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The United States Atomic Energy Commission, the United States Bureau of Mines, Lawrence Radiation Laboratory, Livermore, and El Paso Natural Gas Company have jointly investigated the feasibility of fracturing natural gas reservoirs with nuclear explosives and designed an experiment to test this concept.

The beneficial effects of a nuclear explosion in a gas reservoir should be:

1. A network of fractures radiating out from the shot point that will permit more effective drainage of the reservoir;
2. An expanded wellbore that will allow higher sustained rates of production after initial drainage of the fractured zone; and
3. An effective storage volume for short-term high deliverability.

The Pictured Cliffs formation, a gas reservoir in the San Juan Basin of northwestern New Mexico, was selected for analysis to determine if a field test in this area is feasible. This analysis resulted in the finding that nuclear-explosion stimulation of a Pictured Cliffs formation well at the proposed location may increase stabilized deliverability and gas recovery during the initial 20-year producing period by substantial factors over that obtainable by present completion methods. It is also concluded that an effective field test can be designed which would satisfy all safety requirements so that neither the possibility of radioactive contamination of the atmosphere or ground water nor the resulting ground shock would be a serious hazard. Furthermore, calculation of the level of radioactive contamination of the gas resulting from explosion of a fission device suggests that flaring some of the recoverable gas and employing other techniques could reduce the level of radioactivity to safe limits for transmission and ultimate consumption.

Total cost of the experiment, exclusive of the cost of the explosive, is estimated at $3,000,000.00.
ACKNOWLEDGMENT

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A project of this size and scope required the efforts of many people in the organizations listed that have not received mention, but whose contributions are reflected in this study. The cooperation of all was essential and is appreciated.
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I. INTRODUCTION

A. General

Cooperative research by the United States Atomic Energy Commission (AEC) and the United States Bureau of Mines (USBM) under the AEC Plowshare Program, indicates that the use of nuclear explosives (NE) to stimulate low productivity oil and gas reservoirs can be far more effective than present stimulation techniques. This previous work also indicates that the extensive, thick, low-permeability natural gas reservoirs in the Rocky Mountain Region are the most favorable for NE stimulation. A survey of these gas fields and discussion with operators resulted in isolating several locations suitable for a field test.

Proof of the utility of NE stimulation can be determined only by a full-scale field test. Justification for such a test lies in the number and areal extent of low-productivity reservoirs where the ultimate recovery and the rate at which such recovery occurs may be substantially increased.

As early as 1958, El Paso Natural Gas Company (EPNG) investigated the application of NE stimulation to a gas reservoir by initiating correspondence with the University of California, Lawrence Radiation Laboratory, Livermore, (LRL) in connection with the Pinedale Unit Area, covering approximately 92,000 acres in Sublette County, Wyoming. Although EPNG did not propose a field test because of technological problems existing at that time, this area is one that should merit consideration for future application.

B. Project Gasbuggy

Project Gasbuggy was instituted to design, conduct and evaluate a NE stimulation experiment in the Pictured Cliffs formation at one of the most promising of the prospective test sites, located on an EPNG oil and gas lease in the San Juan Basin, Rio Arriba County, New Mexico. Project Gasbuggy is a joint undertaking by the AEC, USBM and EPNG to evaluate the feasibility of a test at this location and to execute the test, pending authorization by the policy-making bodies of these organizations.

This report presents the results of the site evaluation and offers a preliminary design for the experiment. The study was initiated by the AEC San Francisco Operations office. EPNG and USBM, utilizing accepted technology of the industry, performed the necessary calculations and made the engineering evaluations. EPNG furnished the geologic data, ownership and location information, while LRL provided consulting services pertaining to resulting radioactivity in the gas and effects of nuclear explosions.

Performance of this experiment will require drilling and casing an emplacement hole to accommodate the nuclear explosive just below the base of the Pictured Cliffs Formation. The yield of the explosive to be used will not exceed 10 kilotons, the energy equivalent to 10,000 tons of TNT. As an example of its magnitude, the nuclear explosion will generate a force 5,000 times greater than that obtained from 1000 quarts of solidified nitroglycerin, the normal amount of stimulation given a Pictured Cliffs well when the “shot-hole” completion method was practiced.

The energy of the nuclear explosive will be generated in a fraction of a microsecond, vaporizing, melting and crushing the surrounding rock. Within milliseconds, a cavity filled with vaporized and melted rock and debris will be created. The melted rock that initially lines the walls of the cavity will collect in a pool, trapping most of the radioactive fission products as it solidifies. The cavity will be roughly spherical in shape with a radius of approximately 65 feet. Following creation of this cavity, the roof will collapse and a cylindrical chimney of broken rock will develop upward. The radius of the chimney will approximate that of the cavity, and its height is estimated to be 300 feet.

The force of the explosion will also cause fracturing of the rock beyond the cavity and upon this phenomenon rests the success of NE stimulation. Fracturing will cause a gross change in the permeability of the rock in which it occurs, and the number and range of these fractures will determine the extent of permeability change. Production will be accomplished by drilling into the chimney. The plan for this experiment and resultant subsurface effects are illustrated in Figure 1.

4Nuclear detonations under the AEC Plowshare Program to develop peaceful uses for NE are customarily named for vehicles.
PROJECT GASBUGGY
PREDICTED UNDERGROUND EFFECTS

DATA:
CAVITY RADIUS - 65'
CHIMNEY RADIUS - 65'
CHIMNEY HEIGHT - 300'
LATERAL FRACTURING - 195' to 430'

FIGURE 1
II. PROPOSED TEST SITE

A. Criteria for Acceptable Test Site

Criteria for selecting a test site for possible utilization of a nuclear device are as follows:

1. A low permeability depletion-drive reservoir in which conventional stimulative methods are inadequate.
2. Reservoir having sufficient thickness to effectively utilize the anticipated effects of the proposed nuclear explosion. Ideal thickness for a 10 kiloton yield device is approximately 300 feet.
3. Reservoir sufficiently deep to confine the explosion but not so deep as to result in excessive emplacement and testing expenses. Ideally the depth should range from 2000 to 4000 feet.
4. A site reasonably remote from habitation but easily accessible.
5. Sufficient drilling in the surrounding area to provide adequate production and subsurface data, yet not so highly developed as to be subject to heavy liability for possible damage to existing wells and surface field facilities.
6. Uniformity of leasehold ownership and/or withdrawal from leasing of unleased lands adjacent to the test site.

B. Location-Culture-Ownership

The location selected is in the SW/4 of Section 36, Township 29 North, Range 4 West, N.M.P.M., Rio Arriba County, New Mexico, on the eastern side of the San Juan Basin, a structural feature of the Colorado Plateau Province in northwestern New Mexico and southwestern Colorado (Figure 2). Most of the central Basin is open country, broken by occasional low mesas, buttes and wide cuestas, with local relief rarely more than a few hundred feet. The annual rainfall is 8 to 15 inches and only moderate snowfalls occur in the higher elevations.

The location is both remote and uninhabited yet readily accessible by paved highway (Figures 3, 4 and 5). There are no appreciable ground or surface waters in the immediate area. The nearest sizeable town is Farmington, New Mexico, 70 miles to the west, with a population of about 23,000. The nearest community is Dulce, New Mexico, approximately 20 miles to the northeast with a population of about 500. There are no houses or buildings within a five-mile radius.

The proposed test site is within the Carson National Forest and adjacent to the Jicarilla Apache Indian Reservation (Figure 6). Section 36 and the contiguous sections are Federal and Indian lands, some of which are presently unleased. The existing oil and gas leases covering the lands in the immediate area of the test location are held by EPNG (Figure 7). The area surrounding this site contains mesas, canyons and the usual bench-type topography generally associated with these surface features. The elevation ranges from 6800 to 7500 feet in the general area and from 7000 to 7200 feet in the immediate test area. There are no streams of consequence in the area. The San Juan River, at its nearest point, is about 20 miles from the test site and the Navajo Dam about 23 miles away. Vegetation consists of Pinon Pine in the lower levels and Ponderosa Pine and Juniper in the higher elevations. Vegetation rights are administered by the National Forest Service, with cattle grazing permitted during the summer months.

C. Geology of the San Juan Basin

Most of the central part of the Basin is covered by a circular blanket of continental sediments of early Tertiary or very late Cretaceous age. (See Figure 8 for Geologic Time sequence.) The central portion of the Basin is approximately 90 miles in diameter and covers an area of about 10,600 square miles. A roughly circular outcrop of marine and nonmarine Upper Cretaceous formations circumscribes the central part of the Basin. Facies changes within the Basin occur in many formations with intertonguing of marine and nonmarine strata. Overlapping unconformities and local angular unconformities occur in the flanks of the uplifts around the Basin, but in the large central area the beds are generally parallel throughout the section from the deep early Cambrian to the surface Tertiary beds.

Formations in the San Juan Basin range from pre-Cambrian to Eocene, but there was no an uninterrupted sequence of deposition. Some unconformities are present, and to-date no Ordovician or Silurian sediments have been encountered. The total thickness of sedimentary rocks in the center of the Basin ranges from 10,000 to 15,000 feet.

There are eight gas producing formations of Cretaceous age in the central Basin. These formations in descending order are as follows: Kirtland, Fruitland, Pictured Cliffs, Lewis, Mesaverde, Mancos, Graneros, and Dakota. However, the significant production is obtained from the Pictured Cliffs, Mesaverde and Dakota formations, the latter including the Graneros formation as defined by Order of the New Mexico Oil Conservation Commission.

The sequence and thickness of these formations at the test site are shown in Figure 8, based upon the two cross-sections contained in Appendix A. The Pictured Cliffs formation is expected to be 300 feet thick at the test site, exhibiting the characteristics of a low-permeability, depletion-drive reservoir that are specifically described in Section IV-A.
AERIAL PHOTOGRAPH OF PROJECT GASBUGGY TEST AREA

EXISTING SAN JUAN 29-4 10-36 WELL
600' DISTANCE TO
LOCATION OF EMPLACEMENT HOLE

FIGURE 4
GROUND VIEW OF TEST SITE

LOCATION OF EMPLACEMENT HOLE

FIGURE 5
TEST SITE AREA

CARSON NATIONAL FOREST
JICARILLA INDIAN RESERVATION

FIGURE 6
OWNERSHIP MAP OF TEST SITE AREA

- EL PASO
- FEDERAL LANDS TO BE WITHDRAWN
- PAN AMERICAN
- SUNRAY
- UNLEASED INDIAN LANDS
- DRY HOLE (TD-TOTAL DEPTH)
- GAS WELL (IP-INITIAL POTENTIAL)

BOUNDARY OF CARSON NATIONAL FOREST
BOUNDARY OF JICARILLA INDIAN RESERVATION
E.P.N.G. PIPELINE

FIGURE 7
GENERALIZED GEOLOGIC TIME COLUMN
OF THE SAN JUAN BASIN

CRETAUCEOUS FORMATIONS
AT
OPERATION GASBUGGY TEST SITE

QUATERNARY

TERTIARY

CRETACEOUS

JURASSIC

TRIASSIC

PERMIAN

PENNSYLVANIAN

MISSISSIPPIAN

DEVONIAN

SILURIAN

ORDOVICIAN

CAMBRIAN

PRE-CAMBRIAN

3450'  OJO ALAMO SANDSTONE
3550'  KIRTLAND SHALE
3750'  FRUITLAND SANDSTONE
3850'  PICTURED CLIFFS SANDSTONE
4150'  LEWIS SHALE
5775'  MESAVERDE SANDSTONE
6275'  MANCOS SHALE
8010'  GRANEROS MEMBER(SHALE)
290'  DAKOTA SANDSTONE
8300'  BURRO CANYON SANDSTONE
8450'  

FIGURE 8
D. Aquifers

The Ojo Alamo sandstone and the sandstone and coal stringers of the Fruitland formation, known aquifers in some areas of the Basin, are not believed to contain mobile water at the proposed test site based on the information contained in the geologic report, Appendix A. However, the design of the test provides for thorough analysis of these formations during the drilling of the two pre-shot test wells to confirm this conclusion.

E. Acceptability of San Juan Site

The preceding material shows that the selected location adequately satisfies the stated general criteria for an acceptable test site.

Although the feasibility study has been directed primarily toward a test in the Pictured Cliffs formation, there is also the possibility of an alternate or subsequent test in the deeper Mesaverde formation. The Pictured Cliffs and Mesaverde formations have similar reservoir and producing characteristics in the eastern portion of the San Juan Basin and should be representative in many ways of other low-permeability reservoirs in western United States.

Another advantage is that the proposed site is located in the State of New Mexico where there has been previous acceptance of underground nuclear testing. Also, the New Mexico Oil Conservation Commission is familiar with the economic and geologic considerations involved in development in this area. Therefore, it is expected that authorization can be obtained to transfer allowables from wells in the test area to other wells during shut-in test periods and later to produce in excess of normal allowables when testing to determine the effect of NE stimulation.

III. DISCUSSION OF PRODUCTION STIMULATION

A. Present Methods of Stimulation

The rate at which gas flows into a wellbore is directly proportional to the permeability of the reservoir rock, thickness of the productive interval, and the difference in the squares of the static reservoir pressure and the flowing pressure at the wellbore. The rate of flow is inversely proportional to the viscosity of the gas, the logarithm of the ratio of the effective radius of drainage to the radius of the wellbore, temperature of the reservoir and the gas compressibility factor. Two of these factors may be varied or controlled in the drilling, completion and operation of a gas well. The first is the pressure at the wellbore which is controlled by the wellhead or gathering-line pressure. An increased rate of gas withdrawal from a well can be accomplished by a reduction of the gathering-line pressure. However, this can be done only within the economic limits defined by the cost of compression facilities as compared to the value of the additional gas recovered.

The second factor over which there is a measure of control is the radius of the wellbore. Increasing the size of the wellbore by drilling a larger hole cannot be justified because the value of increased gas flow will not offset the higher drilling and casing costs. However, appreciable increases in flow can be obtained by significantly increasing the “effective” radius of the wellbore.

Enlarging the “effective” radius of the wellbore by increasing the permeability of the reservoir immediately surrounding the wellbore is now accomplished by various means. In limestone reservoirs a hydrochloric acid solution can be used to dissolve the calcium carbonate. Fracturing of the reservoir is another recognized technique. This has been achieved by “shooting” the uncased productive interval with solidified nitro-glycerin and by the more recent development now widely used, hydraulic fracturing. The latter is accomplished by pumping a fluid into the formation under sufficient pressure to fracture the formation in the vicinity of the wellbore. The fractures are propped open with sand that is pumped simultaneously with the fracturing fluid.

Hydraulic fracturing usually produces a fracture oriented either horizontally along or vertically across formation bedding planes. The treated interval is often not stimulated uniformly as fracturing may occur mainly where planes of weakness exist. A multiplicity of fractures are produced as a result of “shooting”, but the entire force is not directed into the formation and these fractures are limited in extent.

It is estimated that the use of solidified nitro-glycerin increases initial producing rates approximately five times and hydraulic fracturing results in an initial increase of approximately ten times. However, evaluation of production data indicates that these increases are not permanent. After the initial flush production period both methods exhibit significant declines in deliverability in low-permeability reservoirs, thereby demonstrating the limitations of these two techniques.

5This statement is expressed in reservoir engineering units in the formula contained in Appendix B.
B. Potential for NE Stimulation

The oil and gas industry recognizes the need for some method of more uniformly fracturing the reservoir considerable distances from the wellbore. A possible solution has been found in the application of nuclear energy.

Estimates of the increase in gas production resulting from NE stimulation are based on available knowledge of the characteristic effects of contained nuclear explosions. From a study of these characteristic effects it becomes evident that fracturing will be the prime contributor towards increased flow and recovery from the reservoir. In addition to the creation of a cavity and resultant chimney (Figures 9 and 10), it is expected that a multiplicity of fractures similar to those resulting from high explosives, but of a more extensive nature, will be developed by a nuclear explosion. This will result in an exceedingly large "effective" wellbore radius. In addition, bonus production should be obtained from intervals within the producing formation now considered uneconomical to perforate and fracture. See Appendix C for discussion of the factors affecting fracturing.

The lateral extent of fracturing cannot now be accurately predicted. The chimney or rubble zone, the radius of which is approximately equal to the cavity radius, can be considered an absolute minimum effective wellbore. Boardman, et al., measured bulk permeability increases to four cavity radii laterally from the center of the Hardhat chimney. Results of this work agree with earlier observations of permeability increases. It was considered conservative to assume that permeability increases (effective fractures) will extend three cavity radii from the detonation point and one set of post-shot well performance predictions in this report was made on this basis.

Because of the limited depth range of tests that yielded these data, it does not necessarily follow that the range of bulk permeability improvement scales with cavity radius. The existence of such scaling, the dependence of permeability increase with increasing shot depth, and the relationship between fracturing and permeability increase all remain to be verified by experiment. Therefore, to make optimistic predictions of post-shot well performance, effective fractures were assumed to extend a greater distance than 3 Rc (chimney radius in feet) laterally. In this case, it is assumed that Rc (the radius in feet of effective fracturing) is related to W (the explosive energy yield in kilotons of TNT equivalent) by the formula Rc = 200 W^1/6. This relationship does not contain a depth factor in the denominator as does the equation for cavity radius, contained in Appendix B. Ranges of permeability increase computed with and without the depth dependence diverge with increasing depth. The data indicating that bulk permeability increases out to three cavity radii also fit the relation Rc = 150 W^1/6; however, in applications to the gas reservoirs under study, hairline fractures provide effective permeability increases and should be more extensive than the fractures observed from post-shot exploration. Also, natural fractures and planes of weakness common in these reservoirs can be opened by the blast, resulting in further extensions of permeability increase. For these reasons, the radius of effective fracturing for optimistic performance calculations has been increased from 150 W^1/6 to 200 W^1/6.

Vertical fracture height can be predicted with reasonable accuracy. Data obtained from contained nuclear shots that have been subject to investigation by post-shot re-entry drilling show that the extent of fractures vertically above the shot point is approximately equal to six cavity radii. Fracturing has not been observed at distances greater than 1.5 cavity radii below the shot point.

The cavity or collapse chimney, together with the zone of highly fractured rock beyond the cavity, comprise an expansive permeable volume, the extent of which may be considered for calculation purposes as an exceedingly large effective wellbore. For simplification, the reservoir may be divided into two zones of flow: (i) flow from the effective wellbore, and (ii) flow from the radius of drainage into the effective wellbore. The large effective wellbore would act as a storage volume from which gas initially could be produced at high rates. As gas is produced, continued flow takes place across the outer wellbore circumference. After the storage volume has been depleted, deliverability would be measured by the amount of flow crossing the wellbore radius and roughly approximated by the flow equation contained in Appendix B.

It should be noted that producing a well in a low-permeability reservoir reduces the shut-in pressure at the wellbore below that of the equilibrium reservoir pressure. After the well is shut-in the wellbore pressure begins building up, but the period required to reach equilibrium pressure is normally many months. Therefore, it is expected that gas will continue to flow from the unaffected portion of the reservoir into the effectively fractured area and subsequently into the chimney itself, so that gas will be continuously entering the wellbore even though the producing well be shut-in.

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7Same Reference as Footnote 6.
CAVITY AT PROJECT GNOME, CARLSBAD, NEW MEXICO
DECEMBER 10, 1961

DETONATION OCCURRED IN A SALT BED. CAVITY REMAINING AFTER
DETONATION WAS 165 FEET IN DIAMETER AND 70 FEET HIGH.

NOTE MAN FOR SCALE

FIGURE 9
DETONATION OCCURRED IN GRANODIORITE. NOTE CHIMNEY RUBBLE IN COMPARISON TO ROCK BEYOND FACE OF CHIMNEY.
IV. PRODUCTION STIMULATION WITH NUCLEAR EXPLOSIVES

A. Project Gasbuggy

The Pictured Cliffs formation should be encountered at a depth of approximately 3850 feet at the proposed test site. It is composed of interbedded sand and shale deposits constituting a gross interval of 300 feet with about 190 feet of gas-saturated sandstone. At this location in the eastern part of the Basin, the Pictured Cliffs formation is a low-productivity reservoir due to the general low permeability of the sand deposits except where networks of natural fractures exist. The reservoir is contained by the overlying Fruitland formation, 100 feet thick, consisting of irregularly bedded sandstone, shale, siltstone and coal, and the underlying Lewis formation, over 1500 feet thick, predominantly shale.

The sand members of the Pictured Cliffs formation at the test site should have the following general characteristics based on evaluation of wells drilled in the general area:

- The average permeability is 0.14 millidarcys;
- Average porosity is 11%;
- Average gas saturation is 41% of the pore volume. These sands contain natural gas, predominantly methane, with a calculated amount of in-place gas of 33,000,000 cubic feet\(^8\) per acre.

Well spacing for the Pictured Cliffs reservoir is 160 acres which, therefore, would contain approximately 5280 M\(^2\)cf of in-place gas. However, performance and decline curves indicate only 13% of the in-place gas will be ultimately recovered, 10% in a 20-year period, from a well at this location completed with present stimulation methods. This fractional recovery is an estimate based on the gross amount of in-place gas which includes gas contained in zones not considered economical to conventionally stimulate. Recovery from the stimulated intervals is considerably higher. Data from producing wells in the area indicate that the perforating and fracturing method now used results in an initial stabilized deliverability rate of 275,000 cubic feet per day\(^9,10\) and average production of 74 Mcf/d calculated over a 20-year period.

Detonation of a 10 kiloton device immediately below the base of the Pictured Cliffs formation at a depth of 4150 feet would create a cavity having a radius of approximately 65 feet. Vertical fracturing should extend approximately 390 feet above the shot point and the chimney height 300 feet above the shot point. Values for the conservative and optimistic radii of effective lateral fracturing are 195 and 430 feet. (See Appendix B for calculations.)

Predicted gas recovery after 20 years of production is 3520 M\(^2\)cf for the conservative radius of fracture for a well on 160 acre spacing. If optimistic fracturing occurs and the drainage area is considered to be 640 acres, the ultimate recovery may be increased to 7753 M\(^2\)cf, an increase of 7216 M\(^2\)cf over that expected from conventional stimulation. A comparison of recovery and deliverability for a 20-year period using nuclear stimulation methods based on well spacings of 160, 320 and 640 acres, and the conventional completion method is shown on Tables 1A and 1B.

It should be noted that these tables project the recovery and deliverability resulting from conventional stimulation only on 160 acre spacing. The reason is that there is no evidence indicating that drainage occurs or a wider spacing basis within the initial 20-year period under discussion.

The obvious benefit from NE stimulation is an increase in the recoverable reserves that would be attributable to each tract so stimulated. Of additional benefit is the storage capacity of a large effective wellbore, containing volumes of from approximately 100 M\(^2\)cf to 300 M\(^2\)cf of gas that could be produced upon demand at rates on the order of 10 M\(^2\)cf/d for intervals of from 10 to 30 days, with subsequent deliverability probably in excess of 1 M\(^2\)cf/d.

B. Potential NE Stimulation in San Juan Basin

The proposed test site is located within an area of approximately 1500 square miles where the Pictured Cliffs formation has reservoir characteristics that could be effectively exploited by the use of NE stimulation.

The maximum yield device that could be used for stimulation of the Pictured Cliffs formation, assuming the presence of the Ojo Alamo as an aquifer approximately 600 feet above shot level, is 30 kilotons. The use of a 30 kiloton device should create a lateral fracture radius of from 280 feet (conservative estimate) to 600 feet (optimistic estimate) and recovery for a 20-year period would range from approximately 3625 M\(^2\)cf to 8734 M\(^2\)cf depending upon well spacing and fracture radius. Table 2A and 2B, on page 22, contain estimates of the result obtained from the NE stimulative method using well spacing of 160, 320 and 640 acres and the conventional method for a 20-year period.

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\(^8\) A million cubic feet of gas is commonly expressed as 1 M\(^2\)cf. Therefore the amount of in-place gas can be expressed as 33 M\(^2\)cf.

\(^9\) The term Mcf/d will be used throughout the remainder of this report.

\(^10\) This figure is commonly expressed as 275 Mcf/d. The term Mcf/d will be used throughout the remainder of this report.

\(^11\) Deliverability has been calculated based on producing into the 500 psi gathering system in this area. Elsewhere in the San Juan Basin, Pictured Cliffs formation wells produce into a gathering system with a working pressure not exceeding 250 psi.
Underlying the proposed test site at a depth of approximately 5900 feet is the Mesaverde formation, 500 feet thick, of which approximately 180 feet is gas-saturated sand. Reservoir characteristics of the Mesaverde formation follow closely those of the Pictured Cliffs formation, with an estimated amount of in-place gas of 25 M^3cf per acre as compared to 33 M^3cf per acre in the Pictured Cliffs formation. Present performance indicates approximately 7% of the in-place gas will be recovered from wells on 320-acre spacing in this general area. This estimated recovery, as stated in reference to recovery from the Pictured Cliffs formation, is also based upon the gross amount of in-place gas which includes gas contained in zones not considered economical to conventionally stimulate. Similarly, recovery from the stimulated intervals is considerably higher. The areal extent of the Mesaverde formation in which these or similar reservoir characteristics should be encountered is approximately 2,000 square miles.

The depth of the Mesaverde formation would permit the use of a 100 kiloton explosive. The extent of expected lateral fracture radii ranges from 375 feet to 930 feet. Predicted gas recovery after NE stimulation is from 2920 Wcf to 10,070 M^3cf. Calculated comparisons of recovery and deliverability for a 20-year period using both the nuclear and conventional stimulative methods are contained in Tables 3A and 3B, on page 22.

---

Project Gasbuggy
10 Kiloton — Pictured Cliffs Formation

**TABLE 1A: RECOVERY**

<table>
<thead>
<tr>
<th>Gas-In-Place, M^3cf (Well Spacing, Acres)</th>
<th>M^3cf (% In-Place Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Stimulation</td>
</tr>
<tr>
<td></td>
<td>Conservative</td>
</tr>
<tr>
<td>5280 (160)</td>
<td>537 (10)</td>
</tr>
<tr>
<td>10560 (320)</td>
<td>5170 (49)</td>
</tr>
<tr>
<td>21120 (640)</td>
<td>6124 (29)</td>
</tr>
</tbody>
</table>

**TABLE 1B: DELIVERABILITY**

<table>
<thead>
<tr>
<th>Well Spacing Acres</th>
<th>Initial Stabilized Deliverability - Mcf/d</th>
<th>Average Production Mcf/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>275</td>
<td>74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Well Spacing Acres</th>
<th>Initial Stabilized Deliverability - Mcf/d</th>
<th>Average Production Mcf/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>1564</td>
<td>482</td>
</tr>
<tr>
<td>320</td>
<td>1350</td>
<td>708</td>
</tr>
<tr>
<td>640</td>
<td>1177</td>
<td>839</td>
</tr>
</tbody>
</table>

---

11Appendix B deals specifically with the 10 kiloton device and recovery based on 160-acre spacing; however, it illustrates the method of calculation employed in obtaining the results stated throughout this section.

12Steady-state flow conditions would not prevail during the early production period until the pressure transient reaches the radius of drainage as dictated by well spacing. During the early production period stabilized deliverabilities should be several times greater than those shown in the table. Values shown in the table were calculated by use of the steady-state flow equation (see Appendix B). It should be noted that the stabilized deliverability of a well decreases as the assumed well spacing increases because of the increase of the value of the radius of drainage term (r_e) in the denominator of the steady-state flow equation.

13Values for average production are based on a daily contract delivery rate of 1 M^3cf/d per 8000 Mcf of reserves, which necessarily limits the recovery. The actual capacity of the well to produce is shown in Table 1, Appendix B, where it is correlated with cumulative production.
### 30 Kiloton — Pictured Cliffs Formation

**TABLE 2A: RECOVERY**

<table>
<thead>
<tr>
<th>Gas-In-Place, M^3cf (Well Spacing, Acres)</th>
<th>M^3cf (% In-Place Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Stimulation</td>
</tr>
<tr>
<td></td>
<td>Conservative</td>
</tr>
<tr>
<td>5280 (160)</td>
<td>537 (10)</td>
</tr>
<tr>
<td>10560 (320)</td>
<td>1054 (33)</td>
</tr>
<tr>
<td>21120 (640)</td>
<td>6808 (32)</td>
</tr>
</tbody>
</table>

### TABLE 2B: DELIVERABILITY

1. Conventional Stimulation
   - Initial Stabilized Deliverability - Mcf/d: 275 Mcf/d
   - Average Production Mcf/d: 74 Mcf/d

2. Nuclear Stimulation
   - Initial Stabilized Deliverability - Mcf/d
     - Conservative: 497 Mcf/d
     - Optimistic: 524 Mcf/d
   - Average Production Mcf/d
     - Conservative: 760 Mcf/d
     - Optimistic: 899 Mcf/d

### 100 Kiloton — Mesaverde Formation

**TABLE 3A: RECOVERY**

<table>
<thead>
<tr>
<th>Gas-In-Place, M^3cf (Well Spacing, Acres)</th>
<th>M^3cf (% In-Place Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Stimulation</td>
</tr>
<tr>
<td></td>
<td>Conservative</td>
</tr>
<tr>
<td>4000 (160)</td>
<td>2920 (73)</td>
</tr>
<tr>
<td>8000 (320)</td>
<td>539 (7)</td>
</tr>
<tr>
<td>16000 (640)</td>
<td>8040 (50)</td>
</tr>
</tbody>
</table>

**TABLE 3B: DELIVERABILITY**

1. Conventional Stimulation
   - Initial Stabilized Deliverability - Mcf/d: 275 Mcf/d
   - Average Production Mcf/d: 74 Mcf/d

2. Nuclear Stimulation
   - Initial Stabilized Deliverability - Mcf/d
     - Conservative: 3028 Mcf/d
     - Optimistic: 8874 Mcf/d
   - Average Production Mcf/d
     - Conservative: 400 Mcf/d
     - Optimistic: 400 Mcf/d
   - Average Production Mcf/d
     - Conservative: 752 Mcf/d
     - Optimistic: 799 Mcf/d
   - Average Production Mcf/d
     - Conservative: 1101 Mcf/d
     - Optimistic: 1381 Mcf/d
C. Potential for Large-Scale NE Stimulation

The recoveries and deliverabilities calculated for a 100 kiloton explosive in the Mesaverde formation were based on the previously stated reservoir characteristics. Only 25 Mscf per acre of gas in-place. However, this figure is representative only of the least productive areas under consideration. A substantial amount of acreage exists in the San Juan Basin containing greater amounts of in-place gas. One of the better areas examined covers approximately 23,000 acres and contains 44 Mscf per acre of gas in-place. This represents an increase of 76% over the 25 Mscf per acre amount and would result in a significant increase above the recovery figures shown on the preceding table. In such an area deliverability levels would also be substantially higher, and the use of NE stimulation much more economical.

The comparison of results from conventional and NE stimulation in both the Pictured Cliffs and Mesaverde formations in the preceding tables not only reveals the benefits of NE stimulation but reflects the waste of a natural resource resulting from lack of more effective completion methods.

C. Potential for Large-Scale NE Stimulation

Assuming that the use of nuclear explosives is practicable for stimulation of reservoirs in the San Juan Basin, there are several other thick, low-permeability formations found in the sedimentary basins in the Rocky Mountain region that may have greater quantities of in-place gas than those in the San Juan Basin. Such formations offer more attractive possibilities for economic application of NE stimulation. A summary of three of these major basins is presented below as an example of the vast areas and sand thicknesses in existence. The location of these and other large adjoining basins that could be amenable to NE stimulation are shown on Figure 11.

For a specific illustration, the Fort Union formation in the Finedale Unit Area, located in the Green River Basin, Sublette County, Wyoming, has an estimated 3,790,000 Mscf of gas in-place in an area of just 13,551 acres where there is an average gross sandstone thickness of 587 feet. However, unless stimulated beyond the limits of conventional methods very little of the in-place gas will be recovered.

Evaluation of the three major basins described above and the San Juan Basin indicates a potential market for approximately 30,000 explosives of various yields in these known gas producing areas. Costs involved in NE stimulation may be grouped as follows:

1. Explosive (including emplacement and firing);
2. Emplacement hole;
3. Post-shot re-entry well; and
4. Any necessary safety studies and decontamination facilities.

It has been established that the anticipated results of NE stimulation of a natural gas reservoir justify conducting such a field test. If Project Gasbuggy and/or subsequent tests prove the feasibility of NE stimulation, the size of the potential market for nuclear devices suggests certain refinements and developments that would permit its maximum economic utilization.

The latest information made available by the AEC is that the projected charges for nuclear explosives will range from $350,000.00 for yields of 10 kilotons to $600,000.00 for yields of 2 megatons. These charges are projected on the assumption of production in quantity and include arming and firing, but not safety studies, site preparation, transportation, emplacement or support. However, significant reductions in cost might be achieved through improvements in the technology of explosive design and production techniques.

Reducing the diameter of the explosive would result in considerable savings because the cost of an emplacement hole at any given depth increases exponentially with hole size. An explosive that could be emplaced in 7" O.D. casing would reduce the cost of the emplacement hole to that of a conventionally drilled well and might entirely eliminate the emplacement hole cost where such wells already exist.

Another desired development would be a means of channeling the force of the nuclear explosion laterally into just the pre-selected productive zone to obtain greater concentration of its effect. This might be accomplished by firing arrays of shots at the same depth simultaneously or sequentially. By further increasing the size of the "effective" wellbore and radius of fracturing, there is the potential of even more efficient recovery of in-place gas and higher deliverability rates.

If safety studies are made on a field-wide basis, prorated cost to individual wells may be insignificant. Similarly, the cost per well for any decontamination or dilution of the produced gas that may be necessary should be low. As a preliminary estimate, costs of drilling and completion of a post-shot re-entry well should be no greater than twice that of a conventionally completed well.

Ideally, the combination of a smaller explosive at

<table>
<thead>
<tr>
<th>Basin</th>
<th>Areal Extent With Productive Potential</th>
<th>Number of Known Gas-Bearing Formations</th>
<th>Thickness of Potential Gas-Bearing Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uinta</td>
<td>8,000 sq. mi.</td>
<td>4</td>
<td>1,700 feet</td>
</tr>
<tr>
<td>Piceance</td>
<td>3,900 sq. mi.</td>
<td>4</td>
<td>1,200 feet</td>
</tr>
<tr>
<td>Green River</td>
<td>19,000 sq. mi.</td>
<td>7</td>
<td>2,500 feet</td>
</tr>
</tbody>
</table>
MAJOR BASINS OF THE ROCKY MOUNTAIN STATES

THESE BASINS CONTAIN SUFFICIENT RESERVOIR THICKNESSES TO MERIT CONSIDERATION FOR NE STIMULATION.

FIGURE 11
V. RADIOACTIVE CONTAMINATION

A. General

There are two types of nuclear explosive devices and they are designated according to the mechanics by which they function, namely fission and fusion. A fission device splits heavy nuclei into lighter ones to release energy, whereas the fusion device forms heavier nuclei from lighter ones to cause the release of energy.

When either type explosive is used certain radioactive isotopes\(^{13}\) are produced. The major gaseous contaminants resulting from underground detonation of an all-fission explosive are xenon 133, iodine 131, and krypton 85. Solid contaminants such as strontium 90 and cesium 137 are also present. However, the majority of these solids are trapped in the melt at the bottom of the cavity and any particles of solid or liquid contaminants in the gas stream can be removed by filtration. If a fusion explosive is used, tritium will be produced in addition to the fission products. The gaseous radioisotopes that cannot be filtered out, resulting in contamination of the produced gas, would be krypton 85, xenon 133 and perhaps carbon 14 in the form of gaseous compounds such as CO$_2$ or methane, and, in the case of a fusion explosive, tritium.

B. Decay of Radioactive Contaminants

Each radioactive material disintegrates at a specific rate. The term half-life is used as the unit of measurement to denote the length of time in which one-half of the atoms in a radioactive substance disintegrate. In application, if a radioisotope\(^{14}\) has a half-life of 12 hours, after 12 hours the decay would reduce the quantity of that radioisotope to half its original amount. During the second 12-hour period decay of half of the remaining amount would occur. In this example, in 2 half-lives or 24 hours, the quantity of the radioisotope will be reduced by 75% of its original amount and its radioactivity will be similarly reduced. Applying this concept further, in 3 half-lives the original quantity of the radioisotope would be reduced \(87.5\%\) and in 4 half-lives, \(93.8\%\), etc.

Xenon 133 has a 5.3 day half-life, iodine 131 an 8-day half-life, krypton 85 a 10.3-year half-life and tritium a 12-year half-life. Therefore, the concentrations of xenon and iodine would be greatly reduced within a reasonably short period of time through the normal decay process.

C. Permissible Levels of Exposure

The Federal Radiation Council was established by the Federal Government in 1959 to recommend to the President the standards that should be established for control of radiation. The Atomic Energy Commission is empowered to set standards for its own operations and licensing the operations of others. It does so on the basis of its experience and on the recommendation of both the Federal Radiation Council and the National Committee on Radiation Protection and Measurement, composed of notable scientists, physicians and government officials experienced in the use of radiation.

The Maximum Permissible Concentration (MPC) is the concentration of radioactive materials that an industrial worker may be exposed to continuously that is not expected to have a deleterious effect on the health or well-being of the individual during his lifetime. Tolerances recommended by the Federal Radiation Council for the exposure of the general population are set at \(\frac{1}{500}\) of the MPC.

The License Exempt Concentration (LEC) is the maximum concentration of radioactive materials that can be legally handled without an AEC license. The LEC's have been established by the AEC on the basis that these concentrations are low enough to assure safety of the public. In the case of krypton 85 and tritium, the LEC is the same as the MPC.

D. Contamination of Chimney Gas

Assuming the use of an all-fission 10 kiloton device for the experiment, the resulting gaseous radioisotopes of particular concern will be xenon 133, iodine 131 and krypton 85. After 60 days following the explosion, these radioisotopes will be present in the following amounts:

- Xenon 133 \(- 2500\) curies\(^{15}\)
- Iodine 131 \(- 7200\) curies
- Krypton 85 \(- 200\) curies

It has already been calculated that the amount of gas in the chimney will be 100 MCF and, therefore, these quan-
tities of radioisotopes are expected to be mixed in that amount of gas. As a result of the decay process, after 9 months the concentration of xenon 133 and after 10 months the concentration of iodine 131 becomes negligible. However, after a 9-month period the concentration of krypton 85 will still be 690 times the concentration permissible to the general public and 23 times the LEC.

The calculations for these three radioisotopes are considered reliable. However, should a part-fusion explosive be employed, an estimate of tritium contamination is subject to uncertainties because of lack of knowledge of the chemical reactions occurring under the extreme pressures and temperatures during and after explosion. It is known that approximately 1000 times more tritium than krypton 85 is produced per kiloton and also that tritium will exchange with hydrogen and, therefore, can be present in water as well as in methane. Only the experiment will determine which of many possible chemical reactions will occur, resulting in either a high tritium concentration or virtually none. Detailed calculations and discussion of radioactivity are contained in Appendix D.

It is important to acquire more specific information about the reaction of tritium in a gas reservoir because large yield devices can be produced more economically using fusion fuels. If tritium, with its long half-life, undergoes favorable chemical reactions which result in low concentrations in the methane, then the use of fusion devices can be expected to permit lower charges for the explosives when large yield explosives are employed.

For experimental purposes, a fission device with a tritium tracer added could be used to determine the amount of contamination caused by fusion as well as fission without obtaining excessive tritium concentration in the gas. A more definite understanding of the chemical reactions that take place during a fusion explosion in a gas reservoir should also be gained.

**E. Testing and Production of Chimney Gas**

Gas sampling for experimental purposes will be accomplished by the drilling of the post-shot re-entry well shortly after the detonation. At that time the concentration levels of the various isotopes present will be determined. When this is accomplished, the extent of the contamination problem will be more clearly defined and the methods of contamination control formulated.

Substantial quantities of gas would be produced from the Gasbuggy experimental well for testing purposes in order to determine the increase in productivity of the reservoir resulting from the nuclear fracturing and the level of radioactivity present in the produced gas. This test gas would be disposed of in a safe manner not delivered into the pipeline. Final decisions regarding the disposal of the radioactive gases must be based upon safety investigations and actual analysis of gas samples obtained after the detonation. This production will permit migration of uncontaminated gas from the formation into the chimney so that dilution of the remaining contaminants will take place. Estimates of the effect of different rates of withdrawal of contaminated gas to attain the LEC level at the wellhead for krypton 85 have been made and are graphically presented in Figure 12.

It is important to obtain information concerning the correlation between removal of specific amounts of gas at particular rates and the resultant decrease in the level of radioactive contamination. This aspect of the problem requires experimentation and subsequent evaluation of the data to arrive at the most effective rates of gas withdrawal so that guidelines for the economic feasibility of NE stimulation can be projected.

It is assumed that the Gasbuggy experiment would be executed under the control of the AEC, who would retain direct responsibility in matters of radiation safety. After the experimental requirements of Gasbuggy are satisfied, commercial sales of gas from the well would be permissible under licensing arrangements between the AEC and the El Paso Natural Gas Company. Such a license could be issued by the AEC after a determination has been made that use of the gas will not result in a significant increase in the radiation exposure normally received by the general public. The existing gathering and transmission facilities would mix and dilute the contaminated gas so that the level of contamination in the transmission line would be reduced to below LEC concentrations. Capacity of the system at the Blanco Plant and Gallup Station is shown on Figure 13. In addition, usage of the gas requires further dilution to permit combustion and to maintain the concentration of CO₂ below specified levels. These factors are covered in more detail in Appendix E.

It is therefore apparent that the gas reaching the consumer will be well within the limits presently prescribed, and that these levels will be constantly lowered as further production from the test well introduces cleaner gas into the chimney.
I. Unrestricted flow to atmosphere thru 7" casing for approximately 3 days.
Initial flow rate - 100 M$^2$cf/D.

II. Unrestricted flow to atmosphere thru 2-1/2" tubing for approximately 2 months.
Initial flow rate - 14 M$^2$cf/D.

III. Normal flow to sales at stabilized producing rate of about 2 M$^2$cf/D.
LEC reached in about one year.

NOTES
1. Calculations based on fracture radius of 195'.
2. After producing quantities of gas shown on curves I & II at end point of 1 x LEC, it is necessary to wait for pressure in chimney to build up to stabilized reservoir pressure.
E.P.N.G. TRANSMISSION FACILITIES
FROM TEST SITE TO CALIFORNIA MARKET

FIGURE 13

Note:
Gathering systems
not shown.
VI. FIELD TEST

Experimental Objectives

In order to answer the many unknowns involved in evaluating the feasibility of stimulating natural gas production with nuclear explosives, an experiment should be carried out designed to measure the following effects:

1. Change in productivity of existing wells within effective range of the shock effect.
2. Productivity of the post-shot well drilled into the chimney, as compared with the productivity of the unstimulated formation.
3. Increase in producible reserves.
4. Extent of radioactive contamination of produced gas.
5. Extent of mixing of formation gas with contaminated chimney gas, and investigation of production techniques for controlling the degree of mixing.

B. Experimental Design

1. Pre-shot Test Wells

Two pre-shot test wells will be drilled, the first located approximately 100 feet from the site of the emplacement hole. The purpose of the first well will be to confirm by intensive coring and analysis the absence of mobile water in the Ojo Alamo and Fruitland formations, the stated reservoir conditions of the Pictured Cliffs formation, and flow behavior of the Pictured Cliffs formation by means of flow tests.

The second pre-shot test well will be located approximately 200 feet from the site of the emplacement hole. It will provide additional confirmation data as to mobile water and reservoir conditions, in addition to later providing data as to the extent of fracturing after detonation.

Both of the pre-shot wells and the emplacement well will be located as shown on Figure 14 so that the indicated distances exist from the emplacement well to the pre-shot wells and unit wells numbers 4, 10-36 and 16-36.

2. Emplacement Hole

Upon confirmation of the suitability of the test site from data obtained from the pre-shot wells, the emplacement hole will be drilled to accommodate the nuclear device and will later furnish data as to depth of the point of casing collapse after detonation.

3. Post-shot Re-entry Well

The post-shot re-entry well will be drilled into the rubble or chimney zone overlying the point of detonation as soon as safety factors permit. The function of this well is to obtain production from the formation after nuclear stimulation.

4. Additional Post-shot Test Wells

Two additional post-shot wells will be drilled in order to further evaluate the effectiveness of nuclear stimulation. These wells will be located at distances and directions from the emplacement hole determined after testing the post-shot re-entry well, the two pre-shot test wells and the existing unit wells.

C. Operational Site Safety Program

The Project Gasbuggy experiment is designed with full consideration of the primary safety factors, namely, the possibility of venting radioactive contaminants to the atmosphere, damage resulting from ground shock, and contamination of produced gas and ground water. The procedures that will be followed to provide operational safety for the experiment are similar to those used by the AEC in contained nuclear detonations located off the Nevada Test Site. A general discussion of seismic and other safety factors is contained in Appendix G.

1. Atmospheric Contamination

The danger of atmospheric contamination because of venting radioactive gas to the surface through fractures developed by the explosion or by failure of the stemming in the emplacement hole is considered remote, based on AEC's experience with over 100 contained shots. Some venting occurred at Giome (3.1 kilotons at 1,200 feet) because of the underground excavation necessary for the scientific experiments that were conducted. Only minor venting occurred through fractures to the surface at Hardhat (5 kilotons at 939 feet). However, no venting occurred at Shool (12.5 kilotons at 1,200 feet). Because of the depth involved and the yield of the device that will be employed for Project Gasbuggy (10 kilotons at 4,150 feet), no venting is expected.

Although the experiment is planned for complete containment, provision will be made for any mishap that could result in venting radioactive material to the atmosphere. To do this, a maximum credible release mechanism will be hypothesized and the U. S. Weather Bureau will prepare a fallout pattern prediction. Weather predictions and on-the-spot observations made by the Weather Bureau will determine the time of detonation so that any conceivable fallout would be restricted to an acceptable area. An investigation of the potential fallout area will be made by the U. S. Public Health Service (USPHS) to determine if any hazard might result from accidental venting and to anticipate the precautions necessary to safeguard the public. This requires complete USPHS pre-shot surveys of population and livestock location and concentration plus the usual pre-shot public information work in the area.

The USPHS will also perform its customary post-shot monitoring of the off-site area, such as collecting air, water, milk and vegetation samples. The USPHS preliminary survey in a 100-mile radius of the test site concluded that the experiment will create no particular

17See Appendix F for Drilling Schedule.
LOCATION PLAT

PROJECT GASBUGGY TEST SITE

SECTION 36: TOWNSHIP 29 NORTH - RANGE 4 WEST, N.M.P.M.
RIO ARRIBA COUNTY, NEW MEXICO

EXISTING PICTURED CLIFFS GAS WELLS

SECTION CORNER

FIGURE 14
The Federal Aviation Agency will prepare an Air Space Closure plan to safeguard aircraft from any material which may be vented. An on-site radiological safety program will be installed to provide monitoring personnel, telemetry, air sampling trailers, counting equipment, decontamination facilities and medical care facilities.

The post-shot drilling program will remain under the control of the AEC as long as is necessary to protect the public safety. A radiological monitoring program will be required at shot time and during post-shot drilling to establish and document the presence, if any, of radioactive material.

As specified in Appendix F, the drilling equipment will be used with blowout preventers and the means of controlling the gas flow during post-shot operation. Once the level of contamination of the gas is determined, suitable testing and production techniques will be employed to prevent contamination problems of any nature until permissible levels of radioactivity are achieved so that normal testing and production methods become acceptable.

2. Ground Water Contamination

Results from gas wells drilled in the test site area indicated no mobile water in the formations that might be affected by the test and no ground water is utilized for water supply purposes in the test area. The nearest existing water wells in the Ojo Alamo formation are 50 miles away and 1,700 feet updip, as stated in Appendix A. However, these conditions will be confirmed by the following hydrologic investigation program:

In the pre-shot drilling program, the two test wells located 100 and 200 feet from the test site will be cored and drill stem tests run in the Fruitland and Ojo Alamo formations. If the drill stem tests fail or indicate high water transmissibility, a pump test will be made of the zone in question. These tests are to be supervised by the United States Geological Survey (USGS). Further study should be made of the potential water-bearing zones in the Lewis formation immediately below the Pictured Cliffs formation and these zones tested in the same manner as the Ojo Alamo and Fruitland formations.

3. Ground Shock Damage

A preliminary reconnaissance of the area indicates that there are no structures, not owned by El Paso Natural Gas Company, close enough to Ground Zero to be damaged by the shock effect. However, attention will be given to the presence of existing gas wells and pipelines in the area, together with seismic predictions and evaluation of possible methods of protecting these facilities from damage. Results from previous testing indicate that no damage to cased holes should occur at distances beyond approximately 1,300 feet (600 WPA) at the Gasbuggy site. The only well within this range is the San Juan 29-4 Unit #10-36 Well located in the SW/4 of Section 36, T-29-N, R-4-W. Shock damage to this well will be considered as part of the experiment to determine the extent of shock damage to gas field installations.

Limited mine and structural surveys and seismic instrumentation for documentation purposes may also be required. Decisions regarding these matters will be made prior to detonation in sufficient time for pre-shot installation.

D. Public Information and Observer Program

Should the proposed nuclear experiment be authorized, it would require the development of an appropriate public information program similar to those developed by the AEC for previous nuclear experiments conducted off the Nevada Test Site, such as Projects Gnome, Shoa and Dribble. It is anticipated that the public information activities would be conducted jointly by the AEC, USBM and EPNG, with full coordination of plans between these organizations. Details of the information program would be developed in a mutually acceptable plan well in advance of field activities.

As in the case of the other Plowshare projects proposed for execution off-site, public officials, civic organizations, and news media would be kept informed of the status of the experiment during the pre and post-shot phases.

Each of the concerned organizations participating in the experiment would be in a position to issue information to the various media in the area of its responsibility, as would be agreed upon in the information plan. It is expected that EPNG and USBM would place particular emphasis on reporting to the trade and industrial interests while the AEC would bear the major responsibility for those matters involving public safety.

It is anticipated that an observer program would be established to permit representatives of industry, news media, public officials, and other interested organizations to attend the detonation. Following execution of the experiment, the public information plan would continue, and a technical reporting plan would be implemented so that the results of the experiment would be made available to both the public and technical interests.

E. Project Management

The Project Management concept of operation for Gasbuggy should be similar to that of Project Shoa and Project Dribble, two underground shots executed off the Nevada Test Site. There will be an AEC Project Manager with responsibility for public safety, device protection and authority for device detonation, who will also provide assurance that the nuclear operation is conducted in accordance with AEC policies and procedures.

The AEC Project Officer will be the Project Manager's on-site representative. He will coordinate the requirements
of AEC safety contractors, provide for their implementa-

tion and monitor the progress of work to assure con-

formity with approved plans. The Project Officer will

remain at the site during post-shot drilling activities and

exercise control of the post-shot drilling with respect to

radiological safety and possible release of radioactive

material.

F. Cost Schedule and Timing

A preliminary estimate of the total cost of the experi-

ment is $3,000,000.00 exclusive of cost of the explosive.

Although not tabulated in this cost figure, eight producing

wells costing $631,665.00 and pipeline facilities costing

$223,531.00 are located within a two-mile radius of the test

site that may be made available for test purposes by

EPNG. The following estimate is indicative of the amo-

and nature of the cost that will be incurred.

It is estimated that nine months would be required

from the time of authorization for the experiment to

detonation time, as indicated in Figure 15.

Total elapsed time from commencement of operations
to completion of the re-entry well would be approxi-
mately 11 months.

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<th>COST ESTIMATE</th>
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<td>Emplacement hole</td>
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*Communications, supporting personnel, vehicles, etc.

VII. CONCLUSIONS AND RECOMMENDATION

A. The shock effect of a nuclear explosion will have

a beneficial effect upon the producing characteristics of

gas wells in formations of low permeability. Estimates

based largely upon anticipated fracturing effects indicate

that production rates and producible reserves will be
greatly increased by this treatment, thereby providing the
means by which the natural gas resources of the United
States could be more effectively exploited.

B. The gas produced from such a well would contain

some gaseous radioactive material. The amount of such

radioactivity is difficult to estimate accurately because of

the lack of knowledge of the chemical reactions that might

occur in the cavity after the explosion. It is possible that

the contamination would be slight, and could be readily

reduced to acceptable limits by dilution with field gas. It

is also possible that the well could be produced in such a

way that if a small portion of the gas made available by

the treatment were disposed of (e.g., by flaring), the well

would be flushed of most of its gaseous contaminants.

C. It is believed that a nuclear experiment to test the

concept can be executed safely with no serious inconveni-

cence to the population in this remote area.

Because of the magnitude of the benefits that might

be obtained at a reasonable cost, without risk, it is recom-

mended that an experiment be carried out to test and

investigate the concept of nuclear stimulation of gas wells.
PROJECT GASBUGGY

SCHEDULE - MONTHS

Pre-Shot hole #1
Pre-Shot hole #2
Pre-Shot production test
Emplacement hole
Field Construction
Seal pre-shot holes
Scientific occupancy
Weather
Security
Radiation Safety
Shot execution
Reentry hole
Reentry to pre-shot holes
Post-shot hole #1
Post-shot hole #2
Post-shot production test

PRE-SHOT POST-SHOT

FIGURE 15
APPENDIX A

Charles F. Brown (EPNG)

General Water Characteristics of the Ojo Alamo and Fruitland Formations with Emphasis on the Southeastern Part of Township 29 North, Range 4 West, Rio Arriba County, New Mexico.

PURPOSE

The purpose of this report is to investigate whether the Ojo Alamo and Fruitland formations are water-producing formations in the area of interest.

LOCATION OF AREA OF INTEREST

The area of interest is the general vicinity of the common corner of Townships 28 and 29 North, Ranges 3 and 4 West.

ILLUSTRATIONS

Figure 1: East-West Cross Section of Electric Logs through Test Area
Figure 2: North-South Cross Section of Electric Logs through Test Area
Figure 3: Map of General Area of Interest Showing Pertinent Well Locations
Figure 4: Core Analysis of Fruitland-Pictured Cliffs Formations in San Juan 28-4 #4 Well by Core Laboratories, Inc.
Figure 5: Core Analysis of Fruitland-Pictured Cliffs Formations in San Juan 28-4 #4 Well by KOR-AN Laboratories

GENERAL INFORMATION

In this area the Ojo Alamo and Fruitland formations occur at a subsurface depth of 3350 to 3800 feet. This was established by the use of electric logs of wells drilled in the immediate area. From these electric logs two cross-sections were constructed, east-west and north-south, through the proposed test area (Figures 1 and 2). They show the interval between the base of the Pictured Cliffs and the top of the Ojo Alamo to be rather uniform in thickness, approximately 725 feet. They also show the type of section that might be expected under a well drilled in the SW/4 of Section 36, Township 29 North, Range 4 West.

WATER CHARACTERISTICS

The Ojo Alamo Sandstone is generally water-bearing in the vicinity of its outcrop which is the area around the town of Farmington, approximately 70 miles west of the proposed test site. The formation dips below the surface a mile or so east of Farmington where it is cut by both the Armas and San Juan Rivers, and is probably being water-charged from these sources and the numerous washes in that area.

There were no indications of water flowing from either the Ojo Alamo or the Fruitland formations during the drilling of the wells located near the test site. (See Figure 3 for map showing pertinent well locations.)

The electrical logs of the following wells were interpreted for porosity and water saturation of the Ojo Alamo Sandstone:

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<td>Section 4 (Zone per-</td>
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In the absence of evidence of flowing water from these wells, the amount of water saturation of the Ojo Alamo Sandstone does not indicate it to be an aquifer in this area.

Although shows of water have been recorded in the Fruitland formation, it has not been found to be a water-producing formation anywhere in the San Juan Basin.

Six wells were drill-stem tested in the Fruitland formation within a six-mile radius of the test site and only one, the San Juan 28-4 #1 Well, NE/4 of Section 18, Township 28 North, Range 4 West, approximately five miles to the southwest, recorded a show of water. The data obtained from this drill-stem test are as follows:

DST #1 4150-4265
Tool open one hour, gas to surface 30 minutes, gauged 34 Mcf, recovered 320 feet gas cut mud and 100 feet of water, flow pressure 130 pounds, shut-in pressure none, hydrostatic 2200 psi.

A completion attempt was made in the Fruitland formation of the El Paso Natural Gas Company Indian #1-F Well, NW/4 of Section 4, Township 28 North, Range 3 West, approximately two and a half miles east.
**CORE LABORATORIES, INC.**

*Petroleum Reservoir Engineering*

**DALLAS, TEXAS**

---

**Company:** EL PASO NATURAL GAS COMPANY  
**Date Report:** JANUARY 1, 1954  
**Page:** 1 of 8

**Well:** No. 1 SAN JUAN 28-4 UNIT  
**Cores:** DIAMOND  
**Field:** WILDCAT  
**Formation:** RUTLAND  
**County:** RIO ARIBA  
**State:** NEW MEXICO  
**Elevation:** 7282 FT  
**Remarks:** SERVICE NO. 5

---

**CORE ANALYSIS AND INTERPRETATION**

(Figures in parentheses refer to footnote remarks)

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**NOTE:**  
(*) REFER TO ATTACHED LETTER.  
(1) INCOMPLETE CORE RECOVERY—INTERPRETATION RESERVED.  
(2) OFF LOCATION ANALYSES—NO INTERPRETATION OF RESULTS.

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---

**FIGURE 4**
### SAMPLE NUMBER

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### PICTURED CLIFFS

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**NOTE:**

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2. (2) OFF LOCATION ANALYSES—NO INTERPRETATION OF RESULTS.
3. (1) INCOMPLETE CORE RECOVERY—INTERPRETATION RESERVED.

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FIGURE 4 (CONTINUED)
EL PASO NATURAL GAS COMPANY

SAN JUAN UNIT 28-4 #4

RIO ARIBA COUNTY, NEW MEXICO

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**Figure 5 (Continued)**
APPENDIX B

R. F. Lemon (EPNG)

Calculations
Project Gasbuggy
10 Kiloton Device – Pictured Cliffs Formation

I. EFFECTS OF UNDERGROUND NUCLEAR EXPLOSION

A. Cavity

When a nuclear explosive is detonated underground, one of the prompt effects is the creation of an unstable cavity within the earth. The cavity will be roughly spherical in shape, and the radius, \( R_c \), can be calculated using the following formula:

\[
R_c (\text{ft}) = \frac{C(W)^{16}}{(dh)^{14}}
\]

Where:
- \( C \) = a constant which varies depending upon the type rock\(^1\)
- \( W \) = yield in kilotons
- \( d \) = overburden density in grams per cubic centimeter
- \( h \) = depth of burial in feet

The cavity radius created in the Pictured Cliffs formation by detonating a 10 kiloton device buried at 4150 feet is calculated to be 65 feet, by application of the foregoing formula as follows:

\[
R_c = \frac{C(W)^{16}}{(dh)^{14}} = \frac{300(10)^{16}}{[(2.3)(4150)]^{14}} = 65 \text{ feet}
\]

B. Chimney

After a period of time ranging from seconds to hours, the roof of the cavity is expected to collapse, and a roughly cylindrical chimney of broken rock extends upward as the cavity fills with rock falling from the roof. The volume of the cavity is translated into interstitial space between the fallen rock fragments. The radius of the chimney is approximately equal to the cavity radius. Generally the height of the chimney will be four to five times the cavity radius, varying with the rock type. For the Pictured Cliffs formation it is anticipated that a factor of 4.6 times the cavity radius will define the chimney height. Thus a chimney of approximately 300 feet will be created.

C. Fracturing

Fracturing of the rock by the nuclear explosive extends outward beyond the cavity walls in all directions based upon analysis of information available from previous explosions. The extent of these fractures are defined and applied to the Pictured Cliffs formation for a 10 kiloton device as follows:

Vertical fractures:
- Above shot point: \( 6 R_c \)
- Below shot point: \( 1.5 R_c \)

Lateral fractures:
- Conservative estimate: \( 3 R_c \)
- Optimistic estimate: \( 200(W)^{16} \)

\[
= (3)(65) = 195 \text{ feet}
\]

\[
= (200)(10)^{16} = 430 \text{ feet}
\]

II. PREDICTED WELL PERFORMANCE

The radial flow of gas into a well under steady-state conditions may be expressed by:

\[
Q = \frac{10.320 \text{ kh} \left( P_e^2 - P_w^2 \right)}{\mu \ln \frac{r_e}{r_w} T_f (15.025) z}
\]

Where:
- \( Q \) = rate of flow cubic feet per day at a pressure base of 15.025 psia and 60° F.
- \( k \) = permeability, millidarcys
- \( h \) = net sand thickness, feet
- \( P_e \) = formation pressure at radius \( r_e \), psia
- \( P_w \) = flowing pressure at wellbore, psia
- \( \mu \) = viscosity, centipoise
- \( r_e \) = radius of drainage, feet
- \( r_w \) = radius of wellbore, feet
- \( T_f \) = formation temperature, degree Rankine
- \( z \) = gas deviation factor

Properties for the Pictured Cliffs formation are:

\[
k = 0.14
\]

\[
h = 188
\]

\[
P_e = 1259
\]

\[
\mu = 0.015
\]

\[
r_e = \sqrt{160 \text{ ac}/\pi} = 1490
\]

\[
r_w = 195, \text{ conservative}
\]

\[
r_w = 430, \text{ optimistic}
\]

\[
T_f = 577
\]

\[
z = 0.85
\]

\(^1\) A constant of 300 was chosen for sandstone based on experience with other rock types.

Utilizing this formula and the properties of the Pictured Cliffs formation the absolute open flow (AOF) potential \( P_s = 0 \) for a wellbore equivalent to the conservative and optimistic fracture radius is calculated as follows:

Conservative AOF = 1900 Mcf/d

and

Optimistic AOF = 3130 Mcf/d

The corresponding stabilized AOF of a well completed in this area by conventional methods is approximately 340 Mcf/d, the equivalent of 275 Mcf/d against a 500# line pressure.

To predict the future producing rates, back pressure curves which are shown in Figure I were constructed at wellhead conditions from the calculated absolute open flow potentials and the slope of the back pressure curve of \( n = 0.85 \) which is in conformance with that established by the New Mexico Oil Conservation Commission for the Pictured Cliffs formation. Performance curves relating the average daily capacity against a given line pressure and cumulative production were calculated from the back pressure curves. These curves are shown in Figures 2, 3 and 4.

Future projection of production has been scheduled on the basis of 1 M\(^2\)cf/d for each 8000 M\(^2\)cf of reserves to insure an even supply of gas over an extended period of time. The forecast of future production schedules in this manner for a conventional completion and for a nuclear stimulated well for the conservative and optimistic fracture system are shown in Table I.

---

**FIGURE 1**

BACK PRESSURE CURVE
PICTURE CLIFFS FORMATION

Original Wellhead Pressure - 1132 psia
Wellhead Potentials:
Conventional - 340 Mcf/d
Nuclear Stimulation:
Conservative - 1900 Mcf/d
Optimistic - 3130 Mcf/d

Deliverability, Mcf/D
Predicted Performance of a Conventionally Completed Pictured Cliffs Well Pressure, Deliverability, and Cumulative Production - Graphical Relationship -

I. Wellhead Pressure vs. Cumulative Production
II. Deliverability Against 500 Psig Line Pressure
III. Deliverability Against 300 Psig Line Pressure
IV. Deliverability Against 100 Psig Line Pressure

FIGURE 2
Predicted Performance of a Nuclear Stimulated Pictured Cliffs Well, Using a 10 Kiloton Device. - Based on a Conservative Fracture Radius of 195 Feet Pressure, Deliverability, and Cumulative Production - Graphical Relationship -

I. Wellhead Pressure Vs. Cumulative Production.
II. Deliverability Against 500 psig Line Pressure.
III. Deliverability Against 300 psig Line Pressure.
IV. Deliverability Against 100 psig Line Pressure.

FIGURE 3
Predicted Performance of a
Nuclear Stimulated Puddled Cliff Well - Using a
10 Kiloton Device - Based on an Optimistic Fracture Radius of 430 Feet
Pressure, Deliverability, and Cumulative Production
- Graphical Relationship -

I. Wellhead Pressure Vs. Cumulative Production.
II. Deliverability Against 500psig Line Pressure.
III. Deliverability Against 300psig Line Pressure.
IV. Deliverability Against 100psig Line Pressure.
TABLE 1
FORECAST OF PRODUCTION FOR CONVENTIONAL COMPLETION AND NUCLEAR STIMULATED WELL (10 KILOTON DEVICE) PICTURED CLIFFS FORMATION

Gas volumes are expressed at a pressure base of 15.025 psia and 60° F.

**Average Daily Production**

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1/ Line pressure reduction.
3/ Computed on basis of 1 M2cf/D for each 8000 M2cf of original gas reserve.
APPENDIX C

Dr. A. Holzer and D. E. Rawson (LRL)

I. WELL PRODUCTION, PERMEABILITY AND FRACTURING

A. Introduction

Underground nuclear detonations result in chimney creation (a large volume above the detonation filled with rubble and caused by the collapsing cavity) as well as more or less pronounced fracturing and differential motion of the rock, decreasing with distance from the shot center. These effects increase the bulk permeability in the neighborhood of the detonation. No quantitative statements concerning the relation between permeability changes and induced fractures can be made at this time; hence this note will discuss only the ability to predict fracturing caused by underground detonations, and available empirical data on fractures and permeability changes.

B. Idealized Rock Breaking Mechanisms

At this time there is no general agreement as to exact mechanism causing a brittle material such as rock to fail, nor does any theory attempt to predict the extent and rate of crack formation and differential motion when a geological formation is shock-loaded by a detonation occurring within the formation. Some general statements and simple laws can nevertheless be made, based on laboratory observations and elastic theory.

Failure in rock can take two forms; by rupture (or cleavage) or by shear. The first of these is the separation of the rock along a fracture plane, with material motion perpendicular to this plane, and takes place when the applied tensile stress exceeds the cohesive strength of the rock. A shear failure, on the other hand, results in motion parallel to the plane of failure, and occurs when the applied shear stress exceeds the ability of the rock to sustain it.

These ideas can be made more precise by some simple mathematical statements. The inequality

\[ \sigma \geq T_0 + \rho gh \]  

states that cleavage will occur when the principal (tensile) stress \( \sigma \) exceeds the tensile strength \( T_0 \) plus the overburden force \( \rho gh \). An equation known as Coulomb's law of failure can be used to describe shear failure:

\[ \tau \geq T_0 + \sigma \tan \varphi \]   

where \( \tau \) is the applied shear stress, \( \sigma \) the normal stress, and \( \varphi \) the angle of internal friction of the rock. \( \tan \varphi \) is in nature of a coefficient of internal friction and is a property of the particular rock.

Another form of failure which should be mentioned is the crushing of material under a triaxial state of stress. While basically a failure in shear, this effect can be expressed by

\[ \frac{1}{2} (\sigma_1 + \sigma_2 + \sigma_3) \geq Y_c \]   

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the principal stresses and \( Y_c \) is the compressive crushing strength of the material.

C. Calculation of Cracking

A one-dimensional, hydrodynamic-elastic-plastic computer code named SOC has been used to calculate the extent of cracks and fractures of the Gnome event. Basically, the code handles cracking using the simple ideas of the previous section, with the exception that it does not include failure in shear. Rarefaction waves from the surface and intervening low-impedance layers are included in the calculation. SOC, being one-dimensional, cannot treat the lateral extent of this effect; a two-dimensional code is being developed.

The pertinent dynamic properties of the medium must be known in order to make sensible predictions. These are: the initial tensile strength, the compressive strength (confined as well as cracked), and the maximum difference between radial and tangential stress allowed for the shock front, the unloading portion of the wave, and for the crushed material. These quantities are in addition to the other properties, such as the equation of state, which must be known for the stress calculation. In the last section, the calculated extent of cracking in the Gnome detonation is compared with observations.

D. Cracking and Fracturing Around Underground Detonations

The accompanying schematic section, Figure 1, through an underground environment resulting from a nuclear explosion illustrates the major features contributing to cracking and permeability increases in that environment. These are listed and discussed below:

1. Chimney Rubble

Following the growth of the cavity resulting from the explosion is ceiling collapse and the distribution of the cavity void as pore spaces between rock fragments and blocks throughout the chimney region. Generally the chimney height is 4 to 5 times the cavity radius and varies with the medium properties and collapse mechanism; there is good evidence that it is bounded by a shear zone. The rubble porosity generally varies from 10 to 30% and the interstitial void is well connected so that permeability increases in this zone are very large for most rock types. At greater distances, above the top of the chimney, there is not much evidence of changed permeability and
it is difficult to determine the existence of the shear zone. Properties of the chimneys and their variation with rock type are discussed in UCRL-7350.

2. Dynamic Cracks

Dynamic cracks here refer to new cracks or fractures produced by the explosion in the nearly spherical region surrounding the cavity. Included would be microfractures in the rock and the radial and tangential fractures surrounding the cavity.

As the amplitude of the shock wave emanating from the detonation drops below values where vaporization and melting of the rock takes place, a zone of crushed material will follow where the intensity of the stress wave exceeds the confined crushing strength of the rock. This zone will be carried to a larger diameter by the cavity expanding behind it, and will get thinned out in the process.

Beyond this crushed region, more moderate plastic flow takes place. As this zone unloads into the elastic region, tangential tensile stresses are caused by the radial motion of the material. These lead to radial cracking when they exceed the initial tensile strength of the rock and the overburden. It is of course possible that this cracked material will subsequently crush, since the unconfined crushing strength must be considerably less than the confined crushing strength.

Measurable changes in permeability are associated with microcracking and the tangential fractures. Radial cracks are often filled with melt injected from the cavity and may not be very permeable. The radius of the zone of dynamic cracks is generally 1/2 to 3 times the cavity radius.

3. Motion Along Pre-Shot Weaknesses

In almost all natural environments there exist weaknesses in the rock such as faults, joints, bedding planes, etc., that define the real strength properties of a rock mass subjected to a nuclear explosion. It is obvious that the strength properties of these weaknesses are related to overburden pressure. Also, the orientation of these weaknesses with respect to the free surface and the stress field produced by the explosion will have a controlling effect upon motions along them and, therefore, permeability changes associated with them. The frequency and the number of different orientations will affect the degree of interconnection between these weaknesses and permeability changes resulting from motions along them. Motions along pre-shot weaknesses occur during the dynamic cavity growth period and during the unload period that follows. The major permeability changes are observed laterally away from and above the explosion center rather than below. This suggests that the rarefaction wave from the surface has a large role in creating permeability. It would be expected that the further from the explosion, the less would be the motion along these weaknesses and the permeability change. Because of the obvious complexities associated with pre-shot natural weakness in a given environment, their great variation from place to place and rock type to rock type, and the complex stress history they experience, permeability changes associated with the response of these weaknesses can only be qualitatively understood, and large variations should be expected.

While there are no observational data on the change in the extent and nature of cracks with a change in depth of burst, one would expect a smaller amount of cracking at greater depths for the same amount of energy released. Since the effective tensile strength increases with overburden (see Eq. 1) higher stresses are needed to produce cracks. Since the cavity expands less at greater depths, less radial motion takes place, inhibiting radial cracking. The rarefaction wave from the surface will be weaker, since it has attenuated over a longer path length. Differential motions due to geologic inhomogeneities should be less, since the internal friction term in Eq. 2 should increase with depth. The same can be said for the confined crushing strength of the material.

E. Some Observed Data

Following is a summary of some of the pertinent observations regarding fracturing and permeability changes associated with underground explosions in several rock media.

Gnome. 3.1 ± 0.5 kt at 1184 feet depth in bedded salt. Average cavity radius below the working point is 57 and 80 feet laterally from the working point.

Dynamic fractures extend 125 feet above the working point 131 feet out laterally and 80 feet below. These dynamic cracks compare well with a calculated (symmetrical) fracture radius for Gnome of 115 feet.

Significant permeability increases were observed out to 150 feet laterally and 345 feet vertically above the working point. These changes were determined by drill fluid circulation losses and are sensitive to only gross changes. Gnome data is further discussed in PNE 107 F (to be issued).

Hardhat. 5 ± 1 kt at 935 feet in jointed granite. The average cavity radius is about 63 feet. Permeability measurements were made in drill hole from the drift crossing the chimney 90 feet above the working point. Generally the increase in permeability near the chimney edge but outside the chimney was well above background -10 to 100 times the background permeability of the rock. The permeability increase decreases with lateral distance, but is still many times background at 170 feet laterally from the working point. By 300 feet laterally, there is a question if the permeability increase is significant. I approached the background which, of course, is variable.

Circulation losses of drilling fluid vertically above the working point indicate increased permeability as high as 400 feet above. Permeability increases associated with explosions i
volcanic tuff and alluvium are generally much less than in the above two examples, indicating the more compactable and plastic behaving materials are less susceptible to permeability stimulation by nuclear explosions.

SCHEMATIC SECTION THROUGH AN UNDERGROUND ENVIRONMENT RESULTING FROM A NUCLEAR EXPLOSION

NOTE: Scaling not intended for REGION OF PERMEABILITY INCREASE.

FIGURE 1
A. Assumptions

Important to the future of nuclear explosions for stimulation of gas wells is the concentration of radioactivity in the resulting gas. A hypothetical fission nuclear explosive containing a tritium tracer will be considered; solutions to the problem can then be scaled directly to any real device. The purpose of the tracer is to give empirical data on any tritium problem which might arise from the use of fusion explosives at higher yields.

It will be assumed that the experiment consists of detonating a 10 kt fission explosive at a depth of approximately 4150 feet, which is at the base of the gas bearing Pictured Cliffs formation. This formation is a sandstone with 11% porosity. The pore volume is filled with liquid water (59% of the volume) and methane gas at 84 atm. (41% of the volume). A small amount (perhaps 0.1% by weight) of liquid and solid hydrocarbons is also present. The overall density is 2.3 g/cc.

These conditions correspond to $1.57 \times 10^5$ moles of H$_2$O per gram of rock and $7.3 \times 10^5$ moles of CH$_4$ per gram of rock.

The cavity radius at maximum expansion is estimated to be 65 feet, corresponding to a volume of 1.2 million cubic feet. This volume will be filled with gas at a formation pressure of 84 atmospheres. The total volume of gas will thus be 100 M$^3$cf, or $2.8 \times 10^{12}$ cubic centimeters at one atmosphere. The cavity gas will be mixed with the gaseous fission products from 10 kilotons of fission, the tritium tracer, water vapor and the products of any chemical reactions which may occur.

B. Fission Products

The earliest time at which it would be practical to use the chimney gas, assuming no dilution or decontamination, is limited principally by the $^{131}$I because of the very low tolerance from this nuclide. Assuming that all the $^{131}$I produced is distributed uniformly in $2.8 \times 10^{12}$ cm$^3$ of gas at STP, the concentration of $^{131}$I in the gas is:

<table>
<thead>
<tr>
<th>Time (mo)</th>
<th>Concentration ($\mu$ c/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$5 \times 10^{-1}$</td>
</tr>
<tr>
<td>1</td>
<td>$3.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>3</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>6</td>
<td>$9 \times 10^{-8}$</td>
</tr>
<tr>
<td>12</td>
<td>$1.6 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

The tolerance level$^1$ for $^{131}$I for the general population is $1 \times 10^{-10}$ $\mu$ c/cm$^3$ of air. Most of the iodine could be removed from the gas stream by a decontamination treatment; however, by allowing the iodine to undergo radioactive decay underground for about 8 months, the iodine decontamination treatment can be eliminated. The waiting period is uncertain, as some of the iodine will not be produced with the gas, but will remain underground.

The only important completely gaseous species at 8 months is $^{85}$Kr. Other partially volatile nuclides might possibly be present as hydrides, oxides or methyl compounds. The amounts expected are small and could probably be removed from the gas by a simple scrubbing system. The yield of $^{85}$Kr depends somewhat on the fissioning nucleus and neutron energy. It varies from 12.7 curies/kt for Pu$^{239}$ plus fission neutrons to 24 curies/kt for U$^{235}$ + thermal neutrons. Here it will be assumed that the yield of a typical device is 20 curies/kt.

If this $^{85}$Kr is distributed uniformly in $2.8 \times 10^{12}$ cm$^3$ of gas at STP, the concentration would be $7.1 \times 10^{-6}$ $\mu$ c/cm$^3$ of gas.

C. Tritium

It has been reported$^2$ that the amount of tritium produced in a thermonuclear device is in the range $7 \times 10^5$ to $5 \times 10^6$ curies/kiloton. A tracer of 10,000 curies will be used in the calculations. This is approximately equal to the tritium from 0.5 kt of fusion.

It is reasonable to assume that during the initial high temperature phase of the explosion, while the cavity is expanding, the tritium will be distributed uniformly among the hydrogen atoms present in the cavity region.

After the expansion has stopped and the cavity pressure drops due to cooling and collapse, methane from the rest of the formation will flow in and stabilize at formation pressure. This methane will mix with the tritiated methane and other gases formed in the explosion. This would seem to be the minimum amount of gas that the tritium would mix with, and thus gives an upper limit to the expected tritium concentration.

The calculations are straightforward up to this point, but a large uncertainty arises when we try to estimate what fraction of the tritium is in the gas phase. The uncertainty arises because of lack of knowledge of the chemical reactions which will occur under the extreme and unusual conditions existing in the cavity during and after the explosion.

$^1$The tolerance levels for all nuclides have been taken as 1/10 of the NBS handbook 69 values for a 168 hour week occupational exposure. The levels obtained in this way may be too high since it would not allow exposure to any other source of radioactivity.

$^2$See, for example, J. Miskel, AEC report TID-7695, Characteristics of Radioactivity Produced by Nuclear Explosives, in the proceedings of the Third Flowshare Symposium, April, 1964.
Let us consider several cases.

Case I. — The most pessimistic assumptions.

The key assumption here is that the hydrogen in the methane coming into the cavity after the explosion exchanges with all tritium-containing molecules (H2O, etc.). In this case most of the tritium will be in the methane. This leads to a tritium concentration of 10,000 curies in $2.8 \times 10^{12}$ cm$^3$, or $3.6 \times 10^3$ microcuries per cc.

This is a rather unlikely assumption and gives an upper limit to the concentration.

Case II. — Slightly less pessimistic and more realistic.

Assumptions: 1) Exchange reactions do not occur after the explosion phase is over. 2) The iron in the hole casing and device canister (about 40 tons) reacts with water to produce hydrogen gas. 3) All hydrocarbons are converted to tritiated methane or hydrogen. 4) No other chemical reactions occur.

In this case about half of the tritium will be in the form of hydrogen or methane. The concentration is thus $1.8 \times 10^3 \mu$ c/cc.

Case III. — Other possibilities.

If the gas bearing formation were immediately above a very tight layer of rock containing a reasonable amount of water and no hydrocarbons, most of the tritium would be trapped as water, and therefore not available to the methane. In principle, this too could reduce the tritium concentration in the methane to zero. However, it seems unlikely that any experiment could be designed such that less than about a percent of the tritium would be in the form of methane or hydrogen. All other optimistic experiments thus probably reduce to this Case, i.e., $3.6 \times 10^5 \mu$ c/cc.

APPENDIX E

M. A. Lekas (AEC)

PRODUCTION OF CAVITY GAS

I. General Discussion

One of the important considerations involved in utilizing natural gas produced as a result of a nuclear explosion is the concentration and handling of the resultant radioactivity.

Appendix D was prepared by the Lawrence Radiation Laboratory, which is operated by the University of California under a contract with the Atomic Energy Commission, in order to assist in the analysis of the handling and production of gas produced by this method. As noted therein, predicted concentrations of the significant radioactive isotopes, viz., radioiodine, krypton, and tritium, are given as they would be initially present in the first gas produced from the chimney. These concentrations have been used as a basis for developing the following discussion which considers the means by which these concentrations of radioactivity can be reduced, eliminated, or operationally minimized.

This discussion was developed mainly as a general assessment of the magnitude of the problem which might be presented by radioactivity resulting from the nuclear explosion. It is not intended to present definitive measures and procedures for the handling of the radioactivity.

II. DILUTION OF THE CAVITY GAS

A. Dilution in Combustion, and Room Dilution of Combustion Products

The MPC's for krypton and tritium are given in terms of maximum concentrations of those isotopes in air, as breathed by the general population. Obviously, the concentrations in natural gas cannot be applied directly, since no one is going to be living continuously in an atmosphere of methane gas! It is, therefore, not meaningful to apply the term MPC to concentrations in methane without further discussion and elaboration.

To give meaning to such concentrations, they must be reduced to the actual situation which, in the most restrictive case, would involve breathing the combustion products from an open gas burner (such as a stove) in a closed room. It is expected that in this case there would result a manyfold dilution, for the following reasons:

1. Dilution of the gas with air necessary for combustion — 15 to 1.

2. Additional dilution of combustion products with room air must occur to bring CO$_2$ generated by combustion down to at least the threshold limit values for CO$_2$ (5,000 ppm)$^1$ — 13 to 1.

3. A person would not conceivably be exposed continuously for a 168-hour week in such an environment. For purposes of this study, however, no increase in permissible concentrations is made to allow for this favorable factor. Based on the foregoing, the concentration of contaminants in the natural gas as it emanates from the burner will be reduced by a factor of approximately 200 to 1. ($\frac{1}{200} \times \frac{1}{13} = \frac{1}{1500}$)

In practice, should commercial production of gas by this technique materialize, the AEC would make a determination of the reasonable amounts of contaminants to

$^1$Maximum CO$_2$ permissible in air for industrial workers on an 8-hour daily exposure.
be expected in the room under the most pessimistic conditions in order to arrive at a permissible level of contaminants in domestic gas for use by the general population.

B. Dilution in Field Processing of Natural Gas

Production from the general area of the test site in the eastern portion of the San Juan Field is transmitted to the Blanco Plant, a distance of close to 50 pipeline miles. There it is treated to remove liquid hydrocarbons, compressed and introduced into one of the main lines to California. The throughput at Blanco is 600 Mscf of gas per day. At the Gallup Station the capacity of this line reaches 1000 Mscf to 1140 Mscf per day. The initial stabilized deliverability from a nuclear stimulated Pictured Cliffs well would range from approximately 1,000 to 2,500 Mcf/d (See Table 1B, Page 21). Thus the gas coming from a particular nuclear well would be diluted by a ratio of as much as 1140 to 1 before it reaches the consumer, simply as a result of its dilution and mixing in the pipeline system.

C. Underground Effects — Dilution and Flushing

Each explosion will introduce a fixed quantity of gaseous radioactive material into the chimney. As the methane is produced from the well, these radioactive gases, originally formed by the explosion, will be removed from the chimney, and uncontaminated gas from the formation will move into the pore spaces of the chimney, displacing, and to a lesser extent, mixing with the chimney gas. In this manner, the wells will “clean-up” as they are produced. It is estimated that production of the first chimney volume of gas would remove more than half of the gaseous radioactive explosion products.

III. PRODUCTION ASSUMPTIONS

It is assumed that the El Paso Natural Gas Company would be licensed to handle gas with concentrations of radioactivity above LEC in the field gathering system and in the Blanco Plant. For operational advantages, it is assumed that the gas leaving the Blanco Plant will be at or below LEC due to the field dilution effect described above. As discussed in 1A above, gas entering the household is diluted by a factor of 200:1 as a result of combustion and dilution with air in the room. Consequently, contaminants reaching the consumer at LEC levels would be reduced to \( \frac{1}{500} \) of the permissible concentration for the general population, under the worst situation, i.e., maximum exposure.

The Blanco Plant has a throughput of 600 Mscf per day. To keep the concentration of radioactivity at LEC levels, such a system could accept 85 curies per day from stimulated wells, if the contaminant is tritium, or 51 curies/day if the contaminant is Kr-85.

Because of exposure of the general population, the above discussions treat the most restrictive utilization of gas produced by this technique. If such gas were utilized for certain industrial purposes, the radioactivity concentrations and considerations would be considerably less significant.

APPENDIX F

W. T. Hollis (EPNG)

DRILLING SCHEDULE — PROJECT GASBUGGY

I. Pre-Shot Test Wells

A. Location:
   
   Section 36, SW/4, T-29-N, R-4-W, Rio Arriba County, New Mexico
   
   Elevation: 7200’ DF (Est.) Total Depth: 4185’

B. Geology

1. Formation Tops: Ojo Alamo 3460
   
   Kirtland 3630
   
   Fruitland 3760
   
   Pictured Cliffs 3900
   
   Lewis 4185-

   Total Depth


3. Natural Gauges: Natural gauges to be taken in gas drilled hole each time core barrel is pulled at 10’ interval while not coring or at any noticeable gas increases. Coring not to be interrupted to take natural gauges.

4. Samples: Take samples at 5’ intervals from top of Ojo Alamo to 7” casing point.

5. Coring: Core 8” full hole w/diamond corehead from 3460’ - 3630’, core 8” full hole w/diamond corehead 3820’ - 3900’. Drill 7” float with wate and conventional bit, pressure test casing to 1500 psi for 30 minutes, drill shoe and blow casing dry. Core 6” full hole with diamond corehead.

\(^*100\) Mscf in the case of a 10 KT explosion.
using gas for circulating fluid 3900'-4185'.
6. Drill Stem Testing:
   - DST #1 - Cored Interval - 3460'-3630'
   - DST #2 - Cored Interval - 3829'-3900'
   Drill stem test with conventional formation packers, the tests to be conducted over time intervals sufficient to secure representative samples of formation fluids and pressure data.

C. Drilling
1. Mud Program: 0 - 500' - Spud Mud
   500'-3900' - Pressure test surface casing to 600 psi for 30 minutes, drill shoe with water, commence mud up with gel chemical mud in order to have the following mud properties at 3360': Mud weight 8.7 - 9.2#/gal., viscosity 38 - 44 Sec./quart, water loss 15 cc. or less, and maintain to 7" casing point at 3900'. Desander to be used at all times after drilling out under surface casing.

D. Materials
1. Casing & Cementing Program:
<table>
<thead>
<tr>
<th>Surface Hole</th>
<th>Casing Size</th>
<th>Weight &amp; Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>15&quot; 500'</td>
<td>9&quot; 32.30# H</td>
<td></td>
</tr>
</tbody>
</table>

Texas Pattern shoe, Baker spring type centralizers or bottom 3 joints, use top wooden plug. Cement w/460 sacks regular cement w/2% gel, % cu. ft. Strata-Crete "6"/sk., and 2% HA-5, to fill 100% of the 361 cu. ft. annular space and circulate cement to surface. W.O.C. 24 hours. Production:
   - 8" 3900' 7" 20# J-55
   Baker #102-01 7" guide shoe, Baker #161-01 7"
   Flex-flow fill up float collar (to be run on top of 2nd joint from bottom), top rubber plug, Baker spring type centralizers on shoe joint and every alternate joint to top of Ojo Alamo (3460'). Cement w/100 sacks regular cement w/2% gel, % cu. ft. Strata-Crete "6"/sk., followed by 50 sacks neat cement, to cover above top of Ojo Alamo. W.O.C. 18 hours.

Open Hole:
   - 62" 3900' - 4185' - Total Depth.

2. Tubing Program: (If used) 22" EUE, J-55, 4.7# set at 4150'.

E. Well Completion
After drilling to total depth and completing natural tests, plug open hole and casing with pea gravel or sand and cement plugs. If re-entry after shot is determined feasible, plugging material will be blown from wellbore using gas as circulating medium. Re-entry may be impossible due to collapsed or parted casing. Run tubing if necessary and conduct tests.

F. Estimated Cost
$70,000.00 per well

II. Emplacement Hole
A. Location
   - Section 36, SW/4, T-29-N, R-4-W, Rio Arriba County, New Mexico
   - Elevation: 7200' DF (Est.) Total Depth: 4400'
B. Geology
   1. Formation Tops: Ojo Alamo 3460
      - Kirkland 3630
      - Fruitland 3760
      - Pictured Cliffs 3900
      - Lewis 4185
   2. Logging Program: Gamma-Ray-Neutron, Induction-Electric, Micro-Log, Fracture Finder. 12½" pilot hole to be drilled & logged prior to enlarging hole for 16" casing.
   3. Natural Gauges: None
   4. Samples: Catch 5' samples from Ojo Alamo to total depth.
   5. Coring: None
   6. Drill Stem Test: None
C. Drilling
1. Mud Program: 0 - 300' Spud mud
   300 - Total Depth. Pressure test surface casing with 600 psi for 30 minutes. Drill out with mud having the following properties: Weight 9.5#/gal. or less, Viscosity 38-50 Sec./qt., water loss 30 cc/30 min. or less, filter cake 1/16" or less.

D. Materials
1. Casing & Cementing Program:
<table>
<thead>
<tr>
<th>Surface Casing Size</th>
<th>Weight &amp; Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 300' X52</td>
<td>.500 Wall, N52</td>
</tr>
</tbody>
</table>
   - Cement with 635 sks, regular cement, % cu. ft. Strata-Crete "6"/sk., 2% calcium chloride. W.O.C. 24 hours. (Based on 200% of calculated volume required to circulate).
   Production Casing:
<table>
<thead>
<tr>
<th>Hole</th>
<th>Size Depth Casing Size</th>
<th>Weight &amp; Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>24&quot; 2500-4400 16&quot; 109#</td>
<td>J. Diam. Butt 0-2500 16&quot; 84#, J. Diam. Butt</td>
<td></td>
</tr>
</tbody>
</table>
   Baker cement guide shoe (#102-01), Baker cement float collar (#101-01), B & W G. P. oversize hole type centralizers series 56000 on shoe joint and every other joint to surface.
   Center with 3445 sks, Class "C", 6% gell, % cu. ft. fine gilsonite/sk., followed by 200 sks. regular cement. (Based on 100% of Calculated vol-
1. Casing & Cementing Program:

<table>
<thead>
<tr>
<th>Hole</th>
<th>Size</th>
<th>Depth</th>
<th>Casing Size</th>
<th>Weight &amp; Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Casing</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>Depth</td>
<td>Casing Size</td>
<td>Weight &amp; Grade</td>
<td></td>
</tr>
<tr>
<td>17&quot;&quot;</td>
<td>500'</td>
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<td>48# H-40 S&amp;</td>
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</tr>
<tr>
<td>Size</td>
<td>Depth</td>
<td>Casing Size</td>
<td>Weight &amp; Grade</td>
<td></td>
</tr>
<tr>
<td>12&quot;&quot;</td>
<td>3700'</td>
<td>9&quot;&quot;</td>
<td>36# J-55 ST&amp;S</td>
<td></td>
</tr>
</tbody>
</table>

Texas Pattern Shoe, Baker spring type centralizers on every joint. Use top wooden plug. Cement with 410 sacks regular cement w/2% gel 3/4 cu. ft. Strata-Crete “6”/sk., 2% HA-5. W.O.C. 24 hrs. (Based on 200% of calculated volume required to circulate cement).

Production Casing:

<table>
<thead>
<tr>
<th>Hole</th>
<th>Size</th>
<th>Depth</th>
<th>Casing Size</th>
<th>Weight &amp; Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Depth</td>
<td>Casing Size</td>
<td>Weight &amp; Grade</td>
<td></td>
</tr>
<tr>
<td>12&quot;&quot;</td>
<td>3700'</td>
<td>9&quot;&quot;</td>
<td>36# J-55 ST&amp;S</td>
<td></td>
</tr>
</tbody>
</table>

Baker #102-01 9"" guide shoe, Baker #161-0 9"" Flexiflow fill up collar, top rubber plug Baker spring type centralizers on shoe joint and every alternate joint to top of Ojo Alamo (3460'). Cement w/100 sacks regular cement w/2% gel 3/4 cu. ft. Strata-Crete “6”/sk., followed by 5 sacks neat cement, to cover above top of Ojo Alamo. W.O.C. 18 hours.

Production Liner: Will be run only if movable water encountered in Fruitland Formation.

<table>
<thead>
<tr>
<th>Hole</th>
<th>Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Interval</td>
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<td>8&quot;&quot;</td>
<td>3600-3860</td>
</tr>
<tr>
<td>Burns 9&quot;&quot; x 7&quot;&quot; Liner Hanger w/neoprene seals</td>
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Cement w/100 sacks regular cement, 4% gel 3/4 cu. ft. fine gilsonite/sk. Pump 20 bbls. of g water ahead of cement. After cement has been displaced from liner, set the liner hanger seal, load casing w/water and reverse out excess cement. W.O.C. 18 hours.

Open Hole: 6% open hole to Total Depth.

2. Tubing Program: 2% EUE 6.5# J-55 tubi set at 10' to 30' from Total Depth. The port of the tubing string set in the open hole w consist entirely of Halliburton Sand Screen 10' joints.

3. Wellhead Equipment: Casinghead 12"" 2000# WP flange to 13"" female thread, 13% x 9% automatic setting slips and seal assembly, xmas tr 12"" x 10"" flanged, 2000# WP tubing head with two 2"" 2000# WP outlets and 8"" bore. Equ xmas tree and casing head with 2000# WP 2"" fl opening valves, xmas tree to hang 2% EL tubing.

E. Well Completion

After reaching total depth, strip drill string fr hole and lubricate logging tools into and out of hole. Strip production tubing into hole.

F. Estimated Cost

$70,000.00
APPENDIX G

Dr. D. B. Lombard (LRL)

SEISMIC AND OTHER SAFETY FACTORS

Shock and seismic effects from an underground nuclear explosion are functions of the nuclear energy yield and the geology of the shot site. On the basis of experience one might expect gas well damage in the San Juan Basin within about 1300 ft. of 10 kt, or 3000 ft. of 100 kt.\(^1\) Forced vibration damage radii for residential plaster cracking would be about 1.6 miles for 10 kt and 4.5 miles for 100 kt. Seismic effects of the explosion would be felt at much greater distances, and in some circumstances settlement-type damage to structures might occur beyond the plaster damage range.

The possibility of dynamic venting in any gas stimulation experiment should be studied carefully. Such venting in general will not occur if the shot is fired at a depth equal to the anticipated chimney height plus 500 feet. This would make the minimum depth of burst for 10 kt about 900 ft. Post-shot leakage of high-pressure gas out to the atmosphere or into a permeable formation other than the one being stimulated, is undesirable. The chimney produced by the detonation must not therefore communicate by cracks with any region to which gas could escape. Should such a danger exist, careful selection of yield and shot placement may provide adequate control. Cracks seldom extend as much as four cavity radii above the top of a chimney. Pre-shot geological analyses of the joints and fractures in and above the gas-bearing strata will be important in achieving safe designs.

Ground water is another important factor in safe design. There are basically two problems; first, to prevent large amounts of ground water from flooding the nuclear chimney, thereby killing the well. This will not occur if the chimney does not intersect or communicate with aquifers containing substantial amounts of mobile water. The second problem involves the injection of radioactivity into aquifers. It is not expected that aquifers more than three cavity radii below a shot point will be contaminated. In cases where any possibility of aquifer contamination exists, the movement of water into the aquifer must be carefully analyzed to determine how far the contamination would spread before radioactivity has decayed to acceptable levels. Computer codes have been developed for predicting the post-shot movement of underground waters.

\(^1\)UCRL-7964.
of the test site. The result was a slight amount of gas but no water. The well was plugged back to the Ojo Alamo and perforated to test for gas or water. Neither was recovered.

The San Juan 26-4 #4 Well, SW/4 of Section 26, Township 28 North, Range 4 West, four miles southwest of the test site, was cored through the Fruitland formation. Core analysis of the well showed the sands of the Fruitland to have a high residual water saturation. (Figures 4 and 5.) However, there was no evidence of water flow occurring in the Fruitland formation during drilling operations.

CONCLUSIONS
1. Water is not expected to flow from the Ojo Alamo or Fruitland formations at the test site.
2. The depth of the formations in this area prohibits their use as a domestic water supply.
3. The nearest water wells to the test site from which water from the Ojo Alamo formation is used are approximately 50 miles west and 1700 feet updip.
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PROPOSED LOCATION

S.W. SEC. 36 TWP 29-N RQ. 4-W

INDEX MAP

A-A'

CROSS - SECTION

TOP OJO ALAMO
TO
BASE PICTURED CLIFFS

T-29-N R-4-W RIO ARIBA CO., NEW MEXICO

ANALOG BY C.F. BROWN
DURING BY W. HUGHES
MAY 1964

Figure 1
PROPOSED LOCATION

INDEX MAP

B-B' CROSS SECTION

TOP OJO ALAMO TO BASE PICTURED CLIFFS

T-28 & 29-N, R-4-W, RIO ARRIBA CO., NEW MEXICO

GEOLOGY BY C.F. BROWN MAY 1964 Drafting By J. Houghton

Figure 2
FIGURE 3

LEGEND
- COMPLETED WELLS
- DRILL STEM TEST
- CORE
- COMPLETION ATTEMPT
- TEST SITE

SCALE: 1" = 2 MILES

GEOLOGY BY: C.F.BROWN
Drawn By: J.Hopkins
MAY 1964