PLOWSHARE

a program for the peaceful uses of nuclear explosives

The Soviet Union's decision to terminate the three-year moratorium on nuclear testing by conducting a new series of experimental explosions of nuclear weapons brought an abrupt halt last month to the test-ban talks in Geneva. On September 5, after the detection of the USSR's third nuclear explosion in the atmosphere, President Kennedy ordered the resumption by the United States of "nuclear tests in the laboratory and underground with no fall-out". The following is a discussion of some of the forms such testing may take in the months to come. The author is a physicist at the University of California's Lawrence Radiation Laboratory, Livermore, Calif.

By David B. Lombard

THE development of thermonuclear weapons in recent years has placed within the grasp of mankind a new, cheap, and almost inexhaustible source of energy. The principal ingredient in thermonuclear reactions is deuterium, a heavy isotope of hydrogen. Deuterium occurs naturally wherever hydrogen is found, since about 0.015 percent of all hydrogen is the heavy isotope, H^2. Although the percentage seems low, the total amount of deuterium is extraordinarily large, and a relatively inexpensive process for extracting the deuterium from natural hydrogen has been invented. The atmosphere and oceans of the earth contain enough thermonuclear fuel to last mankind for millions of years at a thousand times the present rate of energy consumption. But, since thermonuclear energy has so far been available only in explosive form, it has not yet been harnessed for nondestructive purposes. Several major research programs currently under way in the United States and other countries are aimed at developing methods of containing and controlling fusion reactions to permit adapting their power output to conventional power-distribution systems. Substantial progress has been made in this field, but it may be many years before a practical controlled-fusion machine will be a reality.

Meanwhile, many people have devoted their attention to the possibilities of utilizing explosive nuclear and thermonuclear energy for accomplishing industrial objectives. Since 1951, a Frenchman, Camille Rougeron, has advocated the use of thermonuclear explosives for peaceful purposes; in 1956, he published a book on the subject. Scientists in the United States engaged in nuclear weapons development were simultaneously considering possible nonmilitary applications for this new energy source. However, very little progress was made in developing these concepts until the Rainier event in September 1957. This was the first contained underground nuclear explosion, and it forcefully demonstrated that nuclear explosives can be set off in a safe and potentially useful manner.

Project Plowshare was initiated by the AEC to investigate and develop ideas for possible industrial application of nuclear explosives. The mission of Plowshare is to conduct theoretical and experimental research, both in the laboratory and in the field, aimed at providing the information and techniques necessary to ensure safe and efficient industrial use of nuclear explosives. Cooperation with industries and government agencies interested in this research is an important part of the program. Once an idea has been proven practicable, the necessary information will be made available through publications and discussions to all potential users. As industrial usage of these explosives is currently envisioned, the AEC would make devices available under a licensing arrangement to responsible companies for an appropriate fee, but would retain control of the nuclear devices, provide arming and firing services, and be responsible for public safety.

PRIOR to the time the weapons-test moratorium went into effect (October 31, 1958), the Lawrence Radiation Laboratory had exploded several nuclear devices underground at the AEC Nevada Test Site as part of the weapons-test program. Some of these explosions were completely contained. The nature and performance of the nuclear devices as weapons are not of direct interest to Plowshare, though principles of design are important in developing special Plowshare explosives. But the effects which they had on their rock environment is of great interest.

The Rainier event of September 19, 1957, has been the object of extensive postshot exploration. A reconstruction of the phenomenology of this event gives the following picture: Rainier, a 1.7-kiloton * nuclear explosion, was detonated in a mesa composed of a rock called volcanic tuff, about 900 ft below the mesa top and 790 ft from the nearest point on the sloping mesa face. The device was located at the end of a tunnel curved in a short spiral at the shot end so that it would be self-sealing (Fig. 1). The tunnel was plugged with sandbags for about 15 ft near the device. The original shot room was about 6 × 6 × 7 ft. About 0.1 second after the device was set off, there was a cavity about 125 ft in diameter, lined with about 4 inches of molten rock. Most of the radioactivity from the explosion was trapped in this 700 tons of slag. The lining had begun to drip and flow to the bottom of the cavity, and after a period of 30 to 180 seconds the puddle at the bottom was about 7 ft deep. During this time the cavity had cooled considerably and the steam pressure had dropped to a few atmospheres. Then the roof fell in. The top of the cavity collapsed into the puddle and, by a process of collapse of successive layers of rock, a "chimney" (or stope) was produced which extended upwards about 400 ft above the original shot point and contained some 200 000 tons of crushed and broken rock. Figure 2 illustrates this chain of events.

Postshot exploration has also determined that the tunnel was tightly sealed, having completely collapsed to a radius of 200 ft (Fig. 1), and was damaged out to about 400 ft. However, the ground shock was so attenuated by the time it reached an observation point 2.5 miles from the mesa that few observers felt it. Air blast was reduced to a muffled boom at this range. From the results of Rainier and subsequent confined explosions, it was concluded that safety considerations do not preclude the industrial use of underground nuclear explosions.

It was now evident that a number of suggestions for using nuclear explosives for industrial purposes were worthy of further serious study. In February 1957, the University of California Radiation Laboratory at Livermore sponsored a secret Symposium on the Industrial Uses of Nuclear Explosives, involving employees and consultants of three AEC laboratories. Two years later, a much larger public symposium was held at San Francisco, to which representatives of interested government agencies and private industry also were invited, both as observers and as contributors. Shortly thereafter, a formal Plowshare group was organized at LRL in Livermore. This report is concerned with some of the ideas which the group has been studying and some of the experiments which have been planned.

* One kiloton of nuclear explosive has an energy release approximately equal to that from 1000 tons of TNT.

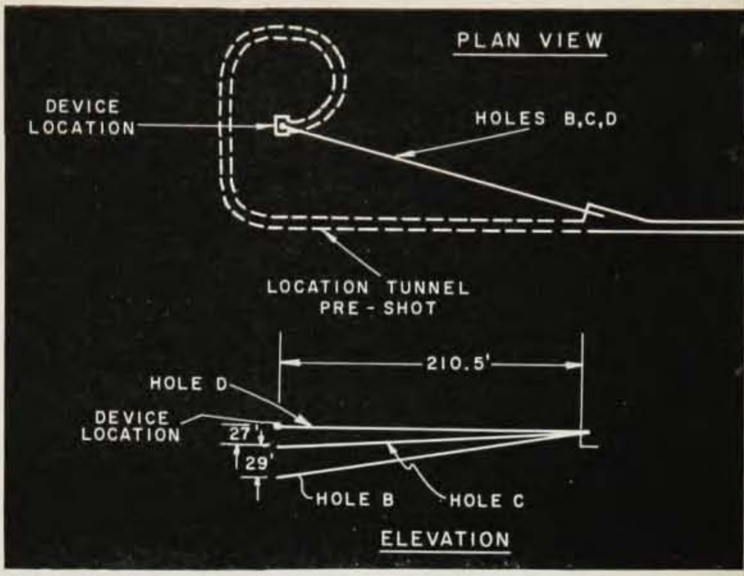


Fig. 1. Rainier: Tunnel layout and postshot, drilling.

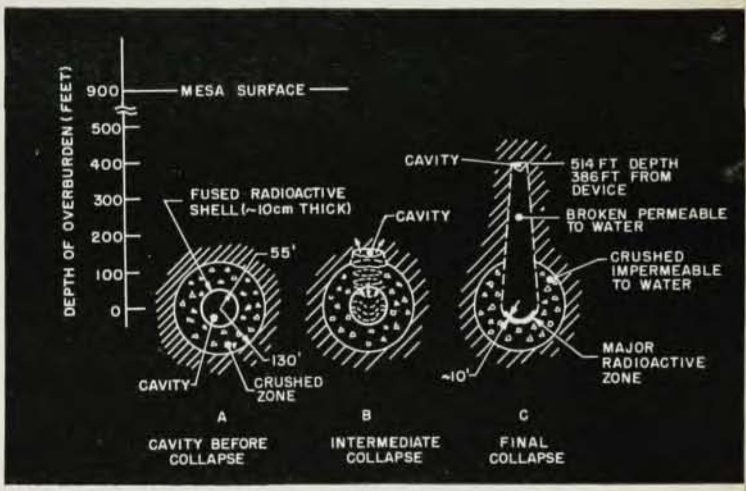


Fig. 2. Rainier: Phenomenology, three stages.

EARLY in 1960 the AEC announced that site preparation and construction had been authorized for the first Plowshare nuclear experiment, called Gnome, near Carlsbad, N. M., although presidential approval to fire the shot had still to be obtained. The plan calls for detonating a 5-kiloton device at the end of a long tunnel in a bedded salt formation some 1200 ft be-

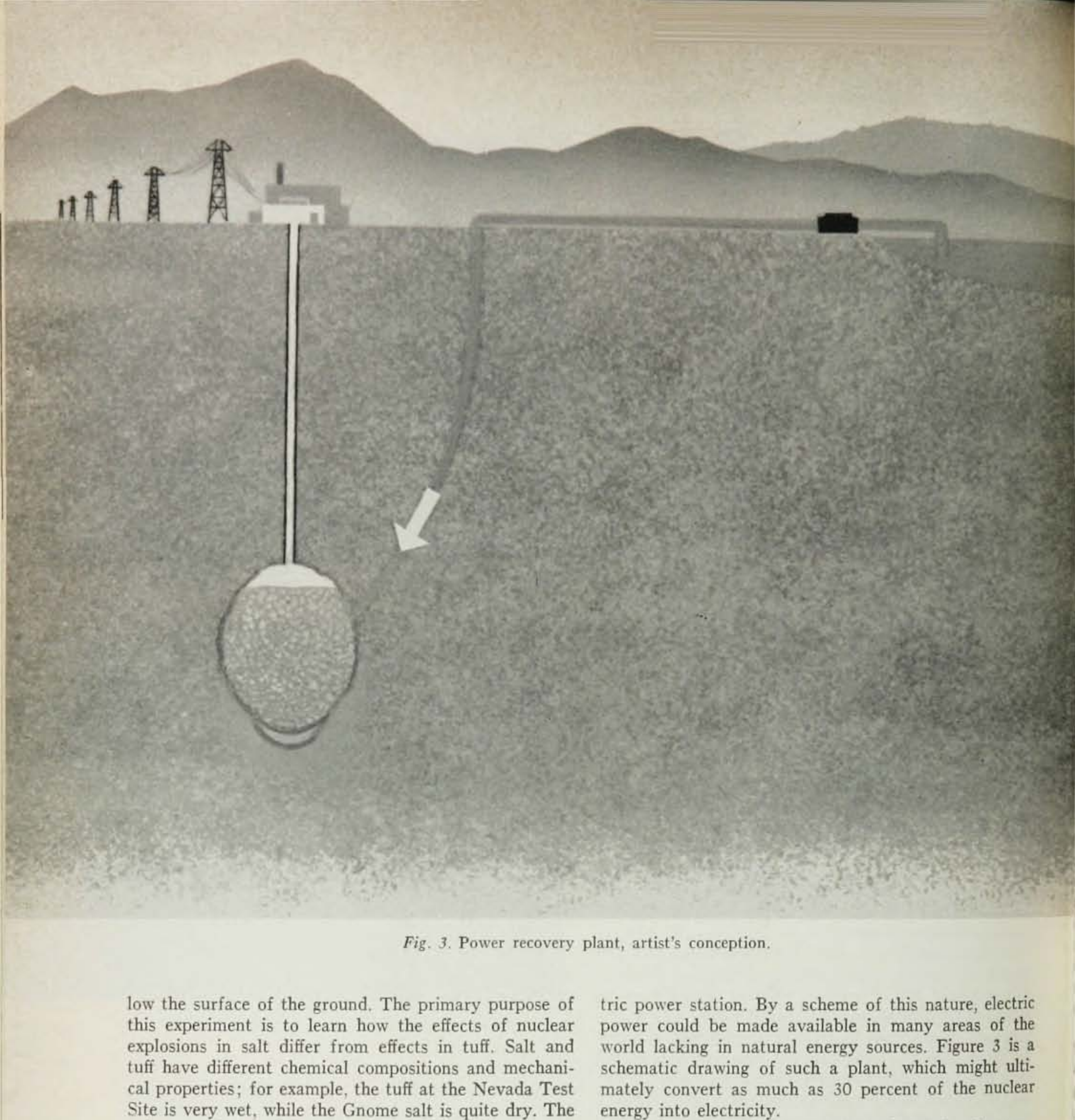


Fig. 3. Power recovery plant, artist's conception.

low the surface of the ground. The primary purpose of this experiment is to learn how the effects of nuclear explosions in salt differ from effects in tuff. Salt and tuff have different chemical compositions and mechanical properties; for example, the tuff at the Nevada Test Site is very wet, while the Gnome salt is quite dry. The existence of such differences in the two media suggests that one might expect differences in the amount of material broken by a nuclear explosion, the stability of the cavity, the postshot distribution of heat energy, and the extent of cracking.

Another purpose of Gnome is to investigate the problem of recovering heat energy from the vicinity of the explosion. About 50 percent of the energy liberated by the device is expected to be retained locally as heat; it is expected to melt some 6500 tons of salt and to raise significantly the temperature of a similar amount of salt. If the heat from this sort of explosion can be successfully recovered, it could be used to operate an electric power station. By a scheme of this nature, electric power could be made available in many areas of the world lacking in natural energy sources. Figure 3 is a schematic drawing of such a plant, which might ultimately convert as much as 30 percent of the nuclear energy into electricity.

A third purpose of Gnome is to determine the practicability of recovering the radioisotopes produced by the high neutron flux during the detonation. For this reason, the postshot distributions of the radioactive isotopes of more than twenty chemical elements will be studied. The manufacture of isotopes as a by-product of underground explosions could insure an economical supply of some species which are currently rare and expensive.

Additional experiments are planned in conjunction with Gnome: The copious neutron flux available at the moment of detonation will be utilized in experiments on high-resolution neutron spectroscopy, fission cross-sec-

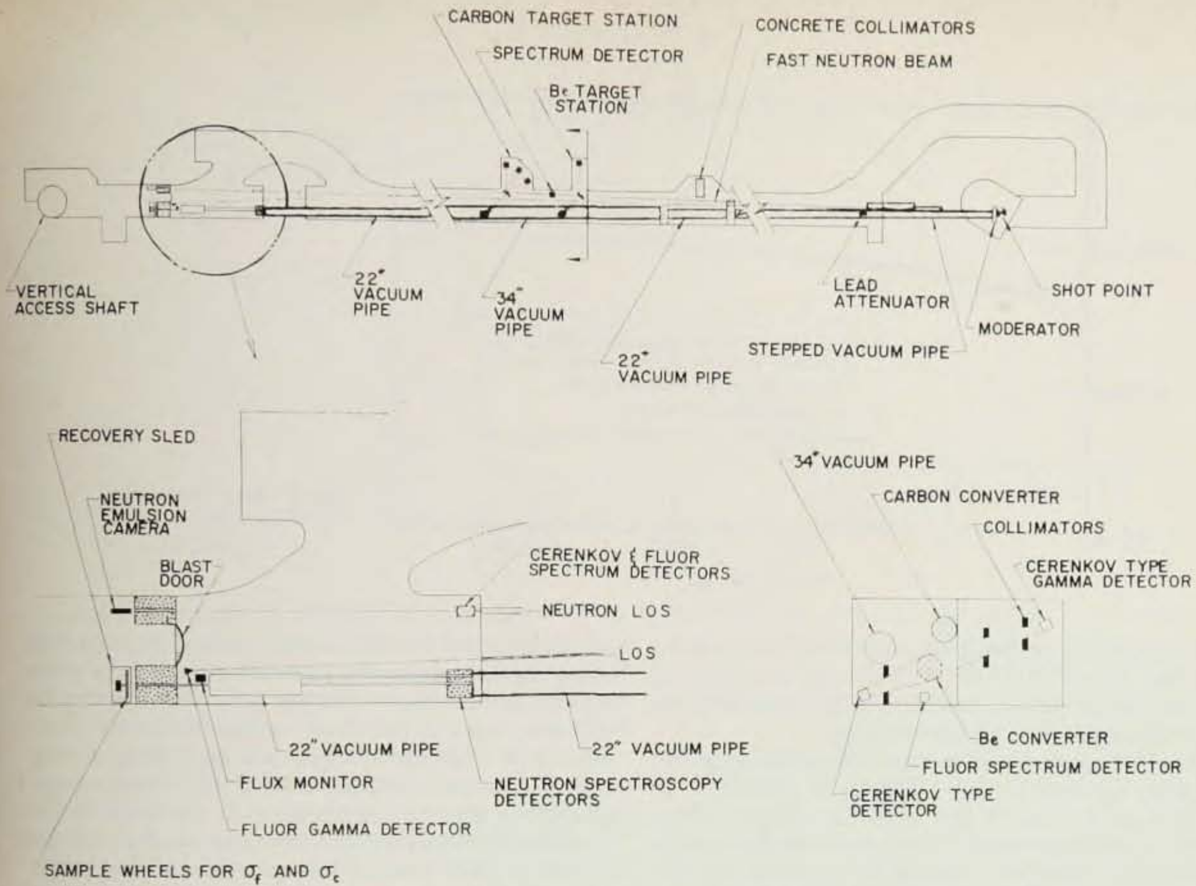


Fig. 4. Gnome tunnel and neutron experiments.

tion measurements, capture cross-section measurements, and an inelastic-scattering experiment (Fig. 4). Instruments developed at LRL especially for the purpose will measure strong-shock parameters in the salt near the explosion point. Furthermore, an extensive postshot program of digging and drilling into the shot site is under consideration at the Laboratory. Such a program would yield valuable additional information about subterranean nuclear explosions.

ONE industrial use of nuclear explosives which suggests itself immediately to many people is excavation. We believe that some very large excavation projects can be carried out with the aid of thermonuclear devices at a small fraction of the cost of conventional methods. The radioactivity associated with nuclear and thermonuclear explosions is, of course, a potential hazard. A one-kiloton nuclear explosion produces about as much radioactive fission products as one day's operation of a 55-megawatt nuclear reactor. However, our investigation of the technical problems of radioactivity control has yielded very encouraging information. First of all, only a small fraction of the total radioactivity escapes from the explosion of a nuclear charge buried at sufficient depth. Experiments to date suggest that nearly optimum cratering efficiency can be attained at depths of burial sufficient to contain over 95 percent of the gross radioactivity. Second, almost all of the radioactivity which does escape from nuclear detonations at these depths of burial adheres to fairly large particles which fall out locally and will not contribute to worldwide contamination. Results of our research in meteorology and experience in past weapons tests will permit us to predict fallout patterns with very good accuracy. Third, the use of explosives with high fusion-to-fission ratios can greatly reduce the amount of fission products produced for a given energy release. Such explosives may prove advantageous in many situations. Edward Teller, formerly Director of the Lawrence Radiation Laboratory at Livermore, in his statements to the Joint Committee on Atomic Energy, has indicated that great progress can be made in developing cleaner nuclear explosives in many sizes and for many jobs. He has said, "I can say, not with certainty but with quite a bit of hope, that we can make nuclear explosives so clean that the worry about radioactivity in its peaceful applications may disappear completely."

The large neutron flux generated by a buried nuclear explosion can be expected to induce a small amount of additional radioactivity in the medium immediately adjacent to the shot. This phenomenon can be effectively attenuated, if necessary, by blanketing the device with a neutron-absorbing material. From the technological viewpoint we are convinced that, while radioactivity

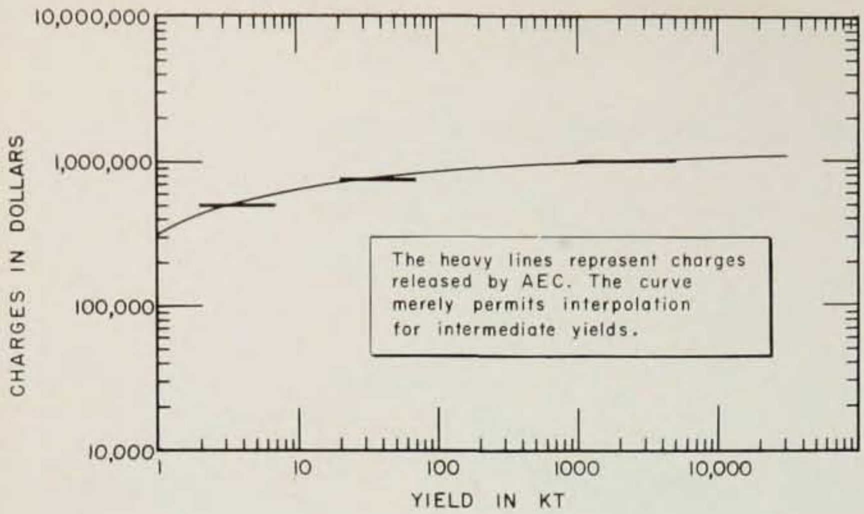


Fig. 5. Chart of nuclear explosive costs.

cannot at present be completely eliminated from nuclear cratering explosions, it can be controled to the extent that radioactive hazards need not be an obstacle to the industrial exploitation of this technique.

The great advantage of nuclear excavation over conventional methods is that material is shattered and driven from the hole in one operation because of the high energy concentration. By contrast, excavation with conventional techniques involves two separate and distinct processes: fracturing the rock with a chemical explosive, and using machines to remove the broken material from the hole. The latter is a very expensive operation. Approximate cost figures for nuclear explosives have been announced by the AEC (Fig. 5). They seem most attractive, on an available-energy basis, for the larger devices; evidently, conventional methods will be cheaper for small projects.

In order to become proficient at excavating in various earth materials with nuclear energy, we must learn about the mechanism of excavation at very large yields. Specific information which we will need includes the optimum depth of burial for various media, the proper spacing of large line charges, and the spatial distribution of excavated material. Part of our current research program is aimed at answering such questions. Several experimental studies in the laboratory and in the field have been undertaken to determine the physical properties of various types of rock under shock conditions, and to establish empirical scaling laws. These laws, employing the results of small cratering explosions, may be used to predict the results of large ones. The relationships thus far established by this research differ significantly from those previously thought to be correct, particularly in the energy range of nuclear explosives. The new scaling relations are illustrated in Figs. 6 and 7. In addition to single experimental explosions (ranging

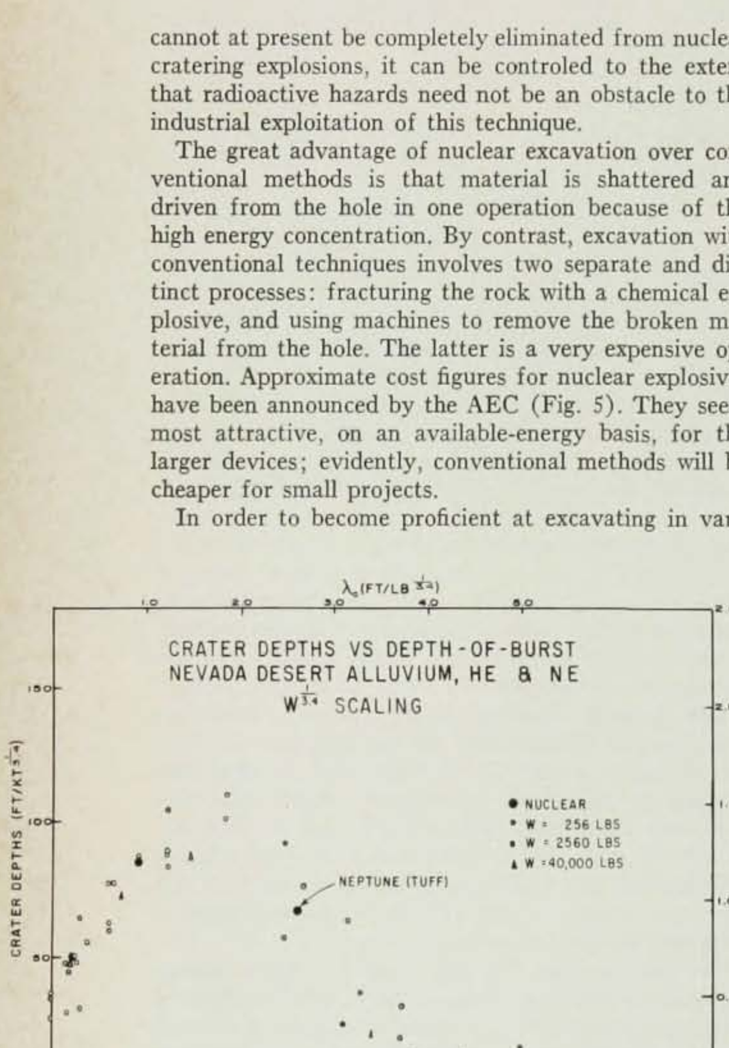


Fig. 6. Graph of crater depth scaling (revised 1–18–61).

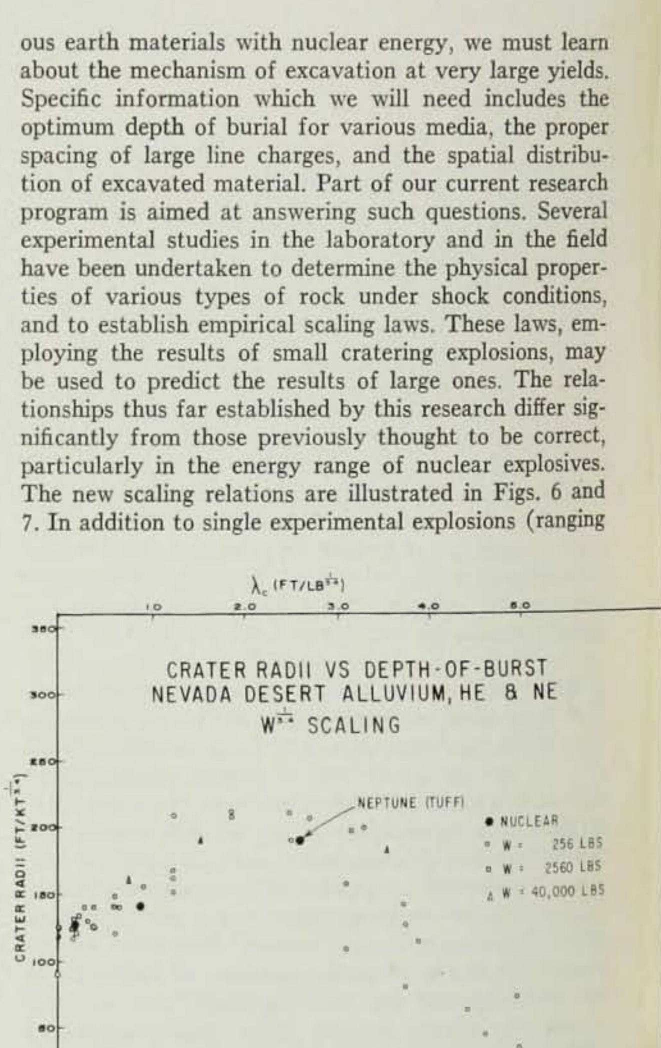


Fig. 7. Graph of crater radius scaling (revised 1–18–61).

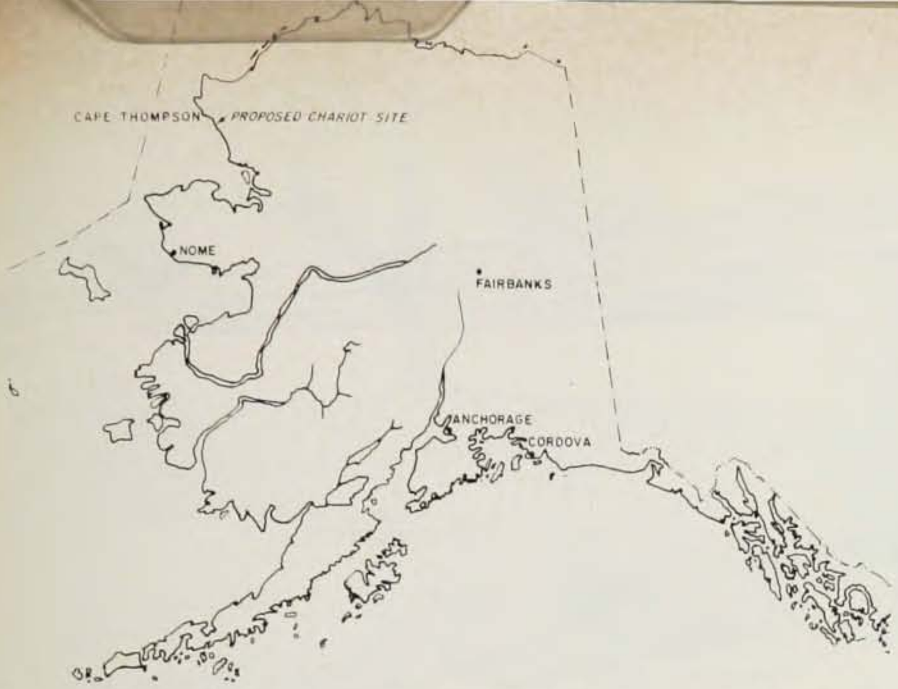


Fig. 8. Map of Alaska, showing Chariot site.

from a few pounds to 500 tons of high explosive) in several media, several multiple-charge experiments have been conducted, with the result that scaling laws for buried line and row charges have also been established for a fairly wide range of charge sizes in one medium and at small scale. Future cratering experiments, utilizing both chemical and nuclear explosives, will be aimed at extending the data to larger charges and different media. We also hope to determine more precisely the differences in cratering mechanisms between chemical and nuclear explosive charges.

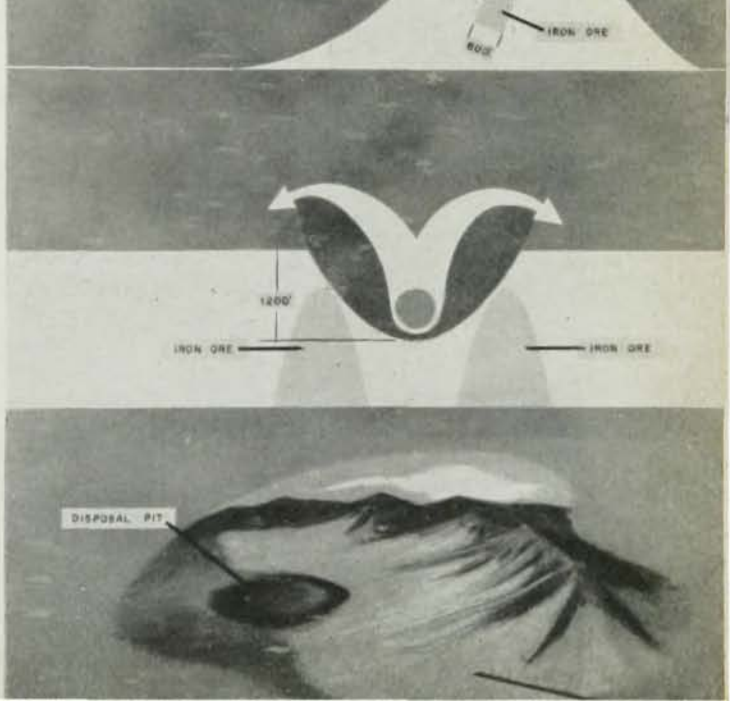
An important part of the cratering program is the Chariot experiment, which is to be conducted on a barren and remote stretch of Alaskan coast near Cape Thompson (Fig. 8). This experiment will take place within the next few years, if approval is granted by the President and the AEC. As Chariot is presently planned, five buried nuclear charges will be detonated simultaneously. The four 20-kiloton explosions in a linear array and one 200-kiloton explosion at the end of the string are designed to extend the validity of scaling laws for both row and point charges to very large explosions. The information gained from the Chariot experiment will enhance our technical ability to perform nuclear cratering operations that are economically useful.

The Chariot experiment will prove valuable from yet another viewpoint. The AEC has authorized the University of Alaska, in cooperation with other agencies, to conduct an exhaustive bioenvironmental study of the vicinity of the proposed experiment, both before and after the explosion. Although the fallout of radioactivity will not be large, the study should shed much light on the detailed behavior of radioactive isotopes and the potential radioactive hazards in the context of the local land and marine ecology.

In mining, nuclear explosives can be used to remove the overburden from deep-lying beds of ore not rich enough to be recovered by conventional techniques. Figure 9 is a schematic illustration of this possibility. However, the potential applications of nuclear explosives in mining are not limited solely to excavation.

Consider, for example, the chimney of broken rock which was formed above the Rainier detonation (Fig. 2). A raise from the main tunnel has been constructed at the edge of this zone of broken rock, and a drift extended into the broken zone. Four finger raises from the drift have recently been installed. We have found that large amounts of crushed rock entering the drift can be moved by dragline to the top of the raise, where it can fall into ore cars on the main haulage level. This

Fig. 9. Strip mining, schematic.



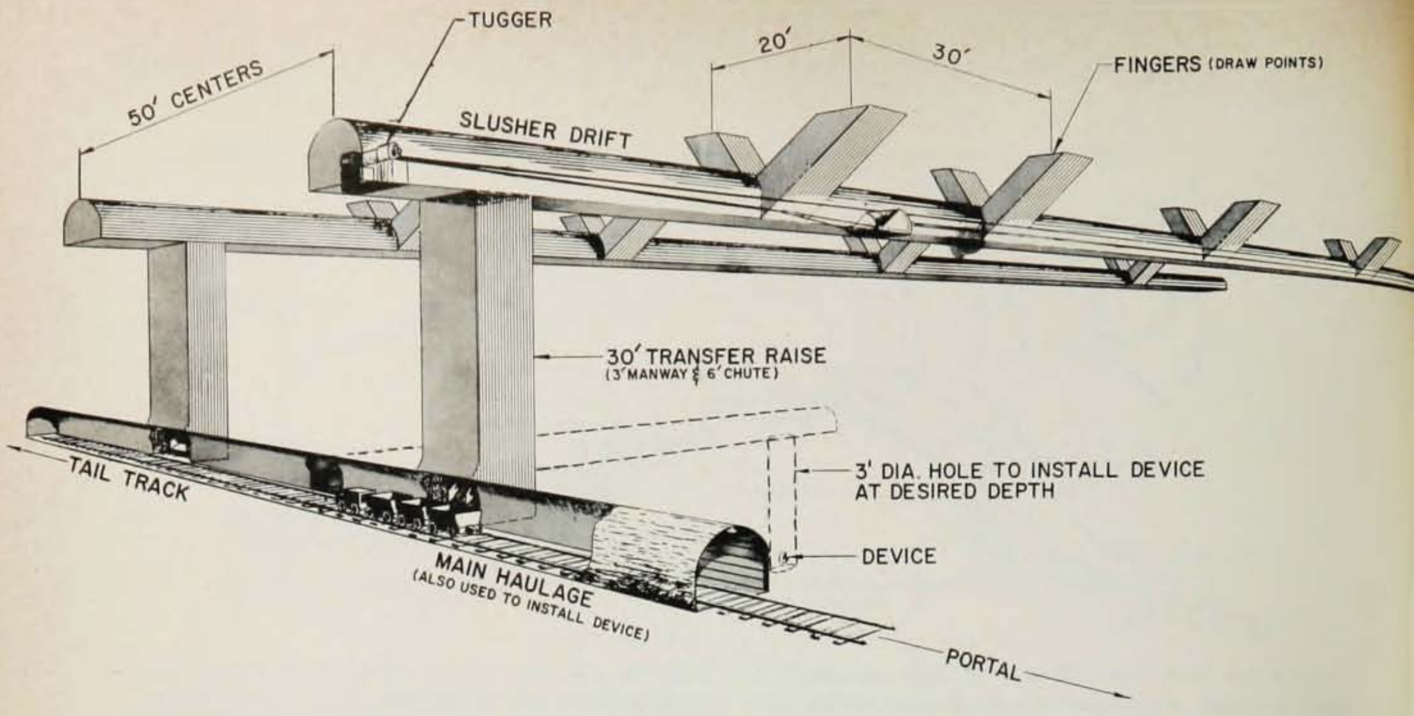
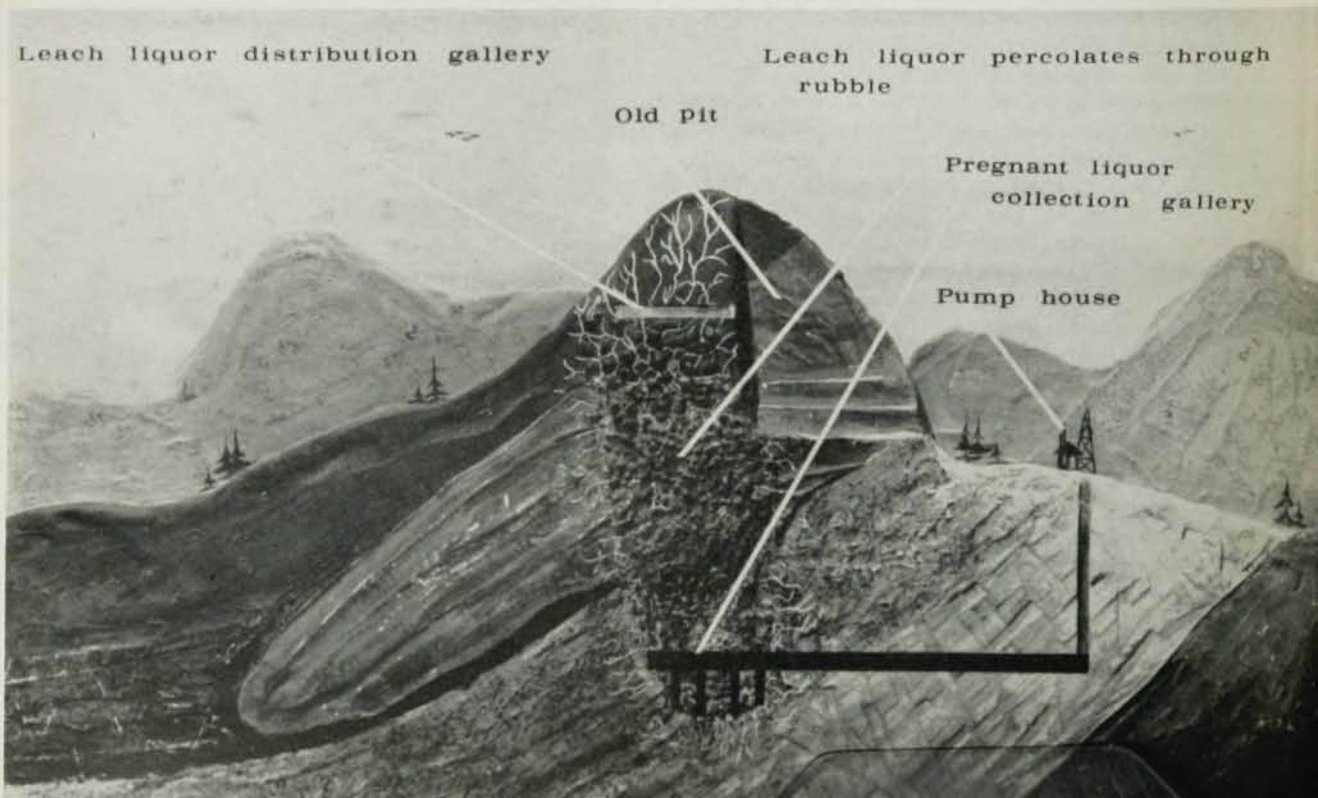


Fig. 10. Block caving method of ore recovery.

method of breaking ore is known to miners as block caving; in many situations, block caving can be exploited economically on a large scale with completely contained nuclear explosions (Fig. 10). The Rainier chimney was mined in this manner purely as a demonstration of the method, since the broken rock has no commercial value.

There is another potentially economical method of recovering valuable minerals from such broken zones in low-grade ores. One might allow leaching solutions to percolate down through the fractured material, as shown schematically in Fig. 11. The pregnant liquor, now containing minerals in solution (such as copper sulfate), can be precipitated by standard methods. However, it is not clear under what geologic conditions and for what charge sizes chimneys will be formed in rock media other than tuff. Calculations can provide us with some insight into these problems, but only nuclear experiments in different rock media can ultimately dispel our ignorance in this area.

Fig. 11. Leaching operation, artist's conception.



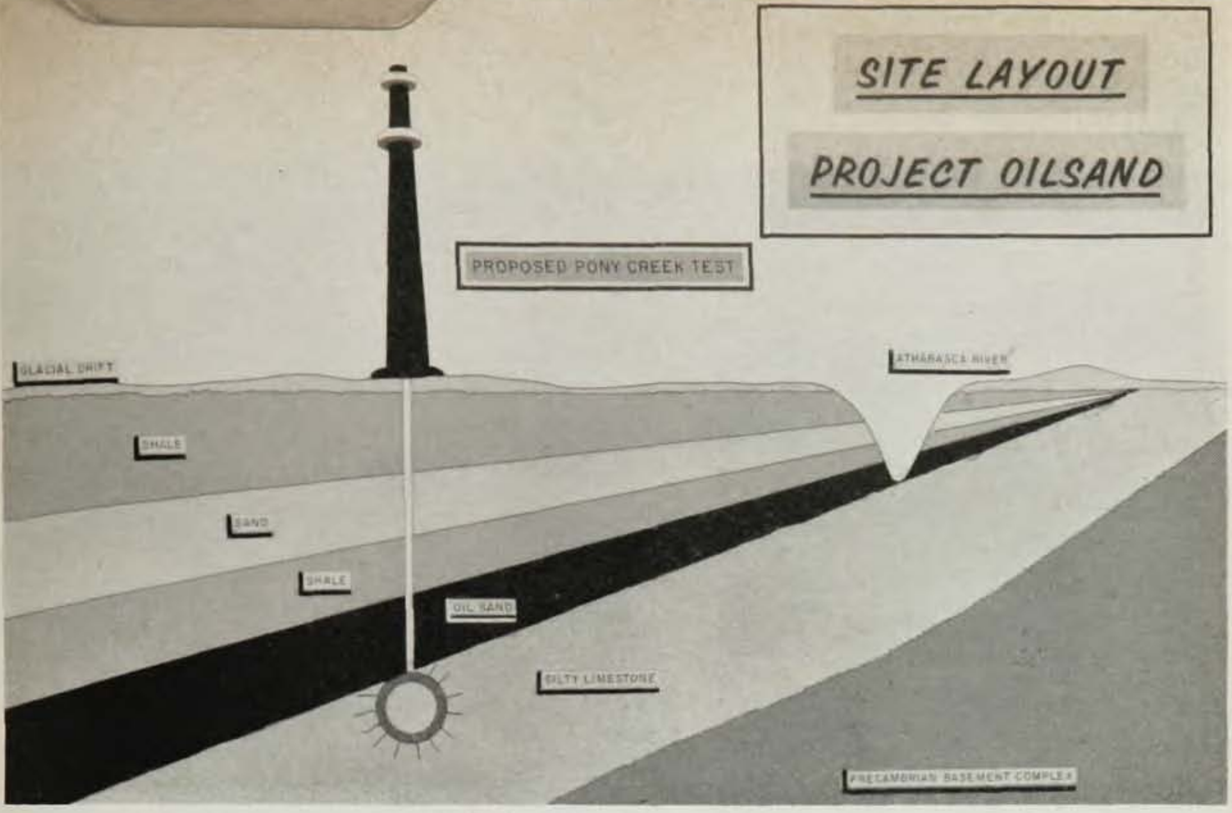


Fig. 12. Oil sand experiment, schematic.

SEVERAL ideas for recovering petroleum by using nuclear explosives have also been advanced. Reserves of petroleum recoverable by conventional methods are undoubtedly dwindling; at present rates of consumption, known reserves will be exhausted within a few decades. New sources of petroleum must therefore be developed.

A potential source of petroleum, as yet untapped, is the oil sand of Canada and the United States. The amount of oil in these formations is estimated to exceed the proven oil reserves of the rest of the world. Unfortunately, it is not possible to recover petroleum from these sands by conventional methods. The fluid is very viscous and cannot be pumped. But, if it can be heated to about 90°C, the oil will become less viscous, and may be recoverable. The cost of mining the sand and then heating it is too high in view of the value of the product. If, however, the energy from an underground nuclear explosion can be used to heat nearby oil sand, the petroleum might be recovered at a competitive cost.

The Lawrence Radiation Laboratory and the AEC, in cooperation with the Alberta Provincial and Dominion Governments of Canada and several oil companies, have given a great deal of consideration to the planning of an experiment to test the feasibility of this technique. The consent and cooperation of the Canadian government will, of course, be a prerequisite to final preparations for the experiment. As the program is currently envisioned, a 9-kt nuclear device will be exploded just under the oil sand deposit at a depth of about 1400 ft (Fig. 12). The proposed location is about 190 miles northeast of Edmonton, Alberta, on a claim under development by the Richfield Oil Company. After the detonation, a well 500 to 700 ft from ground zero will be drilled for logging temperatures, pressures, and other parameters. On the basis of the information thus obtained, additional holes may be drilled to gather more extensive data and to determine the amount of recoverable oil produced by the explosion. As much as 200 000 barrels of oil could be produced in this experiment. If conditions are favorable, an empirical study of the problem of recovering this oil may be undertaken.

Some new empirical evidence, recently obtained in laboratory experiments at LRL, suggests that a nuclear explosion in or near an oil-sand deposit will produce a significant amount of light hydrocarbon products. In these experiments we observed the formation of low-molecular-weight hydrocarbons in oil sand caused by the breakup of heavier molecules, a process known as cracking. The cracking in this instance is a direct result of a shock generated by high explosives. This phenomenon of shock-induced cracking may improve the economic outlook for the recovery of oil sands by nuclear explosive techniques.

There are, in addition, vast quantities of petroleum contained in a rock called oil shale, which is plentiful in the United States. Known oil-shale deposits contain even more petroleum than the oil sands. Unfortunately, this rock must be "cooked" to release the oil. The high cost of mining the shale, crushing it, and then extracting the oil makes the end product too expensive for commercial exploitation at the present time. Plowshare techniques, however, may offer a way of cutting the cost to reasonable levels. Nuclear explosives would be used to fracture large quantities of oil shale, thereby reducing mining costs. Alternatively, the fractured shale might be retorted in place, eliminating the expensive mining step in the recovery process. In cooperation with the US Bureau of Mines, the Lawrence Radiation Labora-

WATER RESOURCES

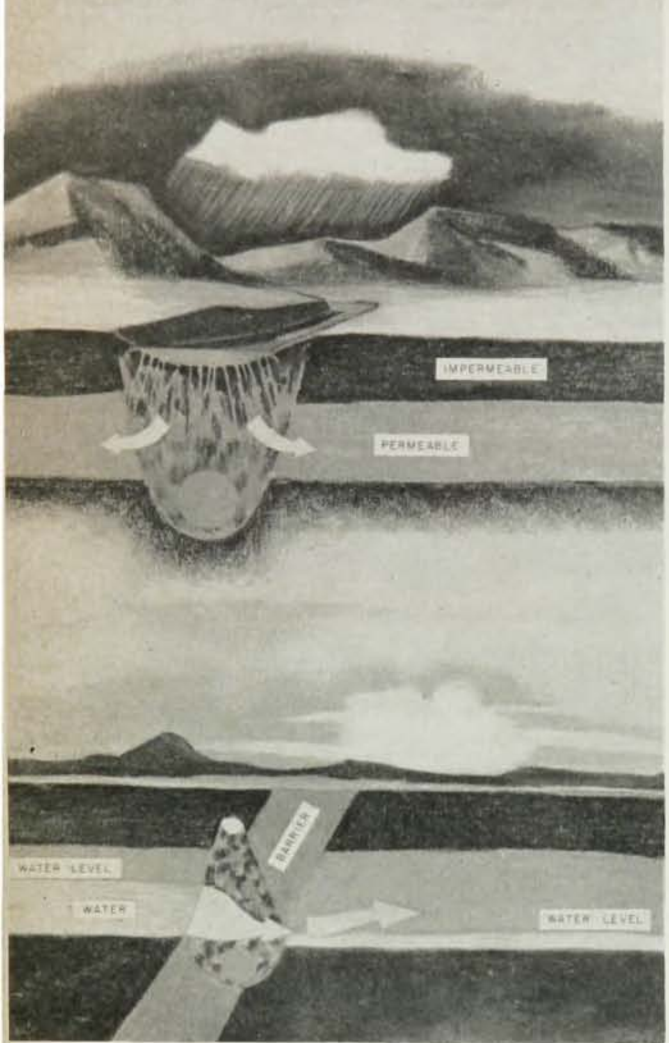


Fig. 13. Recharge and connection of aquifers.

Fig. 14. Ship canal, artist's conception.

tory is studying the feasibility of recovering oil from oil shale with the use of nuclear explosives.

CONSERVATION, as well as exploitation, of our natural resources is among the potential applications of nuclear explosives. In many areas of the world the problem of obtaining adequate amounts of fresh water is a serious one. Ground water supplies are being consumed at a record rate. Yet, because of the impermeable nature of the surface, waters run off and ultimately find their way to the ocean. Hence replenishment or recharge of underground water resources is frequently low. Many such regions lie in arid or semiarid areas of the world, where water stored in conventional reservoirs evaporates rapidly. Plowshare offers the possibility of new approaches to these and similar problems. Subsurface explosions under some conditions can form large vertical chimneys filled with broken and crushed rock, as demonstrated by the Rainier event. Such a chimney, in an appropriate location, could serve as a conduit to connect two underground aquifers (water-bearing rock strata) separated by an impermeable rock layer. A similar technique could be used to breach an undesirable barrier to horizontal underground water flow (Fig. 13). The bottom of a large conduit in the proper location could serve admirably as a pumping basin to increase significantly the yield of an aquifer.

Conduits extending all the way to the surface might be created in some formations, and would be useful in a variety of ways. Surface water running down the conduit could provide needed aquifer recharge (Fig. 13). In other instances, undesirable brackish waters could be diverted, via such a conduit, into aquifers already mineralized or to appropriate permeable strata.

Fig. 15. Madison Canyon slide.

Under some conditions a chimney could provide low-evaporation water storage. In creating such a reservoir, one can achieve a potential storage capacity of about 4×10^6 gallons per kiloton of explosive. A structure of this nature might also be used for underground storage of, say, radioactive wastes from nuclear reactors, provided that the stored material could be kept sufficiently localized.

In many parts of the world the supply of good water, even underground, is insufficient, and water must be imported from more liberally endowed regions hundreds of miles away. Here too, the application of nuclear explosive technology to the problem may result in an economically feasible solution. The large-scale cratering efficiency of nuclear explosives may prove very advantageous in constructing the canals and diversionary channels that such a project requires. In other civil construction projects as well, nuclear explosives may be employed profitably. Among the most promising of these applications are the building of ship canals and the blasting of rock for fill. Figure 14 suggests how a ship canal might look if constructed with nuclear explosives.

The reader may recall news of the violent earthquake which rocked Yellowstone National Park in summer of 1959. The earthquake shook loose part of a mountainside, which fell into the Madison River and created a large earthfill dam. The Army Engineers were quick to build a spillway, and their current opinion is that the dam may be permanent. Figure 15 is a photograph of the dam and the lake behind it. Similarly, recent earthquakes in Chile have created earthfill dams, and, of course, a survey of geologic records throughout the world brings to light many other examples. Perhaps, under the right geological conditions, one could "induce" part of a mountain to move into a river bed by using nuclear explosives. Alternatively, at a place where a slide has formed a dam, one might use nuclear explosives to quickly ameliorate an undesirable or unsafe situation before dangerous amounts of water can collect behind the material. While the construction of a useful and safe earthfill dam with a man-made landslide is obviously a very difficult undertaking, the possibility is sufficiently promising to justify a thorough study of several man-made and natural earthfill dams.

Evidently, there are several basic criteria for an acceptable earthfill dam: it must be strong, sufficiently watertight, and firmly supported. In addition, it must have a suitable spillway. It is not unreasonable to expect that, under proper geologic conditions, nuclear explosives can be employed with economic advantage in the construction of large earthfill dams, provided that some of the construction work (including a spillway) is completed prior to the explosion.

AT the Second Plowshare Symposium, one speaker * advanced several ideas about how nuclear explosions might be employed by the chemical industry. He envisions the cavity produced by an underground nuclear detonation as a huge retort in which industrial chemical production can be carried out; the nuclear device itself might be thought of as a Bunsen burner which supplies heat energy and pressure to the reaction. It is assumed that the device would be exploded under conditions which would preclude collapse of the cavity. (Further experimentation with underground explosions will be necessary before the conditions for cavity stability are fully established.) As an example of such a process, a detonation in limestone ($CaCO_3$) would yield CaO and CO_2. The CO_2 can be recovered by drilling; then another explosion in the same cavity with the addition of carbon might yield a reasonable amount of CaC_2 which can be used to produce acetylene, C_2H_2. Moreover, the addition of nitrogen to the hot CaC_2 would give $CaCN_2$, which is a valuable chemical for the production of ammonia, NH_3. Laboratory studies, now under way, to investigate these and other chemical reactions under conditions of high pressure and temperature, must proceed considerably further before it becomes clear whether optimism about this potential application of nuclear explosives can be justified.

A nuclear explosive in rock generates a very strong shock which expands rapidly into the surrounding medium. Many of the desirable effects of subsurface detonations (and some of the less desirable ones) are attributed wholly or partly to the action of the shock. Cracking, crushing, and heating of rock, and the mechanics of crater formation are among these. Reliable preshot estimates of the magnitude and extent of such phenomena will be important in industrial explosions, where economic considerations are paramount. Such calculations are also important in minimizing possible damage to existing underground structures, such as mines and tunnels. Plowshare is therefore engaged in studying strong shocks in solid materials, particularly in various types of rocks. Currently in progress are measurements of the dynamic equations of state and dynamic yield strengths of rocks, as well as development of instruments to measure shock parameters.

Within recent years strong shocks have also been shown to induce chemical reactions and phase changes in solids. Small diamonds have been produced by high-explosive shocks in carbon, and have also been observed in meteorite fragments. In the latter case they are believed to have been formed under the shock conditions resulting from the impact of a meteor on the earth's surface. Similarly, the existence of coesite, a high-density phase of SiO_2, in meteor craters can be ascribed to shock effects. At the Nevada Test Site coesite has been identified in samples of desert alluvium shocked in nuclear explosion. Such evidence suggests that nuclear explosions might prove useful in providing the proper shock conditions for other reactions of economic or scientific interest. The shock cracking of petroleum, which was mentioned earlier in this article, is an example of such a reaction. Our continuing study of the effects of shocks in solid materials may uncover more shock-induced reactions which could be profitably exploited by Plowshare techniques.

AS one might imagine, the study of all these ideas and the planning, investigation, and research required before any of them can be translated into industrial practice must be very extensive. Our interests, of necessity, cover many fields, including geology, geophysics, engineering, chemistry, and physics. Because we must be very careful about radioactivity, we are interested in the development of cleaner thermonuclear devices. At any rate, it is clear that with presently available devices and techniques it is possible to control radioactivity to an extent that nuclear explosions for many industrial purposes can be conducted in a safe manner.

In any one situation, a particular application of nuclear explosives might not prove economically feasible. However, a combination of applications associated with a single explosion might justify the operation from a financial viewpoint. For instance, in conjunction with a block-caving operation, one might add radioisotope production and shock-induced chemical reactions at a small extra cost. Singly, none of these operations might prove attractive to an industrial concern; but taken together, the three operations might enable the company to utilize nuclear explosives profitably.

The next few years will be important ones for Plowshare. In a series of experiments employing both nuclear and chemical explosives we hope to demonstrate that many of the ideas outlined in this report are sound and practical ones. If we are successful, the huge quantities of exceedingly cheap energy available from nuclear and thermonuclear explosives can help fulfill many of the world's basic economic needs.

* John J. Grebe of the Dow Chemical Company.