Fracturing Thick Hydrocarbon Reservoirs with Nuclear Explosives

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INTRODUCTION

Energy from fuels is vital to our comfort and to the economy of our country. Approximately three-fourths of our energy demand is now suppiled by petroleum and natural gas. In addition, many other materials that we use commercially and domestically are made from petroleum and natural gas. Each of us knows that some energy must be expended to produce hydrocarbons, which in turn are used as a source of energy. The energy required to move the gas into natural-gas reservoir wells and to the surface fortunately is present in the reservoir because the gas is under pressure. In petroleum reservoirs the requisite energy is present in the form of pressure from a gas cap, dissolved gas, or a water drive. Gravity sometimes is an appreciable aid. This energy, however, never is adequate to produce all of the oil and, when the reservoir energy is depleted to the point that oil no longer will flow at an economical rate, extraneous energy often is added to the reservoir by injecting fluids under pressure, such as gas, water, miscible fluids, steam, or air to maintain combustion in thermal processes.

A further requirement for hydrocarbon production is that the substance produced either must be a mobile fluid or converted to a fluid by some suitable in situ process or it must be mined. Fortunately, natural gas has a very low viscosity and high mobility. Many crude oils have viscosities so low that there is no trouble in producing them. However, some crude oils are too viscous to flow at reservoir temperatures. The same is true of what we call bituminous sands, such as the Athabasca sands in Canada. Also, in our vast deposits of oil shale, the hydrocarbons are a solid kerogen, interspersed with the marlstone that makes up the rock matrix. So, if we reduce the viscosity of heavy oils and bitumens by applying heat or if we convert kerogen to shale oil by in situ retorting, energy again is required.

A third necessity for producing hydrocarbons is that the reservoir rock must have permeability adequate to permit the flow of fluids through the formation. This is no problem in many reservoirs. However, in other reservoirs the permeability is entirely too low to permit free fluid flow. Increasing permeability by breaking up the reservoir rock in place also requires energy. Conventionally this is done by gun or jet perforating, acidizing, shooting with chemical explosives, or hydraulic fracturing. However, these techniques have not proved to be economically practicable in some very thick reservoirs and it is yet to be demonstrated that they will fracture oil-shale deposits enough to permit in situ retorting.

We may conclude, then, that the petroleum industry needs a compact, efficient source of energy that may provide a driving force in the reservoir, reduce the viscosity of heavy oils and bitumens by heat, and fracture thick formations more effectively than present techniques.

Following the first nuclear explosion that was contained underground at the Atomic Energy Commission's Nevada Test Site, on September 19, 1957, several forward looking oil men and researchers thought that this could be the needed source of energy. This nuclear test, with the code name Rainier, utilized a 1.7-kiloton (kton) explosion in a volcanic tuff formation at a subsurface depth of 899 ft and no detectable radioactivity was vented to the surface. (A kiloton is equivalent to the energy of 1,000 tons of T.N.T.)

Although initial enthusiasm for the prospect of using nuclear explosives in hydrocarbon deposits was high, subsequent consideration revealed numerous problems for which answers were not available. This paper discusses some of those problems, current thinking concerning them, and the present status of nuclear-explosive stimulation as a result of some seven years of study by scientists and engineers of the Bureau of Mines (USBM) [1,2,3,4,5] the Atomic Energy Commission (AEC), the University of California

Lawrence Radiation Laboratory at Livermore (LRL), and several oil and natural-gas producing companies. [6,7]

CHARACTERISTICS OF NUCLEAR EXPLOSIVES

Among the features that distinguish nuclear explosives from chemical high explosives are the high energy-size ratio of the nuclear explosive and the ionizing radiation that is produced as a result of its detonation. There also are differences in the heat-blast ratio and the speed of sequence of events in nuclear and chemical explosions; however, these are not as important to hydrocarbon stimulation as the volume occupied by the explosive and the resultant radioactivity from the nuclear device.

Size is a most important consideration. The dimensions and construction of nuclear devices in general are classified, but according to information recently released to the public, a device with a yield up to 10 kton can be fabricated with an outside diameter of 12 in. An example shows the tremendous difference in volume of nuclear and chemical explosives. One can readily recognize the difficulty and cost of excavating a chamber with a volume of 50,000 cu ft at a subsurface depth of 1,000 ft, as schematically represented in Fig. 1, and of emplacing 1 kton of chemical explosive in the chamber. Many applications for large-yield explosive treatments in stimulating hydrocarbon production would be at depths greater than 4,000 ft. This amount of overburden would permit using devices with considerably greater yields than the 1 kton used as an example. It would not be feasible, for instance, to emplace 10 kton of chemical explosive at a subsurface depth of 4,000 ft. By contrast, a 10-kton nuclear device may be emplaced, checked, armed, and fired on a cable or drill pipe through a conventional hole cased with 16-in. pipe.

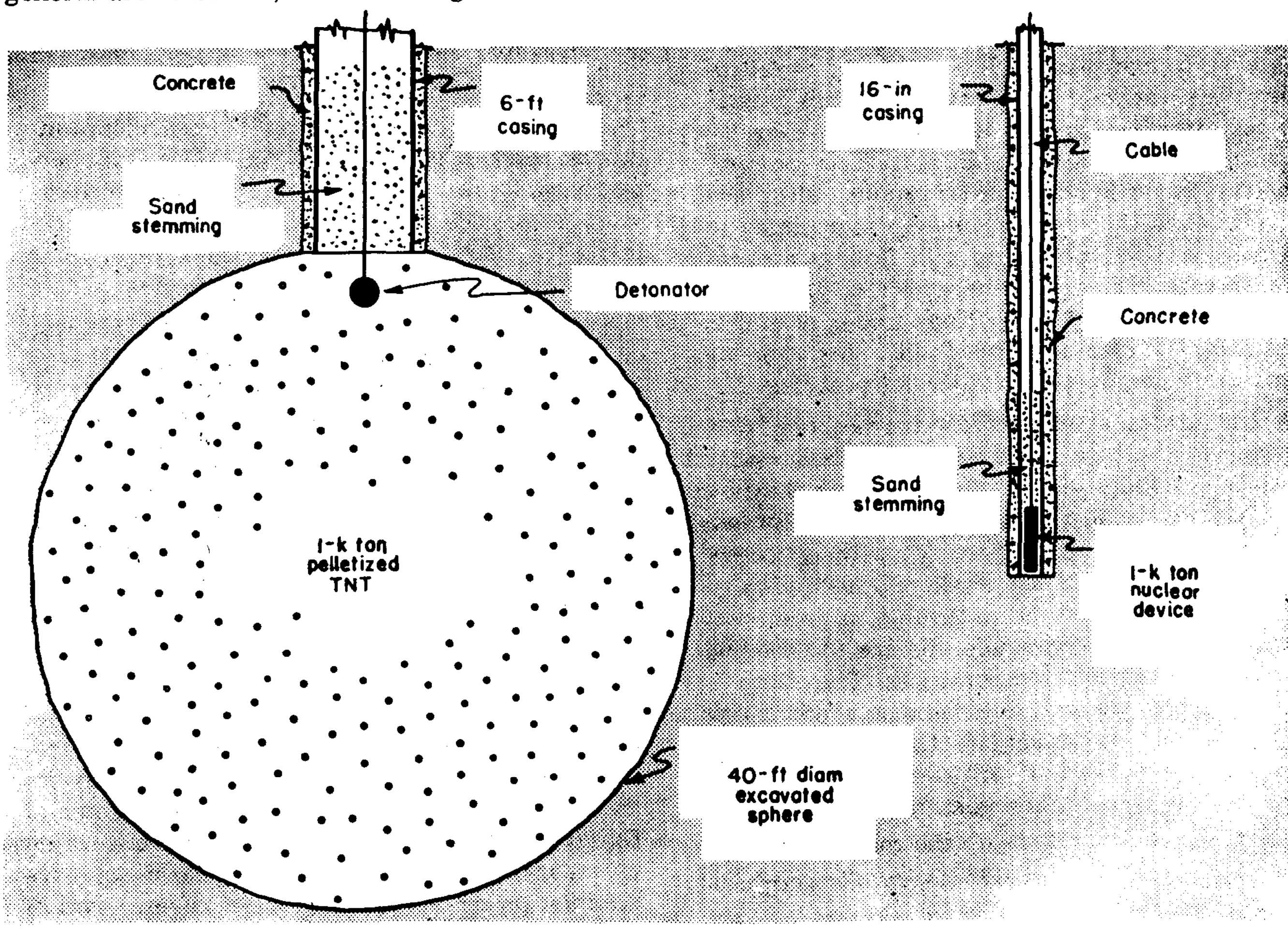

FIGURE 1.- Comparative Emplacement Techniques for Nuclear and Chemical Explosives.

Radioactivity caused by fission products and substances activated by the neutrons produced from a nuclear detonation is a problem that must be considered. Because of the Limited Test Ban Treaty, no detectable radioactive substances may be released that may be airborne outside the borders of the United States. Also, regulations of the Atomic Energy Commission place restrictive limits on the maximum amounts of radioactive substances that can be present in any products that are marketed to the general public. Comprehensive studies, however, have revealed that the specter of radioactivity is not nearly so formidable as it originally appeared to be. In fact, it is almost certain that nuclear explosives can be used to stimulate hydrocarbon production without venting radioactive material or contaminating subsurface waters, if adequate knowledge of the subsurface geology and groundwater hydrology of the area are available before nuclear explosives are used. Research is in progress on the contamination of hydrocarbon-deposit liquids and solids by contained nuclear detonations. At least for natural-gas stimulation, and very likely for stimulation of production from oil reservoirs, tar sands, and oil shale, it now appears that nuclear explosives can be used and the produced fluids marketed within existing radiation regulations. If necessary, radioactive contamination can be reduced through a combination of dilution of the fluids, removal of radioactive contaminants, fusing of fission products into an essentially insoluble glassy substance at the time of detonation, absorption of neutrons by surrounding the devices with substances having a high absorbing capacity for neutrons, the development of "clean" explosives (those having a low fission-product yield), and allowing the relatively short-lived radioactive products to decay before the fluids are marketed.

In a contained detonation, no radioactive material is vented to the surface. What happens is

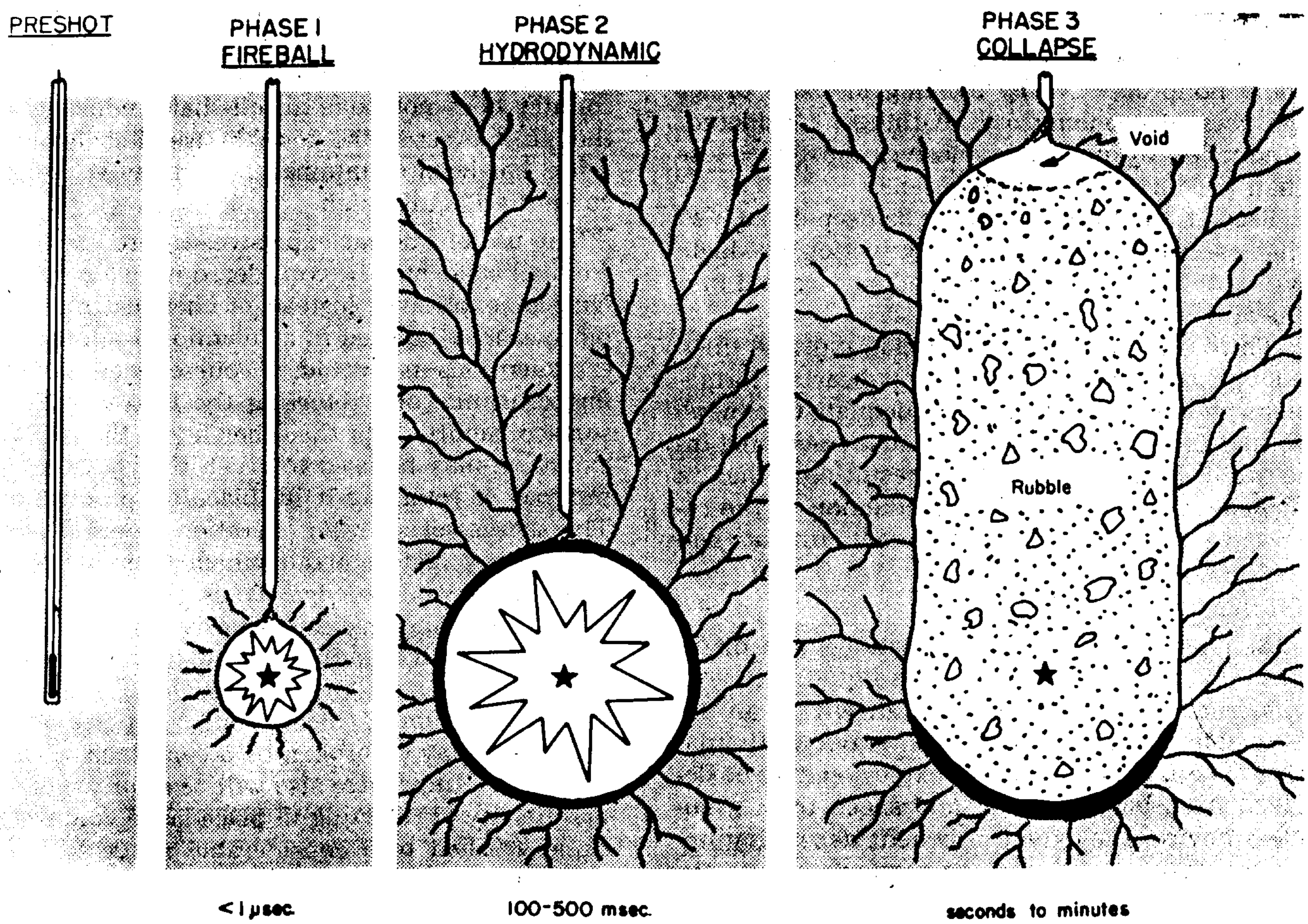

FIGURE 2.- Predicted Sequential Phases From Detonation of Nuclear Explosive to Minutes Afterward.

illustrated in the sequential, schematic drawings in Fig. 2. In a fraction of a microsecond the device materials are vaporized and a rapidly growing fireball is formed. The heat and shock rapidly move outward, vaporizing, melting, and crushing the surrounding rock and forming a cavity. Within seconds or minutes after the detonation, the cavity cools and the roof usually collapses, leaving a chimney of rubble, roughly cylindrical in shape and with a height usually four to five times the radius of the cavity. Essentially all of the radioactive fission and activation products are fused in a glassy substance and buried at the bottom of the cavity under rubble. A huge cylinder of broken rock results. Radiating outward from this cylinder are fractures in the surrounding rock.

APPLICABILITY OF NUCLEAR EXPLOSIVES TO TYPE OF HYDROCARBON DEPOSITS

In determining the applicability of nuclear explosives for fracturing hydrocarbon reservoirs, three primary criteria must be considered. First, the hydrocarbon resource either must be essentially nonproductive by existing methods under the present economy or, all things considered, production by nuclear explosives must cost less than production by other means.

Second, the formation must be deep enough so that radioactive fission and activation products will not be vented to the ground surface and into the atmosphere.

Third, the productive formation must be thick enough or separated from water-bearing formations by impermeable beds of adequate thickness, so that the explosion will not cause fracturing into water-bearing formations, resulting either in drowning out hydrocarbon production or the release to aquifers of radioactive contaminants and hydrocarbons.

Oil Sands

In most oil-productive formations, the oil in place may truly be considered a liquid, although oils from different reservoirs fall within an appreciable range of viscosity and gravity. Stimulative benefits from a nuclear explosion may be derived from both the heat and shock from a nuclear device; the extent of benefit depending upon the characteristics of the particular reservoir.

Tar Sands

Bituminous and tar sands have an advantage over oil shale as a potential medium in that the bitumen contained therein is a liquid, although a very viscous one, and the sands themselves do have permeability. Thus, the heat from the explosion might be expected to have a limited beneficial effect in reducing the viscosity of the bitumen either through cracking, simple heating, or both. Inasmuch as bituminous sands in general, and the Athabasca tar sands in particular, are relatively unconsolidated and friable, it is probable that the force of the explosive would not be as effective in stimulating production through fracturing as would be the case in harder and more consolidated rocks of oil and gas reservoirs.

Also, although there are appreciable deposits of tar sands in the United States, many of the known deposits are too shallow and of too limited area to be favorable media for nuclear stimulation. Until more knowledge is available of deeper, more extensive tar sands, it does not appear that there is a potential within the United States of using nuclear explosives for bitumen production.

Oil Shale

Considerable technology has been evolved on the mining, crushing, and retorting of oil shale, the refining of shale oil, and the utilization of shale-oil products. As of today, however, this country does not have an oil-shale industry, although interest in the possible use of shale oil as a fuel has been maintained over many years and currently is quite high.

The use of nuclear explosives in producing oil from oil shale may be considered in two respects. Nuclear explosives instead of chemical high explosives may be used in conventional mining operations. This use would, of course, entail removing, crushing, and retorting the broken rock in surface facilities. On the other hand, the nuclear explosive may be used to crush the rock for the purpose of retorting it in place to produce oil. The success of such an operation would depend upon many factors about which there is inadequate present knowledge. To assess the feasibility of combining nuclear-explosive crushing and fracturing with in situ retorting, it will be necessary to know much more about the size range and distribution of blocks and particles of oil shale that may be broken by a contained nuclear explosion. Knowledge also will be required of the practicality of retorting in place large volumes of shale crushed to a considerable range of block and particle sizes.

Some research has been performed by the petroleum industry on in situ retorting of oil shale. However, the literature is essentially devoid of the results of these experiments. Research is being conducted by the Bureau of Mines on methods of fracturing oil shale in situ, including the use of nuclear explosives, and on retorting methods that may be used in fractured oil-shale deposits. The results to date are not definite enough to show that a combination of nuclear-explosive fracturing and in situ retorting will work. Neither do they rule out the possibility of doing so. Because of this, it is probable that an experiment with a nuclear device in oil shale is somewhat farther from materializing than one in a natural gas-reservoir. The tremendous resource represented by oil shale, however, is a great incentive for continuing to study the feasibility of using nuclear explosives for oil-shale fracturing. This especially is true because much of the oil shale making up this resource is in beds so thick and deeply buried by other types of rocks, that these deposits are not now commercially amenable to mining by existing methods.

In considering methods for in situ retorting of oil shale, following nuclear-explosive fracturing, it is concluded that the method of retorting to be used will depend largely upon the fragment size and distribution of the broken shale. Two methods that may prove applicable are horizontal-sweep and vertical-sweep retorting.

Horizontal-sweep retorting is illustrated in Fig. 3. In this method, after combustion is started, air would be injected into wells drilled

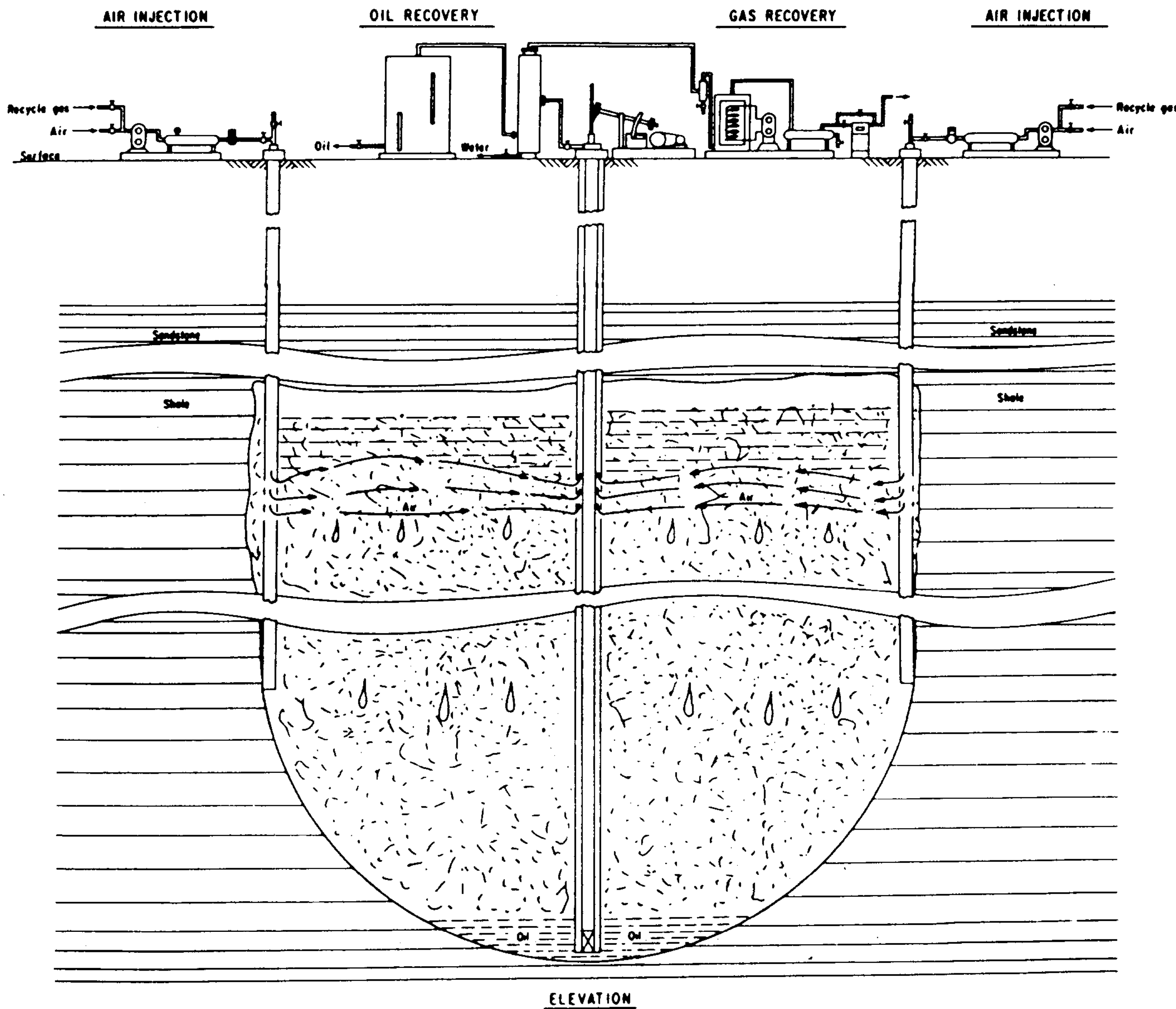

FIGURE 3.-Horizontal-Sweep Retorting.

through the edge and on the periphery of the mass of broken oil shale, sweeping the retorted shale oil to a central production well which would be equipped with a pump for pumping oil from the bottom of the cavity to the surface. The casings of the peripheral wells would be perforated at suitable vertical intervals to allow retorting of segments of the bed.

In the vertical-sweep retorting method, illustrated in Fig. 4, combustion air would be introduced through a central well at the top of the broken oil shale to retort the shale downward. Oil and gas would be produced from the peripheral wells drilled to the bottom of the mass of broken shale. Not enough data are available now to indicate which of these two methods of retorting would be the most efficient or whether some other system may be better.

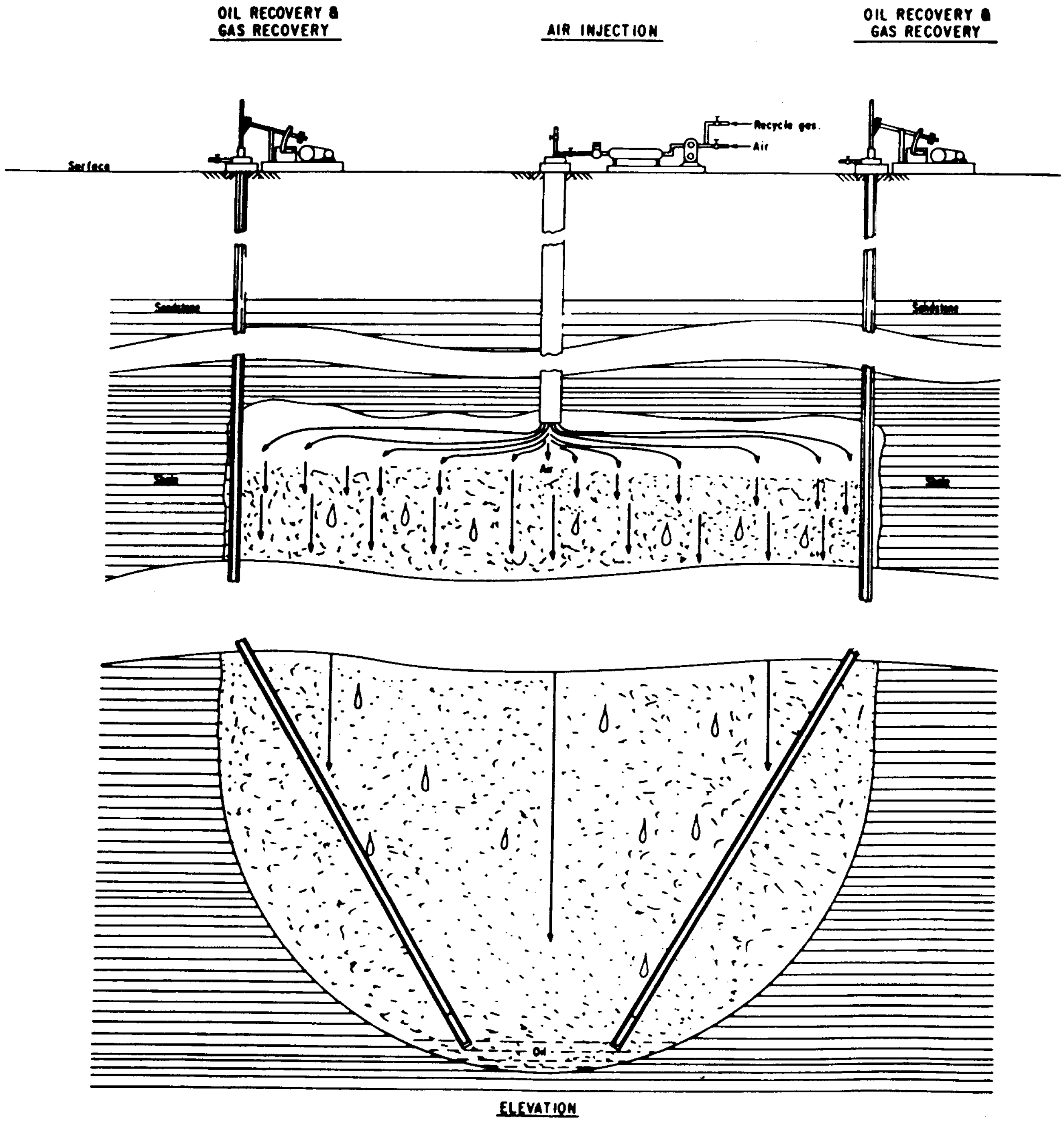

FIGURE 4.-Vertical-Sweep Retorting.

ting would be most efficient or whether some other system would be better.

Gas Sands

In some respects the possibility of using nuclear explosives to increase the production of natural gas originally was not considered favorably. First, natural gas usually is considerably more producible than oil under similar reservoir-rock conditions. Second, if an equivalent reservoir volume is affected by nuclear explosion, the potential economic returns should be somewhat greater from producing a liquid than from producing a gas because of the large differences in value of equivalent volumes.

There are, however, appreciable reserves of natural gas in the United States in formations which are relatively nonproductive because of inadequate permeability and which have depths and thicknesses adequate for consideration of stimulation by nuclear explosives. Also, the problem of radioactivity contamination of produced fluids would be minimized considerably if the fluid produced is a gas, rather than a liquid, because most of the radioactive fission products are solids or condense to solids which have a high solubility in liquids.

EXPERIMENT WITH NUCLEAR EXPLOSIVES IN A LOW-PRODUCTIVITY GAS RESERVOIR

Bureau of Mines engineers have been intensively studying the feasibility of using nuclear explosives for stimulating production from low-productivity, deep, thick, natural-gas reservoirs. The technical feasibility appears very good. Many questions remain unanswered and cannot be answered until an experiment is conducted. Among these are the radial extent of fractures outside the column of broken rock, the resultant drainage area thereby created, the consequent increase in deliverability, and its duration. Another problem that cannot be answered without an experiment and that is vital to both technical and economic feasibility is the amount of contamination of gas within and without the chimney by radioactive substances. Because of these unknowns, the economics of nuclear stimulation also are not now determinable with any reasonable degree of accuracy. The feasibility study has progressed to the point that a proposal to the AEC to conduct an experiment very likely will be made soon by one or more natural-gas companies. In fact, an experiment has been tentatively designed.

The Bureau's study has revealed that there are significant deposits of natural gas, for example in New Mexico's San Juan Basin and in other Rocky Mountain basins, that will yield only low percentages of the gas in place when developed by using conventional well-completion and stimulation techniques.

How would we expect to conduct an experiment in a gas reservoir and what might the results be? Let us look at an example based on one field that is being considered for nuclear stimulation. Here we have a formation containing natural gas at the subsurface depth of 3,850 ft to the top of the formation and with a total thickness of 300 ft and a net pay thickness of 190 ft. The average permeability of the formation is 0.14 millidarcy (md), the average porosity is 11 per cent, and the gas saturation is about 41 per cent of the pore volume. The gas in place equals about 33 million cu ft (MMcf) per acre or about 5.28 billion cu ft (MMMcf) per 160-acre tract. An average well on 160-acre spacing, perforated and hydraulically fractured, would have an initial stabilized rate of production of 275,000 cu ft per day (Mcfd) and an average producing rate over 20 years of 73 Mcfd. Thus, over a 20-yr period, one well may be expected to produce 530 MMcf, or about 10 per cent of the gas in place.

To conduct a nuclear experiment, one or two test wells would be drilled and completed in the usual manner perhaps 100 to 200 ft from the emplacement-hole location (ground zero). Producing characteristics of those wells would be carefully measured.

Now a 10-kton fission device would be emplaced through a hole drilled at ground zero to a depth of 4200 ft and cased with 16-inch pipe. The hole would be stemmed with dry sand, and the explosive would be detonated. We would expect the formation of an initial cavity with a radius of about 65 ft. This should collapse within minutes to form a roughly cylindrical zone filled with broken rock about 130 ft in diameter and about 300 ft above the working (detonation) point. Fractures should extend radially outward from the working point a distance of 200 to 430 ft. Thus, we would have a "well" with an effective well bore radius up to 430 ft throughout an interval of nearly 300 ft. Most of the radioactive fission products would be fused into a glassy substance which would be buried near the bottom of the cylinder under the broken rock.

We may predict that the initial stabilized-deliverability rate of a well drilled into the cylinder (for it is expected that the emplacement hold would be lost) would be about 2.6 MMcfd if the maximum fracturing radius is obtained, or about a 10-fold increase over the deliverability of a conventionally completed well. The ultimate recovery, over a 20-yr period should approximate 3.7 MMMcf, equal to an increase of 3.2 MMMcf or an ultimate production of 71 per cent of the gas in place, instead of an estimated 10 per cent.

The advantages gained would be establishing commercial rather than marginal production, creation of a storage "cavern" with an effective volume of about 200 MMcf, which would permit high deliverability for short periods, and the utilization and, thereby, conservation of a now essentially unrecoverable resource. An added advantage would be that a better evaluation could be made of the extent of fractures caused by the contained nuclear explosion, permitting improved feasibility studies of peaceful nuclear-explosives applications in general.

As mentioned earlier, the economics of stimulation through the use of nuclear explosives are difficult to predict. An initial experiment naturally will be more costly than subsequent use for production, if the method should prove practicable, as many measurements would have to be made to obtain necessary data. Proected charges for nuclear explosives cited by the Atomic Energy Commission range from -350,000 (10-kton) to $600,000 (2 megations), with a straight-line exponential interpolated price range between the two values. The charges are projected on the assumption of production in quantity and legislation permitting AEC to sell explosives and services, and cover nuclear materials, fabrication, arming, and firing but not safety studies, site preparation, transportation, emplacement, or support. It is probable that an experiment such as the hypothetical one cited herein would cost between $1,000,000 and $3,000,000, exclusive of the charge for the nuclear explosive. While it is not expected that the initial experiment would prove commercially profitable in itself, it should, however, demonstrate the technical practicability of nuclear stimulation and yield data from which the economics can be determined. The high cost estimated for an initial experiment is by no means indicative of the cost that would be incident to commercial utility of nuclear explosives. Many of the experimental costs are expected to be obligated for site preparation, scientific experiments, support, and a comprehensive safety program. Such costs would be greatly minimized in routine commercial operations.

If nuclear explosives should prove to be economically, as well as technically practicable for stimulating gas production, there is a tremendous potential for commercial application. In the San Juan Basin alone, in 1,500 sq mi of marginally productive Pictured Cliffs sand and 2,000 sq mi of marginally productive Mesa Verde sand, we estimate that the gas in place equals 64 trillion cu ft. If nuclear stimulation works as it appears it might, as much as 45 trillion cu ft should be recoverable. Compared to our present proved reserves of 276 trillion cu ft , this indeed is a substantial quantity of natural gas. Even larger resources in other areas may be converted to recoverable reserves through nuclear stimulation.

CONCLUSIONS

The results of our studies to date indicate that: (1) Low-productivity natural-gas reservoirs offer the best immediate possibility for nuclear stimulation; (2) some petroleum reservoirs may be stimulated similarly; (3) nuclear fracturing of oil shale may permit in situ retorting; (4) conclusions concerning nuclear stimulation of production from deep tar-sand deposits in the United States cannot be drawn because of inadequate knowledge of their occurrence; (5) radioactive contamination of hydrocarbon fluids is a problem that can be solved by various means, and nuclear stimulation can be conducted safely and within existing regulations; and (6) actual experiments in the field are needed to help determine technical and economic feasibility.

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ACKNOWLEDGMENTS

Research of the Bureau of Mines on which this paper is based has, during the past few years, been conducted cooperatively with the San Francisco Operations Office of the Atomic Energy Commission.

Assistance in providing data used in this research by personnel of the University of California Lawrence Radiation Laboratory (Livermore), Oak Ridge National Laboratory, the Nevada Operations Office, El Paso Natural Gas Company, and Continental Oil Company is gratefully acknowledged. The author especially thanks Charles H. Atkinson and Don C. Ward of the Bartlesville Petroleum Research Center, and Harold W. Sohns and Harry C. Carpenter of the Laramie Petroleum Research Center, all of the Bureau of Mines, for providing data and assistance in preparing this paper.