAL REPORT
RIO BLANCO SAMPLES

Sample No.	521	522	523	524
Hole No.	So. Sulfur Creek #4	So. Sulfur Creek #4	Fawn Creek #3	Fawn Creek #3
Depth (ft.)	6411-12	6399-6400	5200-5230	5600-5640
Rock Type	Sandstone	Sandstone	Shale	Shale

						*Accuracy
Wt. %	Ca	1.48	2.0	2.18	1.48	$\pm 2\%$
	Mg	0.66	0.87	1.06	1.03	$\pm 2\%$
	ACID CO ₂	2.39	3.76	2.99	1.30	$\pm 5\%$
	Total C	0.94	1.41	1.56	1.10	$\pm 5\%$
	C as CH _x	0.29	0.37	0.74	0.75	$\pm 5\%$
Wt. ppm	Li	6.7	6.7	46	46	$\pm 10\%$
	B	25	25	70	70	$\pm 50\%$
	Sc	3	3	12	12	"
	Y	15	15	25	20	"
	La	30	30	50	50	"
	Ce	25	25	50	50	"
	Nd	15	15	50	50	"
	Eu	<2	<2	<2	<2	"
	Dy	<5	<5	<5	<5	"
	Yb	1	1	2	2	"

*Probable accuracy expressed as a percent of the concentration.

APPENDIX C
RIO BLANCO ROCK COMPOSITIONS

March 9, 1971

UOPKL 71-25

M E M O R A N D U M

TO: R. Taylor
FROM: D. Emerson
SUBJECT: Rio Blanco Rock Compositions

The only available sandstone core is from So. Sulphur Creek #4, about 8 miles WSW of the Fawn Creek #1 site for Rio Blanco. It is a sand of the Mesaverde II, below the zone to be stimulated but should be representative of the better gas sands.

The shale is from chips collected while drilling Fawn Creek #3, about 3 miles SSW of the site. They should represent the other extreme in compositions.

The shales average 4.5 wt % carbonates of which 67% is calcite while the sandstones average 6.5 wt % carbonates with only 8% calcite. I would weight the sandy shales with the shales in their carbonate content. With 45% sandstone, the grand average would be about 5.4 wt % carbonates of which 40% is calcite. Although the Rulison core shows a greater variation, the average values would be about the same.

DOE:mn

cc: J. Toman
H. Tewes

APPENDIX D

X-RAY DIFFRACTION PHASE ANALYSIS OF SAMPLES FROM FAWN CREEK #3 AND SOUTH SULFUR CREEK #4

March 9, 1971

UOPKK 71-16

M E M O R A N D U M

TO: D. Emerson
FROM: R. L. Braun
SUBJECT: X-ray diffraction phase analysis of samples from
Fawn Creek #3 and Sulfur Creek #4.

The mineralogical composition of four samples from Fawn Creek #3 and Sulfur Creek #4 was determined by x-ray diffractometry. The calcite and dolomite content was quantitatively determined from the calcite/dolomite ratio obtained from the x-ray diffraction pattern and the total CO₂ content obtained by acid evolution by J. H. Hill.

	<u>Fawn Creek #3</u>		<u>Sulfur Creek #4</u>	
	<u>5200- 5230</u>	<u>5600- 5640</u>	<u>6399- 6400</u>	<u>6411- 6412</u>
Quartz	M	M	S	S
Feldspar	W	W	M	M
Illite group	M	M	M	M
Kaolinite group	M	M	-	-
Dolomite, wt %	2	1	7	5
Calcite, wt %	4	2	1	0

Key: S > 50 wt % M 10 to 50 wt % W < 10 wt %
--

APPENDIX E
MERCURY IN RULISON CORE

June 21, 1971

MEMORANDUM

TO: Distribution
FROM: J. H. Hill
SUBJECT: Mercury in Rulison Core

The mercury assay for seven sections of Rulison core is given below:

Sample depth (ft)	Rock type	ppb Hg (wt)
8404.5	Sandstone	19
8404.5	Sandstone	97
8404.5	Sandstone	16
8433.5	Sandstone and Siltstone Interbedded	46
8439.5	Shale	86
8441.5	Sandstone	9.2
8441.5	Sandstone	14
8443	Shale	100
8443	Shale	32
8443	Shale	130
8446	Shale	77
8451-52	Siltstone	30
8451-52	Siltstone	30
8451-52	Siltstone	20

Samples for chemical analysis consisted of small chunks taken from the center of core specimens. Each core specimen contained 3 in.³ to 4 in.³ of rock.

Results for individual determinations are given above to show the heterogeneity of the mercury content of the rock. These results indicate

that the mercury content of the core varies by a factor of 14 in the depth from 8404.5 ft. to 8452 ft.

Replicate determinations are given for three specimens (8404.5 ft., 8443 ft., and 8451-52 ft.) to indicate the heterogeneity within each specimen. The largest variation is a factor of 6 in the concentration found on the three samples taken from the 8404.5 ft. specimen.

The probable accuracy of the analytical procedure is $\pm 20\%$ of the concentration or better for concentrations of mercury in the range covered by these samples.

J. H. Hill

JHH:gw

APPENDIX F
MINERALOGY OF RIO BLANCO SPECIMENS
FROM SOUTH SULPHUR CREEK #4

UOPKK 71-19

MEMORANDUM

March 12, 1971

TO: D. Emerson

FROM: I. Borg

SUBJECT: MINERALOGY OF RIO BLANCO SPECIMENS FROM SULPHUR CREEK #4 HOLE

The four samples studied (6305, 6370, 6399, and 6411) are greywackes from the Mesaverde II horizon. The mineralogy of the four samples is similar. Qualitatively they fall somewhere between Wagon Wheel and Gas-buggy types in so far as make-up, grain size, angularity, cementation and breakdown of contained detritus (rock fragments) is concerned. Modal analyses were not carried out for lack of time; however, the mineralogy is resumed below.

MINERALOGY

Quartz, plagioclase (in process of chemical breakdown), chert particles, coarse-grained dolomite grains, minor sericite (muscovite), clay minerals (derived chiefly from breakdown of detritus), carbonaceous accumulations as stringers between grains.

CEMENT AND TEXTURE

There is no cement per se. Interlocking quartz is typical of all three specimens. This is clearly due to development of "overgrowths" on angular and sub-angular quartz grains during chemical processes subsequent to deposition. The interlocking of siliceous phases has tended to eliminate porosity and produced a tight formation which appears to be inherently mechanically strong.

GRAIN SIZE

Average grain size:

6305	134 μ
6370	192 μ
6399	102 μ
6411	160 μ

They are medium-grained and intermediate between comparable Wagon Wheel and Gasbuggy rocks.

IYBstd

APPENDIX G

UCID - 15922

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Lawrence Radiation Laboratory

UNIVERSITY OF CALIFORNIA

LIVERMORE

94550

PREDICTION OF SPALL PHENOMENA AND NEAR
SURFACE EFFECTS FOR PROJECT RIO BLANCO

R. W. Terhune

October 18, 1971

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

OFFICIAL USE ONLY

PREDICTION OF SPALL PHENOMENA AND NEAR SURFACE EFFECTS FOR PROJECT RIO BLANCO

ABSTRACT

Project Rio Blanco is a proposed multiple nuclear explosive gas stimulation experiment. The gas sands to be stimulated are overlain by a rich oil shale section. This paper presents a computer study to determine if the oil shale will be fractured by the Rio Blanco experiment.

The calculations used the material properties measured for the Green River oil shale, logging data from two nearby wells, and also material properties developed for Wagon Wheel shale.

The calculations predicted that compressive fracture would not extend beyond 5 cavity radii (350 ft) from the detonation point and that tensile fracture is confined to within 170 ft of the free surface. The peak spall velocity at the surface directly above the detonation point was predicted to be 2.5 m/sec. A series of calculations, using zero tensile strength and the failure surface for a highly fractured shale were made in which layers of various impedance mismatch were examined. Fracture or separation on previous existing fractures was not predicted even though a sharp discontinuous impedance mismatch up to twice those observed was examined.

INTRODUCTION

Project Rio Blanco is a multiple nuclear explosive gas stimulation experiment. Three 30-kt explosives will be placed in a single wellbore, spaced about 420 ft apart, and detonated simultaneously. The top explosive will be emplaced at a depth of about 6000 ft. In this area of the Piceance Basin, the gas sands are overlain by a rich oil shale section lying between the 400- and 2900-ft depth.

The purpose of this study is to determine if the shock wave expected from the detonation of the Rio Blanco explosives will fracture the Green River formation which contains the oil shale.

PHENOMENOLOGY OF A NUCLEAR EXPLOSION

Detonation of a deeply buried nuclear explosive creates tens of megabars of stress discontinuity which propagates into the surrounding media. This stress discontinuity (shock wave) departs its energy into the rock and thus attenuates as it propagates radially from the source.

Initially enough energy is released in the region immediately surrounding the explosive to vaporize the rock. Approximately 70 tons of rock are vaporized per

kiloton of explosive energy; additional energy is deposited from the outgoing shock wave to melt the rock up to about twice the radius of vaporization. Beyond this, the rock is fractured until, at large distances from the source, the shock wave has decayed to a point where it propagates elastically. The cavity (formed by the vaporized region) expands until the pressure in the cavity is in equilibrium with the stresses in the rock. This equilibrium point is defined as the cavity radius R_c . Tensile and compressive waves are reflected when the shock wave interacts with the ground surface or other interfaces where there is a change in the material properties. Such a subsurface interface may be manifested as a consequence of variations in the material properties between various grades of oil shale (or other geologic layering) that exist 400 to 3000 ft beneath the ground surface. Fracturing will occur if the reflected stress is greater than the tensile strength of the rock layer into which the reflection takes place or if the shear strength of the rock is exceeded by the shear stress in the stress wave. The reflection of the shock wave at the free surface causes layers of the medium to separate and move with the velocity characteristic of the energy that has been trapped in these layers. This phenomenon is referred to as "spall."

METHOD OF ANALYSIS

Computer programs developed by Cherry and Petersen¹ in conjunction with a compatible determination of material properties developed by Stephens, Schock, and Heard²⁻⁴ have led to a reliable predictive capability for phenomena associated with shock wave propagation. Phenomena such as peak shock stress, particle velocity, extent of fracturing, and spalling have been predicted for numerous underground¹ and cratering⁵ experiments. The computer program selected for this analysis is the one-dimensional version named SOC.

The actual design contemplated for Rio Blanco presents a two-dimensional problem. A simplifying assumption required for a one-dimensional analysis is to assume the full yield of Rio Blanco at a point source. For the region above the detonation point this is a conservative assumption, since the top cavity will shield the rock toward the surface from the other two detonations.

GEOLOGY DESCRIPTION

The detonation points are planned below 5500 ft in the Fort Union formation, which consists of bedded layers of sandstone and shale. Between the depths of 2900 and 5500 ft is the Watsach formation consisting primarily of a dense shale. Between the depths of 400 and 2900 ft is the oil shale. This region is highly bedded with considerable variation in material properties between layers depending upon the grade of the oil shale. Between depths of 800 and 900 ft is an oil rich impermeable region called the Mahogany Zone which separates two aquifer subsystems.

MATERIAL PROPERTIES

A basic input requirement for the computer models is a description of the material properties. These material properties must include density, sonic velocity, hydrostatic compressibility, and failure envelope. The material properties for the Watsach and the Fort Union formation have not been determined, but they are expected to be similar to the shales from both the Rulison and Wagon Wheel sites.⁶⁻⁹ The material properties for the Wagon Wheel site have been measured in fairly complete detail. The material properties parameters used for this rock were: density, 2.45 g/cm^3 ; sound velocity, 4 km/sec ; and a Poisson's ratio of 0.2. Fortunately, a number of material property measurements have been made on oil shale.^{2,4} As mentioned previously, there are considerable differences in the material properties of the oil shale depending upon the amount of oil the shale contains.

Figure 1 illustrates the variation in the material properties with the grade of the oil shale. It can be seen that the density can vary between 1.6 g/cm^3 and 2.6 g/cm^3 . Sonic log travel time ranges from $160 \text{ } \mu\text{sec/ft}$ to $60 \text{ } \mu\text{sec/ft}$ where $160 \text{ } \mu\text{sec/ft}$ corresponds to a compressional velocity of 6250 ft/sec or 1.9 km/sec . A sonic log travel time of $60 \text{ } \mu\text{sec/ft}$ corresponds to a velocity of 16600 ft/sec or 5 km/sec . Figure 2 shows the shear strength of the shale as a function of the mean pressure. The solid lines represent the failure envelope through the unfractured shale. The dashed line is the failure envelope for highly fractured shale. As the amount of oil in the shale increases, the shale becomes ductile at lower pressures. Note that all three curves have a common unconfined compressive strength near the origin.

THE CALCULATIONAL MODEL

As previously discussed, the site at Rio Blanco has a region from the surface to approximately 3000 ft in depth that is highly layered and variable in its properties. From 3000 ft to the planned detonation point at approximately 6000 ft, the shale is fairly homogeneous. Figure 3 shows a plot of the compressional velocity in feet per second and the density in grams per centimeter cubed for the first 2800 ft from two holes near the Rio Blanco site area. The compressional velocities are from the Fawn Creek No. 3 Well approximately 2-1/2 mi from ground zero. The density logs are from Ryan No. 2 approximately 7 mi from surface ground zero. A consistent feature of the two logs is the discontinuity in both compressional velocity and density at a depth of about 1800 ft. This is consistent with the reflective layer that was determined from the seismic survey conducted in Rio Blanco County.¹⁰ Boardman¹¹ calculated the impedances (that is velocity times density) for the oil shale at depths between 400 and 2300 ft at the Fawn Creek No. 1 well. The impedances were determined by converting the grades of oil every 10 ft into a density and compressional velocity as shown on Fig. 1. Boardman found the maximum ratio of impedance discontinuities was approximately 1.7 in this interval.

Fig. 1. Relationships between density, velocity, and oil assay established by various investigators.

Fig. 2. Shear strength of shale as a function of pressure.

Fig. 3. In situ density and velocity data.

The first calculation used the homogeneous Wagon Wheel shale in the depth interval between 2000 and 6000 ft. From the surface to 2000 ft an oil shale containing approximately 25 gal/ton of oil was used. Such rock has a density of 2.193 and a compressional velocity of 2.79 km/sec. This results in an impedance ratio at the interface between the two shales of approximately 1.65, which is essentially the same as the maximum as determined by Boardman from the Fawn Creek No. 1 well.

Figure 4 shows the velocity profile resulting from the deposition of 100 kt of energy at 6000 ft depth taken 560 msec after the detonation. The maximum limit of fracture as determined from this calculation was 132 m from the detonation point. This is equivalent to approximately 5 cavity radii. (Note that this is in excellent agreement with the experimental data determined by Borg¹² and shown in Fig. 5, where no appreciable fracturing has been experimentally found beyond 5 cavity radii from a shot point). This calculation also showed a very weak tensile wave being reflected from the interface represented by the maximum impedance discontinuity in the oil shale. The calculation showed that the shear stresses developed at and near this interface were insufficient to overcome the effects of overburden, and thus were incapable of initiating fractures. This calculation also indicated a peak spall velocity at the free surface of 2.5 m/sec. The spall depth at which fracturing could occur was calculated to be 52 m (170 ft). The maximum depth of spall, (that is, where there was some relief of the overburden stresses but an insufficient amount to cause separation) was approximately 360 ft. It should be noted that for this calculation the oil shale from 0 to 2000 ft was assigned a zero tensile strength, and that the tensile strength of the lean oil shale from a depth of 2000 to 6000 ft was measured to be 100 bars. Figure 6 shows a pressure profile from this calculation at 800 m from the detonation point. This pressure profile was used as the source function for the rest of the calculations.

Figure 7 shows the model for the remainder of the calculations. The pressure profile as shown in Fig. 6 is applied at a depth of 3378 ft. The layer between this depth and 1966 ft is assumed to have the properties of Wagon Wheel shale. Two more calculations were made in which shale B (the layer from the surface to a depth of 1966 ft) was assumed to be an oil shale of 40 gal/ton and oil shale of 60 gal/ton, respectively. The densities, compressional velocities, and impedance values are also shown in Fig. 7 for each of the four shale types. In all the following calculations, a zero tensile strength has been assumed for all rock types.

The next two figures should be extremely helpful in interpreting the results of the remainder of the calculations. They illustrate the effect of fracturing caused by a tensile wave reflected from a free surface. A similar behavior would be expected by a reflection from a subsurface layer. Figure 8 shows the absolute value of the shear stress vs the normal stress for unfractured shale 30 m below the ground surface. The shear stress strength is shown by the dashed line. Initially, the zone is at point A where the shear stress is zero and confining pressure due to overburden is present. As the stress wave approaches, the shear stress and the normal stress both increase to point B. As the stress wave passes, the shear stress and the normal stress both relax

Fig. 4. Velocity profile for 100 kt at 6000 ft depth at time 560 msec.

Fig. 5. Observed horizontal fracture distance.

Fig. 6. Pressure profile at 800 m from 100 kt.

Material Properties

Shale type	Density $\rho(\text{g/cm}^3)$	Compressional velocity C_p km/sec	Impedance
A(Wagon Wheel)	2.45	4.12	10.1
B1(Oil shale 25 gal/ton)	2.193	2.79	6.12
B2(Oil shale 40 gal/ton)	2.0	2.23	4.46
B3(Oil shale 60 gal/ton)	1.7	2.0	3.4

Fig. 7. Model for layer calculations.

Fig. 8. Absolute value of the shear stress vs normal stress for unfractured shale 30 m below ground surface.

to point C, passing through zero. From C to D, the shear stresses are negative. At D they exceed the tensile strength of the rock; that is, they have exceeded the overburden stresses plus the shear strength of the rock. Consequently, the rock fails at D and the stresses then relax to zero at E. The zone is now in spall.

Figure 9 also shows the absolute value of the shear stress vs the normal stress for prefractured shale at the same point (30 m below the ground surface) as that considered in Fig. 8. The tensile failure is the same as in Fig. 8, but the shear strength has been reduced to that for a prefractured rock as shown. The initial overburden is the same at point A with the shear stresses at zero. As stress wave approaches, the shear stress and normal stress both increase to point B. This point represents the onset of shear failure, and a crack is propagated through the zone. At C, the effect of the crack becomes a dominant factor in relaxing the shear stresses. The relaxation of the shear stress can be seen from C to D. From D to E the shear stresses are negative. At E the shear stress has been exceeded once again, and the stresses are rapidly adjusted, this time to zero. At this point the zone is in tension and in the process of spall.

The next calculation used the properties consistent with an oil shale containing approximately 40 gal of oil per ton. Figure 10 is a plot of the shear stress vs the normal stress 10 m below the interface between the two shales. At this depth, the normal overburden pressure is approximately 120 bars. As can easily be seen, the shear stress does not approach the failure envelope nor does it approach the tensile failure envelope.

In the next calculation the surface layer (shale B) was given properties consistent with oil shale containing approximately 60 gal of oil per ton of rock. Figure 11 shows the shear stress vs normal stress for a zone 5 m below the interface and Fig. 12 shows the same parameters for a zone 5 m above the interface. As can be easily seen, fracturing is not possible either below or above the interface. It should also be noted that the ratio of the impedance between the two shales across the interface is approximately 3.4. This is twice the observed ratio as determined by Boardman.

Calculations were also completed for layered problems in which a thin layer between 1 to 30 m in thickness was located at a depth of approximately 2000 ft. These calculations indicated that while the tensile wave was reflected from the lower surface, a compressive wave was reflected from the upper surface; these tended to cancel as they propagated back towards the shot point. Consequently, there was even less chance of fracturing in this case than there was with a solid layer to the free surface. In the case where there are many layers and the material properties of the layers are contrasting, the stress wave tends to be scattered by the various layers. The emerging stress wave then has the characteristics of a stress wave propagated through a region whose material properties were the average of those of all of the layers.

Figure 13 illustrates the reflected and transmitted portions of the radial stress wave.

Fig. 9. Absolute value of the shear stress vs normal stress for prefractured shale 30 m below ground surface.

Fig. 10. Shear stress vs normal stress 10 m below interface for 40 gal/ton oil shale.

Fig. 11. Shear stress vs normal stress 5 m below interface for 60 gal/ton oil shale.

Fig. 12. Shear stress vs normal stress 5 m above interface for 60 gal/ton oil shale.

Fig. 13. Reflection for various layer thickness.

A 30-m zone reflects similarly to an infinitely thick zone except for the compressive wave returning from the outer surface of the layer. A 1-m zone will cause only a small perturbation on the existing stress field.

CONCLUSION

Calculations have been presented in which the mechanism of fracture has been illustrated for the reflection of a shock wave off of a free surface. Using the measured material properties for the near surface rock (assuming no tensile strength) at the Rio Blanco site, a spall velocity of 2.5 m/sec and a fracture depth of 170 ft have been calculated for a total yield of 100 kt at 6000-ft depth.

The same calculations that predicted fracture at the ground surface also illustrated that there is no possible means by which fracture can occur between the depths of 360 and 5000 ft. This is true even though impedance mismatches up to twice those observed were examined, and the reduced shear strength of fractured shale with zero tensile strength was used.

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APPENDIX H
DIVINING GAS PRESSURE AT RIO BLANCO

CHEMISTRY DEPARTMENT TECHNICAL NOTE NO. 71-76

"Divining Gas Pressure at Rio Blanco"

R. W. Taylor

1. INTRODUCTION AND SUMMARY

The purpose of this note is to estimate the maximum gas pressure that may be sustained in the Rio Blanco chimney following chimney collapse.

The assumption is made that the cavity gas, initially at $\sim 2000^{\circ}\text{C}$, flows into all the cracks between the rubble and cools. Estimates of the amount of gas released and the cooling rate of the gas make it possible to estimate the rate of pressure fall. The rate of release of natural gas out of the rubble and CO_2 and steam out of heated rock also affects the rate of pressure fall. All the gas expected in the chimney from these two sources is assumed to be released at the time of chimney formation. This is not realistic; the assumption tends to make the pressure estimates too high at early times.

I conclude that during the first 10 seconds after the chimney is formed, the gas pressure may exceed lithostatic pressure. Within one minute after the cavity gas is mixed with the rubble, the pressure will fall to formation pressure (190 atm). At times of one hour (after the condensation of steam) to about one month, the gas pressure in the chimney is expected to increase from 110 atm to formation pressure.

The most important factor in the rate of pressure fall is the rubble size. If the rubble is assumed to consist of 1 meter cubes, and the cracks between the cubes are 1/10 meter wide (corresponding to a void volume of $\sim 25\%$), the pressure will fall to formation pressure about two minutes after the rubble and gas are mixed. If the rubble were 0.2 meter cubes, the increased surface area would cool the gas much more rapidly, and the gas pressure would be expected to fall to formation pressure about 10 seconds after the gas is mixed with the rubble.

2. $P = nRT/V$

According to everyday experience, the pressure of a gas (P) is proportional to the amount of gas (n), gas temperature (T), and inversely proportional to the volume of the container (V).

The volume available for gas in the case of an underground nuclear detonation is the cavity volume. This can be calculated rather well by empirical and semi-theoretical ways based on the depth of the explosion and the energy yield of the explosive. Following collapse the void volume which had been the cavity becomes interstitial volume in the rubble which fills the original cavity and most of the chimney. The total void volume to be created by the three Rio Blanco 30 kt explosives is about $1.3 \times 10^{11} \text{ cm}^3$. Thus the pressure can be expressed as the following function of n and T : $P = 6.3 \times 10^{-10} nT$.

3. RAPID RELEASE OF NATURAL GAS FROM FRACTURED ROCK

The amount of gas expressed as the number of moles of gas (n) in the above expression can be estimated. First of all, there is the natural gas released rapidly from the rubble in the chimney. For the present model it is assumed that all the rock has a porosity of 10% and that the pores are half-filled with natural gas at formation pressure (190 atm) and at ambient formation temperature ($\sim 100^\circ\text{C}$). Under these assumptions the rock contains $\approx 1.3 \times 10^{-4}$ moles of CH_4 per gram. (This estimate represents the maximum gas content, and is probably high by a factor of 2 to 10.)

The total amount of rubble in the chimney is expected to be about 10^{12} g . Thus, the maximum amount of CH_4 which can be released from the rubble is 1.3×10^8 moles. If this were the only gas in the chimney, the pressure as a function of chimney temperature would be

$$P_{\text{CH}_4} = 8.2 \times 10^{-2} T,$$

where P_{CH_4} is equal to the pressure due to CH_4 and T is the temperature in degrees Kelvin. Figure 1 shows P_{CH_4} as a function of temperature for the Rio Blanco chimney. The formation pressure and lithostatic pressure are also shown.

4. GAS RELEASED FROM HEATED ROCK

In addition to natural gas which is rapidly released from the fractured rock, gas released from rock by heat must also be taken into account. These gases are mostly steam (H_2O), carbon dioxide (CO_2), and hydrogen (H_2).

In order to estimate the amount of gas that is liberated from rock by heat, we must know:

1. The concentration of water, carbonates and other volatile components of the rock.
2. The temperature to which the rock must be heated in order to release these volatile components.
3. The amount of rock heated to various temperatures as a function of time.

5. WATER IN RIO BLANCO ROCK

The concentration of water in Rio Blanco rock has not been measured, but other similar rocks such as those at Gasbuggy and Rulison contain 2 to 4 wt % water. In the laboratory we find that about half of this water is liberated when the rock is heated just above the boiling point of water. This corresponds to the water in the pores in the rock. (A rock having 10% porosity and 50% water saturation contains about 2 wt % pore water.) The remaining water comes off more-or-less continuously up to a temperature of about 1100°C where the rock begins to melt.

6. CARBONATE CONCENTRATION OF RIO BLANCO ROCK

The amount of carbon dioxide, as carbonate, in typical methane-bearing rock is not known very well. Our limited analysis to date on a few samples from four sites suggests an average value of ~ 5 wt % CO₂. Samples from the same site have a range from 2 to 10%. The principal carbonate minerals are calcite (CaCO₃) and dolomite (CaMg(CO₃)₂). Because these minerals are roughly half CO₂ by weight, a rock containing 5 wt % CO₂ contains 10 wt % of carbonate minerals. In general, sand-rich rocks tend to contain more carbonate than shales.

7. THERMAL DECOMPOSITION OF CARBONATE-BEARING ROCKS

The thermal decomposition of these carbonate minerals has been studied for many years. The equilibrium CO₂ pressure generated by calcite and dolomite is known as a function of temperature. However, when R. La Pointe, J. Hill and I heated samples of Rulison rock we found that they gave up CO₂ rapidly down to a lower temperature than do pure carbonate minerals alone. Further investigations have shown that the gas-bearing shales and sandstones

are very fine-grained mixtures of quartz (SiO_2) and carbonates which, when heated to 500°C , react to form calcium-magnesium silicates. The reactions take many hours at 500°C , but only minutes at 700°C .

As a result of this work, I conclude that Rio Blanco rock heated above about 700°C will probably give up CO_2 rapidly enough to increase the chimney gas pressure. Rock heated many hours in the temperature range 450 - 550°C will also liberate CO_2 , but probably not at a rate which will exceed the rate at which gas can flow into the fractured rock around the chimney.

8. ESTIMATING THE AMOUNT OF ROCK HEATED HOT ENOUGH TO VAPORIZE H_2O AND CO_2

The amount of rock heated to various temperatures has been estimated in several ways.

French and American workers have examined the sites of several nuclear explosions in detail. At the bottom of the chimneys they found a mixture of melted rock (glass), baked rubble, and unaltered rubble. (The maximum temperature observed was 600°C a month or two after the explosion.) The amount of melted rock was 1000 ± 300 tons per kt. The range of this number is probably due in part to the fact that silicate rocks have a melting range. That is, they start to melt at $\sim 900^\circ\text{C}$ and may be totally melted at temperatures around 1200°C . One observer will identify a sample as having been melted, whereas another observer looking at the same sample, may think it is only partly melted. However, even rocks found to be partly melted ($\approx 1000^\circ\text{C}$) have been heated hot enough to release all the CO_2 and H_2O they contain.

The amount of CO_2 produced at Gasbuggy and Rulison suggests the thermal decomposition of the carbonate minerals in 1500 to 3000 tons of rock per kt. As I noted in Section 7, this required a temperature above $\sim 500^\circ\text{C}$.

Theoretical estimates of the amount of rock heated to various temperatures have been made by Higgins,¹ Nuckolls,² Butkovich,³ and Stephens.⁴ These estimates are based on experimental measurements of shock wave velocity and particle velocity in rocks. According to this approach, inelastic shock wave heating results in the melting of about 400 tons of rock per kt. The shock also heats an additional 600 to 900 tons of rock per kt to temperatures between 450°C and

1000°C. Thus, according to this method, some 1000 to 1300 tons of rock per kt are heated above 450°C in a very short time by the shock wave, without any other energy transport process considered.

The explanation for the difference between the observed 1000 tons of glass per kt (implying a temperature of ~ 1100°C) and the 400 tons of rock melted by shock heating is simply that the liquid rock produced by shock heating is all hotter, some much hotter, than the melting temperature of the rock. Liquid rock far above its melting range undergoes radiation cooling which in turn heats and melts additional rock. Thus, theoretical calculations of the amount of rock melted are not actually in disagreement with experimental observations.

In order to estimate the gas pressure, it is important to know the rate at which this "secondary melting" (the melting due to the transfer of heat from the shock melted rock) takes place. Because this study is intended to give the maximum pressure following collapse of the cavity, it is prudent to consider this secondary melting as essentially instantaneous.

In certain respects we can foresee that the Rio Blanco test will result in a different thermal history than we have seen before. Immediate collapse of the cavities is assured by the simultaneous detonation of more than one explosive. The mixture of melted rock and rubble in the upper chimneys will have little time to come to the same temperature ("stew") before the mixture falls into the top of the chimney below. Such a jumbling probably decreases the CO₂ evolution, but it may increase the short-term steam evolution by exposing hot glass to additional cold water-bearing rocks. As much as 1000 tons of rock per kt may lose pore water (in addition to the 1000 tons per kt that is melted). That is, 1000 tons of rock per kt will lose all of its water (~ 4 wt % of the rock) instantaneously and an additional 1000 tons will lose water amounting to 2 wt % of the rock during the first minute after collapse.

Thus for a first approximation, the total amount of gas released from the melt-rubble mix by 90 kt of explosive energy is 10^8 moles of CO₂ and 3×10^8 moles of H₂O. (All the CO₂ and 2×10^8 moles of H₂O are assumed to be released in much less than one minute after collapse. About an additional 1×10^8 moles

of H_2O are assumed to be released during the first minute due to heating of additional rock by contact with glass or hot gases.) The pressure as a function of temperature for this mass of gas in the Rio Blanco chimneys is shown in Fig. 1. I have neglected the H_2 produced by the combustion of free carbon in the shock melted rock. This amount of H_2 (3×10^7 moles) is small compared to the uncertainty in the amount of H_2O .

To estimate the gas pressure in the chimney, the gas temperature must first be estimated (see Section 9).

9. GAS TEMPERATURE AND GAS PRESSURE BEFORE CONDENSATION OF STEAM

The principal concern in this note is the seepage to the surface of radioactive gas due to sustained chimney gas pressure. I have made estimates of the amount of gas that is released during the first minute following chimney formation. From Fig. 1 it is obvious that pressures above lithostatic pressure in the chimney can be sustained only if the average gas temperature is above about $1300^\circ K$. When the average temperature of the gas in the chimney is above about $600^\circ K$ the gas pressure will exceed the formation pressure.

Chapin⁶ has suggested that "blowoff" of the cavity wall rapidly reduces the temperature of the gas in the cavity to $\sim 2000^\circ K$. Upon cavity collapse this $2000^\circ K$ gas is displaced upward. The rubble which displaces it is heated. At first the rate of cooling of the gas depends upon the 4th power of the gas temperature less the 4th power of the rubble surface temperature, the emissivity of the gas, and the absorptivity of the rubble. The gas emissivity depends upon the amount of dust in the gas and the chemical composition of the gas. The absorptivity of grey rocks is high, 0.8 - 0.9.⁵ I assume the transmission of heat by radiation at temperatures above $1000^\circ K$ is very rapid compared to heat transmission by convection and conduction after the gas has cooled to $\sim 1000^\circ K$.

At temperatures below $\sim 1000^\circ K$ the rate of heat transmission depends mostly upon the difference in temperature between gas and rubble times a heat transfer coefficient of $\sim 0.01 \text{ cal deg}^{-1} \text{ cm}^{-2} \text{ sec}^{-1}$ for dry gas and about 1 for condensing steam.

One must keep in mind that during most of the time heat is supplied to the rubble surfaces more rapidly than it can be conducted into the interior of the rubble. That is, the rubble surface temperature increases rapidly, decreasing the heat transfer to the rock surface and thus the rate of cooling of the gas.

The total amount of heat to be transmitted to the rubble to cool the gas from 2000°K to $\sim 600^{\circ}\text{K}$ is 6×10^{12} cal, based on an average gas heat capacity of $10 \text{ cal deg}^{-1} \text{ mole}^{-1}$. A critical factor for both radiation and convective cooling rates is the total surface area of the rubble. Estimates of the size of most of the rubble chunks in chimneys range from 10 to 50 cm.⁷ The mass of rubble in the Rio Blanco chimney is expected to be about 10^{12} g. Thus, as shown in Table I, the surface area for cubic rubble chunks 20 cm on a side is $1.2 \times 10^{11} \text{ cm}^2$. The amount of heat to be deposited per cm^2 to cool the gas is $\sim 50 \text{ cal}$; the time necessary to accomplish this cooling is ten seconds. This time estimate is based on the rate heat is transported to rubble (having a thermal conductivity of $4 \times 10^3 \text{ cal deg}^{-1} \text{ cm}^{-2} \text{ sec}^{-1} \text{ cm}$) from a gas at 825°C . This is the average temperature between the temperature where convective cooling becomes more important than radiation cooling ($\approx 1000^{\circ}\text{K}$), and the gas temperature at which the pressure is nearly formation pressure (650°K). A method given by McAdams (p. 39)⁵ for transient conduction into a semi-infinite solid was used because the maximum depth of heating of the rubble surfaces was small relative to the rubble size. Solving the problem by assuming a constant gas temperature midway between the temperatures at the start and end of cooling is a crude approximation. A more exact solution will be used in the future when we learn how to better estimate the initial gas temperature and the gas release rate.

TABLE I

Size of Rubble Block (cm)	Total Rubble Surface Area (cm^2)	Heat Transmitted to Rubble to Cool Gas to 600°K (cal/cm^2)	Time to Cool Gas to 600°K (sec)
10	2.5×10^{11}	24	~ 1
20	1.2×10^{11}	50	10
50	5×10^{10}	120	25
100	2.5×10^{10}	240	100

The calculational results are given in Fig. 2. The chimney pressure is shown as a function of time and rubble size. Don't forget that the time used in this figure is the time after the hot gas is mixed with the rubble after collapse of the cavity. This mixing may take a minute or two.

For the rubble size expected (0.2 to 0.5 m), the chimney gas pressure will remain above lithostatic pressure for about ten seconds after the gases are mixed with the rubble, and the gas pressure will remain above formation gas pressure for about 30 seconds. If most of the rubble blocks are about 1 m on a side, it will take about 100 seconds for the gas to be cooled to $\sim 600^{\circ}\text{K}$ and for the pressure to fall to 200 atm, approximately formation pressure.

10. CONDENSATION OF STEAM

As the chimney gas cools below $\sim 600^{\circ}\text{K}$, condensation of steam begins and the rate of cooling of the chimney gas will be sharply decreased. Also, as the gas temperature falls below $\sim 600^{\circ}\text{K}$, the gas pressure in the chimney falls below the gas pressure in the surrounding rocks, and gas will flow into the chimney decreasing the rate of pressure fall (see Figs. 1 and 2). It is difficult to estimate what the pressure history will be during this time because in addition to these two factors it seems probable that some steam will be added to the chimney gas as hot glass heats adjacent rubble.

The gas temperature in the chimney is expected to approach the final equilibrium rubble temperature⁸ (250°C , 523°K) before the rubble all comes to the same temperature. Notice in Fig. 1 that as the temperature falls from 600°K to 523°K the partial pressure of steam falls from about 100 atm to 33 atm. During this time about two-thirds of the steam, about 2×10^8 moles, will condense. The condensation results in the deposition of the heat of vaporization (10 kcal/mole H_2O) on the rubble surface. The total heat released to the rubble by this condensation is 2×10^{12} cal, about one-third the amount of heat necessary to cool the chimney gas (CO_2 and H_2O) from 2000°K to 600°K . For 50 cm rubble blocks the condensation deposits about 40 cal per cm^2 of surface area. If the condensing gas temperature is 100° above the average rubble temperature, it will take about 500 to 1000 seconds to deposit this amount of heat. For rubble blocks 1 m on a side, the heat to be deposited is $\sim 80 \text{ cal/cm}^2$. This

will take 1000 to 2000 seconds as shown in Fig. 2. The length of time required to conduct this additional heat into the rubble will be prolonged by the water film on the surface of the rubble as well as by the depletion of the gas in H_2O near the surface of the rubble.

The minimum gas pressure that can be reached at the expected minimum temperature of the chimney gas ($523^{\circ}K$) is about 109 atm. The gas pressure under these conditions will be divided as follows: $P_{CO_2} = 33$ atm, $P_{H_2O} = 33$ atm, $P_{CH_4}^* = 43$ atm. (The symbol, $P_{CH_4}^*$, stands for the pressure due to the CH_4 I assume escapes rapidly from the rubble in the chimney as described in Section 3.)

11. RATE OF REPRESSURIZATION AFTER CONDENSATION

In order to bring the chimney pressure up to formation pressure after the steam condenses, about 2.4×10^8 moles of formation gas (mostly CH_4) must flow into the chimney. This is about half a chimney volume at $523^{\circ}K$. The mass of rock which contains this mass CH_4 corresponds to about twice the mass of rock in the chimney. (Gas must be drawn from a distance of 3.3 times the chimney radius.) In order to fill the chimney nearly to formation pressure, a mass of rock equal to at least 20 times the mass of the rubble in the chimney must contribute $\sim 10\%$ of the natural gas it contains. This means that gas must flow into the chimney from a distance 4 to 5 times the chimney radius away from the axis of the chimney. Perhaps the best model for the length of time this flow may take is Rulison. The first draw-down test reduced the chimney pressure to ~ 100 atm, half the formation pressure. The chimney pressure never recovered. Thirty days later the chimney pressure had increased to only ~ 130 atm. One may assume that Rulison also had an early rapid depressurization due to the condensation of steam. This removed formation gas from nearby and had the effect of decreasing the rate of pressure buildup after what we call the first production test, but what in effect may have been the second depressurization. In any case it appears that it will probably take days to a month for the Rio Blanco chimney pressure to return to formation pressure after the condensation of steam. After $\sim$ one hour but before $\sim$ one month, I expect the chimney gas pressure to be less than formation pressure, but above 110 atm.

12. DISCUSSION

According to this model, natural gas will be displaced away from the edge of the chimney for a short time leaving water in the cracks in the surrounding rock. With continued cooling and steam condensation, the pressure in the chimney will fall below formation pressure and formation gas from outside the chimney (as well as the chimney gas which had previously been forced into this fractured region) can flow into the chimney. Evidence for this behavior was found by Smith⁹ when studying Rulison. Toward the end of production testing, when the pressure was very low, he noted an increase in $^{14}\text{CO}_2$ relative to ^{85}Kr and H_2 . This CO_2 may be coming out of solution in water as if some $^{14}\text{CO}_2$ were driven into the surrounding formation to be dissolved in the water which condensed from steam.

RWT/dc

Fig. 1. Rio Blanco gas pressure.

Fig. 2. Rio Blanco chimney-gas pressure history for rubble of various sizes (in meters).

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APPENDIX I
GAS FLOW TO MULTIPLE NUCLEAR CHIMNEYS
Donald W. Beaver

ABSTRACT

This study examines the gas flow to three interconnected nuclear chimneys in an effort to determine how the degree of interconnection will be reflected in a gas production test. The work was carried out by means of numerical simulation of a hypothetical production test. An analysis of the pressures in the three chimneys indicates that while some information regarding the degree of interconnection of the chimneys can be obtained by merely monitoring the pressure at the top of the upper chimney during the test, pressure data from all three chimneys would have to be obtained in order to get a more complete picture. A proposal to introduce inert gas tracers into the chimneys and monitor the concentrations of these tracers in the produced gas appears likely to be able to give a good idea of the degree of interconnection between the chimneys.

INTRODUCTION

The use of nuclear explosives to stimulate gas-bearing formations of low permeability has received a great deal of study in recent years. Two experimental projects, Gasbuggy and Rulison, have already been carried out in the United States, and the results of these nuclear explosions and subsequent gas production tests are currently being studied. However, each of these experiments involves the use of only a single nuclear explosive.

Future projects are envisioned in which multiple nuclear explosives will be detonated in a single emplacement hole. Ideally, the resulting high-capacity chimneys will be well connected due to a high degree of fracturing in the region between the chimneys.^{*} Thus a large thickness of the gas-bearing formation can be stimulated and the gas produced from a single hole. A complete statement of the nuclear-explosive gas stimulation program is given by Werth et al.¹

The purpose of the present study is to examine the gas flow to multiple interconnected nuclear chimneys, in an attempt to determine how the degree of interconnection will be reflected in a production test. The basic parameters considered are the permeability and dimensions of the regions connecting the nuclear chimneys. The study was carried out by means of numerical simulation of a hypothetical gas-production test.

^{*}In the limiting case, the chimneys and the regions connecting them will coalesce into one large chimney.

DESCRIPTION OF THE MODEL

The system studied consisted of three chimneys produced by nuclear explosions of approximately equal yield. Each chimney was assumed to be connected to an equal thickness of gas-bearing formation of low porosity and low permeability. The gas formation was assumed to be completely saturated with gas; however, the results of this study should also apply to systems containing significant water saturation, so long as negligible amounts of water are produced.

The gas flow was studied by assuming one-dimensional darcian flow in cylindrical geometry, with horizontal radial flow in the gas reservoirs and vertical linear flow in the regions connecting the chimneys. Neglecting gravity, and basing the calculations on gas quantities measured in standard volumes, the flow can be described² by the equation

$$\epsilon(\gamma/P_0)(\partial P/\partial t) = \nabla \cdot [(K\gamma/\mu P_0) P \nabla P] \quad (1)$$

where ϵ is the porosity of the medium, K is the permeability of the medium, μ is the viscosity of the gas, P is the pressure, $\gamma = Z_0 T_0 / ZT$, Z is the compressibility factor of the gas, T is the temperature of the gas, and a zero subscript denotes a quantity measured at standard temperature (520°R) and pressure (14.7 psi).

Equation (1) was solved by means of the TRUMP finite-difference computer program^{2,3} for a hypothetical production test consisting of a 90-d postshot period of pressure buildup, followed by a period of constant production and then a 60-d period of pressure recovery. A number of runs were made in which the properties of the two regions connecting the chimneys were varied. The results are presented mainly as plots of time versus pressure within the three chimneys.

It was assumed that each chimney was formed by a nuclear explosive of approximately 30-kt yield, producing a cavity radius (R_c) of 70 ft. The resulting chimneys were each assumed to be cylinders of radius R_c and height $4 R_c$. The chimneys were assumed to be connected by highly fractured cylindrical regions of radius R_c and height $2 R_c$. It should be noted here that the gas flow through these connecting regions is governed by the quantity KA/ℓ , which can be called the conductance of the medium where K is the permeability, A is the cross-sectional area normal to the flow direction, and ℓ is the length of the flow path (i.e., the height of the connecting region). Since it was the effect of varying this conductance which was principally studied, the actual dimensions of the connecting regions assumed in the model are relatively unimportant.

Each chimney was also assumed to be connected to a gas-bearing formation (reservoir) 130 ft in height, with an effectively infinite radial extent. This could represent either a single homogeneous formation 130 ft thick or a system of interbedded shales and gas sands with a net pay height of 130 ft. The portion of the gas formation nearest the chimney, out to a radial distance of $3 R_c$ from the axis of symmetry of the chimney, was assumed to have a permeability 25 times the reservoir permeability, due to fracturing produced by the nuclear explosion. The dimensions and properties of

the chimneys, the surrounding fractured regions, and the reservoirs were taken as being fairly representative of contained nuclear explosions in tight gas formations, as determined from the Gasbuggy and Rulison projects and the data reported by Butkovich and Lewis.⁴ Figure I-1 is a sketch of the system studied.

Table I-1 gives the values of the properties of the chimneys, fracture regions, and reservoirs, which were held constant for each run. The chimney porosity (ϵ) was determined from the cavity volume divided by the total chimney volume:

$$\epsilon = \frac{(4/3) \pi R_c^3}{(4R_c) (\pi R_c^2)} = \frac{1}{3}.$$

The 5 percent porosity of the rocks comprising the chimney rubble was neglected in determining the chimney porosity. The porosity of the fractured region around the chimney was assumed to equal the reservoir porosity. The gas within the chimneys and the regions connecting them was assumed to have an initial pressure of 1000 psi; this pressure may be attributed to the natural gas initially trapped within the chimneys, as well as gases produced by the explosions. The gas pressure in the upper, middle, and lower reservoirs was assumed to be initially 2400 psi, 2600 psi, and 2800 psi, respectively. This corresponds approximately to a hydrostatic pressure gradient of 0.433 psi/ft of depth below the surface, with the upper reservoir at an average depth of approximately 5550 ft. The values of the viscosity and the compressibility factor were determined for natural gas of 0.65 gravity (relative to air), at the appropriate temperatures and pressures, from graphs reproduced in Amyx *et al.*⁵ The viscosities and compressibility factors were assumed to remain constant at their initial values.

The simulated production test began with a 90-d postshot period of pressure buildup in the three chimneys, produced by gas flowing from the reservoirs into the chimneys, as well as some flow from the lower chimneys into the upper one. This was followed by 20 d of production from the upper chimney at a constant rate of 3×10^7 SCF/d and then a 60-d period of pressure recovery following shut-in of the well. In some of the

Table I-1. Chimney, fracture region, and reservoir properties.

	Chimney	Fractured zone	Reservoir
Radial extent—ft	0-70	70-206.5	206.5-2866.5
Height—ft	280	130	130
Porosity— ϵ	0.333	0.05	0.05
Permeability—K(md)	∞	1.0	0.04
Temperature—T(°R)	860	660	660
Viscosity— μ (CP)	0.015	0.02	0.02
Compressibility factor—Z	1.0	0.95	0.95
Gas deviation factor— $\gamma = (Z_0 T_0)/(ZT)^a$	0.603	0.823	0.823

^a Z_0 = standard compressibility factor = 1.0; T_0 = standard temperature = 520°R (60°F); P_0 = standard pressure = 14.7 psi.

Fig. I-1. Schematic diagram of the chimney system.

cases studied, the pressure decline during the production period was so rapid that 20 d of production could not be sustained without producing physically meaningless negative bottom-hole pressures. In these cases, the production was terminated when the bottom-hole pressure had fallen to 300 psi; consequently, the production tests modeled were not all of the same duration.

RESULTS

The first problem was to determine how much of a variation in conductance (KA/ℓ) of the regions connecting the chimneys would give a significant variation in the bottom-hole pressure behavior, where the bottom-hole pressure is measured at the top of the upper chimney (i.e., the bottom of the re-entry hole).

To this end, a series of runs was made in which the conductances of the two connecting regions were equal. The conductance was first taken as being zero and then increased until further increase produced no discernible change in the bottom-hole pressure curve. This maximum conductance was designated as "high." On the basis of the bottom-hole pressure decline curves during the production period, two other values of the conductance were designated as "medium" and "low"; these conductances gave decline curves which were roughly equally spaced between those for high conductance and zero conductance (curves A, B, C, and D of Fig. I-3).

The chosen values for high, medium, and low conductance, in darcy-feet, were: high, 29; medium, 1.45; low, 0.29. This is a high:medium:low conductance ratio of 100:5:1.

A more detailed analysis of the flow behavior in the system was then carried out for various combinations of high, medium, and low conductance in the two connecting regions. Table I-2 lists the various combinations studied. Throughout this first series of runs, the porosities in the connecting regions were taken as being equal to the reservoir porosity, 5 percent.

Table I-2. Combinations of conductance studied.

Case	Conductance in upper connecting region	Conductance in lower connecting region
A ^a	Zero	Zero
B	Low	Low
C	Medium	Medium
D	High	High
E	High	Low
F	High	Medium
G	Medium	Low

^aSingle isolated chimney.

Figure I-2 shows the bottom-hole pressure buildup during the first 90 days postshot for each of the cases studied. Except for the case of no connection between the chimneys, it is practically impossible to distinguish one case from another on the basis of this initial bottom-hole pressure buildup. The case of zero connection exhibits a much slower pressure increase because the upper chimney has absolutely no connection to the lower reservoirs with their higher initial pressures.

Figure I-3 shows the bottom-hole pressure decline during the production period for all seven cases. During this period of the production test, each case exhibits distinct bottom-hole pressure behavior. Nevertheless, on the basis of bottom-hole pressure information alone, it would probably be difficult to determine the degree in interconnection between the chimneys in any detail. The best that could be said is that the interconnection is relatively good or relatively poor.

Figure I-4 shows the bottom-hole pressure recovery following shut-in of the well for each case. Note that the curves are plots of bottom-hole pressure versus shut-in time: i.e., elapsed time since production was terminated.

These curves illustrate a number of interesting points. Except for the case of no connection between the chimneys, the pressure recovers more rapidly in the cases of lower conductance. If the conductance of the region connecting the upper chimney with the middle chimney is fairly low, during the production period the upper chimney and the fractured region surrounding it are rapidly depleted, while the lower chimneys are less affected by the production. Consequently, when production is terminated, there is significant flow into the upper chimney from below, producing a rapid rise in pressure.

If the conductance of the connecting region is relatively high, all three chimneys can undergo some depletion during the production period. Thus, when the production is terminated, less gas flows into the upper chimney from below, and more flows into it from the lower-pressure reservoir it is connected to. This results in a lower rate of bottom-hole pressure recovery.

In the case of no connection between the chimneys, the production produces very rapid depletion of the upper chimney and its connected fractured region. On termination of the production, gas can flow into the chimney only from the upper reservoir, with no flow from below, resulting in a much lower rate of pressure recovery.

Where there is different conductance in the two connecting regions, note that the conductance of the upper region appears to be the predominant factor influencing the bottom-hole pressure recovery. This is especially true for the cases of high conductance in the upper region, as can be seen by comparing curves D, E, and F in Fig. I-4. This is also demonstrated, although not quite so clearly, by comparing curves C and G.

Some of the points mentioned above are also illustrated in Figs. I-5 through I-8, which show plots of time versus rates of gas flow into the upper chimney. Gas can flow into the chimney from both the reservoir it is connected to and from the lower chimneys. In fact, during the recovery period, gas can flow from the chimney into the reservoir.

Figure I-5 shows the total rates of gas flow into the upper chimney during the production and recovery periods for the cases of high, low, and zero conductance in the

Fig. I-2. Postshot bottom-hole pressure buildup.

Fig. I-3. Bottom-hole pressure decline during production.

Fig. I-4. Bottom-hole pressure recovery.

Fig. I-5. Total gas flow rates into upper chimney during production and recovery periods.

Fig. I-6. Gas flow rates into upper chimney during production and recovery periods—case D, high conductance.

Fig. I-7. Gas flow rates into upper chimney during production and recovery periods—case B, low conductance.

Fig. I-8. Gas flow rates into upper chimney during production and recovery periods— case A, zero conductance. All flow is from the reservoir.

connecting regions between the chimneys. Note that the higher the conductance, the greater the rate of gas flow into the chimney during production, and hence, as seen above, the lower the rate of bottom-hole pressure decline. During recovery, however, the highest rate of flow into the chimney, and hence the highest rate of pressure recovery, occurs for the case of low conductance.

Figure I-6 shows the rates of gas flow into the chimney from below and from the upper reservoir for the case of high conductance. Note here that during production, most of the gas flows into the chimney from below, while during recovery, most of the gas flows in from the reservoir.

Figure I-7 shows the rates of gas flow from below and from the reservoir for the case of low conductance. In this case, the gas flow is about equally distributed between that from below and that from the reservoir during production. During recovery, however, most of the gas flowing into the chimney comes from below. In fact, the negative rates of gas flow from the reservoir indicates that gas is actually flowing from the chimney into the reservoir.

Figure I-8 shows the rate of gas flow into the upper chimney for the case of no connection between it and the lower chimneys. This case has a higher rate of flow from the reservoir than the preceding one, but has a lower total rate of flow because no gas can flow into the chimney from below.

Figures I-9 through I-15 give a good picture of the overall pressure behavior of the system. These figures show the pressures in all three chimneys, for the entire duration of the simulated production test, for each of the cases studied except for that of no connection between the chimneys.

Figure I-9 shows the case of high conductance in both connecting regions. In this case, there is essentially no difference in the pressure curves for the three chimneys, so the system behaves as one large chimney connected to three gas reservoirs at different initial pressures.

Figure I-10 shows the case of medium conductance in both connecting regions. Here the pressures in the three chimneys are largely the same during the initial post-shot buildup and after about 10 d of recovery from the production, although there is a significant difference in the three pressure decline curves during production.

In the case of low conductance in the connecting regions, Fig. I-11, there is a significant difference in the three curves during all phases of the production test. Note here that the pressures in the lower two chimneys continue to decline for about 10 d after production has been terminated.

Figures I-12 through I-15 show the pressures in all three chimneys for the cases in which the two connecting regions have different conductances. In the first two figures, for which the upper connecting region has high conductance, the pressures in the upper two chimneys are essentially the same throughout the test, but the pressure in the lower chimney is somewhat different. When the lower connecting region has medium conductance (Fig. I-13) rather than low conductance (Fig. I-12), the pressure in the lower chimney remains much closer to that in the upper two chimneys.

Fig. I-9. Pressure in all three chimneys; both connecting regions have high conductance—case D.

Fig. I-10. Pressure in all three chimneys; both connecting regions have medium conductance—case C.

Fig. I-11. Pressure in all three chimneys; both connecting regions have low conductance—case B.

Fig. I-12. Pressure in all three chimneys; high conductance in the upper regions, low conductance in the lower regions—case E.

Fig. I-13. Pressure in all three chimneys; high conductance in the upper region, medium conductance in the lower region—case F.

Fig. I-14. Pressure in all three chimneys; medium conductance in the upper region, low conductance in the lower region—case G.

Fig. I-15. Pressure in all three chimneys; high conductance in the upper region, zero conductance in the lower region (i.e., two isolated chimneys).

When the upper region has medium conductance and the lower region has low conductance (Fig. I-14), the pressure curves are qualitatively much like those of the preceding case, except that differences in the pressures in the three chimneys are greatly exaggerated.

Figure I-15 shows the pressures in all three chimneys for one additional case with high conductance in the upper connecting region but zero conductance in the lower region: i.e., a case of two isolated chimneys.

Although the curves in Figs. I-9 through I-15 give a good picture of the pressure behavior of the system, they would be hard to correlate with field data from an actual production test because of the extreme difficulty, if not impossibility, of monitoring the pressures in all three chimneys. However, it has been suggested that inert gas tracers could be incorporated with the nuclear explosives in a multiple-shot experiment and the concentrations of these tracers measured in the produced gas. The distinct pressure differences in the three chimneys shown in Figs. I-10 through I-15 indicate that distinct ratios of tracer gases should be observed for different degrees of interconnection between the chimneys. However, a more complete analysis of the actual gas flow rates between the chimneys, and from the reservoirs into the chimneys, should be carried out before this can be determined with any certainty.

In the series of computer runs reported on above, the porosity of the regions connecting the chimneys was assumed to be equal to the in situ reservoir porosity, 5 percent. Other runs were made in which the porosity of the connecting regions was assumed to be equal to the chimney porosity, 33.3 percent. This may not be as physically reasonable an assumption as the preceding one, but it could occur, for example, if the connecting regions underwent extreme fracturing and collapse, comparable to that in the chimneys, with the chimneys and connecting regions actually coalescing into one large chimney but with the melt from the nuclear explosives disseminated throughout the connecting regions before it solidified. Thus, the connecting regions would have high porosity and hence a high capacity for gas storage but a relatively low permeability due to restriction of the gas flow caused by the solidified melt.

Figures I-16 through I-19 show the effect on the chimney pressures of this higher porosity in the connecting regions.

Figure I-16 compares the bottom-hole pressure curves for high and low porosity, with high conductance, in the connecting regions. Note that the higher porosity results in slower rates of pressure buildup and pressure recovery following production. This is due to the fact that the higher gas storage capacity in the connecting regions results in a slightly lower rate of gas flow through these regions. The lower rate of pressure decline during production for the case of higher porosity is probably a result of release of some of the gas stored in the connecting region during the initial buildup period.

Figures I-17 and I-18 compare the bottom-hole pressure curves for high and low porosity for the cases of medium and low conductance in the connecting regions, respectively. Again, the effect of the higher storage capacity in the case of higher porosity is shown by a slower rate of pressure buildup and a slightly slower rate of pressure decline.

Fig. I-16. Bottom-hole pressure: both connecting regions with high conductance.

Fig. I-17. Bottom-hole pressure: both connecting regions with medium conductance.

Fig. I-18. Bottom-hole pressure: both connecting regions with low conductance.

Fig. I-19. Pressure decline during production in the middle and lower chimneys.

Figure I-19 shows the pressure decline during production in the middle and lower chimneys for the cases of high, medium, and low conductance, and high and low porosity, in the connecting regions. In all cases, the higher porosity results in a lower rate of pressure decline. Note, however, that especially for the lower chimney, the rate of pressure decline is more strongly influenced by the conductance than by the porosity of the connecting regions.

One other factor that was examined slightly in this study is the effect of the duration of the initial postshot period of pressure buildup. In all of the cases mentioned above, production was begun after only 90 d of pressure buildup. However, in the Gasbuggy and Rulison projects, at least 180 d had elapsed before production was begun. Thus one other run was made in which both connecting zones had high conductance (28.94 darcy-ft) and low porosity (5 percent). This run simulated a production test consisting of 180 d of postshot pressure buildup, followed by 20 d of production at a constant rate of 3×10^7 SCF/d and then 100 d of pressure recovery.

Figure I-20 shows the pressure in all three chimneys for the duration of this test. Since the conductance in both connecting regions is high, there is practically no difference in the pressures among the three chimneys, except for a slight variation during the producing period. Figure I-21 shows a comparison of the bottom-hole pressure curves during the last 30 d of the initial buildup period, the production period, and the first 60 d of the recovery period. There is a slight difference in the curvatures of the initial buildup and recovery curves, but in general the pressure for the longer test is about 100 psi higher than that for the shorter test.

Although this is only a very cursory examination of the effect of a longer initial buildup period on the overall pressure behavior of the system, it is felt that the results indicate that the longer buildup period will produce only slightly higher bottom-hole pressures than the shorter test. However, in the cases of lower conductance in the connecting regions, a longer initial buildup period can be expected to result in somewhat greater flow between the chimneys, and thus in slightly less pressure differences among the three chimneys. Nevertheless, the conclusions drawn from this study should generally hold true even for production tests involving a longer period of initial pressure buildup than those studied here.

Finally, a more detailed examination of the differences in conductance of the connecting regions should be made. As noted before, the conductance, defined as KA/ℓ , depends on both the permeability and the dimensions of the connecting regions. Table I-3 lists values of high, medium, and low permeabilities for different combinations of cross-sectional area and length of the connecting region. It can be seen here that even though the two connecting regions were assumed to have the same dimensions in carrying out this study, the results are applicable to systems in which the connecting regions have differing dimensions and even differing permeabilities, such as might result if the three nuclear explosives were not equally spaced in the emplacement hole.

Fig. I-20. Pressure in all three chimneys; high conductance in both connecting regions.

Fig. I-21. Bottom-hole pressure curves for cases of 90-day and 180-day initial buildup.

Table I-3. Permeability values for various cavity radii, cross-sectional areas, and lengths.

Radius—ft	Cross-sectional area—ft ²	Length—ft	Permeability—md		
			High conductance	Medium conductance	Low conductance
70	1.539×10^4	280	526	26.3	5.26
70	1.539×10^4	140	263	13.2	2.63
70	1.539×10^4	70	132	6.58	1.32
70	1.539×10^4	35	65.8	3.29	0.658
40	5.027×10^3	280	1610	80.6	16.1
40	5.027×10^3	140	806	40.3	8.06
40	5.027×10^3	70	403	20.1	4.03
40	5.027×10^3	35	201	10.1	2.01
20	1.257×10^3	280	6440	322	64.4
20	1.257×10^3	140	3220	161	32.2
20	1.257×10^3	70	1610	80.6	16.1
20	1.257×10^3	35	806	40.3	8.06

Perhaps the most significant result shown in Table I-3 is the fact that even the lowest permeability shown, that of a low-conductance region 70 ft in radius and 35 ft long, is still more than 15 times greater than the assumed in situ reservoir permeability. For a connecting region of radius R_c (70 ft) and length $2 R_c$ (140 ft), even a relatively high permeability of 13.2 md results in a medium conductance and hence a rather significant departure in pressure behavior from that of high-conductance connecting regions. Furthermore, in order to obtain high conductances in the connecting regions, which is the most favorable condition for a multiple chimney gas-stimulation project, the connecting regions must have very high permeabilities of the order of hundreds of millidarcies. Thus it would appear that there is a fairly good chance that the behavior of such a multiple-chimney project may be less than optimum, and that this behavior can be detected during a production test similar to that simulated in this study.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study provide an estimate of the degree of difference in conductances of the connecting regions between multiple nuclear chimneys which produces noticeable changes in the pressure behavior of the multiple-chimney gas-flow system, and some idea of the magnitudes of these changes in pressure behavior. It was found that for reasonable dimensions of the connecting regions (radius R_c and length $2 R_c$), the permeability could be as high as 13 md, more than 300 times as great as the

assumed in situ reservoir permeability, and yet produce a noticeable departure in pressure behavior from that of the more nearly ideal case of high conductance in the connecting regions. Furthermore, the permeability of the connecting regions would have to be as high as hundreds of millidarcies in order to produce a high conductance and thus a high degree of interconnection between the nuclear chimneys.

The effects of high porosity in the connecting regions were also examined in this work, as were the effects of a longer period of initial postshot pressure buildup in the chimneys. Although it was found that varying these parameters does produce some variation in the pressure behavior of the system, the conductance of the connecting regions is a far more influential factor.

Various combinations of conductances in the two connecting regions between the three chimneys produced rather unique pressure curves in the chimneys. Since these pressure curves reflect the rates of gas flow between the chimneys, it is felt that a proposed plan to incorporate inert-gas tracers with the nuclear explosives in a multiple explosive experiment should be able to provide a rather sophisticated determination of the degree of interconnection between the chimneys. Furthermore, for experimental purposes, it might actually be desirable for the two connecting regions to have different conductances. This could be produced if the connecting regions have different dimensions, as well as different permeabilities, such as could result from an unequal spacing of the three nuclear explosives within the emplacement hole.

The present work represents a far from complete study of the gas flow to multiple nuclear chimneys. Probably the most interesting additional study that could be carried out would be an examination of the concentrations of inert gas tracers that would be found in the produced gas for some of the combinations of conductances of the connecting regions which were studied in this work. Since the TRUMP computer program provides gas flow rates as part of its output, the use of that program for the present study has generated data which could be readily used in such an examination. A correlation of such predicted tracer concentrations with the results of an actual field test should give an excellent idea of the degree of interconnection between the nuclear chimneys.*

Further study could also be made of the influence of such things as the porosity and dimensions of the regions connecting the chimneys. For example, it was assumed in the present study that each chimney was connected to a distinct gas reservoir, with the innermost portion of the gas reservoir being a highly fractured region of relatively high permeability. In a multiple nuclear explosive experiment, it might be possible for these fractured regions, as well as the chimneys, to be interconnected, resulting in

* As was noted above, a production rate of 3×10^7 SCF/d in some cases produced such a rapid rate of bottom-hole pressure decline that the production could not be maintained for a full 20 d. Thus it might also be desirable to examine the effects on the pressure behavior of lower rates of gas production than those assumed in this work.

some measure of crossflow between the different gas reservoirs. Furthermore, the effects of flow directly from the gas-bearing formation into the regions connecting the chimneys could also be studied. A more sophisticated picture of the gas flow could also be obtained by including variations of the viscosity and compressibility of the gas with temperature and pressure.

ACKNOWLEDGMENTS

I am grateful to a number of people at LLL for their information, advice, and comments regarding this report, including D. Emerson, R. Terhune, H. Tewes, and A. Edwards. I am especially grateful to D. Montan, who originally suggested the problem and who provided a great deal of advice and encouragement throughout the course of this work.

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APPENDIX J

RARE GAS TRACER LOADING, PROJECT RIO BLANCO

MEMORANDUM

TO: H. A. Tewes

FROM: C. F. Smith - Radiochemistry Division

SUBJ: Rare Gas Tracer Loading - Project Rio Blanco

In order to verify inter-chimney communication following detonation of multiple nuclear devices in an experiment for gas stimulation, the addition of a known amount of a gas tracer to each such chimney is recommended. Analyses of these tracers in the gas produced can provide information on inter-chimney mixing and the contribution from each chimney to the produced gas. Proper selection of these tracer gases and an estimate of the quantity of each required is dependent on the as yet unknown concentrations of these gases in the formation gas, as well as upon production plans and postshot phenomenology. At this stage in the project definition, therefore, it is not possible to finalize plans for gas tracing. The following considerations are presented to illustrate the range of possibilities that exist.

The major rare gas constituent of natural gas is most probably helium. Commercial estimates of its concentration in Rio Blanco indicate 100 parts per million or possibly less. No estimate of argon is available, but we can assume that its concentration is of the order of 10% of that of helium. Other rare gas background concentrations are likewise unknown. For the purpose of argument, they are here assumed to be present in the same proportion to argon as that observed in normal air. Estimates of the amount of each tracer required are based upon an average of 250 million standard cubic feet of gas in each of the three chimneys. To allow a good signal to noise ratio a loading of ten times the background concentration is recommended. Furthermore, if, say a 1% contribution from either of the lower chimneys is to be observed in the produced gas then an additional factor of 100 times background is required. In the uppermost chimney only dilution from mixing must be considered. If an arbitrary factor of 10 cut-off for tracer measurements in this chimney is accepted then the loading estimates are 100 times background in the upper chimney, and 1000 times background in the lower two chimneys. Table I presents the resulting estimates.

TABLE I

Gas	Background Assumed Concentration ppm (a)	Loading Concentration ppm	Total Load Required (ft ³) ^(e)	\$/ft ³	Total Cost \$
He	100	(b)	---	---	---
Ne	0.02	2 (c)	500	21	10,000
Ar	10	1000 (c)	250,000	1.5	370,000
Kr	.001	1 (d)	250	32	8,000
Xe	.0001	0.1 (d)	25	160	4,000

^aBased on 100 ppm He, Ar = 10% of He, and others in same ratio to Ar as that observed in normal air.

^bHelium will be used to determine background contribution for the other rare gases, based upon preshot analysis.

^cConsidered for topmost chimney tracer - assumes load is a factor of 100 over background (x 10 for signal/noise; x 10 for dilution).

^dConsidered for tracing lower chimneys - assumes load is a factor of 1000 over background (x 10 for signal/noise; x 100 for dilution)

^eAssumes 250 M²CF STP gas per chimney.

Clearly Ne, Kr, and Xe are the likely tracers, both from the standpoint of space requirement and cost. These considerations are, however, strongly dependent upon the actual background concentrations observed in Rio Blanco gas. Samples for background measurement (taken from the Pawn Creek #1 well) have been obtained, and their analyses should allow a more realistic appraisal of the tracer requirements.

It should be noted that the ability to measure trace materials depends upon the concentration factor attainable if all "reactive" gases are removed. At 100 ppm He this factor is $\sim 10^4$. Even with this large concentration factor, both the

quantity of Ne, and of Xe indicated in Table I are somewhat marginal when viewed in terms of the possible dilution factors (see comments c) and d)). It is not probable, therefore, that the estimated tracer quantities, nor the \$20-25 K cost estimate can be reduced significantly as a result of actual back-ground determinations.

C. F. Smith
Radiochemistry Division

CFS:em

Distribution:

J. Newton
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F. Momyer
C. Smith

APPENDIX K

PROJECT RIO BLANCO RARE GAS TRACER LOADINGS

MEMORANDUM

TO: H. A. Tewes
FROM: C. F. Smith
SUBJ: PROJECT RIO BLANCO RARE GAS TRACER LOADINGS

Preliminary gross analyses of gas samples taken on March 18, 1971 from Fawn Creek No. 1, and presumed to be representative of the Rio Blanco project formation gas, have been completed. Detailed rare gas concentrations are not yet available. The preliminary analyses indicate a helium content of 80 ± 5 parts per million, and were not sensitive to other rare gases at less than 5 parts per million. These results, therefore, are evidence that enrichment factors of the order of 10^4 can be achieved by chemical removal of reactant gases, but do not permit a reliable calculation of the required quantities of rare gas tracers which would be emplaced with the explosives.

The measured helium concentration is comparable to that assumed in my previous memo on this subject (C. F. Smith to H. A. Tewes dated Mar. 30, 1971). The lack of better estimates of other rare gas concentrations precludes any modification of the required tracer quantities presented there. If design of the downhole emplacement containers is to begin before detailed analytical results are available, it is, therefore, suggested that a volume sufficient to contain a minimum of 500 ft^3 of tracer gas at STP be specified. If space is available for downhole emplacement of larger volumes of gas, I suggest reserving it for that purpose. Furthermore, for the sake of conservatism regarding available emplacement volume, and to simplify the engineering and design, I suggest that all three downhole containers be of the same design.

The only criterion for location of the tracer emplacement containers is that they be within the melt radius expected from each device. At 30 kt design yield this distance is approximately 25 ft. There is no restriction with respect to the minimum distance from the working point so long as the tracer container is external to the device canister.

Chuck

C. F. Smith

APPENDIX L

PROJECT DEFINITION, CHIMNEY GAS
SAMPLING SYSTEM: RIO BLANCO

June 11, 1971

PROJECT DEFINITION

A gas sampling system, installed preshot, is being considered as part of the overall gas quality program proposal for the Rio Blanco experiment. This system would provide the capability of communicating with the chimney(s) at early times.

The primary need for this system is safety related, in that these measurements are needed to document the concentrations of the ^{131}I , ^{133}I , ^{135}I isotopes present in the chimney gas at early times. These values are crucial in formulating operational safety plans for maximum credible seepage of radioactive gas up the emplacement wall.

Experience from Project Gasbuggy demonstrated that the greatest and most rapid changes in both chemical and radiochemical gas composition occurred on the order of days if not hours following detonation. Early time samples of the chimney gas are clearly needed to document such changes. Once a better understanding of such changes is achieved, methods for controlling or altering shot environments to minimize radioactive contamination of the product gas may be considered.

Early gas samples provided by this system will also allow one to estimate the rates of interchimney gas mixing. This estimate would be based on the concentration of gas tracers found in the collected samples.

Finally, early gas samples will allow a fission yield determination of the uppermost explosive if an appropriate tracer gas is emplaced pre-shot.

In addition to gas sampling, pressure measurements can be made in the sampling cable which then can be used to calculate the pressure history of the Rio Blanco chimney. This information is important in the analysis of the potential seepage rates to be used in formulating future operational safety plans, and for a more adequate analysis of the degree to which the well was stimulated by the nuclear explosion.

SAMPLING EXPERIENCE

Sampling systems have been used for obtaining prompt gas sample in underground explosions at the Nevada Test Site. The typical system consisted of connected lengths of 1 1/4" i.d. x 1 3/4" o.d. flexible hose containing within and along its entire length a continuous length of non-rotatable wire rope 1" in diameter. The hose extended to within 1 1/4 cavity radii and the wire rope was extended further to near the shot point. The surface end of the sample cable is connected to skid mounted sampling equipment which is located just beyond the radius of the expected subsidence crater. All of these systems were remotely operated from the control point.

To date, 10 systems have been installed on low yield shots ranging in depth from 350' to 1200'. Maximum observed pressure in the systems was 120 psi. The pressures generally decay to ambient in less than 20 minutes. Usable gas samples were collected in 8 out of the 10 applications. The failure to sample was the result of a collapsed sampling cable in one instance and the inaccessibility of the sampling equipment in the other instance. There was no release of radioactivity that was attributable to the sampling systems in any instance. The table below summarizes the pertinent data from these applications.

Table 1. Summary of Pertinent Data from Nevada Test Site Gas Sampling Systems

<u>Depth of Burial ft.</u>	<u>Max. Pressure Ob- served at Sampling Skig, psig</u>	<u>Duration Positive Pressure, min</u>	<u>Usable Sample Recovered</u>
350	15	20	Yes
500	10	9	Yes
650	120	12	Yes
750	50	14	Yes
800	0	--	Yes
800	6	6	Yes
850	0	--	No
900	60	10	Yes
950	0	--	No
1200	10	2	Yes

The primary differences between NTS sampling conditions and those which are expected on Rio Blanco are:

1. NTS systems are designed to sample cavity gas, whereas the Rio Blanco system would be for sampling chimney gas. Because of the expected greater amounts of non-condensable gases produced and at later times the addition of chimney gas dilution, the specific activity of the Rio Blanco samples should be considerably lower.
2. The non-condensable gases expected on Rio Blanco will also insure a positive pressure gradient for initial sampling. At later times when the chimney is building up to formation pressure, an even higher pressure gradient will exist.
3. The emplacement hole will be completely cased on Rio Blanco, unlike NTS applications. This introduces the possibility that should the casing be crushed, the emplacement hole including the sample cable could be cut off from the chimney. This was not observed, however, on either Project Gasbuggy or Rulison. Any small opening through the casing would be sufficient for sampling purposes.
4. The depth of burial for Rio Blanco is much greater than our NTS experience, but this should not materially affect sampling operation or effectiveness.
5. The emplacement hole will be cemented on Rio Blanco. Provisions will be incorporated to seal the bottom end of the sampling cable during cementing operations. It may also be necessary to pressurize the cable to prevent reduction of the design cross-section of the cable due to the hydrostatic pressure

of the cement column. Provisions will also be made to insure that the seal at the contact surface of the sampling cable and the cured cement will be impermeable. Additional engineering and testing at LRL will be made prior to fielding the system to develop the above design features in their final form.

6. Of particular importance, the surface ground motions that are expected on Rio Blanco will be less than those which the NTS systems were subjected to.

Considering the above differences, we believe a proposed Rio Blanco gas sampling system should have about the same potential for success as the NTS applications. From the NTS experience we can give reasonable assurance that a chimney gas sampling system would neither reduce the design integrity nor compromise the overall containment aspects of the Rio Blanco experiment.

DESCRIPTION OF SAMPLING SYSTEM FOR RIO BLANCO

1. Emplacement Hole Components

A sampling cable will be installed in the annulus of the emplacement hole. The width of the annulus (current design 1.1" - 1.4") is the critical factor in determining the size of the cable. We would recommend an outer jacket assembly consisting of joined lengths of 1/2" i.d. x 3/4" o.d. steel sheathed hose that contains within and along its entire length a 3/8" non-rotating wire rope. The hose will be assembled over the wire rope and joined with couplings which have an o.d. of 1". The length that is required to extend from the surface to a point which intersects the upper chimney (~ 5700') will be rolled on a reel and pressure tested prior to delivery to the site. The sampling cable would have handling characteristic similar to an

electrical cable of equal size and would be lowered down the emplacement hole in a similar manner as the other downhole cables for the explosive.

The internal working pressure of the hose will be 4000 psi (16,000 psi burst pressure). The internal wire rope is itself permeable. Should the hose be compressed at any point, a gas path will still exist. The internal cross-sectional area of the cable through which gas can flow freely is a $3/8$ " x $1/2$ " annulus. This area, over a 6000' length is capable of sustaining a dry gas flow rate of 20 SCFM with a 3000 psi pressure source in the chimney. We would expect lower rates under actual operating conditions. Flow rate measurements will be performed on the cable to determine these values more accurately. Extensive tests will be made at LRL to verify cable specifications and also to determine other properties of the cable which may be important for downhole emplacement.

2. Surface Components

A. 200' from the well head

An instrumentation and sampling skid will be located about 200' from the well head. Most of the sampling activity will occur at this skid. Connection of the skid to the well head will be made with a smaller diameter hose, similar in type to the downhole one, but without the internal wire rope.

The base dimensions of the skid will be approximately 8' x 8' and when fully outfitted will be 4' high. Its weight is estimated to be 1000 lb., mainly concentrated in pressurized cylinders of N_2 gas. This source will be used to retest the surface components following the shot to verify system integrity.

The skid mounted sampling equipment will be assembled and thoroughly tested prior to delivery to the site.

B. 500' from the well head

A cluster of empty high pressure gas cylinders will be located 500' from the well head (300' from the sampling skid) to store gas that is bled from the sampling system when a chimney sample is drawn to the surface. The cluster consists of 7 cylinders, each 16" o.d. and 20' long, with a combined weight estimated at 20 tons. They are conservatively rated at 3700 psi working pressure (15,000 psi burst pressure). Their combined internal volume is 110 ft³, which is about 25 times the internal volume of the sampling system.

FIELD ENGINEERING, PROPOSED EMPLACEMENT, AND SUPPORT

The installation of the sampling system and its interaction with emplacement activities are described. Post shot sampling activities that would require support are also mentioned.

I. Subsurface Emplacement of Sampling Cable

1. The cable would be attached to the emplacement casing and fed down the hole along with the cable for the explosive package. We estimate that 2 additional personnel will be required for control of the sampling cable during downhole operations. The estimated weight of the sampling cable is 1 lb/ft, compared to a timing and firing cable weight of 0.5 lb/ft.

2. A separate additional arm with an i.d. of approx. 4" should be provided at the well head for the sampling cable. The wire rope will be terminated at this point while the hose will be connected to a LRL designed feed through adaptor containing a high quality external valve.

II. Installation of Surface Sampling Equipment

1. On the edge of the general working sector, 200' and 500' from the well head, ground areas that are reasonably level should be provided for the sampling skid (8' x 8', 1/2 ton) and the gas storage cylinders (6' x 20', 20 tons).

2. On site support should be provided to move and install these units. Specifically, the sampling skid will need to be shock mounted and tied securely to the ground. The gas storage cylinder platform must also be tied to the ground. It will be necessary to stake and rope off the area occupied by the sampling equipment.

3. Occasional additional assistance may be necessary from existing on site support personnel.

III. Sampling Activities Requiring Field Support: Post Shot

1. Collection of at least 6 samples is expected by +8 hr. These samples will be trucked to a special aircraft. Each sample including its shipping container, will weigh 150 lb with dimensions approximating a 30 gal drum.

2. During sampling (+1 hr, +3 hr, +8 hr, +1 day, +3 day, +1 week, and possibly longer), radiation monitoring support will be required. Protective clothing and associated equipment should be on hand to outfit at least 3 sampling personnel.

POST SHOT OPERATIONAL PLAN: GAS SAMPLING PROCEDURE

The post shot operations will be planned and conducted such that the integrity of the well head is verified prior to initiating any action with respect to gas sampling. Each separate pressure system which includes the emplacement casing, the annulus between the emplacement and well bore casing, and the gas sampling cable will be remotely monitored for pressure through the ICS system. It is desired that each of these separate systems be pressurized to different levels prior to the detonation. The attached Fig. 1 shows schematically the systems being monitored. This information will provide the Test Manager and Test Director with immediate post detonation information on which to base site reentry. If communication between the chimney and the sampling cable is established quickly, a

Fig. 1. Schematic view of the wellhead showing the ICS pressure monitors (P).

pressure time history of the chimney will be obtained, but chimney gases will not travel through the cable to the well head. If chimney pressures are greater than the existing gas pressure in the cable, some pressure increase and movement of chimney gases up the cable will occur until an equilibrium pressure is reached. Current plans are to design a valve or diaphragm at the bottom of the cable so that communication with the chimney will not occur until additional gas pressure is placed into the cable from the well head. Although the remote monitoring system may indicate a competent well head, a visual inspection of the well head will be made prior to attaching the sampling skid to the sampling cable.

Remotely controlled systems have generally been employed at NTS. It is proposed that the Rio Blanco system be manually operated to reduce the complexity of the sampling skid and the required electronics. A remotely operated system would be considered if it is expected that reentry to the surface ground zero area can not be made within about an hour because of the travel time involved or other non safety oriented reasons. The expected reentry time for this plan is assumed to be within an hour. This is important not only for obtaining the gas samples, but also for obtaining accurate measurements of chimney pressure which can be used to modify the preshot estimates of the maximum credible seep. Obviously, if rapid cavity collapse has reduced the chimney pressures to much lower than assumed values, the potential for a gas seep at early times is diminished and some operational plans may be relaxed at an earlier time.

As soon as the area is cleared for reentry, a sampling party composed of 3 members, plus a radiation monitoring personnel, will perform the following functions.

1. Verify the integrity of the well head.
2. Inspect surface equipment for damage. Connect the sampling skid to the sampling cable. Test surface equipment between the well head and sampling skid by pressurizing with nitrogen gas to 3500 psi.

3. Open the valve on the sampling cable at the well head.
Apply the required pressure to open the downhole cable to the chimney. Simultaneously check for radioactivity and record internal system pressure.
4. Flow sufficient gas into storage tanks to flush internal volume of sampling hose.
5. Collect first sample(s) at +1 hr, or as soon as possible thereafter.
6. Continue periodic sampling at +3 hr, +3 hr, +1 day, +3 day, and +1 week, and longer depending on results.
7. Monitor and record surface pressure at appropriate intervals.
8. Send the initial set of samples (up to +8 hr) to LRL, Livermore, via special aircraft.
9. Send subsequent samples promptly via commercial channels.

INDUSTRIAL SAFETY

1. High Pressure Systems

The sampling equipment will be designed in accordance with industrial safety codes. Pressure vessels will comply with the ASME boiler and pressure vessel code and the surface piping will comply with the American Standard Code for pressure piping, ANSI-B31.1. No surface component will be rated for less than 3500 psi working pressure.

2. Radioactivity

The sampling system will be designed such that radioactive gases will be confined to the lower portion of the sampling cable (below 3000'). Radioactive gas will be drawn to the surface only when sampling commences.

The radioactivity contained in the surface equipment will depend on both the amount of gas drawn to the surface and the time after the shot. The radiation meter readings will be highest at +1 hr when the first sample is collected. For a 150cc sample, at the existing pressure in the chimney, maximum radiation readings of 40 roentgens/hr (R/hr) at a distance of one foot from the sample is possible. An inch of lead shielding would reduce this reading to about 5 R/hr. The radiation readings at one foot from the surface hose connecting the well head to the sample bottles will be less than 5 R/hr without any shielding. The equipment downstream of the sampling skid will be considerably lower since the contained gases would not be at chimney pressure. All of these readings would diminish rapidly with time. At 24 hours, maximum radiation readings at one foot from a sample bottle, without shielding, would be less than 0.2 R/hr.

The operating valves on the sampling skid will be provided with air-driven actuators which can be locally controlled from a short distance away. Should the radiation levels be excessive at very early times (less than 3 hours), the first samples will be collected by local remote operation. During sampling operations, access to the surface ground zero area must be limited to authorized personnel.

3. Disposal of Gas in Storage Cylinders

At the conclusion of the sampling operation the stored gas (maximum volume of 110 ft³ at a pressure not exceeding chimney pressure) can be flared at the appropriate time. Extended storage of the gas will require barriers or fencing to enclose the equipment. Posted signs will be required.

R. Quong
Chemical Engineering Section

RQ:add

APPENDIX M
PROJECT RIO BLANCO GAS QUALITY ESTIMATES

CHEMISTRY DEPARTMENT TECHNICAL NOTE NO. 71-61

"Project Rio Blanco Gas Quality Estimates"

Robert W. Taylor

I. INTRODUCTION

Outlined here are estimates of the chemical composition and radioactivity of gas to be expected upon re-entry of the Rio Blanco chimney. Generalized predictions are also made of the way the chemical composition, radioactivity, and steam content of the gas will change for various production rates. The study will have to be revised when rock samples from the actual site of the explosion become available.

Three different emplacement plans are presently under consideration. In all of the plans the nuclear explosives are spaced about 6 cavity radii ($6 R_c$) apart, and the chimney is expected to extend about $4 R_c$ above the uppermost explosive. Two of the plans call for three explosives of 30 kt each. The main difference between these two plans is the average cavity radius - which has been predicted to be 74.5' (22.6 m) in one case and 70' (21.3 m) in the other. The other plan calls for 2-45 kt explosives and predicts $R_c = 80'$ (24.4 m). Separate calculations for gas quality have been made for all three of these cases, and differences, although real, are small compared to the accuracy of the predictions. For example, one most important parameter to be estimated in order to predict gas quality is post-shot gas temperature. The temperature estimation was done by inferring from incomplete and uncertain evidence that 25% of the energy of the lowermost explosive and 50% of the energy of the other explosives ends up as heat to increase the temperature of the rubble column. Once such an assumption is made, it is easy to show that for an average R_c of 74.3', thus a chimney radius, of $\sim 74.3''$, the average final rubble temperature is 240°C . For a R_c of 70' the final temperature will be 264°C . This difference, the reader will recognize, is small relative to the temperature change that would be calculated for another not unreasonable assumption about the fraction of the total energy ending up as heat in the rubble. Thus for these preliminary Rio Blanco plans, a temperature of about 250°C is assumed.

The same sort of considerations apply to many other calculated differences between the three emplacement plans. In the following report predictions are based

on average values of gas-quality parameters for the three emplacement plans. The errors on results reflect rough estimates of the accuracy of the assumptions and in all cases these errors are much greater than the differences which resulted from calculations made for the alternate emplacement plans.

II. CHIMNEY GAS COMPOSITION

The estimated chemical composition of chimney gas and dried chimney gas is given in Table I.

TABLE I. Chimney Gas Composition
T = 250°C

Component	Wet	Dry	Dry, CO ₂ Removed
"CH ₄ " *	40 ± 10%	50 ± 10%	70 ± 15
CO ₂	25 ± 5	30 ± 5	0
H ₂	15 ± 5	20 ± 5	30 ± 10
H ₂ O	20 ± 5	0	0

*Formation gas, not only methane.

The estimate for steam concentration is based on an average rubble temperature of about 250°C (a temperature increase of 150°C over the pre-shot temperature of 100°C as discussed in the Introduction). At 250°C the steam partial pressure is 560 psi (38 atm). Because the total chimney pressure must equal the formation pressure of 2800 psi (190 atm), the steam concentration is about 20% ($560 \times 100 / 2800$).

Hydrogen concentration is based on the assumption that about 1000 tons of rock per kt are heated hot enough to burn all the free carbon (≈ 0.5 wt %) in steam to form H₂ and CO₂.

The CO₂ concentration is based on the thermal decomposition of all of the carbonate minerals in 2000 tons of rock per kt as deduced from Gasbuggy and Rulison. The estimated CO₂ concentration at Rio Blanco, based on J. Hill's analyses, will be about 2.5 wt %. CO₂ is probably released from rocks for some time after the explosion as more and more rock is heated to temperatures between 500 and 1000°C by thermal conduction. It seems probable that multiple detonations will tend to break

up the mixture of melted rock and rubble which, in the case of single detonations, is allowed to "cook" undisturbed. For this reason less CO_2 may be released per kt in a multiple detonation than in a single detonation.

The amount, and thus concentration of formation gas, is calculated on the assumption that formation gas will flow in to fill the remaining void volume in the interstices of the rubble column to a pressure equal to the formation pressure, and that diffusive mixing of gases in the pores in the rock surrounding the chimney is negligible.

Bear in mind that if the estimate of average chimney temperature is low by $\sim 100^\circ\text{C}$, and the final rubble temperature actually ends up to be $\sim 350^\circ\text{C}$ or higher, no formation gas will be found in the chimney upon re-entry. In such a case, the steam concentration would be 60%. The dry gas composition would be 60% CO_2 , and 40% H_2 . Such a case could occur if the spacing between shots is decreased or if the extent of the chimney above the uppermost shot is less than expected, or if the cavity radius is less than expected. The effect of average chimney temperature on the steam pressure, and thus on the composition of chimney gas, is shown schematically in Fig. 1. The relation between the percentage of the total yield as heat in the chimney and the chimney temperature is also shown for the case where the explosives are located $6 R_c$ apart.

III. KRYPTON-85 CONCENTRATION AND TRITIUM DISPOSITION

The principal radioactivity in the produced gas will be tritium and Kr^{85} . The expected concentration of krypton in gas can be predicted because it is an inert gas. It is found exclusively in the gas and its concentration in dry chimney gas is given by the expected production of Kr^{85} ($\sim 2070 \text{ Ci}$) divided by the volume of dry gas expected in the chimney (10^{13} cm^3 at STP), or $2 \times 10^{-10} \text{ Ci/cm}^3$ dry gas.

Tritium on the other hand behaves like hydrogen and therefore can be expected wherever hydrogen is found - that is, wherever hydrogen is found at temperatures high enough to assure isotopic exchange or dilution. Places for hydrogen are the "non-condensable" gases H_2 , CH_4 , C_2H_6 as well as steam and water. The fractionation of tritium among these molecules is complicated by the isotopic or "mass" effect. In particular, tritium is concentrated in both hydrocarbons and H_2O relative to H_2 at temperatures below about 500°C . This is not too important in the final tritium disposition

because the amount of H_2 is so much smaller than the amount of H_2O . The TH molecules, however, may play an important role by distributing tritium into CH_4 and H_2O at temperatures below the range where CH_4 and H_2O alone would exchange tritium.

There is also a slight enrichment of tritium in H_2O relative to CH_4 . At isotopic equilibrium the tritium-to-hydrogen atom fraction (T/H) in H_2O is about $10 \pm 5\%$ greater than (T/H) in CH_4 at the expected chimney temperature.

Roughly, the fractionation of tritium between H_2O and hydrocarbons is given by the ratio of the number of hydrogen atoms in H_2O in the chimney to the number of hydrogen atoms in hydrocarbon, in the chimney. Based on an estimated water concentration of 2.7 wt %, the total mass of water in the 10^{12} g of rubble in the chimney will be 2.7×10^{10} g. This corresponds to 3×10^9 moles of H in H_2O . The 1.3×10^{11} cm³ of void volume in the chimney can hold 5.7×10^8 moles of gas at 190 atm and 250°C. This chimney gas is about 40% formation gas, as discussed in the last section. This means that about 2.3×10^8 moles of CH_4 are available for tritium exchange. The amount of hydrogen in this amount of CH_4 is 9.2×10^8 moles. Thus the fractionation of tritium between H_2O and CH_4 will be in the ratio $3 \times 10^9 / 9.2 \times 10^8$ or about 3/1. That is, about three times more of the tritium is expected to end up in steam and water than in dry gas at 250°C. The reader will realize that if the final average rubble temperature is higher or lower than estimated here, less or more formation gas can flow into the chimney, and the tritium fractionation will change accordingly.

So far we have not found out for sure where the tritium ended up either at Gasbuggy or Rulison. Following Gasbuggy, 5% of the total tritium was found in the gas. The remaining 95% was assumed to be in water in the chimney. At the time this was thought to be a satisfactory explanation for the chimney may have been partially flooded and, in any case, no reliable samples of the water in the chimney were obtained. The problem has had to be re-examined since the Rulison experiment because water samples have been obtained - in fact, more than 16,000 barrels of water have been condensed from the Rulison gas as of March 1, 1971. This water carries 0.35 ± 0.5 μ Ci of tritium per gram. This corresponds to about the atom fraction of tritium expected for water equilibrated with tritiated methane at chimney temperature. Estimates of the total amount of water in the Rulison chimney vary between 5 and 15×10^9 g, depending upon the size of the chimney and the water concentration that is assumed. In any case, only between 20 and 50% of the total

tritium appears to be in water. The measured concentration of tritium in the gas and the estimated amount of gas suggest that 13% of the total tritium is in dry gas. Where is the remaining $40 \pm 20\%$? It has been suggested that only about 1/2 g of tritium rather than 1 g was actually present in which case it is all accounted for. If not, the most likely remaining place is in the silicate glass. This possibility has not been emphasized in the past because it seemed obvious that the fraction of the water that is in a rock that could be dissolved in a glass made from the rock would be small. This is not always the case, however. R. Bedford* has pointed out that when the rock contains only a few percent water, and when the nuclear explosive is detonated deep (the resulting cavity is small and the steam released from melted rock generates a high steam pressure), most of the water in a rock can be dissolved in the glass made from that rock. He has found that the amount of water that can be dissolved in silicate liquids is nearly independent of temperature in the range 1000-2000°C, and for most common silicate rock, the solubility is nearly independent of rock composition. He found that the solubility depends on the steam pressure; in fact, it changes with the square root of the steam pressure. By assuming that at the time the molten rock is saturated and freezing, the only steam in the cavity is the steam released from melted rock and that tritium is confined to this steam, Bedford derived the following expression for the maximum fraction (F) of the tritium that may be trapped in silicate glass:

$$F = A \left[\left(\frac{2}{A} + 1 \right)^{1/2} - 1 \right]$$

$$\text{where: } A = K \frac{(M)(T)}{(V)(Co)}$$

*R. Bedford, "Estimation of the Distribution of Tritiated Water Between the Vapor Phase and Solution in Molten Rock in the Cavity Created by a Nuclear Explosion - with Special Reference to Recent French Data" Inorganic Materials Division Technical Note No. 13, March 6, 1970.

and: $K = 5.11 \times 10^{-6}$

$M = \text{g of glass formed/kt} = \sim 10^9 \text{ g/kt}$

$T = \text{temperature the glass "freezes"} = \sim 1300^\circ \text{K}$

$V = \text{cavity volume/kt} = 1.45 \times 10^9 \text{ cc/kt for Rio Blanco}$

$Co = \text{water concentration, g of water/g of rock} = \sim 0.027$
for Rio Blanco.

Thus for Rio Blanco, Bedford's method would suggest that as much as $40 \pm 20\%$ of the tritium will be trapped in silicate. He warns that in the case of multiple detonations the cavity may collapse earlier than for single detonations which may decrease the steam pressure before the glass has become viscous enough to retain the steam dissolved in it.

The expected tritium distribution for the Rio Blanco project is given in Table II.

TABLE II. Tritium Distribution
Chimney Temperature, 250°C

<u>Location</u>	<u>Percentage of Total</u>
Silicate glass	40 ± 20
Water and steam	45 ± 20
Dry gas	15 ± 10

If we assume the total amount of tritium to be expected corresponds to 0.2 g per explosive, the expected tritium concentrations in gas, water and glass can be calculated. The results are given in Table III.

TABLE III. Tritium Concentrations
(based on 0.2 g tritium per explosion
and a chimney temperature of 250°C)

	<u>3-Explosion Plan</u>	<u>2-Explosion Plan</u>
Dry gas at STP	90 pCi/cm ³	60 pCi/cm ³
Water	0.1 $\mu\text{Ci/g}$	0.06 $\mu\text{Ci/g}$
Silicate glass	0.03 $\mu\text{Ci/g}$	0.02 $\mu\text{Ci/g}$

IV. CHANGE IN GAS COMPOSITION WITH GAS PRODUCTION

Two extremes in the behavior of the Rio Blanco well with production are considered; the actual case will probably be somewhere in between.

If gas is withdrawn slowly relative to the rate formation gas can enter the chimney, pressure will remain high and the concentration of CO_2 and H_2 will decrease with a corresponding increase in the concentration of formation gas. The steam partial pressure will remain constant, as fixed by the temperature of the chimney, until the chimney is dry. This will take place after about 6000 MMCF of gas is produced if the chimney temperature remains at 250°C . The total amount of steam that must be removed by the chimney to dry it is about 2.6×10^{10} g, corresponding to 160,000 barrels of water.

If production is started at a very high rate of gas flow, that is so gas is removed from the chimney much more rapidly than it can flow into the chimney, pressure will fall. During the decrease in pressure, the concentration of steam will increase and the concentration of CH_4 , CO_2 , and H_2 will decrease until only steam is produced. The pressure will remain at the partial pressure of steam fixed by the chimney temperature (33 atm or 482 psi at 250°C) until the chimney is dry, at which time the pressure will fall rapidly.

RWT/dc

Fig. 1. General relation between average chimney temperature and gas composition showing the effect of increasing steam pressure. The upper scale gives the percentage of the total yield as heat in the chimney for the case of three 30-kt explosives located six cavity radii apart.

APPENDIX N

PROJECT RIO BLANCO RADIOECOLOGICAL STUDIES

The Biomedical Division proposes to conduct radioecological studies concerned with the behavior of tritiated water vapor (THO) released to the environment at the RIO BLANCO site during the flaring period. These experiments will be conducted during the low and high volume flaring periods in the vicinity of the flaring site, where THO concentrations in the air will be high enough to trace the ecological behavior of tritium. An adequate base of radiological health studies for project RIO BLANCO has been proposed by the Colorado State Department of Health and the Environmental Protection Agency - W.E.R.L. The Biomedical Division will carry out a sampling program designed to determine parameters affecting the fate of tritium released to an environment, such as are necessary for testing and augmenting the model of tritium transport and behavior which were developed from the Rulison studies (1) (2) (5).

The RIO BLANCO flaring period offers the opportunity for a real-world experiment which will allow us to determine critical parameters associated with the deposition of THO vapor in a specific natural ecological system of importance to the Plowshare program. These parameters, which are basic to determining the radiobiological significance of any planned release of THO, previously have been studied under experimental field conditions at LLL, and at the Rulison site.

The data obtained in the Biomedical Division Rulison studies and from the on-site LLL experiments have indicated that dose estimates made by a variety of organizations for project Rulison were excessively conservative by a factor of 10^3 to 10^4 . Several parameters such as plant uptake and tritium half-times in vegetation were over-estimated by an order of magnitude. Because these tritium half-times values are basic parameters used in the estimation.

of the radiation dose to man, it is important that they are realistic and not overly conservative, and it is highly desirable that they have been determined in the actual ecological system being affected by the THO release.

An important aspect of these radioecological studies will be close collaboration and liaison with the Plowshare Division scientists to utilize predictions and calculations of flaring meteorology, dispersion and diffusion of the flared THO in the placement of study sites and in the experimental design.

The following measurements and determinations will be made in the project RIO BLANCO radioecological program:

1. Deposition of THO vapor on woody, herbaceous, and graminaceous (grasses) vegetation; both native and agricultural species will be compared.
2. Deposition of THO vapor on bare soil surfaces.
3. Deposition of THO vapor in soil-plant systems.
4. The half-time of tritium in plant species and in the soil-plant systems which have received chronic exposure to THO vapor during flaring; these measurements will commence after flaring ceases.
5. The variability in the deposition of THO between species, and the variability observed at specific sites within the same species.
6. THO concentrations prior to, during, and after flaring will be described for at least one site; micro-meteorological data will be obtained at that site and correlated with flaring data, air concentrations of THO, and the THO deposition data.

The presence of other radionuclides that may be deposited on vegetation or soil, such as ^{203}Hg , may be studied with the appropriate methods including the mobile solid-state spectrometer. The mobile Ge(Li) detector has been used by the Health and Safety Lab., New York, to determine the presence of gaseous

radioactivity in the field which was released from a nuclear reactor stack.

These state of the art methods should be evaluated at the RIO BLANCO site.

The measurement of the environmental radioactivity background several times during the flaring period at a single site and in a region of known THO activity will be made with the mobile Ge(Li) detector to determine if deposition of unexpected or predicted radionuclides is occurring. The sensitivity of this spectrometer is more than adequate to describe the natural radioactivity, fallout radionuclides, and any recently introduced radioactivity.

It is also proposed that an investigation of the fate of ^{14}C released during flaring be undertaken. Three factors suggest that this may be a fruitful investigation: (1) the amounts of ^{14}C released, mainly as CO_2 appear to be at a level where uptake is possible by the surrounding vegetation; approximately 1 curie per day will be released at the 20 million SCF rate of flaring, (2) the rapid uptake of CO_2 by vegetation and its incorporation into organic matter, and (3) the long half-life of the radionuclide and of biospheric carbon (three years). The opportunity to study the fate of ^{14}C released to the environment is a unique one, and because of the biological significance of the radionuclide, the fate of flared ^{14}C should be investigated. The ^{14}C studies may be accomplished with the same samples collected and analyzed for ^3H , however, the analyses for ^{14}C are somewhat more complex.

PROJECT PERSONNEL AND SPECIALIZED EQUIPMENT

Project Scientist:	John Koranda
Associate Scientist:	Lynn Anspaugh
Assistant Scientists:	Daniel Wilson
	William Robison

Project Radiochemist: John R. Martin
Project Engineer: Bruce Clegg
Paul Phelps
Field Technicians: Marshall Stuart
Robert Wikkerink
Walter Martin
Electronics Technician: George Huckaby

These scientists will participate directly in the RIO BLANCO project either at Livermore or in the field at Colorado.

MOBILE LABORATORIES

Two Biomedical Division special purpose vehicles will be utilized in the RIO BLANCO radioecological studies. The 3/4 ton van, nearing completion at this time, contains the mobile Ge(Li) detector, a 4096 channel pulse height analyzer, magnetic tape deck, and associated electronics and mechanical systems. The van also carries conventional NaI crystal detectors and other sensitive radiometric instrumentation. This vehicle laboratory is completely mobile, carrying its own power generator for 110 VAC or adequate batteries for extended field operation.

A large 3 ton van in which a liquid scintillation spectrometer, a continuous air-THO samples, and environmental sample preparation and preservation facilities are housed will also be employed in these studies.

One or two additional liquid scintillation spectrometers will be employed in trailers at the RIO BLANCO site. Two additional liquid scintillation spectrometers at LLL will provide backup analytical capability for low-level analyses after the initial measurements are made in the field.

A portable vacuum manifold will be used at the RIO BLANCO site to provide early information on the uptake of THO by plant species, and to extract water from milk samples if these are available. Soil samples are also processed on this vacuum system.

Micro-meterological instrumentation to record wind speed and direction, temperature and relative humidity will be used to support radioecological studies on the deposition of THO vapor. At each intensive study site, the recording of these ecological and meterological parameters in addition to the air concentrations of THO will enable a more detailed description of THO deposition than has ever been obtained under natural conditions.

A recently-developed sequential air-THO sampler will be used to collect time sequence samples of air moisture throughout intensive study periods in the field so that the complete history of THO exposure may be described. It is possible that several of these samplers will be employed. Preliminary studies of the performance of the sequential air-THO sampler are being conducted at the present time.

SUPPORT REQUESTED:

Based on our experience at the Rulison site in 1970-71, the experiments described above can be carried out with less than twelve scientists and technicians at the RIO BLANCO site. Modest field support at the flaring site will be required for these studies. Between 200 and 300 square feet of trailer space, suitable for a liquid scintillation spectrometer and other small laboratory equipment, and a source of 110 VAC power, 1-2 KW., will be needed at the RIO BLANCO site for approximately two months.

In view of the additional travel and related support above and beyond our normal off-site program levels, support at \$15,000.00 is requested. This level of support is almost the amount calculated for travel. The Biomedical Division commitment to this program has been estimated to be in approximate \$75,000.00 including F.T.E. costs.

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