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PROJECT RIO BLANCO
ADDITIONAL PRODUCTION TESTING AND RESERVOIR ANALYSIS

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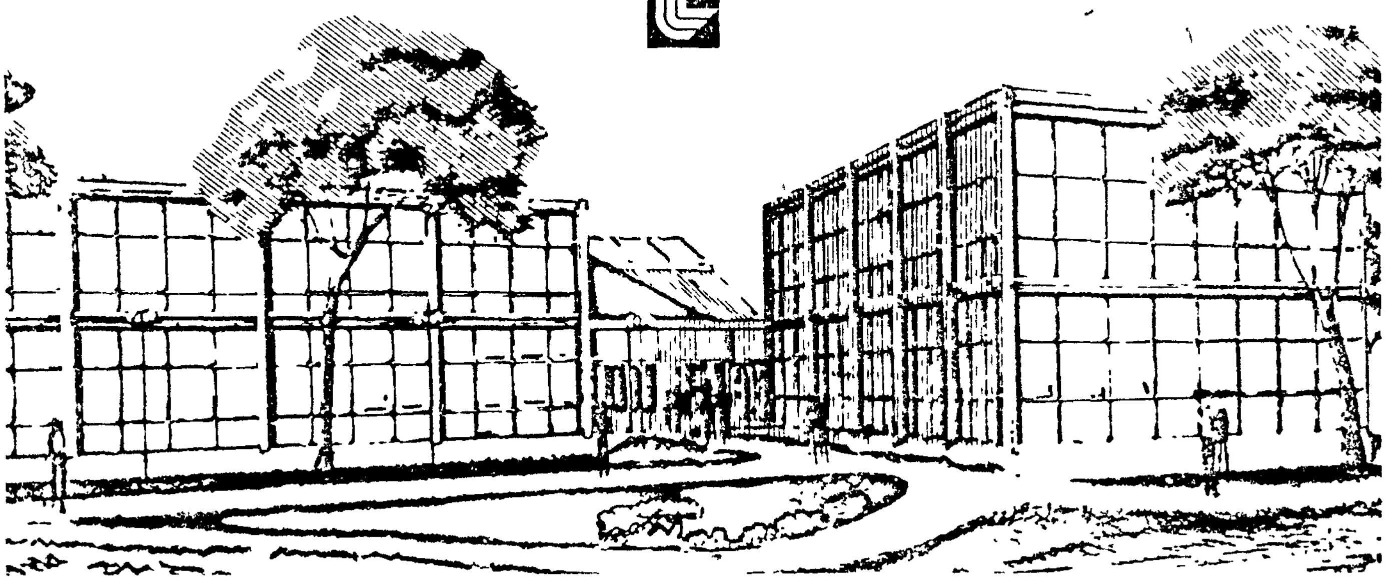

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TABLE OF CONTENTS

ABSTRACT ii

1. INTRODUCTION & SUMMARY 1

2. LOWER EXPLOSION REGION INVESTIGATION 2

   Geophysical Log Analysis
   Cave Analysis
   Chimney Radius
   Chemical & Radiochemical Analysis
   Production Analysis

3. RESERVOIR CHARACTERIZATION 12

4. MASSIVE HYDRALIC FRACTURING EXPERIMENT 15

5. PROJECT STATUS 17

6. CONCLUSIONS 18

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ABSTRACT

Additional subsurface investigations of the Rio Blanco detonation region and adjacent reservoir have been underway since the last technical meeting at IAEA. The lowermost explosion cavity has been reentered and a production test from it was performed. A dry gas volume of $7.6 \times 10^5 m^3$ (27 Mmscf) was withdrawn. Chemical and radiochemical analyses of this gas show that a) the yield of the bottom explosive was 31 ± 2 kt; b) the cavity/chimney volume was $2.4 \times 10^4 m^3$ (8.4×10^5 ft^3); c) about 7% of the tritium produced is associated with the gas; and d) a slight (∿0.1%) gas contribution from the middle explosion region was noted. The reservoir/chimney model implies an unstimulated reservoir flow capacity of 0.15 mdarcy-m (0.50 md-ft) connected to the bottom chimney region. A cavity radius of 21 ± 3 m (70 ± 10 ft) was deduced.

Unstimulated reservoir production parameters were investigated in a well offset 190 m (625 ft) from the emplacement hole. Insufficient productivity was obtained in the Mesaverde formation (in which the bottom explosive was detonated) to evaluate reservoir properties. The productive sandstones in the Fort Union formation adjoining the top detonation region were individually evaluated. Their aggregate flow capacity was determined to be 0.14 ± 0.2 mdarcy-m (0.45 ± 0.08 md-ft). A numerical simulation model which incorporates these data is described.

The lack of a high-permeability connection between the three explosion regions remains unexplained.

The two chimney reentry wells have been cemented to the surface and abandoned. The offset well has been plugged in a way which preserves the option for additional subsurface investigation in the future. Project facilities have been removed and the site restored to conditions which minimize environmental impact.

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1. Introduction and Summary

Project Rio Blanco was the third experiment conducted in the United States to develop the technology for nuclear explosive stimulation of low permeability natural gas reservoirs. The project was jointly sponsored by industry and the government and was sited in the Piceance Basin in Rio Blanco County in northwestern Colorado. The nuclear explosive operation involved the simultaneous detonation of three 30 kt explosives in a vertical array within a single wellbore. The explosives were detonated on 17 May 1973. At the January 1975 IAEA Technical Meeting in Vienna, the design and execution of the detonation and chimney re-entry phases of the project were described in detail (Ref 1) and a preliminary analysis of the upper explosion region was presented (Ref 2). At that time, we indicated that additional subsurface investigations were in progress and the results would be reported at a later date.

The previous reports covered the project activities from inception to September 1974. Since that date three major activities have been undertaken in the project area. First, a directionally controlled well was drilled which penetrated the chimney produced by the lowermost explosive. Solid cores were recovered from two intervals near the bottom of the hole and a suite of geophysical logs was obtained. The well was completed in a configuration for production testing and a drawdown test was conducted. Chemical and radiochemical analyses were performed on representative samples of the produced gas and entrained liquids and particulates. The well was then shut in for an extended buildup test.

The bottom hole pressure was measured periodically for a total of 17 months. In July, 1976 this well was permanently plugged back and abandoned.

Second, a vertical offset well, located 190 meters from the nuclear emplacement well, was drilled. A suite of geophysical logs was run. An extensive reservoir characterization program was conducted in this well, involving tests of the productivity of individual potential gas sands which form the drainage region for the nuclear chimneys. This well was plugged back in August 1976 in a manner which will permit re-entry in the future.

Third, another well was completed at a location about 1.4 km from the nuclear emplacement well. A series of massive hydraulic fracturing experiments have been performed on several zones in this well for the purpose of comparing the effectiveness of this stimulation method with the nuclear stimulation in the same reservoir environment.

In addition, all the PNE project wells have been plugged back with cement and the related surface production testing equipment has been decommissioned and removed from the site. The project areas have been regraded and seeded to comply with government requirements for restoration to minimize environmental impact.

2. Lower Explosion Region Investigations

In early 1974, following the second major production test from the upper chimney re-entry well, it became apparent that, contrary to predictions, no interconnection existed between the top explosion region and those below. This conclusion was supported by three independent pieces of evidence: the pressure - volume relations indicated a void volume consistent with a single 30 kt explosion at 1780 m. depth; the integrated ^{85}Kr production indicated an explosive yield of 34 $\pm$ 3 kt, or only one of the three explosives; and the virtual absense of the stable rare gas tracers from the two lower explosions indicated no significant contribution to the produced gas from those regions. It was decided to drill a new well to intercept the middle explosion region in order to obtain data on the explosion effects and hopefully gain some insight into the inter-connection problem. (Ref 3)

The design of this well was constrained by a number of unique criteria. It was necessary to avoid the region of significantly increased permeability associated with the upper explosion in order to preclude a major loss of circulating fluid and possible loss of pressure control prior to installation of the protective casing. Implicit in this requirement was the necessity to establish the surface location a substantial horizontal distance from the target and to increase the inclination of the course of the hole very rapidly in the region opposite the top chimney. The directional control and surveying requirements were very stringent due to the relatively small size of the target.

The directional well, designated RB-AR-2, was spudded on 17 June 1974, from a surface location offset 365m from the RB-E-01 explosive emplacement well. A cross section through this region is shown in Figure 1. The drilling operation proceeded normally using a water-based circulating fluid and standard rotary tools to a depth of 1055m. A 10-3/4" O.D. (273mm) intermediate casing was run and cemented at a depth of 666m. The drilling assembly was converted to a downhole circulating fluid driven motor, and a downhole surveying and steering tool to control the course of the hole was installed for operation below 1055m. Considerable difficulty was experienced in building and maintaining sufficient inclination angle to reach the middle explosion target. On 22 August an undetected mechanical failure in the steering tool assembly caused an abrupt loss of inclination at a measured depth (MD) of 1867m or true vertical depth (TVD) 1816m. At this point the inclination of the hole was 42°from vertical and it was determined that a final inclination of 63° would be required to reach the target. It was decided to change the target to the lower explosion region in order to reduce the inclination angle problem to managable proportions. This target could be reached with an angle of approximately 45°, allowing for some loss of inclination during coring operations and while drilling in fractured material near the chimney. Directional drilling operations continued successfully. On reaching a measured depth of 1975m (TVD = 1900m), which is the same depth as the middle explosive emplacement, a complete suite of geophysical logs was run, and a 7" O.D. (178mm) casing was installed and cemented in two stages. The work was completed on 10 September. The second stage cementing, between a depth of 1215m and the surface, was determined to be inadequate to support the casing against thermally induced buckling stresses during production testing when flowing gas temperatures would exceed 250°C. There followed a series of eleven remedial cementing attempts which required 4 weeks to complete. Drilling ahead was resumed on 9 October. Two intervals were cored with a diamond core bit and floating core barrel assembly. These intervals were between measured depths of 2049.7 - 2057.9m and 2107.0 -2111.4m. 95% core recovery was achieved. On 21 October complete loss of circulation was sustained at a measured depth of 2127m. (TVD = 2016m). The hole was advanced another 24m, including an unsuccessful attempt to recover a third core. At that point, all indications were that the lower explosion chimney had been penetrated and the hole was completed with a perforated 5" O.D. (127mm) liner to a measured depth of 2149m. Continued concern for the integrity of the 7" casing resulted in the installation and cementing of a 4-1/2" O.D. (114mm) production casing from a depth of 1875 m to the surface. The final completion operations included installation of a 2-3/8" (60mm) tubing string to a depth of 1980m to accomodate bottom hole pressure and temperature instrumentation, and injection of 700 m^3 (25 mcf) of nitrogen gas to displace the remaining fluids and initiate flow. A two hour flow test was conducted to verify chimney connection and collect gas samples. The drilling rig was then released and demobilized starting on 2 November. Construction of the AR-2 well required a total of 140 days and cost approximately $1.7 million to complete.

The period from 3 November to 9 December was devoted to preparation for production testing. The testing system was essentially identical to that used for the second RB-E-01 test of the top chimney and included a bank of forced air heat exchangers, a conventional liquid/gas separator, instrumented meter runs with gas sampling ports and a flare stack. Tankage for collection of separated fluids and facilities for reinjection of the fluids into an adjacent well were provided. Field capability to collect and analyze gas and fluid samples for radioactivity was also mobilized.

The production test (Ref 4) was initiated on 10 December at a flow rate of 1.59×10^5 m^3/day (5.6 Mmscf/d). The flow rate declined to a rate of 1.03×10^5 m^3/day (3.63 Mmscf/d) on 16 December, when the test was terminated and the well was shut in for long term buildup. The total dry gas produced was 7.62×10^5 m^3 (26.9 Mmscf). A total of 311m^3 (1958 bbls) of water was separated from the flow stream and reinjected into the adjacent well.

With regard to release of radioactivity to the atmosphere, a total of 242 Ci of ^{85}Kr, and 23 Ci of ^{3}H were released through the flaring operation. The injected fluids contained a total of 28 Ci of ^{3}H, 4.3 mCi of ^{137}Cs & 1.0 mCi ^{90}Sr.

The result of these activities in the region of the lower explosion has led to reasonable insight into the explosion phenomenology and associated reservoir stimulation effects. The principle conclusions from the investigations are summarized in the following paragraphs.

Geophysical Log Analysis - The suite of geophysical logs which were run prior to installing the 7" casing were analyzed over the interval from 1585m to 1975m measured depth. In addition to a detailed multipoint directional survey, convertional gamma ray and neutron density and porosity logs, acoustic velocity and induction electric logs were run. These were analyzed and interpreted using the Schlumberger SARABAND computer analysis. No significant variation in reservoir characteristics compared to pre-detonation logs from the emplacement well was noted. Good correlation of gas bearing sandstones was obtained between the two wells which were separated in this interval from 130 to 350m. A consistent dip of 8 ± 2 m/100m toward the north was observed. In addition a high intensity gamma ray log which was run following installation of the 5" production liner confirmed the depth at which the well penetrated the lower chimney.

Core Analysis - (Ref 5) As indicated earlier, two intervals were successfully cored in the lower section of the well. These intervals were carefully selected to include an interface between a sandstone and a shale section. The first core was cut at the depth of the midpoint between the middle and lower explosives in order to investigate the possibility of enhanced fracturing from reinforcement of the converging explosion stress waves.

The horizontal offset from the emplacement well in this interval was 74-78m and the radial distance from the lower explosion was 108 - 115m. The second cored interval was at a radial distance from the lower explosion of 55-57m. The locations of these intervals are indicated on Figure 1. Thin sections were prepared from the core and examined under a petrographic microscope. It was not possible to differentiate sections from the two cores on the basis of the degree of fracturing. Three types of fractures were observed: large, open breaks in the fine-grained silts and clays; grain boundary separations in the coarser sandstones; and intergranular fractures on a very small scale. The latter type is poorly developed in both core intervals. We conclude that the degree of shock induced fracturing is very low - in fact so low as to be seriously disguised by postshot deformation and release phenomena. Whether the released strain was deposited by the explosion stress wave or natural stresses is unknown. The best that can be said is that the degree of microfracturing in the gas-bearing sandstones is very small, and thus the probable limit of significant explosion-induced permeability enhancement, in this case, does not extend as far as 2.6Rc, the range of the closest cores.

Chimney Radius - We have earlier alluded to the problems encountered in directional control for the AR-2 well, particularly with respect to building and maintaining inclination in the vertical plane. The need to know the spacial location of the course of this hole relative to the course of the emplacement well required very precise borehole surveying techniques. A total of nearly 400 survey points were used in the calculations of the subsurface traverses with extensive evaluation of the sources and magnitudes of errors. We conclude that the radius of the lower chimney as defined by a drastic change in the rate and uniformity of drill bit penetration is 23.5 ± 3m (77 ± 10 ft). This point of bit penetration is located 5.7 ± 0.8m above the lower explosion point. The implied cavity radius based on the chemical analysis of the produced gas, which will be discussed in the following paragraphs, is 23.1 ± 0.2m (75.9 ± 0.7 ft).

Chemical and Radiochemical Analysis - (Ref 6) A total of ten gas samples were collected from the flow stream during production from the lower chimney; all were analyzed for chemical composition and gross radioactivity. Five were further analyzed for individual radioactive species and for rare gas tracers. The principal constituents of the gas as a function of cumulative production are shown in Figure 2. The initial points are average of the samples taken in the short flow test at the time of well completion. The remaining data are from the six day production test. For reference, the composition is similar to that found in the top chimney during the first test from it. The H_2 fraction is somewhat higher (14% in AR-2 compared to 10% in E-01), while the CO_2 fraction is slightly lower (52% vs. 58%). No particular significance is ascribed to these variations. The curve labeled "natural gas" represents the sum of formation gas constituents in the produced gas and is 93% methane, 6% ethane, and 1% propane and heavier hydrocarbons.

The Rio Blanco explosives were individually traced with different stable rare gases. The lower explosive was traced with krypton and the middle explosive with xenon. Krypton was the only detectable tracer at the start of the production test. Near the end of the test, very low but statistically non-zero concentrations of xenon were observed. These values suggest that, as an upper limit, 0.12% of the total produced gas came from the middle explosion region. The average krypton concentration (3.50 $\pm$ 0.07 ppm) corresponds to a dilution of the tracer volume with 2.15 $\pm$ 0.06 x 10^6 m^3 (NTP) of chimney gas. It is this volume that, when converted to an equivalant sphere, leads to the 23.1 $\pm$ 0.2 m radius mentioned earlier.

Sampling time concentrations of ^{85}Kr and ^{3}H (tritium) are plotted in Figure 3. Dilution effects are evident but not extensive. ^{85}Kr released during the test (the area under the upper curve) was 250 Ci or 36% of the total, based on the krypton tracer, of 700 $\pm$ 20 Ci. The fission yield, assuming 22.7 Ci/kt of ^{85}Kr, is then 31 $\pm$ 2 kt.

Similarly, the concentrations of the tritrated gases, measured relative to the krypton tracer, indicate a total tritium in gas of 69 $\pm$ 4 Ci or about 7% of the total calculated tritium in the chimney.

As noted earlier, small but measurable quantities of two fission products, ^{137}Cs and ^{90}Sr were found in the separated liquids. The concentrations of these isotopes decreased rapidly during the test, thus indicating a small source; probably local deposition on chimney rubble near the well which was disturbed during the drilling operations. No refractory fission products or fissile materials were removed from the chimney.

A question was raised at the last IAEA meeting with respect to the amount of ^{14}C found in the production tests. Analyses of samples from both the upper and lower chimneys indicate concentrations of 0.2 $\pm$ 0.1 $\mu Ci/m^3$ of ^{14}C, all found as $^{14}CO_2$. None was found in the gaseous hydrocarbons.

Production Analysis - The analysis of productivity which follows parallels the analyses which have been reported previously for the U. S. gas stimulation projects and is based on numerical simulation modeling of the reservoir/chimney system. The objective of this multiple parameter modeling is to duplicate the observed chimney pressure as a function of time during the drawdown and buildup phases of production tests. Due to the number of variable parameters and the single data function available for matching, the resulting model cannot be considered a unique solution. Other data, from chemical and radiochemical analyses and geophysical logs serve to provide additional constraints and increase the level of confidence in the model as it represents the physical system.

In the case of the lower explosion region, the chimney pressure history is plotted as the solid curve in Figure 4. Note that the long term buildup pressure reached a nearly stabilized value at approximately 900 days following the detonation and remained at that value until the measurements were terminated at 1160 days. This behavior is anomolous and can be most readily explained in the context of a reservoir of limited lateral extent. In this case, the effective mean radius of drainage must be reduced to 125m (410 ft.) in order to model the observed pressure history. On the basis of the geophysical logs, there are at least three separate gas-bearing sands in the region intercepted by the lower explosion chimney. The lateral extent of each of these lenticular sands is not known. There is not a good correlation of these sands in the 190m offset well which will be described in the next section. Thus it is a real possibility that the effective drainage radius is less than 200m.

Alternatively, this behavior can also be approximated by cooling effects. For example, a temperature reduction in the chimney of 14°C during the buildup period of 580 days, or an average of 0.025°C/day would also account for this observed pressure history. This large effect on pressure as a function of temperature is produced by the strong dependence of the vapor pressure of water on temperature in the range of interest-approximately 250°C.

We do not have sufficient information to discriminate between these two possibilities. However, the cooling phenomenon is certainly present at an unknown rate. The dotted curve in Figure 4 reflects the model calculation which does not incorporate either cooling or limited drainage radius considerations.

The input parameters of the model which best fits the observed pressure history are summarized in Table I. This modeling technique involves the development of a radially symmetric system in which the input parameters are adjusted until the computer - calculated pressure history agrees with the observed data.

A basic chimney parameter which evolves from the simulation of the production test is a storage capacity of 1.67×10^{6} m^{3} (59.0×10^{6} ft.^{3}) at chimney pressure and temperature. This is equivalent to a physical volume of 2.4×10^{4} m^{3} (8.4×10^{5} ft^{3}).

The simulation of the early pressure buildup data is particularly important to the development of the permeability enhancement factors and the inferred reservoir flow capacity. Of particular interest is the reservoir flow capacity (kh). The net sand thickness parameter was selected on the basis of geophysical log analysis, even though we recognize the inherent hazard of a substantial overestimate. The permeability was then varied to develop a fit to the data. The resulting product of these parameters is 0.15 mdarcy-m (0.50 md ft.) which is in reasonable agreement with the predetonation predictions.

3. Reservoir Characterization

As a result of the production tests from the upper explosion region in the winter of 1973-74 it became obvious that the production characteristics of the reservoir which was supplying gas to the upper chimney were significantly poorer than predicted. The details of this comparison were presented to the last IAEA meeting and can be summarized by observing that the gross permeability-height product (kh) inferred by the production model was a factor of 6 to 10 less than the predetonation predictions based on conventional analyses. This major deviation led to a decision to drill an additional well for the purpose of evaluating the production characteristics of individual gas bearing sands in this reservoir. (Ref 7) The objectives were specifically: a) to determine the net effective kh for selected sands, with emphasis on the Ft. Union sands which supply the upper chimney; and b) to investigate the reservoir properties which were being misinterpreted and were therefore leading to major overestimates of the production potential.

A location was selected 190m northwest of the RB-E-01 explosive emplacement well on the basis that no significant detonation-induced alteration of the reservoir was anticipated at that range, however it might be close enough to the explosion region to detect reductions in the reservoir pressure caused by the transient effects of flow into the chimneys. This new well was designated RB-U-4. A drill rig was mobilized on the location and the well was spudded on 22 September 1974. The well was drilled routinely with conventional rotary techniques and a water based circulating fluid to a total depth (T.D.) of 2142m (7025 ft.). An intermediate casing was run and cemented at 673m (2207 ft.) and a 7" O.D. (178mm) primary casing was installed to T.D. This casing was cemented in the interval from 1350m (4430 ft.) to T.D. Geophysical logs identical to those obtained in the other project wells were run prior to casing. A standard gas production wellhead assembly was installed. The rig was released on 8 November. This well thus required a total of 48 days to complete at a cost of $525,000.

During the period from December 1974 to August 1976 a series of tests were conducted on individual zones in this well. (Ref 8) The intervals tested are identified on Figure 5. In most of these intervals the testing sequence was similar and included the following steps:

a. Perforation of the casing and cement sheath with small explosive shaped charges at intervals of 0.3 to 1.2m (1 to 4 ft.).

b. Isolation of the zone with borehole packers and tubing.

c. Formation breakdown by injection of 20 to 60 m^3 of 2% KCl brine into the zone under pressure,

d. Removal of the breakdown fluid by swabbing, to permit gas flow,

e. Producing a metered quantity of gas from the zone to induce a transient pressure reduction, and

f. Monitoring the pressure recovery for an extended time period.

In the case of the four Mesaverde zones, insufficient flow volumes were obtained to determine realistic values for either formation pressure or flow capacity (kh). Attempts were made to break down the formation with pressurized nitrogen gas as well as water and very precise measurements of pressure recovery were made. We can only conclude that the gross flow capacity, as inferred from the lower chimney test, is a reasonable upper limit for this section of the Mesaverde. Examination of the geophysical log interpretations leads us to suspect that the in-situ water saturation of the formation porosity very closely approaches the cut-off value - i.e. the value at which the permeability to the gas phase is effectively zero. Thus additional water, such as that used to break down the formation, causes local skin damage along the fracture surfaces and drastically inhibits flow to the wellbore.

The detailed evaluation of the Fort Union sands, on the other hand, was much more successful. Each of the three intervals tested yielded results which total 63% of total effective productivity as inferred from the upper chimney tests.

The final interpretation of the upper chimney/reservoir system has not yet been completed. However several comments can be made with respect to the numerical simulation model which was described at the last IAEA meeting. First, the in-situ unstimulated reservoir pressure which was assumed in that model, 14.15 MPa (2050 psia), is in error by $\sim$ 10%. The measured value is 15.55 $\pm$ 0.10 MPa (2255 $\pm$ 15 psia). Second, the three sands have considerably different characteristics than either predicted prior to the detonation or inferred in the perviously described model.

These characteristics are summarized in Table II.

The net effect of these measured values will be to require the model simulation to contain a somewhat larger storage volume and reduced radius of permeability enhancement. In general the conclusions drawn from the previously reported data will not be significantly altered by the new information. The principal effect of the recent data is to reinforce the conclusion that a much more sensitive method for characterization of these reservoirs with geophysical measurement techniques is needed to adequately assess the production characteristics prior to commitment of major development expenditures. More bluntly stated - if we had known in 1972 what we know now about this site, this project would not have been executed there.

4. Massive Hydraulic Fracturing Experiment (MHF)

In 1972 the Natural Gas Technology Task Force indicated that, in addition to nuclear stimulation, another emerging technology, known as massive hydraulic fracturing, should be explored to determine its potential for developing the very low permeability reservoirs. A number of experimental MHF projects have now been conducted in various locations in the Rocky Mountain area. One in particular is of interest as it is located only 1.4 km north of the nuclear emplacement well and is designed to provide a direct comparison of the two technologies. This project is also a jointly sponsored effort of industry and the government. (Ref 9) The project well, known as MHF-3, was drilled during the spring and summer of 1974 and was completed with a 7" production casing to a depth of 2488m (8162 ft). A total of four separate fracture treatments in different sands have been executed in this well, the last of which occurred this month (November 1976) and has yet to be evaluated.

The first treatment took place on 28 October 1974 in a Mesa Verde sand at a depth of 2454-2461m (8048-8073 ft.). The zone was fractured with 445 m^3 (117,500 gallons) of a polyemulsion fluid which carried 182,000 kg (400,000 lbs.) of sand propant. The fluid was 2/3 naptha-diesel oil mixture and 1/3 a 2% KCl brine. A number of unanticipated results were observed following the treatment. A total of only 59% of the fluids injected were recovered during production, including 92% of the brine but only 42% of the oils. Most of the oil recovered was the naptha fraction while the diesel oil was apparently adsorbed in the formation. Flow rates were below predictions by a factor of 5 to 8. The inferred reservoir pressure following treatment was several megapascals higher than before the treatment, and very poor lateral propagation of the fracture was indicated by the analyses. An effective fracture length of 35-50m from the wellbore was inferred. The fracture did not increase the productive capacity of the sand which was on the order of 45 μdarcy-m.

The second treatment was conducted on 2 May 1975. Three separate sands over the depth interval of 2366-2399m (7760-7864 ft.) were treated. The zone was fractured with 1080 m^3 (285,000 gal) of polyemulsion which carried 400,000 kg (880,000 lbs) of sand propant. The fluid was a single phase refined naptha and a KCl brine emulsion. The gas production averaged 3900 m^3/day (137 Mcf/D), a 2.5 fold increase over pretreatment rates but steadily declined without reaching stabilization during a 30 day test. The gas flow rates were again substantially below the predictions.

The third treatment was performed on 4 May 1976, after an extended evaluation of various possible zones. The sand selected for treatment was the horizon which corresponds to the Fort Union II in the nuclear project wells. It is not known to be the same sand in a depositional sense. The sand occurs in the depth interval 1806-1834m (5925-6016 ft.) at the MHF-3 site. The treatment consisted of 1300 m^3 (344,000 gal) of a gelled KCl brine fluid and 368,000 kg (809,000 lbs.) of sand. Near the end of the treatment, the sand plugged the perforations and the operation was stopped. After cleaning out the sand plug, the well was produced for 60 days. The production stabilized at a rate of 4550 m^3/day (160 Mcf/D) or an indicated factor of four increase over the pretreatment rate.

Preliminary analysis of this treatment indicates a much shorter effective fracture length than the design.

The fourth and last treatment took place on 3 November 1976, in the Fort Union I sand in the depth interval 1784-1789m (5851-5869 ft.). The fracturing fluid was 840 m^3 (220,000 gal) of gelled KCl brine carrying 284,000 kg (625,000 lbs.) of sand. The sand was injected intermittantly with fluid spacers at a volume ratio of 6:1. The design fracture length was ∿ 300m. No production test data are available yet on this treatment.

The tentative conclusions from this experimental program, largely supported by other similar efforts in the very low permeability reservoirs, are not encouraging. The fractures do not appear to propagate laterally as designed. Additional research into the viscosity effects on fracture extension and proppant transport is needed. The MHF technology has been very successful in treatment of higher permeability blanket sands in some areas. It is becoming clear that it is not yet a proven technique for the very low permeability basins.

5. Project Status (Ref 10)

The Rio Blanco nuclear stimulation project has now been essentially completed. Some additional effort will be committed to refinement of the numerical simulation models of the chimney/reservoir systems. Documentation of the hydrologic regime in the project area will continue for several years. The two chimney re-entry wells have been permanently sealed and the surface production testing equipment has been decontaminated and returned to the inventory of the various industrial participants. The RB-U-4 reservoir evaluation well was also sealed, but in a manner which would permit re-entry at a future time if it were decided to drill a directional hole to investigate the nature of the chimney interconnection problem. The project site areas have been regraded and seeded to restore vegatation in conformance with government regulations which are designed to minimize the environmental impact.

6. Conclusions

There are no active plans for additional research and development experiments on the PNE gas stimulation application in the U. S. This would therefore seem an appropriate time to review briefly the accomplishments and remaining technical problems in development of the application.

U. S. industry and government has committed well in excess of $50 million over the past twelve years to the development of this option for supplemental natural gas supply. While this is certainly not a trivial effort, it should be compared to the investment associated with other supplemental supplies. It is, for example, about 5% of the cost of a single modern coal gasification plant capable of producing 7 million m^3 per day of synthetic gas. What has been accomplished?

Three nuclear stimulation experiments have been performed and evaluated. An explosive development program has produced a system, less that 200 mm (8 in) in diameter, which can be fired in the multiple simultaneous mode with yields in the range of 20 to 100 kt. It can be emplaced in reservoir conditions of 150°C (300°F) and 35 MPa (5000 psi). The residual tritium is very low - about 100 mg from a 30 kt explosion.

Less than 10% of this radioactivity will be incorporated in the produced gas and detailed studies have shown that the routine domestic use of such gas would result in exposures to man of the order of 1% of natural background.

The ground motions associated with the application have been shown to be predictable and the resulting effects on structures are amenable to analysis and compensation.

With respect to stimulation effects, the lateral permeability enhancement appears to fall within the range of predictions. Although this is a very difficult parameter to measure directly, the simulation-inferred values appear to be reasonably consistant. None of the experimental wells have been produced long enough to remove all the connate water from the chimney and therefore any long term effects associated with this factor have not been evaluated.

Disposal of the produced water has been demonstrated to be relatively straightfoward by reinjection.

The economic viability of the application has been studied parametrically and appears to be within the range of projected costs for supplemental gas supplies. It does not stand out as markedly less expensive than the alternatives and obviously is strongly dependant upon the natural flow capacity of the reservoirs beyond the range of explosion effects. This characteristic, of course, ultimately controls the production from any well.

What are the outstanding technical problems? The most serious one is not unique to the PNE application, but is common to any recovery enhancement scheme. The currently available methods for evaluation of the effective flow capacity of the very low permeability reservoirs prior to commitment of major expenditures for development are not adequate. The basic physical properties which are not being correctly interpreted have not been definitely identified. The massive hydraulic fracturing technique is not proving to be significantly better or worse than PNE stimulation in overcoming this problem. The problem is more acute for MHF in that individual sands must be selected for treatment, whereas the PNE approach tends to be less discriminating by intercepting a thicker vertical section.

The other major technical uncertainty involves the unanticipated failure of the Rio Blanco explosion regions to interconnect. The speculations on the cause of this problem were detailed at the last IAEA meeting and no new data have led to additional insight into that problem. A subsurface exploration effort involving core drilling through the interexplosion region would be required to further the understanding of this matter.

In summary, much has been learned, and some problems have been identified. Perhaps the contining decline in U. S. domestic gas production will cause us to return to the development of the PNE technology in the future. In fact, efforts are now underway to define a technical program to address the reservoir characterization problem. In the meantime, from the U. S. viewpoint, this application must remain in the category of apparent technical feasibility, with additional development required for reduction to economic commercial practice.

Acknowledgements - The author wishes to acknowledge the efforts of many people in the industrial and governmental sectors who have contributed to the Rio Blanco project execution and interpretation. The major technical and financial contributions of CER, Inc. (formerly CER Geonuclear), the Continental Oil Co., and Equity Oil Co. have been essential. The continued support of the U. S. Energy Research and Development Administration (ERDA), and the predecessor agency the Atomic Energy Commission, has been vital to the effort. The diligent efforts of my many collegues at the Lawrence Livermore Laboratory have made this project possible.

RIO BLANCO ALTERNATE REENTRY CROSS SECTION

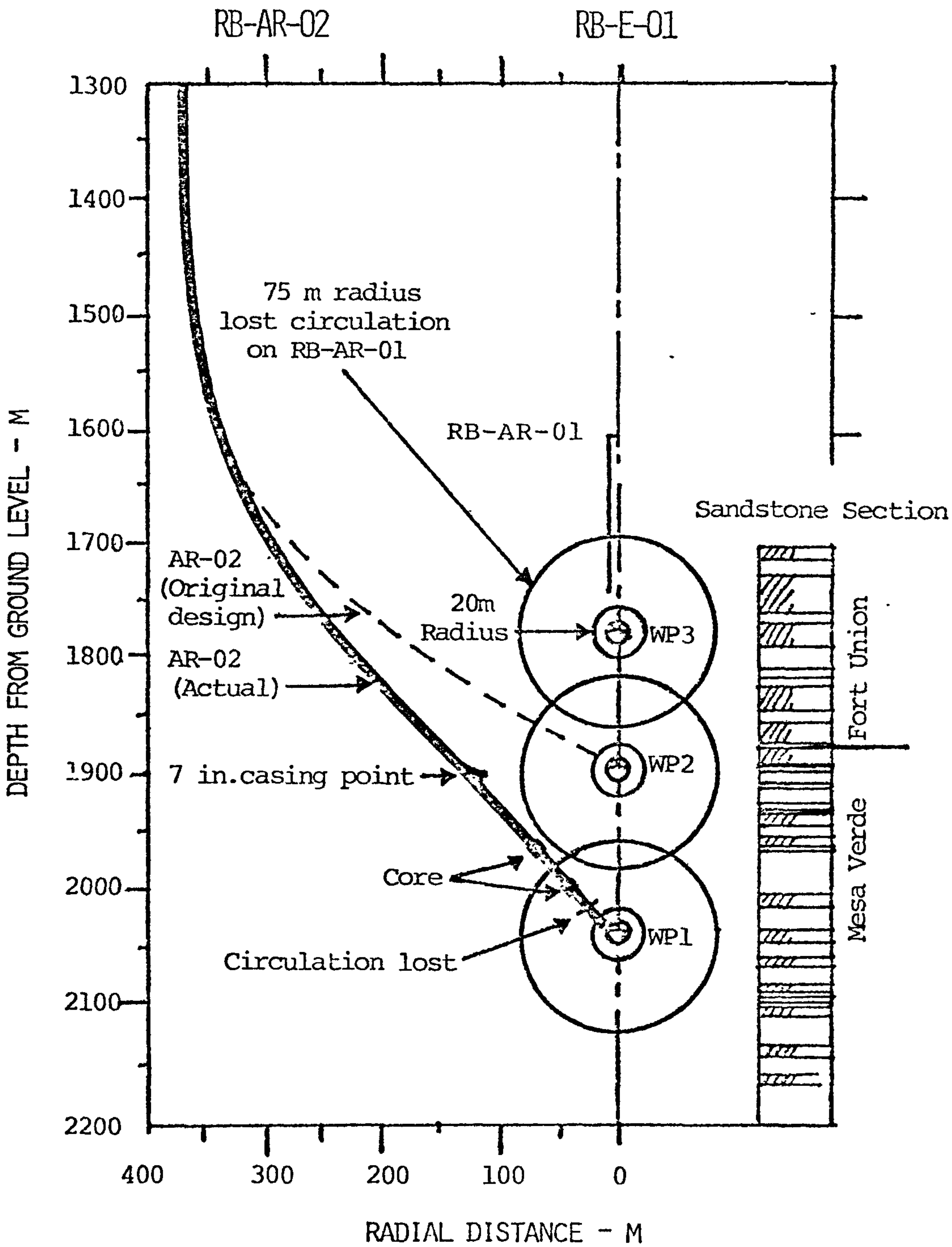

FIGURE 1

PRINCIPAL CONSTITUENTS OF THE RB-AR-02 GAS

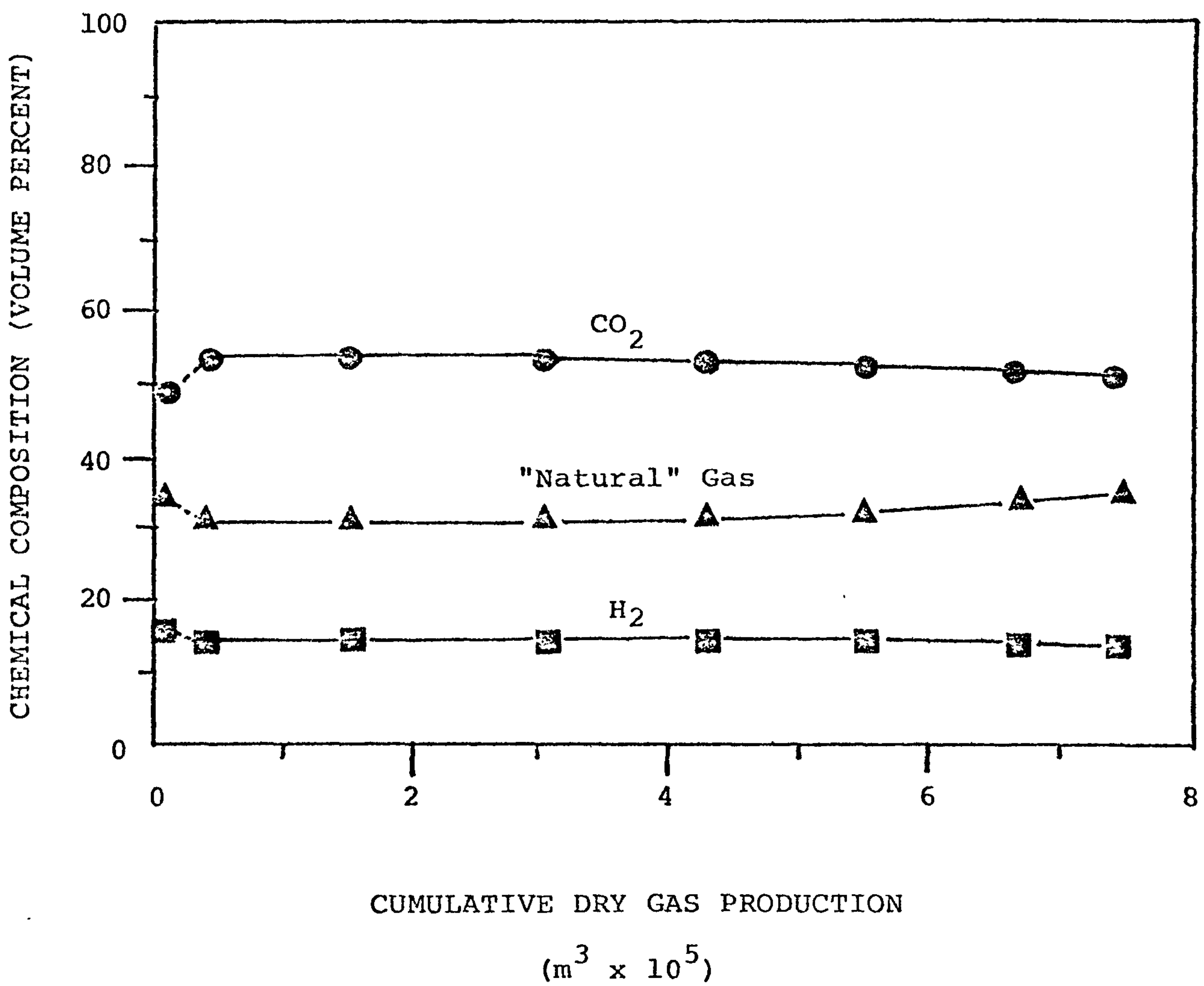

FIGURE 2

PRINCIPAL RADIONUCLIDES IN THE RB-AR-02 GAS

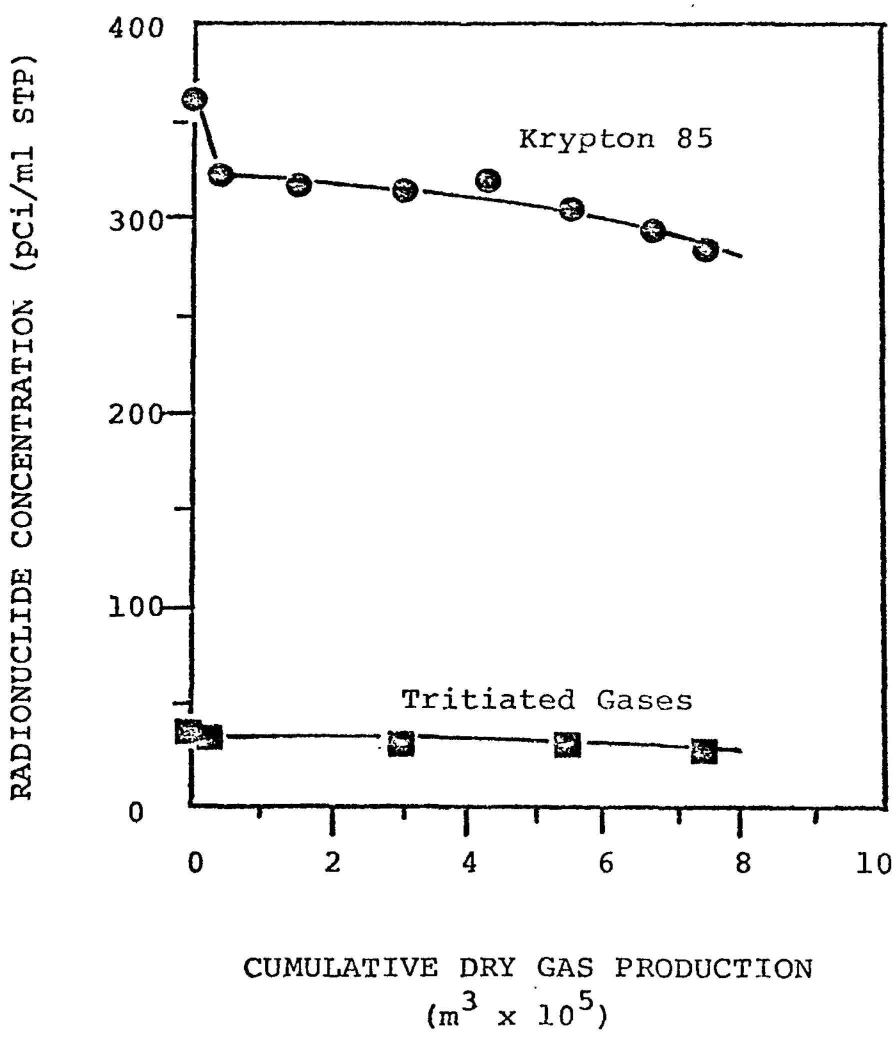

FIGURE 3

RB-AR-2 PRESSURE HISTORY

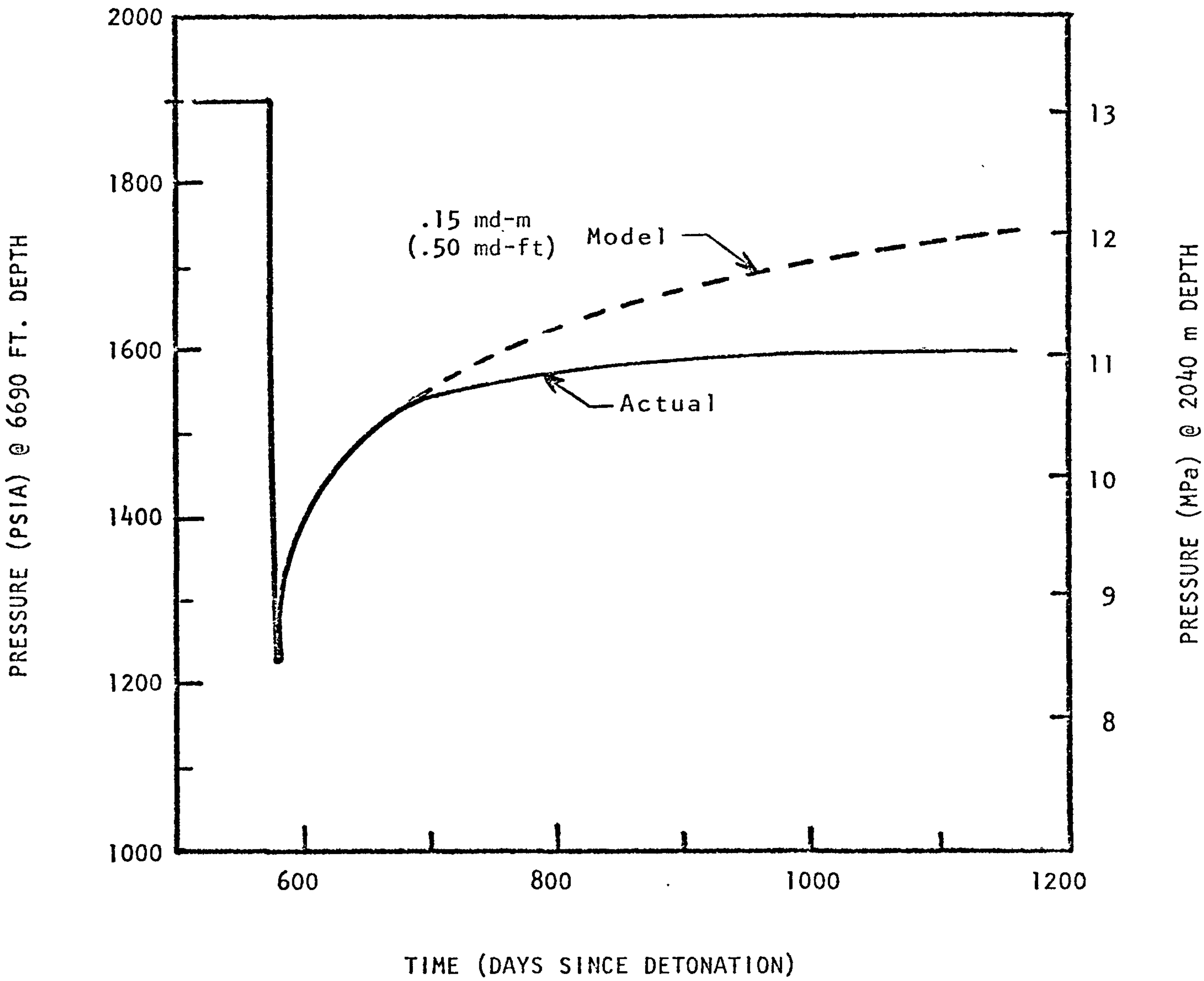

FIGURE 4

LOCATION OF RESERVOIR EVALUATION TESTS IN RB-U-4

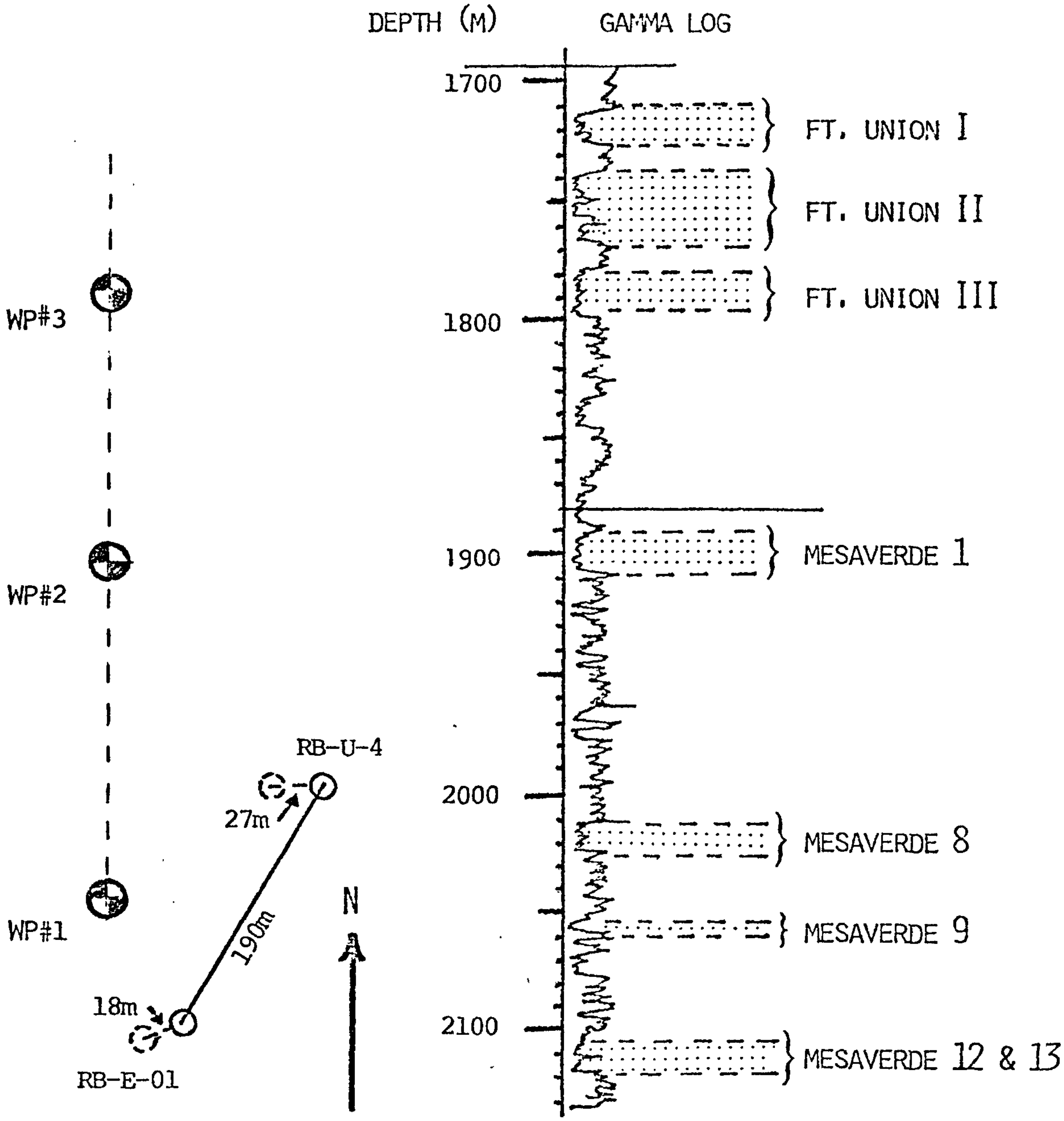

FIGURE 5

TABLE I

LOWER CHIMNEY MODEL PARAMETERS

Chimney:

Radius	(Rc)	=	20.1 m (66 ft.)
Gas Filled Porosity	(Ø)	=	70%
Temperature	(T)	=	260°C (500°F)
Cooling Rate	($^{dt}/_{dt}$)	=	0.007° C/day (0.013° F/day)

Fracture Region:

Permeability Enhancement (k/k_o)	=	20
Enhanced Permeability Radius (R)		$1 \leq R/Rc \leq 2.85$

Reservoir:

Effective Permeability (k_o)	=	10 μd (microdarcys)
Net Sand Thickness (h)	=	15.2m (50 ft.)
Effective Radius (R_f)	=	125m (410 ft.)
Gas Filled Porosity (Ø)	=	4%
Gas Gravity (G)	=	0.65 (Air = 1.00)
Formation Pressure (P_f)	=	13.1 MPa (1900 psia)
Temperature (T)	=	96.1°C (205°F)

TABLE II

FORT UNION SAND PROPERTIES

Interval	Effective Net Thickness(h) (m)	Permeability(k) (μ darcy)	kh (μ darcy-m)
Fort Union I (1711.3-1724.1m)			
Prediction (1)	7.6	25	190
Model (2)	8.2	20	164
Measured (3)	5.2	8	43
Fort Union II (1736.6-1766.5m)			
Prediction	35.4	25	884
Model	30.5	19	58
Measured	11.0	8	88
Fort Union III (1779.3-1796.3m)			
Prediction	17.1	25	427
Model	0	--	0
Measured	3.6	1.7	6
Total Upper Chimney			
Prediction	60	25	1500
Model	38.7	19-20	222
Measured	19.8	1.7-8	137

Notes: (1) The values listed as "Prediction" are those reported by LLL. Other participants also gave predictions in this range.

(2) The values listed as "Model" are those reported by Toman in Ref (2).

(3) The values listed as "Measured" are from a preliminary evaluation of the measured data and are subject to modification. The values listed are probably lower limits.

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