TECHNICAL CONSIDERATIONS FOR PLOWSHARE APPLICATIONS TO OIL SHALE*

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ABSTRACT

Nuclear explosions have been proposed for use in the recovery of oil from deep oil shale deposits. Before commercial feasibility can be established, a variety of technical problems must be examined. Some of these are related to nuclear explosion effects, others to the recovery of oil from the broken rock. Among the primary areas of interest are fracturing, chimney collapse, rubble size distribution, radioactivity, and retorting methods and variables.

To test the concept, nuclear explosion experiments will be needed. One such experiment, Project Bronco, has been designed in detail, and is used here to illustrate a possible direction of development. The design is based on the following objectives: to evaluate the overall feasibility of nuclear breaking, followed by in situ retorting; to investigate the gross physical effects of a nuclear explosion in oil shale, and to assess the role of radioactivities in the production of oil by in situ retorting. The experimental plan provides for the accomplishment of these objectives by appropriate preshot studies, a postshot examination of explosion effects, and experimental retorting of the nuclear chimney.

INTRODUCTION

A domestic hydrocarbon resource capable of supplementing U.S. energy needs for many decades would be an attractive target. Such a potential exists in the oil shale deposits of the Rocky Mountain region, but as yet there is no proven method for economic development.

The bulk of the resource is deeply buried and is not readily accessible with present mining technology; therefore, considerable attention has been devoted to a search for techniques for recovering the oil without mining. A lack of natural permeability in the oil shale deposits has stimulated research on means for creating permeability. It may be possible to provide the needed permeability by fracturing deep oil shale deposits with nuclear explosions.

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The concept of nuclear explosion breakage as preparation for retorting in place has been under consideration for several years.[1] The technical feasibility of the concept is not fully established, and a program of research, including one or more nuclear explosion experiments, will be required to establish the technical as well as the economic potential of the method.

The feasibility of retorting the oil shale in place once it is broken has also been under examination.[2,3] While results from preliminary research are encouraging, it is not yet certain how such retorting can best be accomplished.[4] Several possible approaches have merit and are currently being investigated. A definitive design for retorting in the nuclear environment will depend on the results of current studies and the evaluation of the effects of actual nuclear explosions in oil shale.

Project Bronco has been proposed as an experiment to test the concepts discussed above.[5] The technical design for the project has been carried as far as possible on the basis of available information. The Bronco design is presented here as an example of an experimental approach toward solution of some of the technical problems which have been identified.

EXPLOSION EFFECTS

The feasibility of using nuclear explosions in shale oil recovery can be established only with the aid of large-scale experiments. Because of the number and complexity of the technical problems, a first nuclear experiment would not result in a complete commercial technology. Such an experiment, however, should answer some of the key technical questions and point the way toward further development. Permanent changes in the surrounding rock created by the action of an explosion are of obvious interest because such effects may improve the retortability of oil shale. An objective of a first nuclear experiment would therefore be to measure some of the pertinent explosion effects.

Within microseconds, the detonation of a contained nuclear explosive creates a spherical cavity filled with gas and vaporized rock at very high temperatures and pressures. As the cavity expands and cools, its internal pressure drops. Expansion is complete when the cavity pressure is about equal to lithostatic stresses in the surrounding rock. The cavity expansion generates a very strong shock wave which moves rapidly out into the adjacent rock. The shock wave decreases in intensity as it recedes from the cavity boundary, and becomes the source of seismic disturbance when its amplitude has dropped below the elastic limit of the rock.

A nuclear explosion cavity may or may not be stable, depending upon its diameter and the strength of the rock above it. Typically, the ceilings of nuclear explosion cavities in hard rock have collapsed within a few minutes after detonation. Chunks of broken rock pour down into the cavity. The collapse proceeds upward for a distance of several cavity radii. The resulting rubblized mass, called a nuclear chimney, commonly has an approximately cylindrical shape.

Fracturing

Both microscopic and macroscopic fracturing are found in the vicinity of underground nuclear explosions. Natural fractures, joints, bedding planes and other geological irregularities can be affected by the explosion and may contribute to the presence of fractures in a postshot environment. Figure 1 illustrates schematically several types of fracture which may occur as a result of underground nuclear explosions.

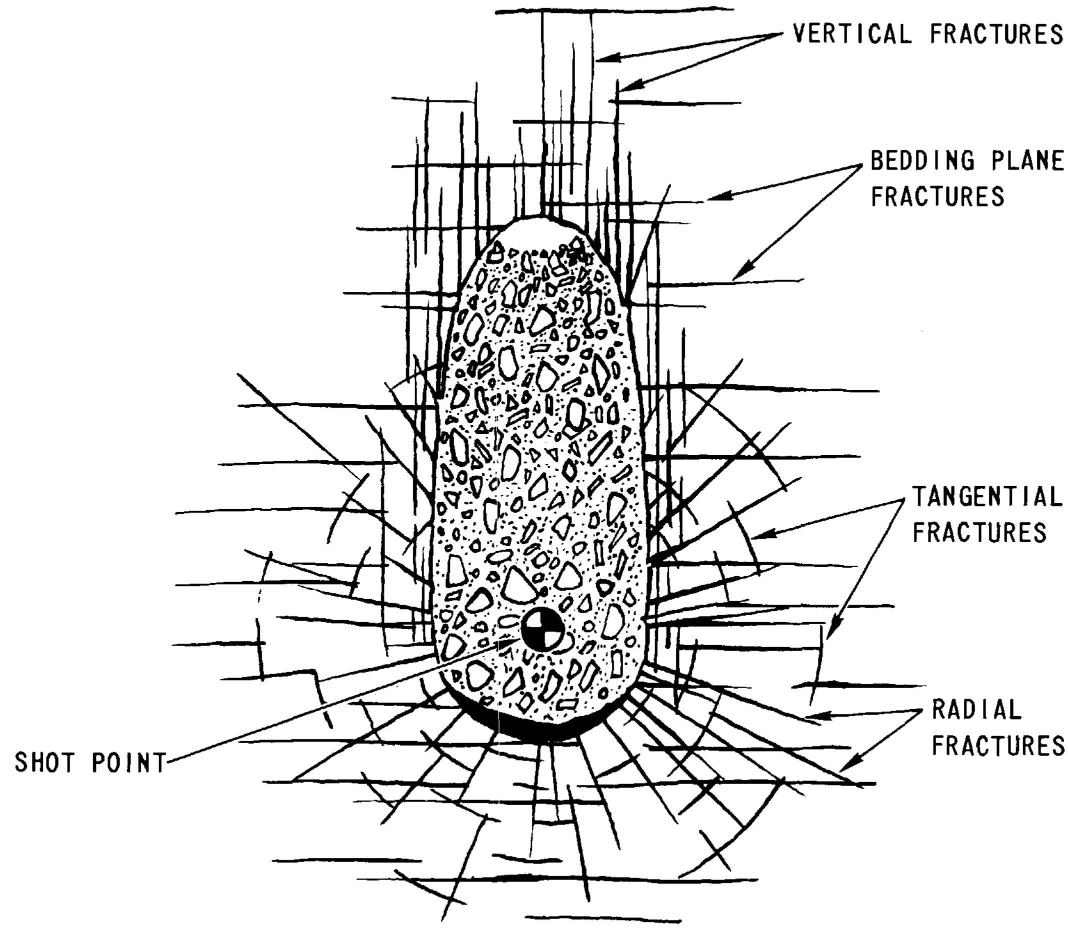

Fig. 1 Schematic illustration of possible types of fracturing near an underground nuclear chimney.

Chimney formation and size, rubble size distribution, bulk permeability of the rock outside chimneys, and the optimum placement of adjacent chimneys in the development of large oil shale tracts are currently believed to be related to fracturing. Fracturing to adjacent formations containing mobile water will probably be undesirable. An ability of predict the degree and extent of fracturing and permeability change due to an underground nuclear explosion in oil shale therefore should be a part of the technology of breaking oil shale with nuclear explosives.

Significant increases in bulk permeability of nuclear-fractured rock have been measured and correlated with distance from the chimney edge, but data are sparse.[6] The effects of fracturing were detected more than 400 ft from the 26-kt, 4200-ft-deep Gasbuggy explosion.[7]

Although the cavity radius is not directly dependent on the extent or intensity of fracturing, the chimney height may be. In a rock as competent as Green River oil shale, the cavity may not collapse to form a chimney if the ceiling rock is not adequately fractured. Collapse will extend upward only as far as sufficient fracturing or bulking of the rubble permits. Thus the volume of rubble available for chimney retorting can be directly related to fracturing.

The size distribution of particles of oil shale rubble in a nuclear chimney will have a major influence on whether the chimney can be retorted at all, which of several possible methods is best, and whether that one can be employed efficiently enough to assure commercial feasibility. The nature and intensity of fracturing will affect the particle sizes and shapes which in turn determine bulk permeability, bulk porosity, and specific surface in the rubble mass. Any retorting process is closely related to these quantities.

If shale oil is to be recovered by in situ retorting in the fractured but unfragmented region outside a nuclear chimney, the importance of fracture intensity, regularity and extent in that region is obvious. At depths of several kilometers, pressures and temperatures are great enough to cause plastic flow in many rock types. Because of its relatively plastic nature, there remains the question of whether oil shale at depths of 2000 to 3000 ft would retain fracture permeability. The oil shale grade would of course be an important factor.

Test drill holes in the Piceance Creek Basin of Colorado have revealed thick, rich oil shale deposits, as shown in Fig. 2.[8] In many locations, water-bearing strata overlie and underlie the oil shale. In some circumstances, it will be desirable to adjust explosion energy yields and shot point locations in order to avoid fracturing to the water.

When large tracts of oil shale are prepared for in situ retorting by nuclear explosion fracturing, the spacing of the explosions will be critical. If the shot points are too close together, fracturing expense may be unnecessarily high. If they are too far apart, insufficient permeability may exist between chimneys, and associated retorting costs may be unnecessarily high. Those designing such tract developments will have to be aware of the degree of fracture enhancement between adjacent chimneys.

The question of inter-chimney fracturing will affect not only the spacing of shots but also their timing, energy yields, and burial depths. In arriving at the most effective plan for nuclear explosion shale oil recovery in a given tract, the designers will be influenced by the following factors:

1. The cost of each nuclear explosive is expected to be approximately independent of the yield.[9]

2. The volume of rock fractured by a nuclear explosion is expected to be approximately proportional to the yield.[10]

3. At a given site, the total yield that can be fired at one time will be limited by seismic considerations.

4. The yield of each individual explosive may be limited by the oil shale thickness and/or the overburden thickness.

Thus the sequential firing of single explosions, each at the seismic limit of yield, may appear to give the greatest economy. In some cases, however, simultaneous firings might be preferable. For example, the interaction of shock waves may prove to enhance fracturing enough to overcome the cost advantage of one explosive over two. The enhanced fracturing concept is illustrated schematically in Fig. 3. In exceptionally thick deposits, one shot above another might be fired in tandem to achieve an adequately tall chimney. Thin oil shale, reduced overburden, or local geologic conditions, on the other hand, might result in a single explosive yield limit significantly less than the maximum dictated by seismic considerations. In such cases the simultaneous detonation of an array of two or more explosives might be the most attractive plan.

The complexity of the design problem is apparent, as is the necessity for developing technical data about the fracturing and the retortability of the fractures. It is clear that adjacent nuclear explosions in oil shale will have to be studied before optimum design criteria can be established.

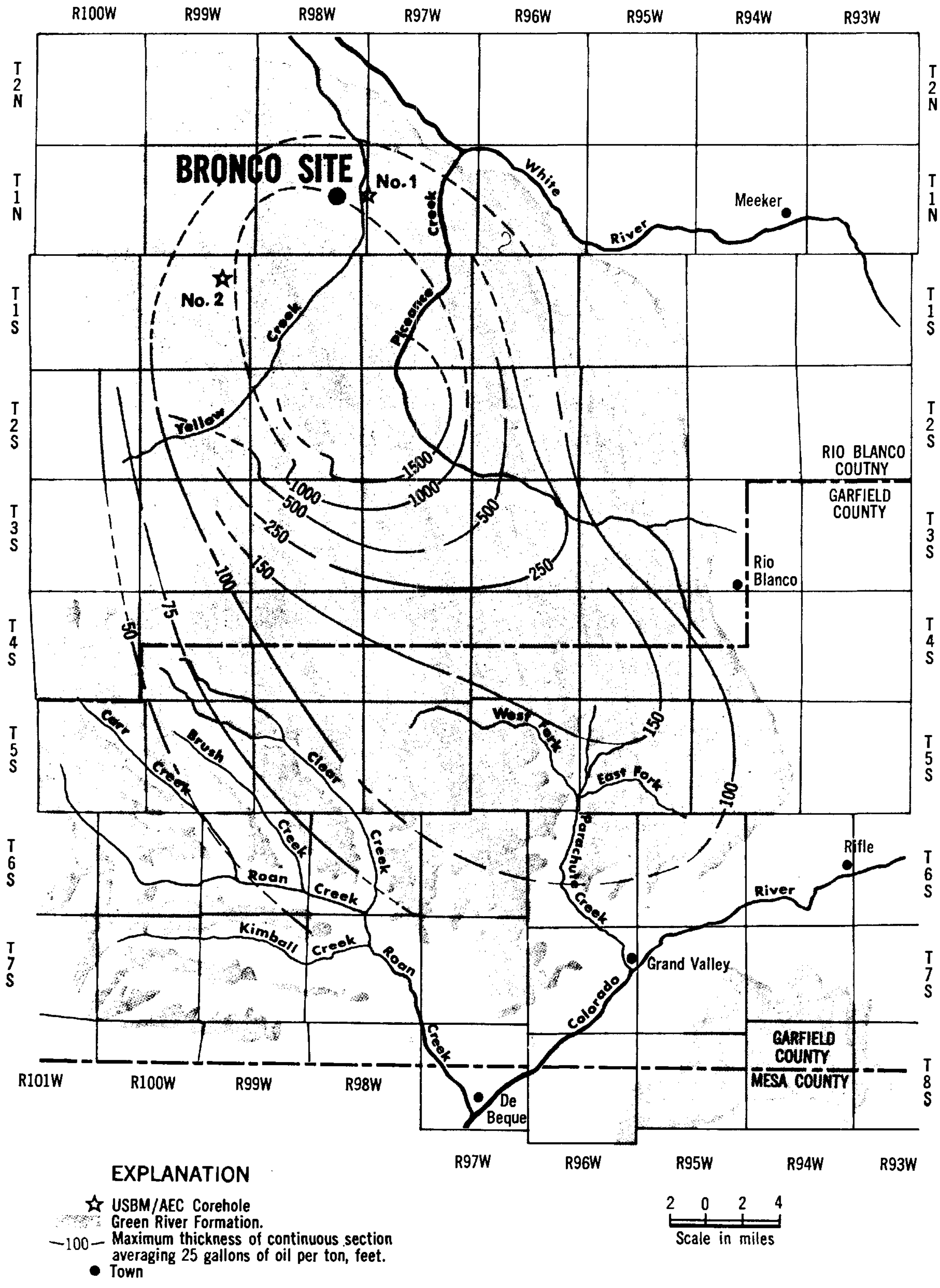

Fig. 2. Isopachous map of 25 gal/ton oil shale, Piceance Creek Basin, Colorado.

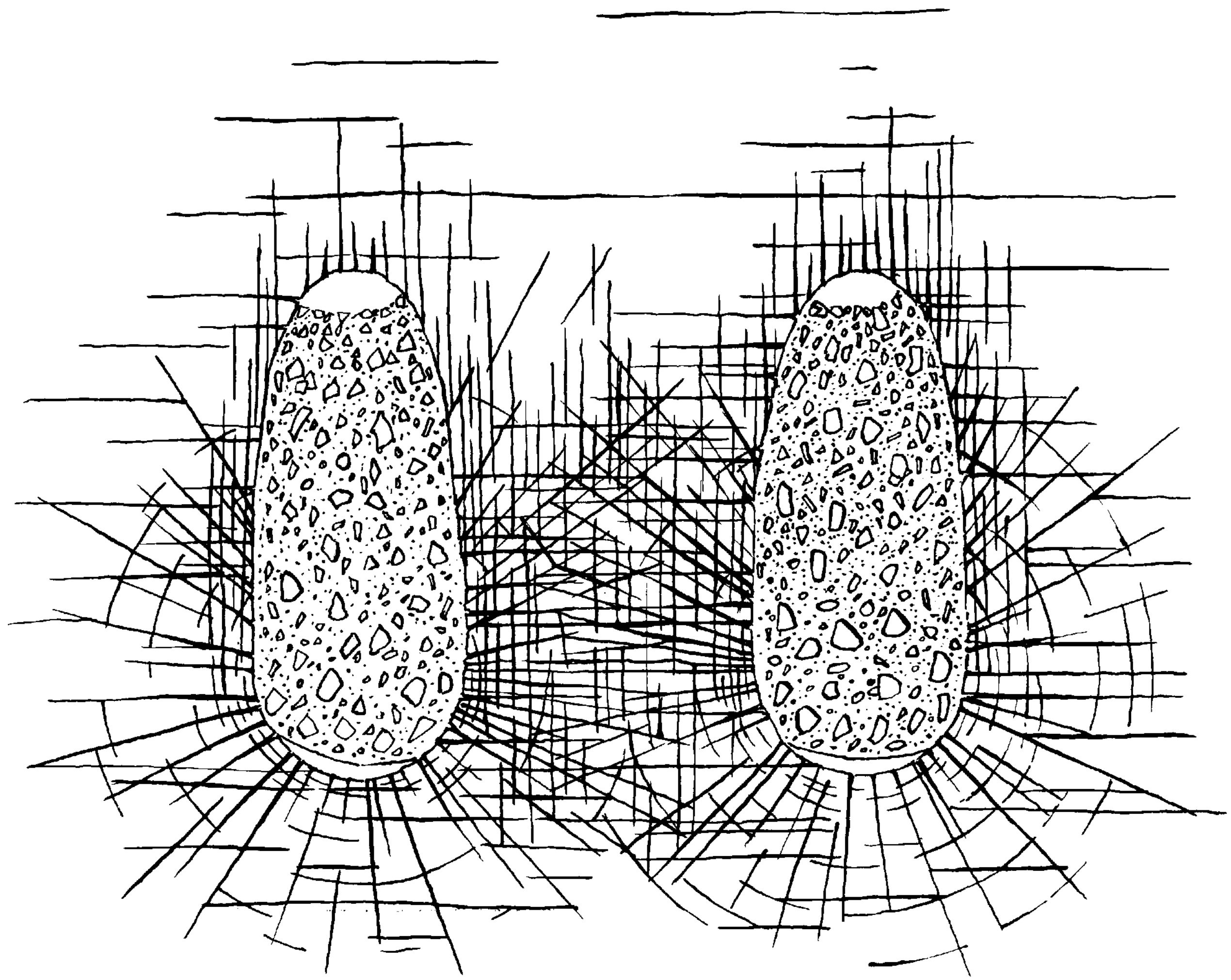

Fig. 3. Concept of enhanced fracturing between nuclear chimneys

Predictions of Fracturing

A needed development is the ability to predict the intensity, permeability, and extent of fractures that will be produced at a particular site by a single nuclear explosion of a given energy yield and emplacement depth. This predictive capability for fracturing cannot be developed on either a purely theoretical basis or a purely empirical basis, but must be founded on a combination of the two. If a mathematical model of the fracturing process is to be developed, it must be verified by experimental observation. On the other hand, the fracture pattern caused by a particular explosion cannot be extrapolated in entirety to other sites or energy yields without an underlying comprehension of the processes involved in the creation of fractures by underground explosions.

A mathematical model has been developed, based on the assumption that fracturing is a response of the rock to the outgoing shock wave.[11] In the model, fracturing occurs in a spherical zone about the detonation point; chimney height is determined by the radius of the fracture zone. The magnitude of the fracture radius depends upon the shock wave amplitude as a function of distance, and upon the brittle-ductile characteristics of the material. The physical properties of the rock are measured in the laboratory and fed into the calculation, which predicts cavity radius, fracture radius, and shock wave characteristics.

The model has predicted chimney height and radii of effects from several underground nuclear explosions (see Fig. 4).[12] Much more checking, however, remains to be done before the model is considered reliable.

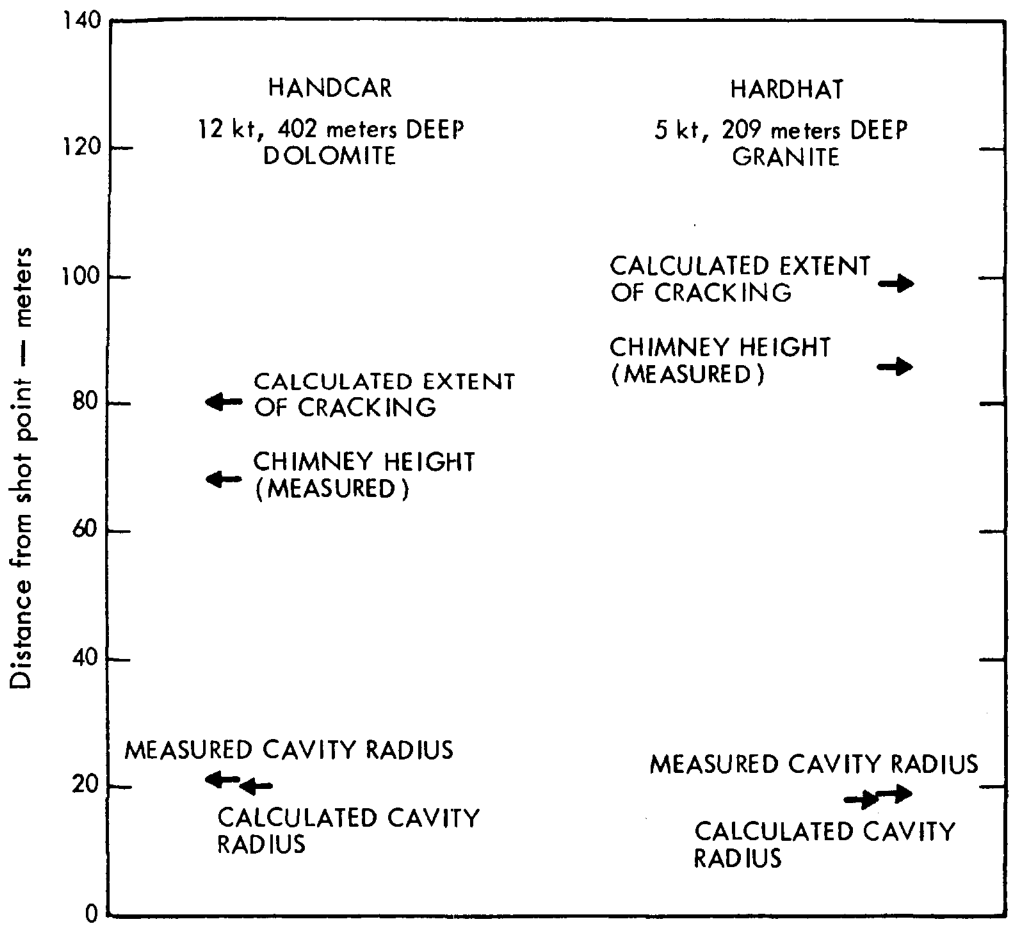

Fig. 4. Calculated cavity radii for Handcar and Hardhat, compared with observed dimensions.[12]

A long-recognized problem with fracture prediction is the influence of geologic irregularities. Since the present model is one-dimensional, it assumes a uniform medium. Natural rock formations are not so uniform; thus the differences between the model and the natural world result in differences between predicted and observed fracturing effects. Relative movement of formations along common boundaries was observed at Gasbuggy[7] at ranges well beyond the predicted radius of intense fracturing. Data from dynamic instrumentation demonstrated clearly that the displacement was caused by the explosion.[13] Geologic irregularities have been identified with other occurrences of fracture caused by nuclear explosions.

Green River oil shale is horizontally bedded in the deep, thick part of the Piceance Basin. Typical sections of the formation show great variations in oil shale grade over short vertical intervals. Such variations in grade are assoicated with large variations in those physical properties important in fracturing. It has been found that the stress at which brittle-ductile transition occurs is a strong function of oil shale grade, and also varies significantly between the principal directions, at least in the 18 to 25 gal/ton range.[14] Because the variations are present only in a vertical plan and because the intervals of uniformity are exceedingly small, it will be difficult to develop a mathematical model for the oil shale.

Fracturing, then, is a key process in the use of nuclear explosions to aid in recovering oil from oil shale. A capability to predict the degree and extent of fractures is needed.

Rubble Characteristics

The time required to retort a block of oil shale varies as the square of its diameter. Therefore, the size distribution of the particles of fragmented oil shale in a nuclear chimney will have an appreciable effect on the rate and the efficiency of the oil recovery method. Post-shot investigations in Hardhat and Piledriver, nuclear explosions in granite, included mining into the chimneys to obtain information on particle size distribution. In Hardhat, an on-the-spot visual estimate of particle size distribution was made; in Piledriver, rubble samples were taken and analyzed.[15,16] Mining to gather samples from nuclear chimneys is very expensive because of the weight and large numbers of samples needed. In oil shale, hot from a nuclear explosion, the presence of noxious and combustible gases would make a sampling operation even more expensive.

A camera, lowered into the apical void at the top of a chimney, can be used to photograph the top of the rubble (Fig. 5). This method, although simple and inexpensive, yields data of limited reliability because the size distribution of the top layer of fragments may not represent the distribution in the rest of the chimney. The particles at the top of the chimney are further from the detonation point, and may be larger than average because they have been subjected to the weaker part of the shock wave, have not fallen as far, and have not been broken by rubble falling from above. A better method for determining particle size distribution throughout the chimney is needed.

Yield Limits

Since the amount of rock broken by an underground nuclear explosion is proportional to the energy yield, and since the cost directly associated with a detonation will be roughly independent of the yield, it follows that the larger the yield, the more economical will be the breakage. There are two fundamental limitations on the maximum energy yield that might be used in breaking oil shale. One is geology of the site; yield might be restricted in a particular location by oil shale thickness, limited overburden, or the proximity of water-bearing strata.

Fig. 5. Top of fragmented rubble in Handcar chimney (dolomite). Large block in foreground has maximum dimension of about 3 ft.

The other yield limitation is seismic. The seismic waves from very large explosions might be felt in neighboring population centers and could cause damage in man-made structures. At some point, for a given site, the benefits of increased yield will be more than offset by potential damage. Because the effect of a seismic wave depends upon geological details and to some extent upon local architectural techniques and building standards, it is not now possible to predict accurately the maximum acceptable yield for a given location. Data from well-documented nuclear explosion experiments will lead to significant improvements in the reliability of seismic damage prediction.

Explosive Design

If nuclear explosives are to be used on a large scale in the development of oil shale, the design of special explosives, with characteristics matched to the job, may be justified. Nuclear explosives can be designed to achieve relatively small diameter, to reduce some types of radioactive contamination, or to minimize cost. However, specifying one of these factors in the design criteria may limit the extent to which the other two can be adjusted. Several years are required to design, test, and produce special explosives. Therefore, the explosives ultimately designed for commercial use will be better adapted to the job than those available at the outset.

Mineral Recovery

A factor in the long-range commercial development of oil shale may be the ease with which other minerals can be extracted from the chimney after oil recovery is completed. For example, aluminum from dawsonite might find a market if it could be produced cheaply. Laboratory tests on the extraction of aluminum from retorted oil shale and oil shale ash are currently being conducted by the Bureau of Mines at College Park, Maryland.

Radioactivity

The amounts and kinds of radioisotopes produced directly and by neutron activations by a given nuclear explosion in a given rock medium can be predicted accurately.[17,18] The chemical forms and spatial distribution of these isotopes and their decay products, however, are more difficult to calculate. In a carbonate rock such as dolomite, most of the fission product radioactivity is confined to the base of the chimney, and this is also expected to be the case in oil shale. Some gaseous or volatile radioactivities—and some with gaseous or volatile precursors—may be distributed through the chimney in low concentrations.

Tritium may be present in the chimney partly because some of the explosive energy may be derived from a fusion reaction and partly because of neutron activation of the oil shale itself. During its growth phase a nuclear cavity in oil shale will contain ions of carbon, oxygen, hydrogen, and tritium—which is chemically identical to hydrogen. These ions may recombine into organic compounds and water as the cavity temperature and pressure drop; the high radiation field may influence such reactions. It is not yet possible to forecast on a theoretical basis just what organic compounds will be formed, or just how the tritium will be distributed among them. An empirical approach must be employed. Measurements of radioactivity postshot and during retorting in experimental nuclear chimneys can be expected to define any problems which might exist. But prior to such experiments, bench scale work with radioisotopes and oil shale samples should provide much worthwhile information. Such work has already begun.[19]

Air and Water Pollution

In the eventual development of a commercial shale oil industry, the questions of air and water pollution must be considered. No matter what method is used for retorting, some gases will have to be disposed of. The most common method of disposal of unwanted gases is to stack them to the atmosphere. However, for a commercial shale oil retorting industry, alternative methods should be considered, e.g., treatment of effluent gases, storage or disposal in burnt-out chimneys, and re-use in the retorting cycle.

An evaluation of these potential problems and a search for solutions should be an integral part of research and development aimed at commercializing the production of oil from oil shale.

Such studies should also consider the possible effects of excess heat created during the retorting process. The question is not important for a single experimental chimney, but eventually several hundred chimneys per year may be involved. When retorting is complete, the retorted oil shale itself will be warm. Much of the heat might be used in preheating new chimneys and in exchange with gases injected into the chimneys being retorted, but some heat will remain. The atmosphere and local streams are commonly used as heat sinks, but on the proposed scale of shale-oil production, heat disposal must be considered carefully. Again, selection of the best commercial retorting method may be affected by these considerations.

RETORT ENGINEERING

In addition to technical questions related to the effects of underground nuclear explosions, there are several concerning the recovery of oil from the nuclear environment. The system consists of basically two parts, the chimney and the surrounding fractured zone. Because the characteristics of the zones are dissimilar, each may require a different retorting process. These differences may increase the complexity of in situ retorting.

The distinction between the explosion effects problems and those related to retorting is not always well-defined, but in general the latter are amenable to direct laboratory investigation, whereas explosion effects must be examined in nuclear explosion environments.

Methods of Retorting

Several methods for in situ recovery of oil from oil shale in a nuclear chimney have been proposed.[5] In one, the heat required for retorting is supplied by the combustion of carbonaceous residues in retorted oil shale. Other methods involve passing preheated inert or reactive gases through the oil shale.

The combustion technique has the advantage of being thermally self-sufficient and of requiring only air as a raw material—except possibly at start-up. The products of combustion, mixed with other gases, carry heat energy through a zone of retorted but unburnt shale to the region where retorting is underway. The gases produced in retorting are added to the stream that preheats the raw oil shale. Part of the exhaust gas may be mixed with air to make up injection gas, and some of the heat carried by the exhaust gas may be delivered to the injection gas via a heat exchanger. The combustion process is shown schematically in Fig. 6.

In the hot gas methods, the gases would be heated prior to being injected into the chimney. The gases might be inert, serving only to carry heat energy to the oil shale, or reactive, entering into chemical reactions with the oil shale or shale oil to improve the efficiency of the retorting process or the quality of the oil.

The hot gas methods may also have an advantage over the combustion process by leaving the retorted oil shale in a stronger, less friable condition. The feasibility of the non-combustion techniques may depend on the long-term availability of suitable raw materials in the Piceance Creek Basin.

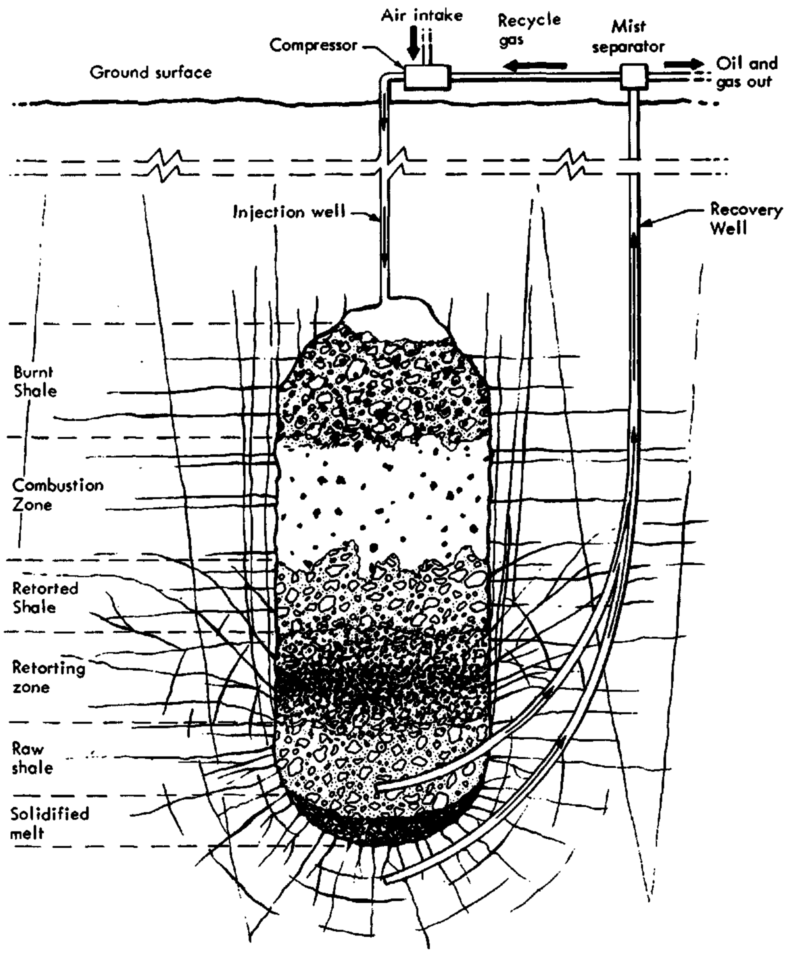

Fig. 6. Concept of retorting a nuclear chimney in oil shale by the combustion process.

Retorting Variables

The experimental retorting of a nuclear chimney will be an expensive procedure. To be of value, it should yield more than just a cursory understanding that if certain conditions are set up, a certain amount of oil is produced. The experiment should reveal some technical details of the response of the retorting process to variations in the controllable parameters. Similar information is needed to establish the optimum set of operating conditions for any of the suggested retorting methods. Acquiring direct knowledge of what is going on in the chimney may be complicated by the problems of installing appropriate instrumentation in the postshot chimney environment.

Three kinds of data would be helpful: pressure, gas composition and temperature, each as a function of time and position in the chimney. However, pressure in the chimney can be estimated with more than adequate accuracy. Gas composition is being examined in experimental retorts prior to the Bronco retorting, and can probably be correlated with temperature.

The bulk permeability of chimney rubble is directly related to the efficiency of various proposed recovery processes. If the particle size distribution and bulk porosity of the rubble vary from place to place within the chimney, the permeability of the rubble column will also be a function of position. The fingering of gases in high permeability zones during retorting may result in the bypassing of a significant portion of the oil shale.

Permeability and particle size distribution may have an effect on combustion front stability if the combustion process is utilized. An unstable combustion front might reach and consume significant quantities of unretorted oil shale. In addition, the relationship of particle sizes to the efficiency of any proposed retorting process must be understood before an efficient recovery experiment for a nuclear chimney can be designed.

Many of these relationships can be investigated in a laboratory situation prior to the nuclear experiment. For this purpose, a 10-ton retort capable of handling shale pieces as large as 20 in. in two dimensions has been in operation at the Laramie Petroleum Research Center for the past two years.[2] A larger unit capable of handling 4-ft pieces of oil shale has been designed and has recently been placed in operation. Figure 7 is a schematic diagram of the larger retort.

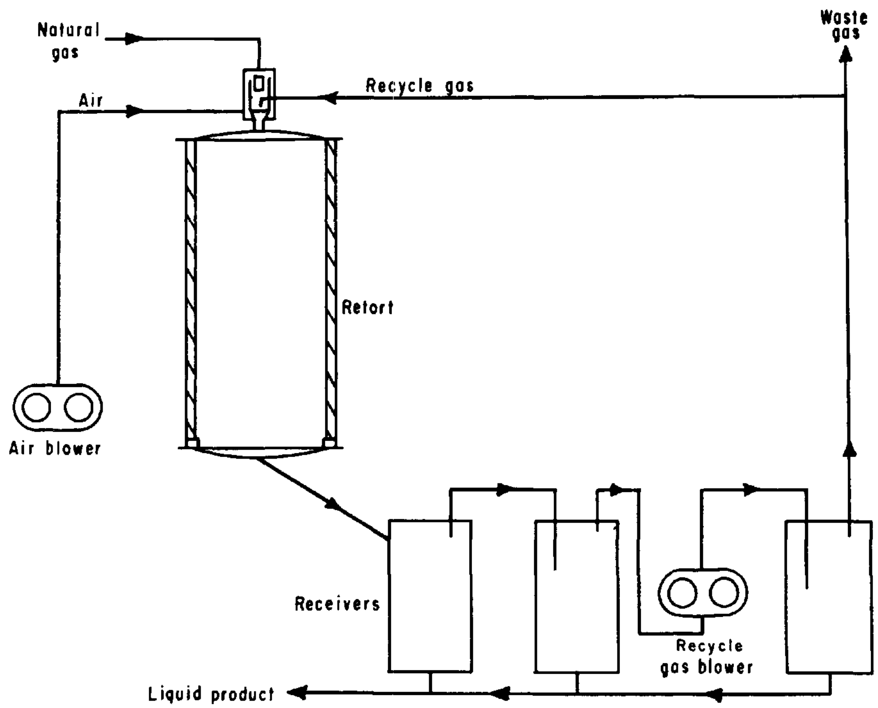

Fig. 7. Schematic diagram of the 150-ton retort.

Yields as high as 80% of Fischer assay have been obtained from the smaller unit.[4] Statistical evaluation of data obtained from this unit indicates that oil yield is influenced mainly by recycle gas rates, shale bed temperatures, and grade of shale. These parameters and their squares and cross products accounted for 91% of the variability in oil yield. Although air rate and particle size of the charge had some effect on oil yield, these variables were not highly significant for the ranges investigated.

Thermocouple records from four runs in the 10-ton retort have been subjected to additional analysis. Ahead of the combustion front, in the temperature range 700°F to 1000°F, the cooler isotherms were found to be advancing more rapidly than the warmer ones (see Fig. 8). These results are consistent with the chimney retorting model illustrated in Fig. 6. It appears that endothermic decomposition of carbonate components of the oil shale does not seriously impede the retorting process in this temperature range.

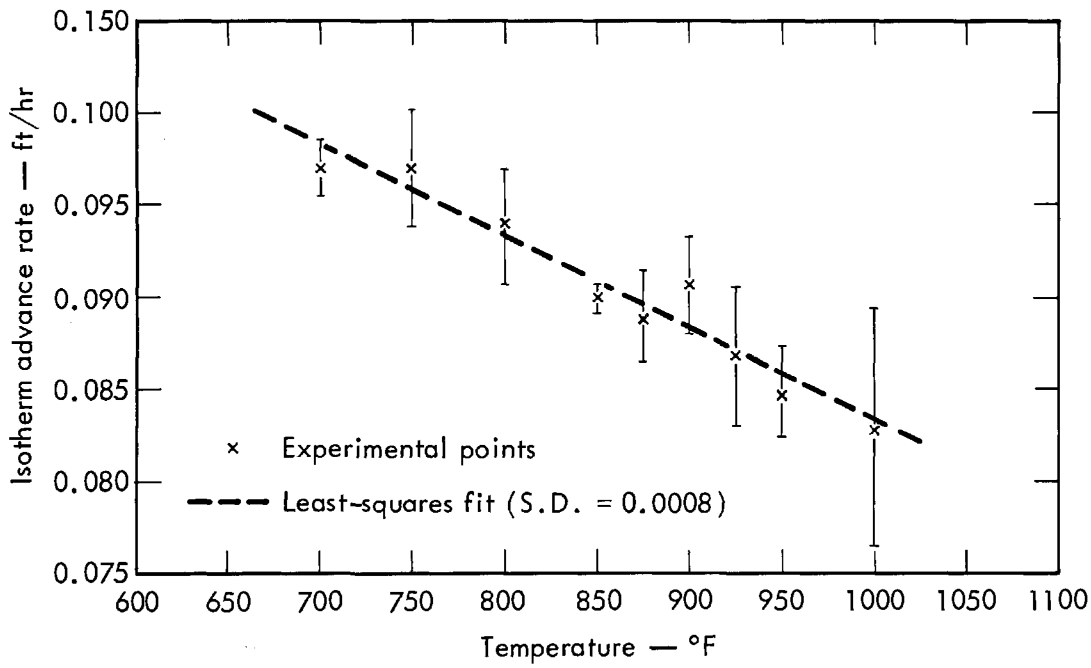

Fig. 8. Isotherm advance rates: Average of Laramie 10-ton retort runs 8, 9, 10, 11.

Laboratory work at the Laramie center has shown that settling and compaction of the shale bed during retorting, due to pressures such as those which might exist near the bottom of a nuclear chimney, reduce bulk permeability. Compaction at pressures corresponding to rubble column heights of 400 ft or more was evident at temperatures as low as 600°F.[20]

A related question involves the retorted or retorted-and-burnt oil shale farther up in the chimney. The strength properties of the oil shale before and after retorting, and before and after combustion, are known to be different. Retorting removes the bulk of the kerogen which serves to bind the mineral particles. But there remain sufficient organics to cement the matrix. After combustion has removed essentially all carbonaceous residue, the resulting burnt shale is relatively friable. If the burnt oil shale crushes to any degree, the fine particles may tend to form a dense mass having relatively low bulk permeability that subsequently would block the flow of gases. Laboratory studies of the strength properties of retorted and burnt oil shale are underway at the Bureau of Mines' Laramie Station.

Enough energy remains in the vicinity of a nuclear explosion, in the form of heat, to retort some oil shale, perhaps as much as 10% of the fragmented material in the chimney.[2] If such retorting occurs, it will probably be at the base of the chimney where the heat is initially concentrated. The presence of water or organic fluids (including retorted oil) will serve to distribute heat energy more uniformly throughout the chimney, by a refluxing action, at a temperature below the retorting threshold.

Because the amount and composition of fluids that the chimney would contain are unknown, it is difficult to predict chimney temperature as a function of position and time. Yet the temperature distribution may very well be an important factor in properly conducting the retorting. If instrumentation can be installed in a chimney for retorting experiments, it will also be possible to measure the temperature distribution before retorting begins. It may also be possible to measure the amount of any fluid shale oil that may have collected at the bottom of the chimney by this time.

PROJECT BRONCO DESIGN

In order to evaluate some of the explosive effects in oil shale and also to study some of the variables of retorting in an explosion-created environment, Project Bronco was conceived and proposed[5] as a fully contained nuclear explosion, approximately 3000 ft deep in the Green River oil shale deposit in the Piceance Basin of Colorado. An energy yield of 50 kt was chosen because it was considered to be large enough to assure chimney collapse. It was also considered to be of the same order of mangitude as potential commercial shots in oil shale. At the same time, 50 kt was small enough that full containment could be expected with a high degree of certainty at the planned depth of burial.

The technical plan for Project Bronco was developed with the following objectives:

1. To assess the technical and economic feasibility of in situ retorting as a method of recovering oil from oil shale fragmented and fractured by an underground nuclear explosion.

2. To confirm and refine the capability to predict physical properties and geometry of the cavity, chimney, and the fractured region produced by a nuclear explosion in oil shale.

3. To investigate the form and distribution of radioactivities left by the detonation, and to assess their behavior during in situ retorting.

The experiment was designed with full consideration for public health and safety. Extensive studies at the proposed site during the initial Site Confirmation phase were envisioned to assure that safety criteria were met.

Extensive geologic information on the proposed Piceance Basin site was available from the USBM-AEC Colorado Core Hole No. 1.[21,22] In addition, Core Hole No. 3 was completed at the proposed site.[23] On the basis of preliminary data from No. 3 and taking into account the regional geology, the oil shale at the nominated site is estimated to be about 2250 ft thick, with an additional 950 ft of overburden.

Site Confirmation

In order to confirm and further evaluate geologic and hydrologic conditions and to establish whether safety criteria were met, three preshot wells were planned. Data to be obtained from the wells were: overburden thickness; oil shale thickness, grade, and uniformity; fracture occurrence and orientation; presence of other minerals; and the existence and characteristics of aquifers. Location of the wells in relation to the proposed explosive emplacement well are given in Fig. 9.

The first exploratory well was planned approximately 400 ft from the tentative shot location. Core was to be taken from the top of the oil shale to total depth, and a complete suite of logs was to be run. An extensive hydrologic testing program was planned.

The second well was planned as a geologic confirmation well and to conduct hydrologic tests, both transmissibility and capacity, in conjunction with the first. The wells were to be located several hundred feet apart on opposite sides of the proposed nuclear explosive emplacement hole.

A third well was planned as a whipstock to pass through the region above where the chimney was expected. Its principal purpose was fracture definition.

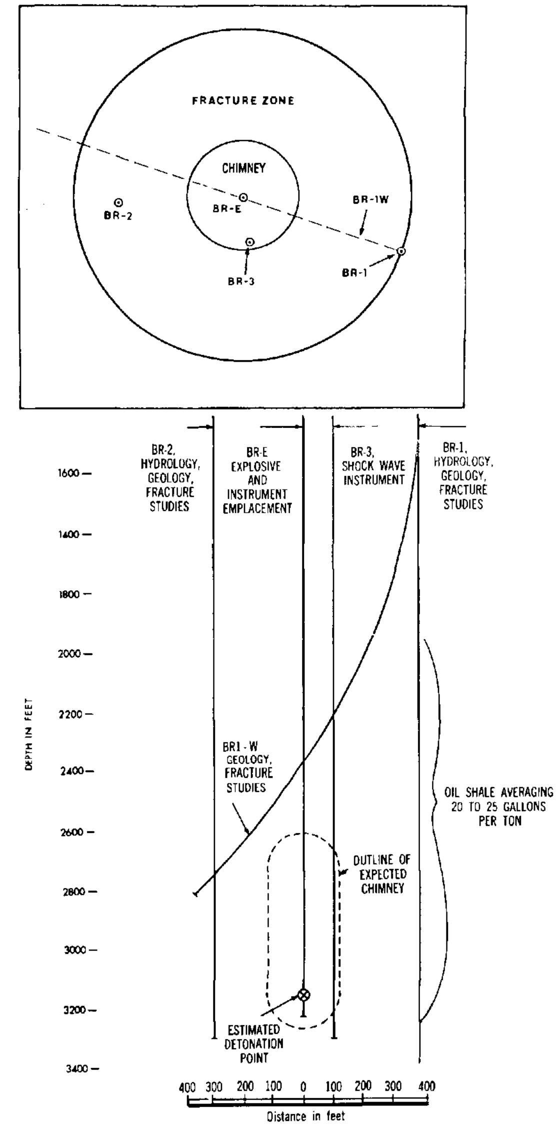

Fig. 9. Preshot well plan.

If any major fracture was encountered in the well, it would be thoroughly tested to determine its extent and capacity.

Should such a fracture exist in the immediate vicinity of the detonation, it could provide a path for water in overlying aquifers to migrate into the chimney. A copious flow of water into the nuclear chimney would complicate the subsequent retorting experiment. In addition, an extensive fracture system communicating to an overlying aquifer or to the ground surface would involve additional safety considerations.

Construction, Detonation, and Evaluation

When preliminary studies had assured that an acceptable site had been found, construction of roads, cableways, trailer pads, etc., were to start. In addition, an instrument well and the explosive emplacement well were to be drilled. Relative locations of these wells are also shown in Fig. 9.

An instrument well to provide dynamic explosive effects information was planned at a distance of 100 ft from the explosive emplacement hole. Instruments for measuring shock-wave phenomena associated with the explosion were to be placed at various levels in the well.

The emplacement well for the nuclear explosive was to be drilled to accept the explosive canister. It was proposed to emplace the explosive at approximately 3000 ft, near the bottom of the oil shale sequence. The well was to be stemmed to prevent the release of radioactivity. The scaled depth of burial for the explosion was about twice that of most completely contained explosions at the Nevada Test Site.

The nuclear chimney would be about 230 ft across and 520 ft high (measured up from the shot point).[5] Fractures would extend as far as 460 ft laterally byond the chimney edge. Such a chimney would contain about 1.2 million tons of fragmented oil shale, and the surrounding fractured region would contain considerably more. The oil content of the chimney alone, assuming 24 gal/ton average, would be about 660,000 barrels.

As soon as possible after detonation, a reentry well was to enter the top of the chimney near the emplacement hole, as shown in Fig. 10. The hole was to be cased through water-bearing zones and drilled dry below that, with core taken to aid in fracture studies. Pressures, temperatures, and radioactivities were to be monitored during drilling. Gas samples from the chimney would be analyzed for chemical composition and radioactivity. The chimney volume and effective fracture permeability were to be studied by gas injection and pressure fall-off techniques. Downhole photographs of the top of the chimney rubble would help define rubble size distribution.

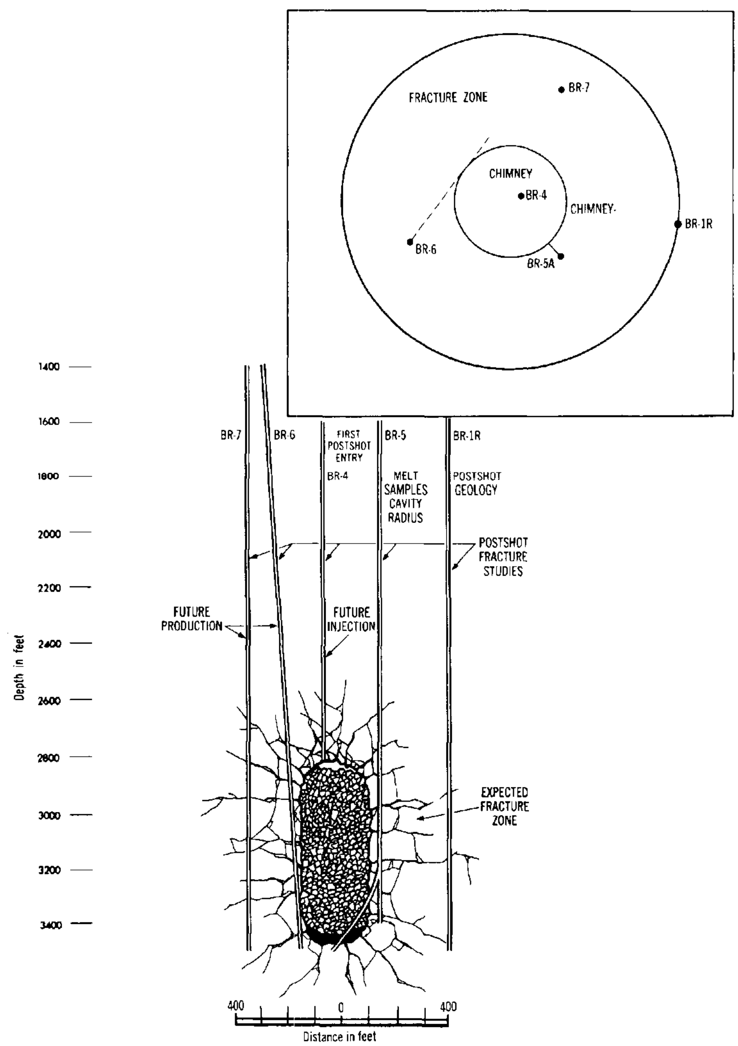

Fig. 10. Postshot environment evaluation plan.

A second reentry well, parallel to the sidewall of the chimney, was planned. Its major purposes were to study the fractures and the chimney boundary from a whipstock oriented to penetrate the bottom part of the chimney.

Three additional holes were to be drilled to further establish the nature and extent of fracturing outside the chimney. These holes also were to be modified later for use during the subsequent treatment phases. The wells would be cased through the upper aquifer and cored in the fractured region.

Isolation of water-bearing zones in all wells was planned to insure that the holes would not serve as paths for water entry to the chimney from the aquifer above and to prevent intermingling of different water zones.

In Situ Treatment

Most of the details for the retorting portion of the experiment are largely dependent upon the characteristics of the explosion environment defined by the postshot evaluation, and also upon results from retorting research currently in progress.

A retorting method that utilized the heat of combustion of retorted oil shale was planned as the basis for the recovery experiment. However, should research and development with preheated inert and reacting gases indicate greater commercial promise, one of these other methods could be selected for the experiment. In such a case there would be no change in the level of technical interest in such fundamental aspects as the amount of recoverable oil, the distribution of radioactivity in the oil, and the importance of variables such as injection rate, temperature, and pressure.

The chimney treatment plan, illustrated in Fig. 11, included three holes to the top of the nuclear chimney for the injection of a mixture of air and recycle gas. Each of these holes would serve, in addition, for the emplacement of pipe extending as far as possible into the chimney rubble for the purpose of installing instruments to monitor retorting process variables. A compressor system would be necessary to force gases into the chimney via the injection holes.

Three wells were to be used for production from the bottom part of the chimney. Tubing with downhole pumps in each of the wells would bring up liquid oil, with return gas and oil mist returning in the annuli.

Separation equipment at the surface would be needed to remove oil and water from the gas stream. A portion of the gas was to be returned to the chimney; the remainder was to be cleaned, if necessary, and flared. The production well fluids were to be monitored continuously for radioactivity and for composition. Because of the possibility of some contaminated water and oil, above-ground storage for water and oil was planned, as was temporary storage for disposable oil.

Upon completion of the recovery experiments in the chimney, the well adjacent to the chimney was to be reentered, and a new well beside the chimney drilled with whipstock or slant holes toward the chimney. The holes were to be cored to give material balance data on the chimney retort treatment.

The design of the fracture zone treatment outside the chimney is also highly dependent upon the results of the postshot evaluation. The extent, density, and permeability in the fractures would dictate the specific details and scope of the recovery treatment plan. Here again, research currently in progress would be utilized in the design. The extent of open fractures, the portion of oil recovered, and the occurrence of radioactivity are factors which should be investigated in such an experiment.

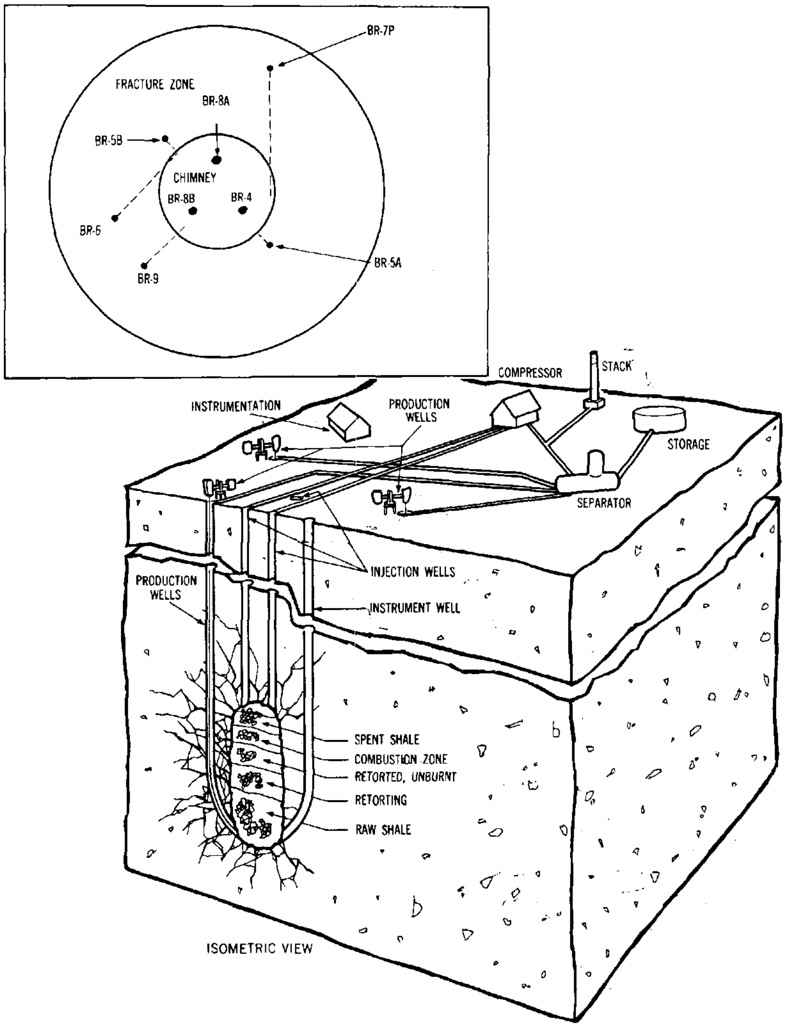

Fig. 11. Experimental chimney treatment concept.

As in the chimney treatment, in situ combustion was planned for the fracture treatment. The plan envisioned use of a 45° segment of the fracture zone with air or gas injection into the chimney. Air, recycle gas rates, oil shale grade, and explosion effects would be primary considerations in the specific experiment design. Figure 12 is a schematic concept of the fracture zone treatment wells.

SUMMARY

Nuclear explosions may be useful for introducing fracture permeability into deep oil shale deposits to prepare them for in situ retorting. The development of a commercial nuclear oil shale technology will involve the solution of several technical problems. A capability to predict explosion effects in oil shale will be needed, as will suitable retorting techniques and methods of controlling pollution. The Bronco design illustrates the key part nuclear explosion experiments will play in the development of this Plowshare application.

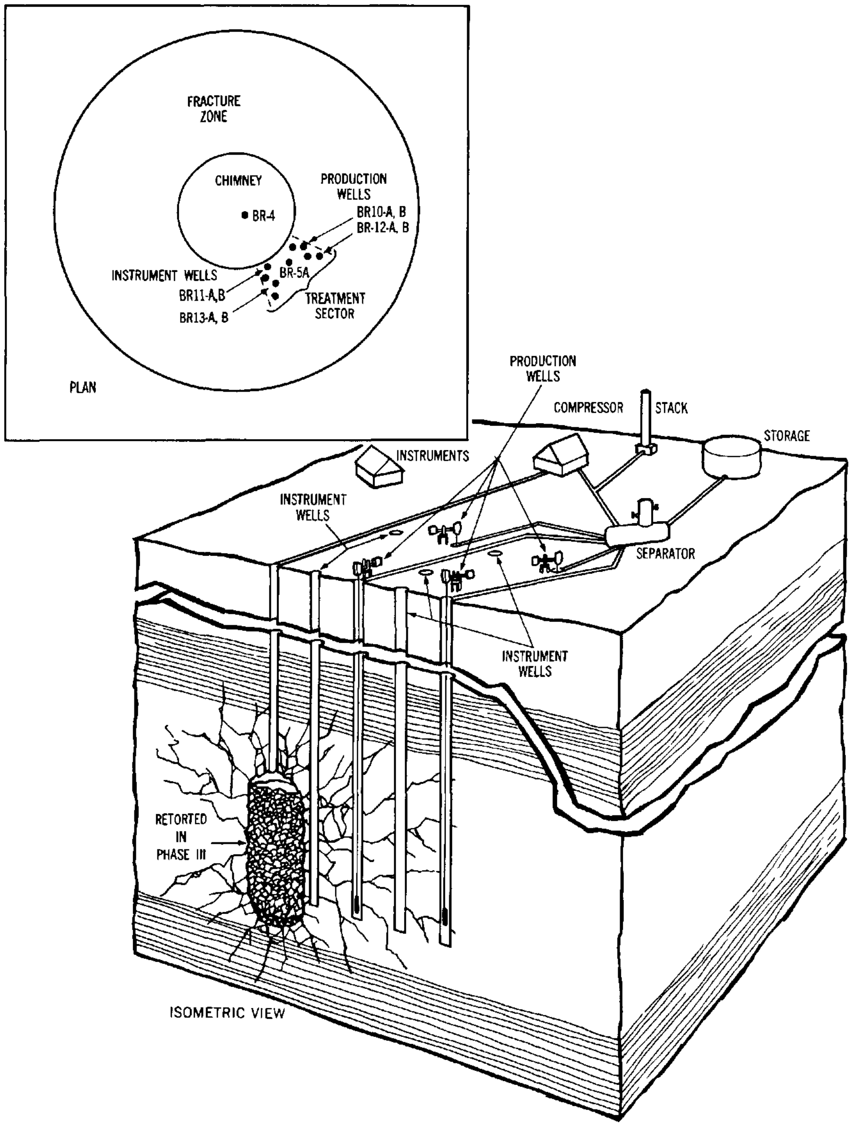

Fig. 12. Experimental fracture treatment concept.

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