PLOWSHARE

U.S. ATOMIC ENERGY COMMISSION / Division of Technical Information

ONE
OF A SERIES ON
UNDERSTANDING THE ATOM

Nuclear energy
is playing a vital role
in the life of
every man, woman, and child
in the United States today.
In the years ahead
it will affect increasingly
all the peoples of the earth.
It is essential
that all Americans
gain an understanding
of this vital force if
they are to discharge thoughtfully
their responsibilities as citizens
and if they are to realize fully
the myriad benefits
that nuclear energy
offers them.

The United States
Atomic Energy Commission
provides this booklet
to help you achieve
such understanding.

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Director
Division of Technical Information

PLOWSHARE

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THE COVER

This powerful statue by the New York sculptor, Moissaye Marans, symbolizes the spirit and the strength of the Plowshare program for peaceful uses of nuclear explosives, with which this book deals. The statue is entitled: *Swords Into Plowshares* (Isaiah 11:IV). The sculpture has received three major awards. The original is 14½ feet tall and appears on the facade of the Community Church of New York. Other versions appear in Chicago, Pittsburgh, Philadelphia, and San Jose, Calif. This photograph of the statue was graciously provided for use on the cover by Mr. Marans, and the National Sculpture Society.

THE AUTHORS

CARL R. GERBER joined the Atomic Energy Commission as a technical intern in 1960 and has been associated with the PLOWSHARE program since 1961. He received a B.A. in chemistry from Oberlin College and a M.S. in inorganic chemistry from the University of Wisconsin.

RICHARD HAMBURGER has been active in the PLOWSHARE program since its early days and now is Assistant Director for Technical Operations in the AEC Division of Peaceful Nuclear Explosives. He formerly was on the staff of the Division of Raw Materials and worked as a geologist and mining engineer. He received an A.B. in geology from the University of Michigan, and has done graduate work in geology at the Johns Hopkins University.

E. W. SEABROOK HULL is an experienced writer and editor in technical and engineering fields, and is the author of *The Bountiful Sea*, published in 1964 by Prentice-Hall. He is the editor of *Ocean Science News* and editor and publisher of *GeoMarine Technology*.

PLOWSHARE

CARL R. GERBER
RICHARD HAMBURGER
E. W. SEABROOK HULL

EXPLOSIVES FOR BUILDING AND LEARNING

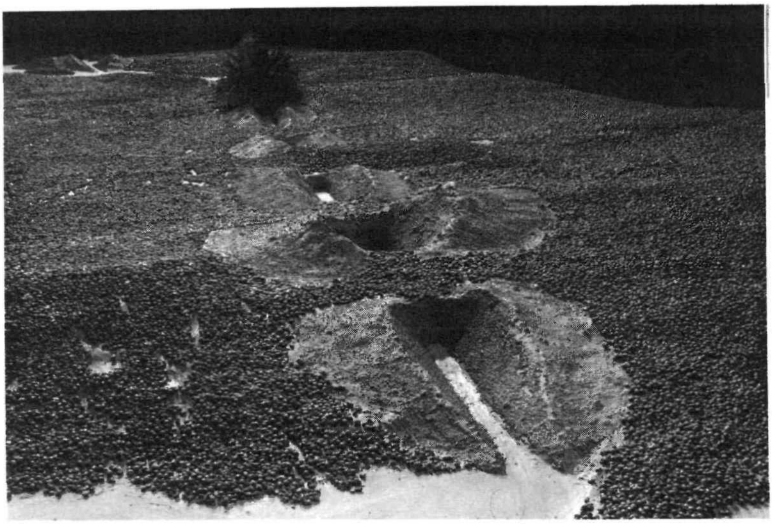
Despite the enormous destructive force that explosives have added to the conduct of wars, it is clear that, in the balance of history, explosives have been used more for good than evil. Although they were used first for war, the ingenuity and needs of man in due course turned these powerful tools to a multitude of constructive purposes.

The peaceful uses of chemical high explosives are many. They helped dig the Panama, Erie, and Corinth Canals. Without them modern mining would be impossible. Explosives start reluctant oil wells flowing, blast menacing rocks from ship channels, remove tree stumps, and dig ditches. They make possible many of the feats of modern construction. They have found their way into production processes — such as the explosive forming of metals — and are employed as space-age laboratory tools — such as shock tubes. Highly specialized explosions power our cars and aircraft. Small charges are used in rockets and flares that help rescuers find lost seafarers. Others give us holiday fireworks. Still others reveal secrets of the earth's inner structure, or effect the stage separations of spacecraft.

One of the world's largest peaceful chemical explosions—2,756,324 pounds (about 1.4 kilotons) of high explosives—in 1958 cleared Ripple Rock, a navigation hazard, from Seymour Narrows, British Columbia. Courtesy E. I. du Pont de Nemours and Company.

There are solid explosives, jellied explosives, and liquid explosives. There are explosives in cartridges, explosives in the form of pellets, powder, and ribbons, and explosives that stick and can be shaped like putty. To employ these many forms of chemical explosives, an elaborate technology enables engineers to select and place explosives so as to accomplish precisely the desired effect.

Although it took nearly 400 years for the chemical "black powder" explosives to be adapted from military purposes to mining, the imaginative mind of man is already defining—with the atomic age only two decades old—an array of peaceful wonders and benefits from nuclear explosives. Uses are as varied as those of chemical high explosives.



Construction of a sea-level canal would require a series of simultaneous nuclear explosions as simulated in this model.

Even as nuclear energy has brought a new dimension to the term "explosion", so man has begun to think in terms of heretofore impossible things he can now do with explosions. Not only is he thinking, he is doing—a nuclear explosion technology for peaceful applications is being developed.

"Geographical engineering" describes the use of nuclear explosives to change the geography of our planet—digging sea-level canals between oceans, stripping overburdens* from deep mineral deposits, cutting highway and railway passes through mountains, creating harbors and lakes where none existed before, and altering watersheds for better distribution of water resources.

Nor do proposals for peaceful uses of nuclear explosives stop with large-scale earth-moving. Also envisioned are constructing underground reservoirs, increasing gas well productivity, and controlling subterranean water movement. Eventually, the energy from nuclear explosives may even be used for underground desalting of sea water, for producing steam, and for creating basic industrial chemicals directly from mineral deposits.

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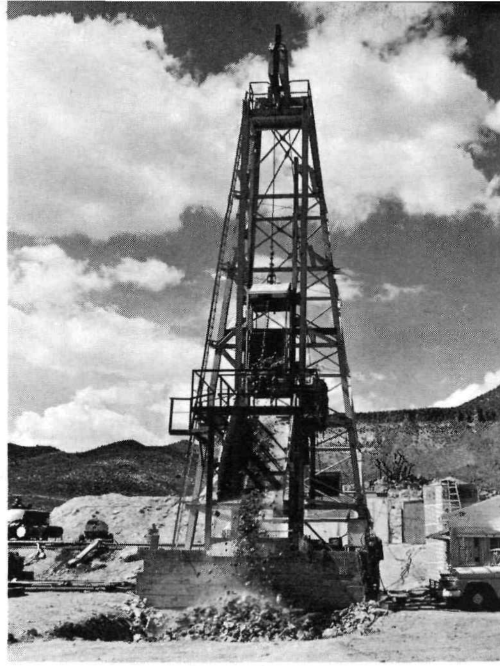
*The waste rock lying between the surface and a mineral deposit.



This highly broken rock, shown here being recovered by standard mining techniques, is the result of a deep underground nuclear explosion.

In mining, nuclear explosives might be used to break up ore bodies to obtain minerals whose recovery is not now economically feasible. The shattering effect and heat of nuclear explosions may one day enable recovery of vast oil reserves from sand and shale formations that are now uneconomical to exploit.

As a tool of research, a nuclear explosion is many things—the most intense source of high-energy neutrons available, a made-to-order seismic signal, a package of extreme pressures and temperatures, and a means of producing transplutonium elements*. Nuclear explosion research possibilities range from studies of the inner structure of the earth to studies of the basic structure of matter.

Possible peaceful uses for nuclear explosives are many and varied. Some have been appraised as feasible, both economically and technically, for use in the immediate future; others have been set aside for consideration until the distant future. Almost all require further evaluation and testing, and a program to provide the needed studies and experiments is under way. PLOWSHARE is the name given to this endeavor.

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*These are man-made elements, heavier than plutonium, which do not occur in nature. For more about them see *Synthetic Transuranium Elements*, a companion booklet in this series.

The Mission

Between the first development of an explosive and its application to peaceful purposes are thousands of man-years of research and development, of learning and doing. More than anything else it is the mission of PLOWSHARE to develop, within years, a technology for using nuclear explosives peacefully comparable to that developed for conventional explosives over a span of centuries. The PLOWSHARE program is an ambitious undertaking but one in which the rewards are commensurate with the effort.

To direct the PLOWSHARE program, the Atomic Energy Commission (AEC) has established a Division of Peaceful Nuclear Explosives. The Lawrence Radiation Laboratory at Livermore, California, which is operated for the AEC by the University of California, has primary technical responsibility in the program. In developing excavation technology, the Nuclear Cratering Group of the Army Corps of Engineers works closely with the Lawrence Radiation Laboratory. The AEC Nevada Operations Office is responsible for conducting field operations safely, and the AEC San Francisco Operations Office has responsibility in administration and program development, including industrial participation.

Other AEC laboratories, other government agencies, and private individuals and contractors participate in the research and development program, as designers of experiments, as suppliers of specialized support services, or as consultants in safety or technical aspects of the entire program or of specific projects.

WHAT IS AN EXPLOSIVE?

Explosives, whether nuclear or chemical, are compact, instantaneous sources of large amounts of energy. Though the specific properties of nuclear and chemical explosives vary, the chief difference between them is that of magnitude.

Source of Energy

Chemical high explosives derive their energy basically from chemical reactions, through either the breakdown or the formation of chemical compounds. An explosive chemical reaction is one in which the explosive materials go from a state of lesser to a state of higher chemical stability. Such a reaction releases energy associated with the bonding between atoms.

Rapid expansion of the gases formed in the heat of the reaction, or as products of the reaction, produces the explosive effect. The heat released by high explosives may be as great as 160,000 calories* per 100 grams of explosive. This compares to 800,000 calories per 100 grams of bituminous coal burned in air. Of course, coal releases its energy slowly, while an explosive releases its energy virtually instantaneously.

Nuclear explosives release energy from *within the atoms* of the explosive material. Nuclear bonding, or the forces holding the center of the atom (its nucleus) together, involves a few million times more energy than chemical bonding. When a nuclear reaction occurs, some of the nuclear mass is converted into energy, according to Albert Einstein's classic equation for the relation of mass and energy:

$$E = mc^2$$

where E is energy, m is mass, and c is the velocity of light. In other words, the total mass of all the products resulting from a nuclear reaction is less than the mass of the original material, the remainder having been converted to energy.

How Do Nuclear Reactions Occur?

The atom may be visualized as having a center, or nucleus, around which electrons orbit, much as the planets circle the sun. Each electron has a negative charge. Within the nucleus there is a heavier, positively charged particle, known as a proton, for every orbiting electron. Also in the nucleus of most atoms are neutrons, particles with about the same mass as protons but with no electrical charge.

*A calorie is the amount of heat required to raise the temperature of 1 gram of water 1 degree centigrade.

The weight of an atom is roughly equal to the sum of the weight of its neutrons and protons. The number of protons, called the atomic number, determines the element.

Atoms are identified by their atomic number and their weight, since the number of neutrons may differ. Atoms with the same atomic numbers but different atomic weights are called isotopes. For instance, uranium-235 and uranium-238 are both forms of the element uranium (92 protons), but one atom has three neutrons more than the other. These lighter and heavier atoms are both isotopes of uranium.

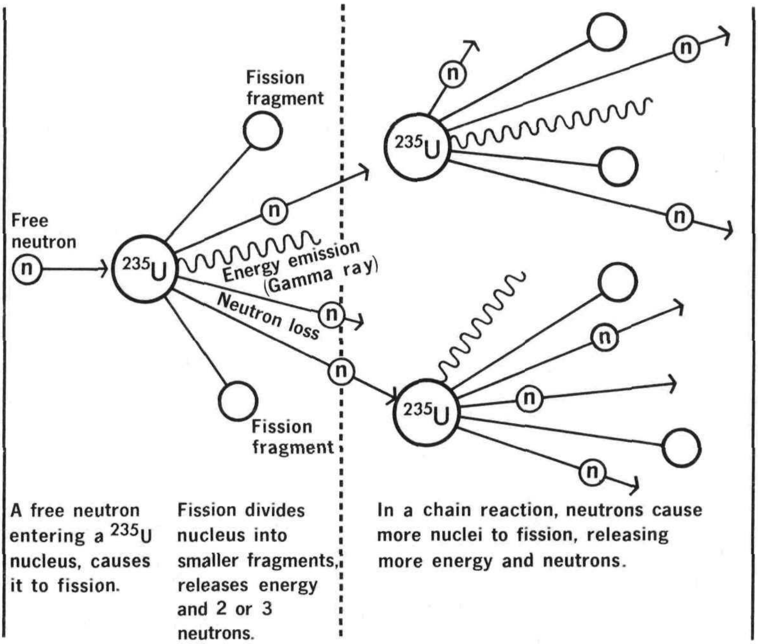
In the nuclei of most naturally occurring atoms a balance of forces exists and the nuclei are *stable*. However, a nucleus that is not stable will eventually change in order to become stable. Usually the nucleus changes by ejecting a small particle, such as a beta particle (an electron) or an alpha particle (a clump of two neutrons and two protons), or by releasing energy as gamma rays. This process is known as radioactive decay or disintegration, and the unstable nuclei are said to be *radioactive*.

However, in atoms of some heavy elements, the method of achieving stability sometimes is more violent—the unstable nucleus flies apart, forming nuclei of lighter elements, emitting free neutrons, and releasing large amounts of energy. This process is known as *fission*. Fission can occur either spontaneously, or when a new particle, such as a neutron, is introduced into the nucleus.

Fission of an atom of uranium-235 (^{235}U), for example, occurs when a free neutron penetrates its nucleus. Free neutrons are like bullets—they have mass and travel in straight lines. Collision of any neutron with a nucleus is a matter of chance, but obviously, the more free neutrons there are, the greater the probability of a collision. Also, the greater the mass of the fissionable material, the more likelihood there is that a nucleus will be in a free neutron's path.

While it takes only one neutron to cause the fission of one ^{235}U nucleus, each fissioning nucleus produces, in turn, two or three more free neutrons. If at least one of these new neutrons penetrates another ^{235}U nucleus and produces another fission, and this process continues, a *chain reac-*

FISSION

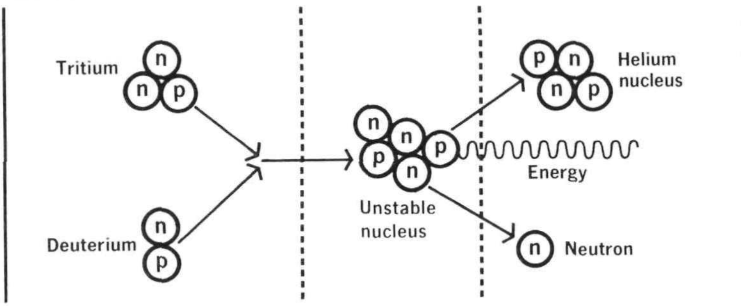


If a free neutron enters a ^{235}U nucleus, the nucleus will divide, or fission, into two smaller atoms, releasing energy and 2 or 3 more neutrons. These neutrons can then go on to cause more ^{235}U nuclei to fission.

tion is established. The amount of fissionable material required to start a chain reaction is known as a *critical mass.*

By increasing the density of the fissionable material or by increasing the ratio of its mass to its surface area (as when the diameter of a sphere of the material is increased), the reaction accelerates, that is, each fission results in more than one additional fission. This rate of acceleration can be increased to the point where the chain reaction is virtually instantaneous. The result is the simplest of nuclear explosives, the fission explosive.

Fusion is another means of releasing energy from the nucleus. In the simplest fusion process, atoms of deuterium and tritium, which are heavy isotopes of hydrogen, combine to form helium atoms. The reaction also produces neutrons and energy. To start a fusion reaction, however, FUSION



When two isotopes of hydrogen, tritium and deuterium, combine or fuse, an unstable nucleus is formed. This releases a neutron and energy, forming a nucleus of helium.

requires temperatures of millions of degrees. Temperatures this high are available from a fission reaction; thus the energy from a fission reaction can be used to initiate fusion. The energy released in fusion is the difference between that required to hold together the nuclei of the hydrogen isotopes and that required to hold together the helium nuclei that are created.*

The Nuclear Explosive

While a single fusion reaction produces less energy than a single fission reaction, each fissionable atom (uranium or plutonium) weighs over 100 times as much as an atom of deuterium. Pound for pound, therefore, thermonuclear explosives, which derive most of their energy from the fusion reaction, are considerably more powerful than pure fission explosives. Moreover, since the thermonuclear materials are relatively inexpensive, a thermonuclear explosive can be made more economically in large yields† than can a fission explosive. Just how thermonuclear explosives compare in cost with other energy sources can be seen in the table on the next page.

Another point of particular interest to PLOWSHARE personnel is that the fusion reaction does not in itself pro-

*For additional description of the fusion process, see *Controlled Nuclear Fusion*, a companion booklet in this series.

†The yield of an explosion is the total amount of energy released.

COMPARATIVE ENERGY COSTS

Energy source	Cost per million (10^6) Btu
2 Megaton thermonuclear explosive	$ 0.075
Lignite	0.14 – 0.17
Soft coal	0.15 – 0.20
Natural gas	0.20 – 0.15
Water power	0.89
Gasoline	1.50
Electricity ($0.006/kwh)	1.78
Ammonium nitrate	4.50
10 Kiloton thermonuclear explosive	8.75
TNT	250.00

duce the same highly radioactive isotopes as does the fission reaction, although some radioactive products are formed. Some radioactivity may also be produced as an explosion side effect—when neutrons from the reaction are captured by nuclei of atoms in surrounding materials. However, this effect can be reduced by encasing the explosive in a shell of neutron-absorbing material, such as boron or boron compounds. The use of a thermonuclear explosive, in which a fission reaction initiates a fusion reaction, reduces radioactive residue, and when used for digging a crater, lessens radioactive fallout.

The energy released by a nuclear explosive (its yield) is defined as the number of tons, thousands of tons (kilotons), or millions of tons (megatons) of TNT that would release the same amount of energy. Energy equivalents of one kiloton of TNT are given in this table.

ENERGY EQUIVALENTS OF ONE THOUSAND TONS OF TNT

Fission of 1.45×10^{23} atomic nuclei
10^{12} calories
4.2×10^{19} ergs
1.2×10^{6} kilowatt hours
4.0×10^{9} British thermal units (Btu)

Nuclear explosives can be designed to give optimum results for specific purposes, just as in the case of chemical high explosives. For example, in excavation, both cost and radioactivity can be reduced by proportionally increasing the fusion yield and encasing the explosive device in a neutron-absorbing shell. Where large quantities of neutrons are needed for scientific research or production of isotopes, other special designs are required. The diameter of the cannister containing the explosive, which is important in some applications, can also be varied. Fortunately, nuclear explosives of large yield, unlike chemical explosives, can be easily transported to remote regions because they are extremely compact sources of energy.

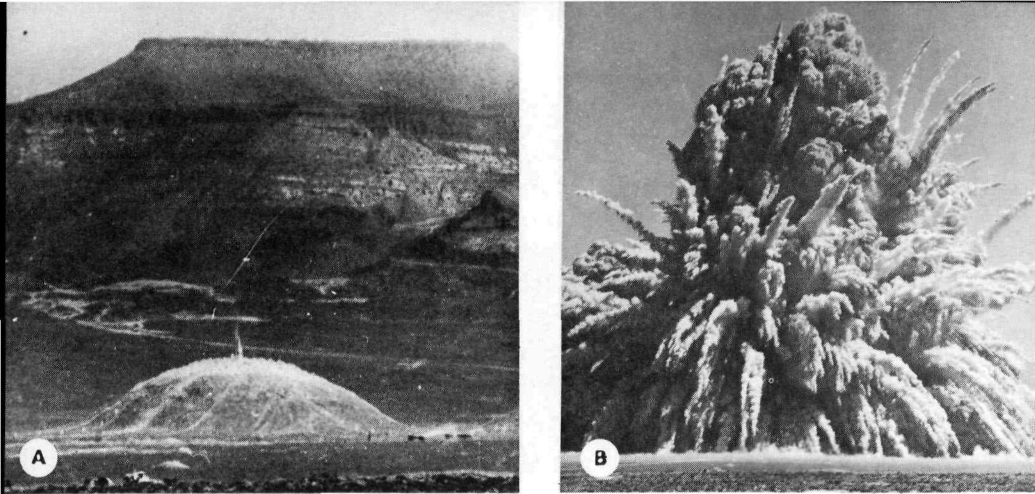
WHAT DOES A NUCLEAR EXPLOSION DO?

Explosion Phenomena

The energy of a nuclear explosive is released in less than one millionth of a second. This energy may be thought of as being divided into three categories: kinetic energy, thermal radiation, and nuclear radiation. Unlike a chemical explosion, in which most of the initial energy is kinetic energy, in a nuclear explosion an appreciable fraction of its initial energy is thermal radiation. The proportion of this thermal radiation increases with the yield. A small part of the initial energy from a nuclear explosion also appears as nuclear radiation, primarily in the form of neutrons and gamma rays, which are of course, absent in a chemical explosion.

A nuclear explosion raises the temperature of materials near its center to tens of millions of degrees, converting them to gases under pressures of many millions of atmospheres (one atmosphere equals about 15 pounds per square inch). Within less then one millionth of a second these hot residues begin to radiate energy as X rays. Neutrons are also released—about a trillion trillion of them from a one-kiloton fission explosion.

The high-temperature, high-pressure bubble of gases and explosion particles expands rapidly, its temperature dropping to about a million degrees. In these first few thousandths of a second much of the energy is transferred to the surroundings as a strong shock wave that rapidly moves outward. In an underground explosion the shock wave

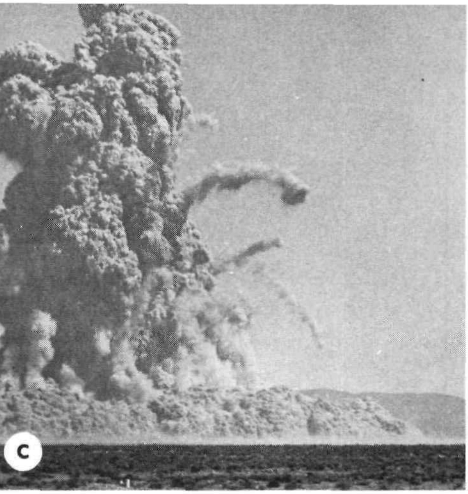


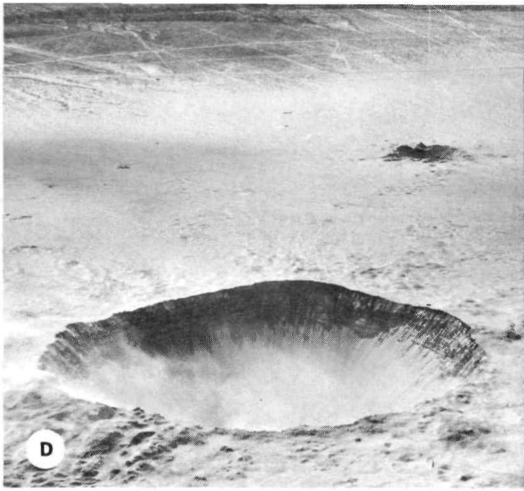
First the desert was calm and quiet. Then as the SEDAN explosion occurred 635 feet below, the desert domed up (A) 290 feet before the explosion broke out; some 12 million tons of rock and earth were lifted (B) by the explosion with

vaporizes, melts, crushes, and cracks the surrounding rock. The denser the surrounding material, the greater the share of the energy expended in this manner. As the shock wave moves out, much of its kinetic energy is converted to thermal energy in doing work, until all that finally remains is an elastic, or seismic, wave. This seismic wave travels thousands of feet in less than a second.

In an explosion to excavate a crater, the shock wave and pressure not only fracture the rock between the point of explosion and the surface, but also set the rock in motion. Then, because the pressure of the rock lying above the explosion point is less than that in the cavity formed around the explosion point, the cavity grows preferentially toward the surface, pushing the rock up and out to the sides, leaving a crater on the surface. The expanding gases may provide much of the force required to throw the broken material out of the crater. Therefore, for a given explosive yield, rocks that contain large amounts of water would produce larger craters than will comparatively dry rocks, because the vaporized water (steam) supplements the effect of other gases.

The depth at which a nuclear explosion occurs and the physical properties of the rock in which it occurs consequently determine whether a crater will be formed and, if



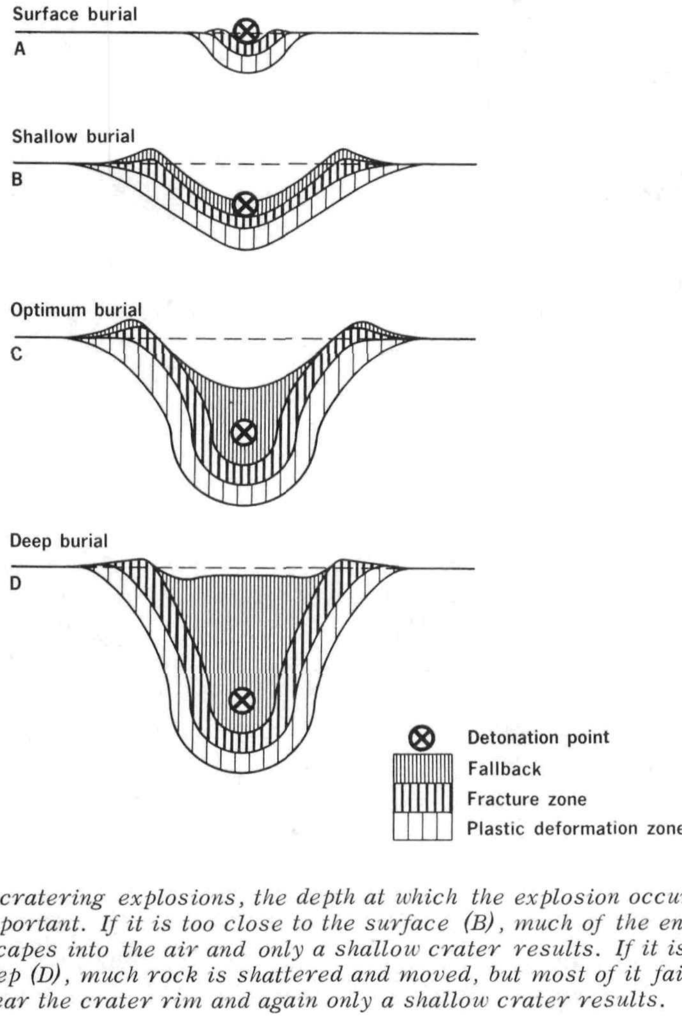


over 8 million tons falling outside the crater as a dense dust cloud, or base surge, rolled out (C) some two and a half miles. When the rock and dust had settled, a crater (D) over 1200 feet across and 320 feet deep remained.

so, how big it will be (see diagram). A surface or near-surface explosion expends most of its energy in the air without doing useful work. A much deeper explosion fractures and lifts a lot of rock, but much of it falls back, leaving only a shallow crater. The best depth at which to place the explosive in order to form the largest crater lies somewhere between the shallow and deep points. The relationships among the various factors in crater formation are discussed in detail in Appendix I. Learning how to produce a crater with specific dimensions in various kinds of rock is one of the main goals of the PLOWSHARE program.

In a very deep underground explosion, after the impact of the shock wave, the heat and pressure vaporize the rock to form a cavity that grows until the pressure inside it equals the pressure of the rock between the point of explosion and the surface of the earth. Consequently the explosion and all its direct effects are completely contained. The size of the cavity depends on the size of the explosion, the depth at which it occurs, and the kind of rock.

When cavity growth stops, broken rock may fall to the floor from the ceiling and walls, resulting in formation of a crudely hemispheric room. In most situations the entire cavity roof falls in, triggering a collapse progressively



In cratering explosions, the depth at which the explosion occurs is important. If it is too close to the surface (B), much of the energy escapes into the air and only a shallow crater results. If it is too deep (D), much rock is shattered and moved, but most of it fails to clear the crater rim and again only a shallow crater results.

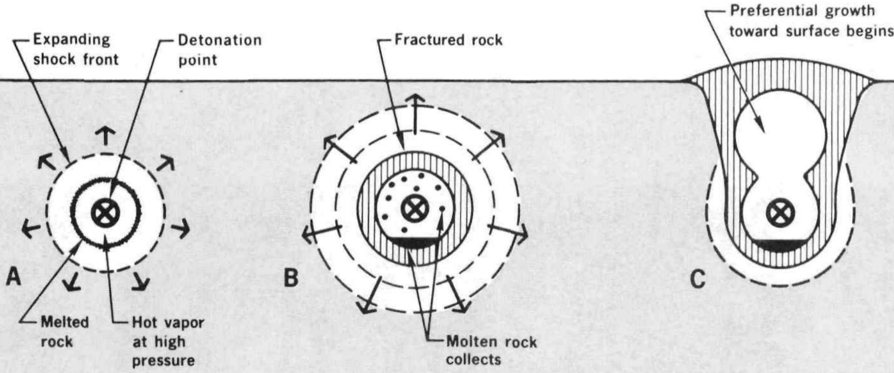
upward through the material fractured by the shock wave. A tall cylinder or chimney, several times the volume of the original cavity, is formed in the rock. This is filled with broken, highly permeable material, usually with a small cavity at the top. If this collapse continues to the surface, a saucer-like depression results, marked by concentric zones of fractured and displaced earth.

All underground nuclear explosions produce fracture zones extending a considerable distance outward from the boundaries of the original cavity. There is also a permanent deformation zone where the surrounding earth is compressed into a smaller volume, pushed upward, or both. In a cratering explosion, this permanent deformation zone extends outward to about 2.5 times the crater radius and in some cases forms about one-third of the crater volume.

If the chimney formed by an underground nuclear explosion reaches the surface, a depression results. Aerial view shows such a depression with equipment in the bottom.

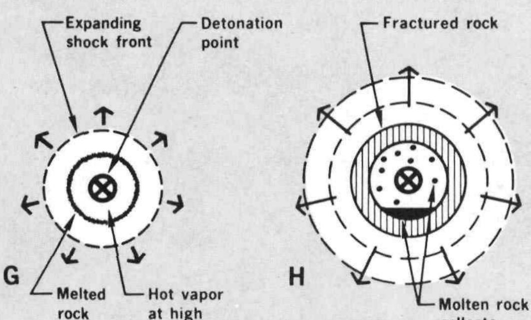
The medium in which the explosion occurs and the topography are important in determining what will result. Most underground nuclear explosions have been conducted in alluvium (deposits of unconsolidated sand and gravel) and tuff (cemented volcanic ash). Exceptions were tests in salt, basalt (solidified lava flow), granodiorite (granite-like rock), and dolomite (carbonate rock). Results of tests in one medium must be corrected and adapted when they are used to predict results from explosions in another. Topography also assumes a role of importance when the project, for example, is to dig a canal of uniform depth and width through terrain of varying altitudes.

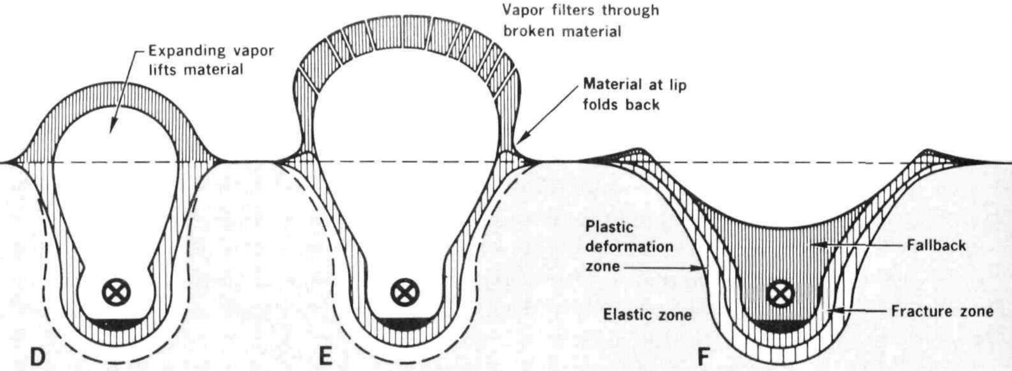
CRATER FORMATION PHASES



When a nuclear explosion occurs it initially (A,G) vaporizes, melts, and fractures the adjacent rock, and sends out (B,H) a shock wave as the cavity of hot vapor at high pressure expands. If the explosive is buried at the proper depth beneath the surface, when the shock wave reaches the surface (C), the cavity begins to grow preferentially toward the surface. The explosion lifts most of the rock and dirt (D,E), some falling back inside, the rest outside the crater (F). If the explosive is buried very deeply, as the cavity begins to cool (I), (in most types of rock) fractured rock begins to fall into the cavity. This collapse continues upward leaving a column, or chimney, (J) of broken rock.

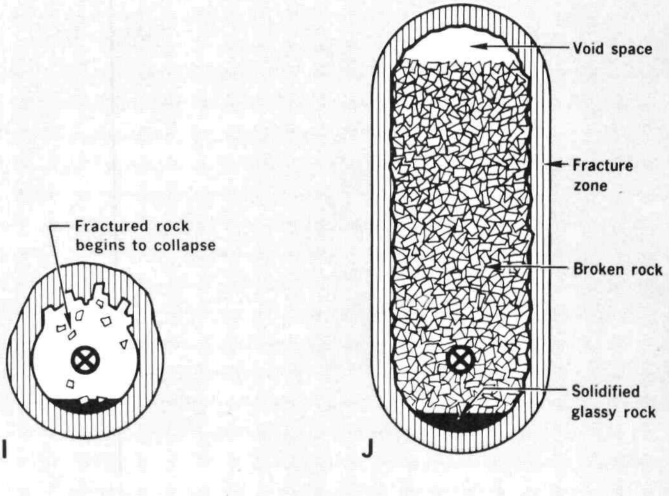
CHIMNEY FORMATION PHASES





Safety

As we have seen, the energy released in a nuclear explosion appears in three forms—mechanical, thermal, and radiation. As with all sources of energy, there are certain effects which could be hazardous if not properly controlled. Consequently, the study of possible applications for nuclear explosives not only involves technical and economic considerations but also the operational measures necessary to ensure safety.



The chief safety considerations are: radiation, ground shock, air blast, and base surge. As the PLOWSHARE program currently deals only with underground explosions, thermal hazards are not an important concern.

Radiation—Experience with completely contained underground explosions has demonstrated that radioactive gaseous material presents a controllable hazard. In an explosion in a medium that turns to slag, almost all radioactive particulate material is concentrated in the melted rock, which, upon cooling, solidifies into a glassy substance. Any residual radioactive material that can be reached by water may constitute a possible hazard. Consequently, studies are being made of the migration and dispersion of radioactive explosion products in ground water. Considerable information has already been gathered for some geologic formations. Scientists are confident that, as they acquire experience with explosions in other formations, they will be able to predict, and thus control, this potential hazard.

Cratering explosions release some radioactivity to the surface and into the lower atmosphere, resulting in local fallout.* For example, with the SEDAN experiment, to be described in detail later, most of the small amount of radioactive material that escaped from the crater was deposited within an area extending approximately 2 miles upwind, 2 miles crosswind, and 4 miles downwind from the crater. A person living 50 miles from the crater at the time of the explosion and continuously thereafter, might have received an estimated maximum dose of external gamma radiation of 1 roentgen† in his lifetime from this source. This can be compared with the United States average lifetime exposure of 7 roentgens from natural background radiation. The highest dose any person in the general population actually received from the SEDAN experiment was about 0.2 roentgen.

Impressive progress in reducing the amount of radioactivity released by cratering detonations is being made by

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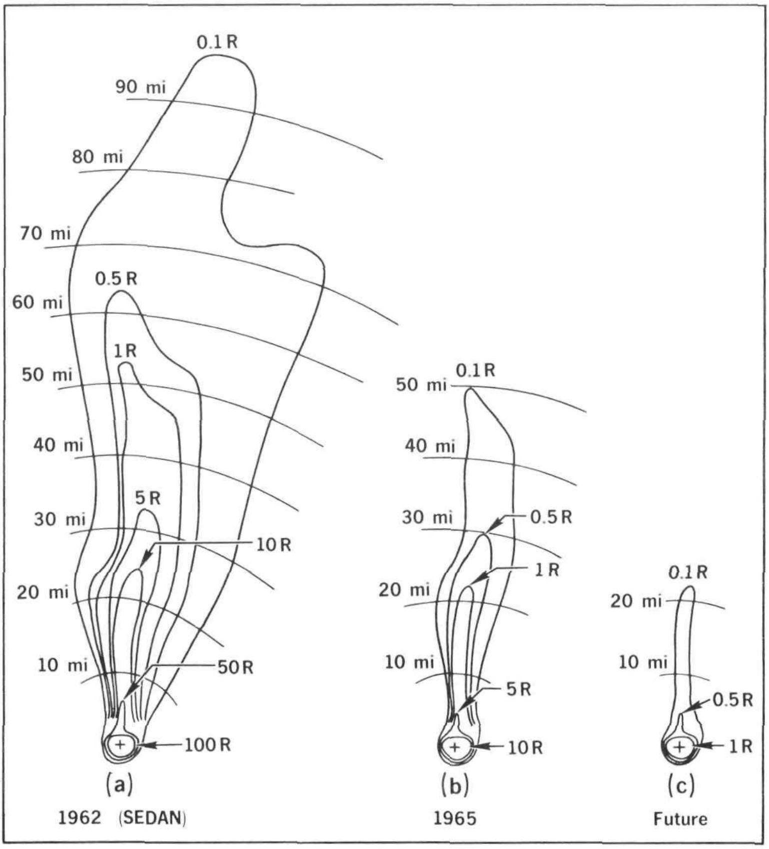
*For additional information on fallout and its effects, see *Fallout from Nuclear Tests*, another booklet in this series.

†A roentgen is a unit of measurement equal to the amount of radiation needed to produce ions carrying 1 electrostatic unit of electrical charge per cubic centimeter of dry air.



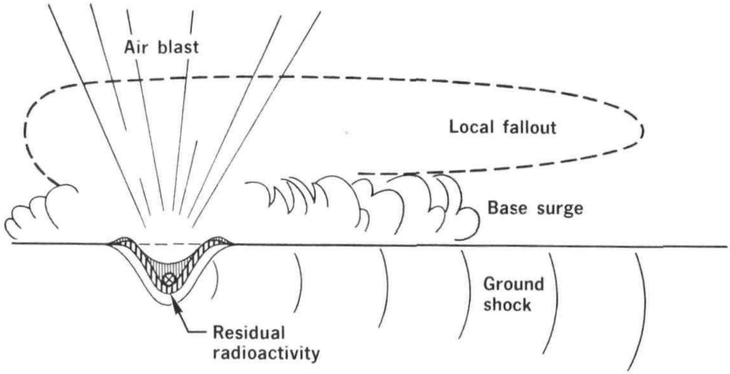
The radioactivity escaping from a nuclear excavation depends both on the total amount produced by the explosion and the fraction that escapes into the atmosphere. The diagram on the left shows the pattern of the fallout that was observed in 1962 from the 100-kiloton SEDAN experiment. The center pattern indicates the fallout that might have been expected if SEDAN had been conducted with 1965 technology. Explosives development and improvements in emplacement techniques are expected to reduce the radioactivity released from nuclear excavations to that shown in the right-hand drawing. The decrease from the left-hand to the right-hand pattern is about one-hundred fold. The amount of radioactivity released is relatively independent of the size of the explosion. These fallout patterns, shown in terms of infinite dose, indicate the dose of external gamma radiation a person living outdoors for a lifetime might receive at various distances from the excavation. For comparison, the average external gamma dose a person in the U. S. receives from natural sources of radiation is about 0.1 roentgen (R) per year.

improvement in the design of the explosives and in emplacement techniques. In addition, work is under way to control the isotopes that are produced in an explosion and that constitute potential internal radiation hazards—that is, isotopes that might enter the body.

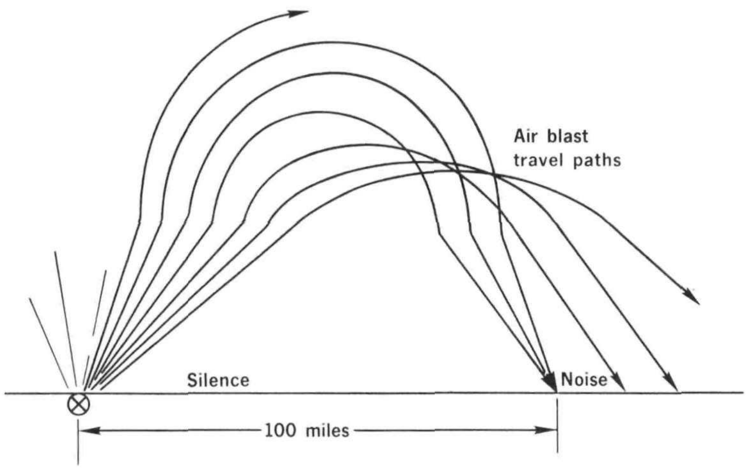
Ground shock—Ground motion close to an underground nuclear explosion is severe but diminishes rapidly. Although seismic signals from one experiment were picked up on seismographs as far as 5000 miles away, they were faint indeed, and might not have been distinguished from local disturbances (such as those from trucks, trains, etc.) if seismologists had not been alerted in advance as to the precise time of the explosion. The distance, however, at which damage to structures may occur from ground shock depends on both the yield involved and the local geology.

Base surge—This is a phenomenon of any crater-forming explosion, chemical or nuclear. Although it is not as noticeable in chemical explosions because they are so small, evacuation of people from the immediate vicinity may still be required. A base surge consists of clouds of dust that are expelled in all directions along the ground by the pressures of the explosion. A base surge from a nuclear cratering explosion may be several hundred feet thick and roll out several miles before dissipating. Much of the radioactivity not contained in the vicinity of the explosion is deposited on the ground over which the base surge travels. Fortunately the particular radioisotopes deposited in this way decay quickly, and the area is soon safe to reenter.

Air blast—This is not a hazard in completely contained explosions (those that are very deep underground). Even in a cratering explosion, air blast fortunately is moderated considerably by the material overlying the explosion. What there is, is directed upward through a cone-shaped path. Discontinuities in the atmosphere, however, may reflect the blast wave back to earth, or jet streams aloft may carry it considerable distances. Since these effects are dependent on atmospheric conditions, detonations can be scheduled so as to minimize possible air blast damage. Air blast monitoring stations 80 to 150 miles away from one cratering explosion recorded pressures no higher than



Several aspects of a nuclear cratering explosion, shown here, could be hazardous to man if not properly controlled.



The air blast resulting from the release of energy to the atmosphere during a cratering explosion may be reflected back to earth many miles from the point of detonation.

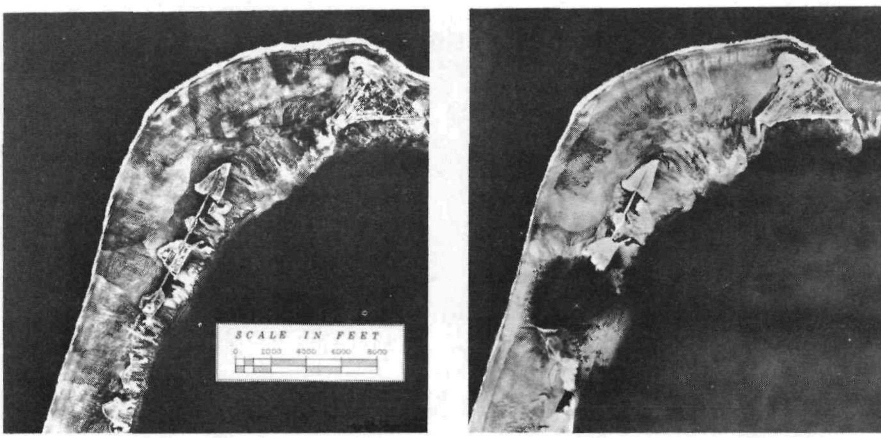
0.0125 pound per square inch—far less than that from a "sonic boom" sometimes produced by a high-speed jet aircraft.

In past projects, the present program, and in all future field work, it is obvious that local conditions, such as geology and the weather, have to be evaluated before any project is undertaken.

WHAT HAS BEEN DONE?

Early Work

One of the first proposals for using nuclear explosives for peaceful purposes came from the famous mathematician, John von Neumann,* in the late 1940s. The only nuclear explosives then available, however, obtained their energy solely from fission, which has some disadvantages: (1) the high cost of fissionable material (uranium-235 or plutonium-239), (2) the limits on the total yield, and (3) the radioactive fission products.



The world's first thermonuclear explosion was detonated at Eniwetok Atoll in the Pacific in 1952. Its 10-megaton yield dug a crater in the reef approximately 5600 feet wide and 160 feet deep. Aerial views show the reef before (left) and after the explosion (right).

In the fall of 1952, however, the United States successfully set off the world's first thermonuclear explosion at Eniwetok Atoll in the Marshall Islands. The practical explosive made possible by this success, utilizing the energy of the fusion reaction, advanced the possibility of application of nuclear explosives for peaceful purposes. Now nuclear explosives were cheaper, because the raw materials were relatively abundant and inexpensive isotopes of hydrogen. Moreover there were fewer fission products to contend

*A member of the Atomic Energy Commission, 1955-57.

with. Finally, the explosive could now have yields "as big as you please". Translated into practical economics, this meant that earth could be excavated for a few cents per cubic yard in some projects in which conventional methods would cost from 20¢ to $5 per cubic yard.

Recognition of these advantages, coupled with the Suez crisis in the fall of 1956, led Harold Brown, then director of the Lawrence Radiation Laboratory in Livermore, California, to consider the possibility of using nuclear explosives to dig a sea-level canal across Israel. In that same year, Camille Rougeron, a French engineer, published a book* that discussed peaceful applications of nuclear explosives.

Although the Suez crisis faded, the idea of peaceful use of nuclear explosives was explored further in February 1957 at a meeting of interested scientists from AEC laboratories. Subsequently, a group was formed at the Lawrence Radiation Laboratory to investigate possible peaceful applications, and in the summer of 1957 the AEC formally established the PLOWSHARE program.

Meanwhile, the AEC, following a suggestion made by the scientists Edward Teller and David Griggs, had decided to conduct underground tests of nuclear weapons. The first of these tests, given the name RAINIER, took place in September 1957. Other underground tests were made the next year. During this period weapons testing in the atmosphere continued, both in Nevada and at Pacific Ocean sites.

Although no nuclear tests designed specifically for PLOWSHARE purposes had been conducted by the time the United States voluntarily began a nuclear test moratorium in late 1958, more than 150 nuclear explosions of all types—atmospheric, surface, and underground—had occurred prior to that time. They provided a store of valuable information for PLOWSHARE scientists. Analysis of data from a number of these tests yielded information on such phenomena as cavity formation, diminution of earth motion with distance, heat transfer to the surrounding materials, rock fracturing, and containment of radioac-

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**Les Applications de l'Explosion Thermonucléaire* published in Paris by Editions Berger-Levrault.

tivity. Thus, these tests contributed directly to development of fundamental PLOWSHARE technology.

Other tests provided data that contributed to evaluation of specific applications. For example, the RAINIER explosion formed a column, or chimney, of fractured rock, and scientists were able, by mining through this chimney, to gather data and draw conclusions regarding the possible use of nuclear explosives in mining. Several surface and underground explosions, which are summarized in this table, provided the first experimental evidence of the feasibility of using nuclear explosives for excavating craters.

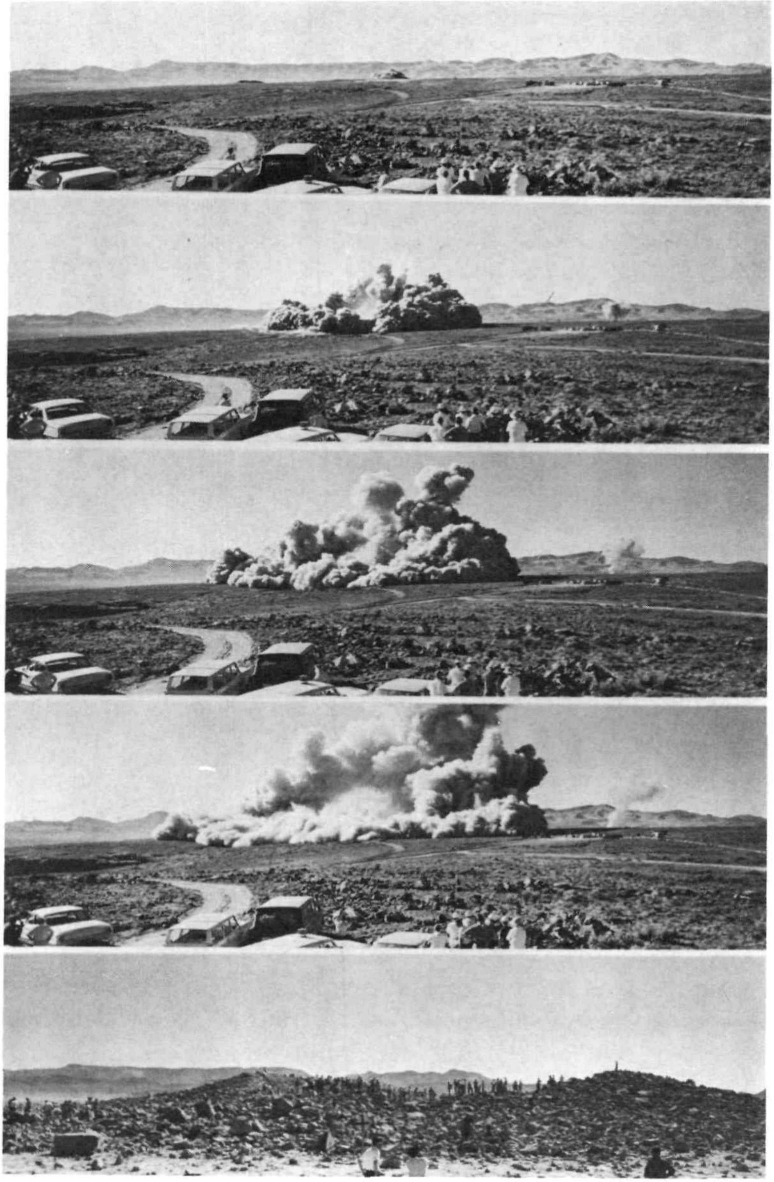
EARLY NUCLEAR TESTS OF IMPORTANCE TO PLOWSHARE

Test name	Date	Yield in kilotons	Medium	Depth of burial, ft	Crater radius, ft	Crater depth, ft	Crater volume cu yd
Jangle-S	1951	1.2	Alluvium	Surface	45	21	1,650
Jangle-U	1951	1.2	Alluvium	17	130	53	37,000
Teapot Ess	1955	1.2	Alluvium	67	146	90	96,000
Neptune	1958	0.1	Bedded tuff	100	100	35	22,000

In addition, from 1958 to 1961 the AEC conducted many experiments with high explosives to aid the nuclear explosion research. More than 100 charges, ranging in size from 256 to 1,000,000 pounds, were set off at the AEC Nevada Test Site. Scientists studied the relationship of the explosive yield, the depth at which the explosive was buried, and the kind of rock to the dimensions of the resulting craters. They also studied the effect of simultaneous detonation of rows of explosive charges, and techniques of collapsing canyon walls to form dams. One of the most interesting things learned from the high explosive experiments was that, when a number of charges are placed in a row and detonated simultaneously, an elongated ditch is formed with the usual "lip" of thrown-out material along the sides but little or none at the ends.

Project GNOME

On December 10, 1961, following the end of the nuclear test moratorium, a nuclear explosive with a yield of 3.1 kilotons was detonated in a salt formation 1200 feet beneath the earth's surface, about 25 miles southeast of Carlsbad,



In the continuing program to develop nuclear explosion technology, an experiment called Project DUGOUT was conducted in June 1964 to gain knowledge of how explosives excavate ditches. This photo sequence shows a row of five 20-ton charges of the chemical explosive, nitromethane, being detonated simultaneously in hard rock.

As this photograph shows, a ditching effect occurs when 5 or more explosive charges are properly spaced and fired simultaneously. Note that little or no debris has been thrown out at the end of the ditch compared to the amount at the sides.

New Mexico. This was Project GNOME, the first nuclear explosion specifically for the PLOWSHARE program.

The GNOME explosion produced a cavity with a total volume of about 960,000 cubic feet and melted about 2400 tons of rock. This melted rock was intimately mixed with about 13,000 tons of salt rock that was hurled into the cavity by implosion. (Steam pressure, produced from water in the rocks, apparently was sufficient to blow off blocks of rock from the cavity walls.) In addition, an estimated 15,000 tons of rock collapsed from the roof. After everything had settled, a dome-shaped chamber 134 to 196 feet in diameter and about 75 feet high remained. Most of the nongaseous radioactive residue was trapped in the mixture of rubble and once-molten salt below the chamber.

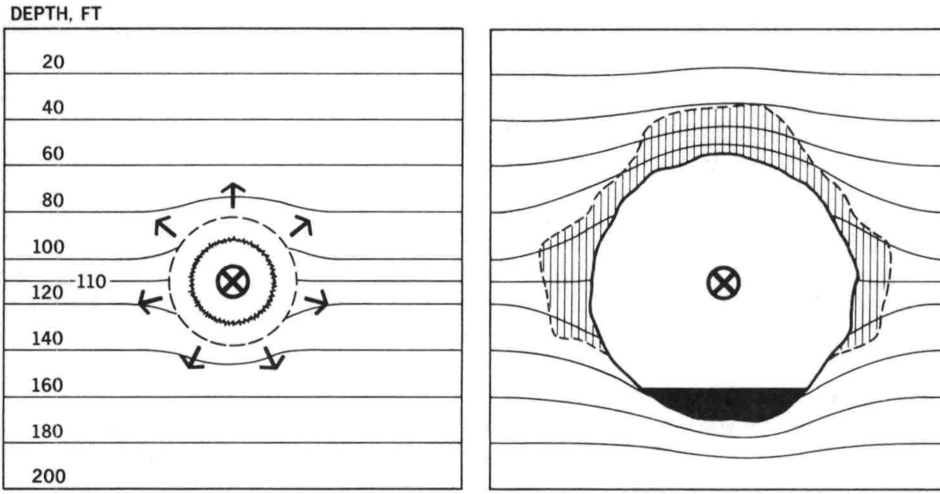
These, in brief, were the physical dimensions of the GNOME event. Impressive as they are, they do not give a full measure of the experiment. GNOME also was a human scientific and engineering achievement of enormous complexity, difficult to describe in a few words. Perhaps a feeling can be gained for the range of effort, skill, and material things that make a successful PLOWSHARE experiment if we quickly scan the highlights of preparation, execution, and follow-up activity in GNOME.

One of the first tasks was to select the site. GNOME's scientists wanted a relatively pure salt formation with low water content, the top of which was not more than 800 feet below the surface, in an area of low population density, and preferably on government land within the continental United States. With the assistance of the U. S. Geological Survey, an area meeting these specifications was found 25 miles southeast of Carlsbad, New Mexico. The specific site was chosen and the land withdrawn from the public domain and placed under AEC control.

Contractors and government organizations then moved in to prepare the site and to conduct studies to assure safety. As a part of this preliminary program a series of high-explosive experiments was conducted during 1959.

To provide independent scientific advice on geophysics, seismology, and hydrology relating to safety, a panel of experts, recommended by the National Academy of Sciences, was established. Panel members evaluated technical data, prepared by the U. S. Geological Survey, the U. S. Coast and Geodetic Survey, the Lawrence Radiation Laboratory, and other organizations, bearing on the suitability of the site from the standpoint of health and safety. The panel evaluated the expected seismic effects, appraised ground water conditions, and reviewed the geology of the region. They agreed that GNOME could be conducted without undue danger to the public, existing and potential mining areas, oil fields, and farm lands, and that it would not contaminate the ground water.

Work on the site could now begin. Engineering and construction plans were prepared by the firm of Holmes and Narver, Inc., using technical specifications prepared by the Lawrence Radiation Laboratory. The construction work

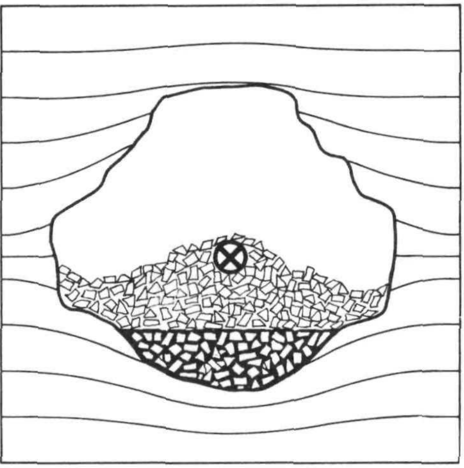


was done on contract by many companies; the largest job was digging a 1200-foot shaft and a 1116-foot emplacement tunnel from the bottom of the shaft to the explosion point. General support and minor construction requirements were handled by several New Mexico contractors and by the Reynolds Electrical and Engineering Company, Inc.

The nuclear explosive was assembled and emplaced by personnel of the Lawrence Radiation Laboratory and armed by workers of the Sandia Laboratory. The firm of Edgerton, Germeshausen & Grier, Inc., designed and installed the timing and firing equipment. Research and development experiments were conducted by personnel of the Lawrence Radiation Laboratory, Los Alamos Scientific Laboratory, Sandia Laboratory, Stanford Research Institute, Oak Ridge National Laboratory, the U. S. Bureau of Mines, the U. S. Coast and Geodetic Survey, and other agencies, under the technical direction of Lawrence Radiation Laboratory.

An extensive information program was undertaken. Observers from this country and abroad were invited to attend. All information except that pertaining to the design of the nuclear explosive was made available and has been summarized in a series of news releases, technical publications, and films.

In September 1961, personnel of the VELA UNIFORM program of the Advanced Research Projects Agency of the



In the GNOME explosion, initially a bubble of vaporized material formed and expanded outward (left). As equilibrium was reached (center), blocks of salt imploded from the cavity walls, cooling the pool of molten material that had collected in the bottom of the cavity. Later, partial collapse of the roof occurred, and a hemispherical cavity remained (right). Scale marks off 20-foot intervals.

Department of Defense became limited participants. VELA UNIFORM is a program to develop means of detecting, identifying, and locating underground nuclear explosions.

Isotope recovery studies, one of the many scientific objectives, were made to determine the possibility of recovering quantities of transplutonium isotopes produced in a nuclear explosion. It was expected that salt, being water-soluble, could be processed to recover the isotopes more simply and cheaply than other rock. The studies indicated that most of the non-gaseous isotopes produced would be concentrated in impurities in the salt and remain with these insoluble impurities when the samples were dissolved.

To study the possibilities of recovering heat deposited in the salt by the explosion was another objective. It was planned that water would be pumped into the hot cavity after the explosion and the quality of the resulting steam measured. It had been thought an explosion in salt was more likely than one in other rock formations to form a standing cavity—one that is open like a room—in which a pool of molten salt might collect.

A standing cavity was indeed produced by the explosion and about 2 trillion (2×10^{12}) calories of heat were deposited in the melted salt. But about 13,000 tons of colder rocks were blown or collapsed into the molten pool from

A hemispherical cavity about 75 feet high and 134 to 196 feet across remained from the GNOME explosion. Note man, standing on rubble, right center.

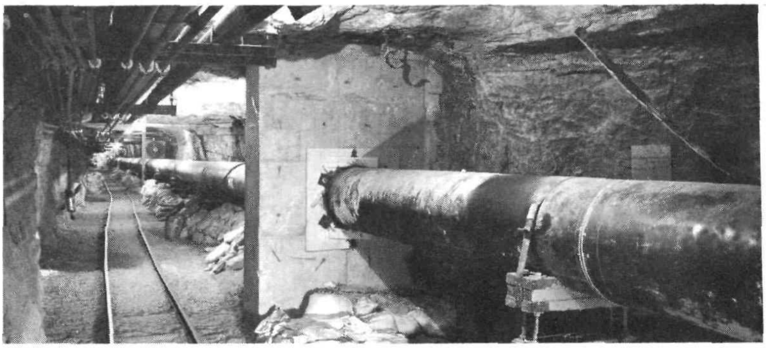
the walls and ceiling. As a result, the melted material was cooled suddenly and the heat distributed throughout a much larger mass. Thus it was not possible to recover any appreciable amount of the heat. Moreover, studies indicated that the steam produced was very corrosive. Its use would require special engineering methods and equipment, and consequently would not be economical.

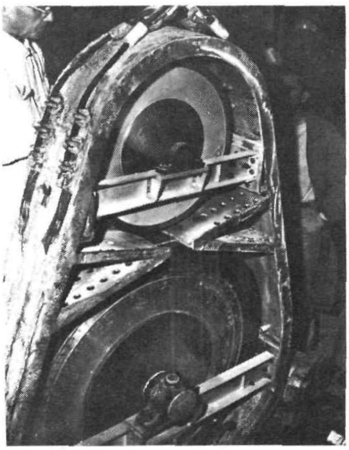
An interesting neutron physics experiment was conducted as part of GNOME. Equipment was arranged so that neutrons released by the nuclear reaction, after passing through a moderator* and an evacuated pipe 1000 feet long, struck samples of material mounted on revolving wheels. Neutrons with different energies have different velocities and so were sorted out by energy levels while in flight down the pipe, the fastest neutrons hitting the turning wheels first. This experiment was designed to gain knowledge from

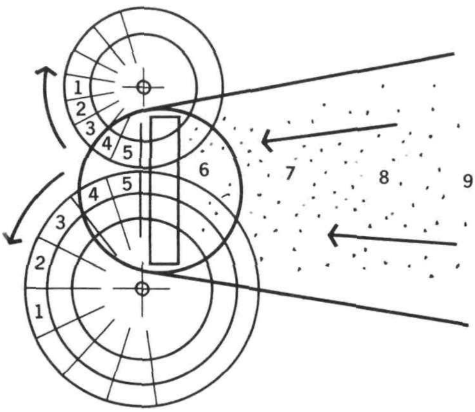
*A moderator is a material used to slow down high-velocity neutrons.

study of the irradiated materials on the wheels. Recovery of the neutron wheels was unexpectedly delayed until 6 days following the detonation, so some data were lost. But the data collected did contribute significantly to understanding of the structure and properties of the atomic nucleus.

Rock, mineral, and organic material samples also were placed so as to receive shock pressures from 5000 to 120,000 times atmospheric pressure. Samples that received up to 45,000 times atmospheric pressure were recovered and revealed interesting changes due to the shock







Neutrons from the GNOME explosion traveled down a vacuum-filled pipe to strike rapidly rotating wheels bearing samples. Top, interior of the tunnel showing vacuum pipe. Left, bottom, engineers adjusting the wheels. Right, diagram of the wheel assembly showing how neutrons arriving at different times struck the wheels at different positions.

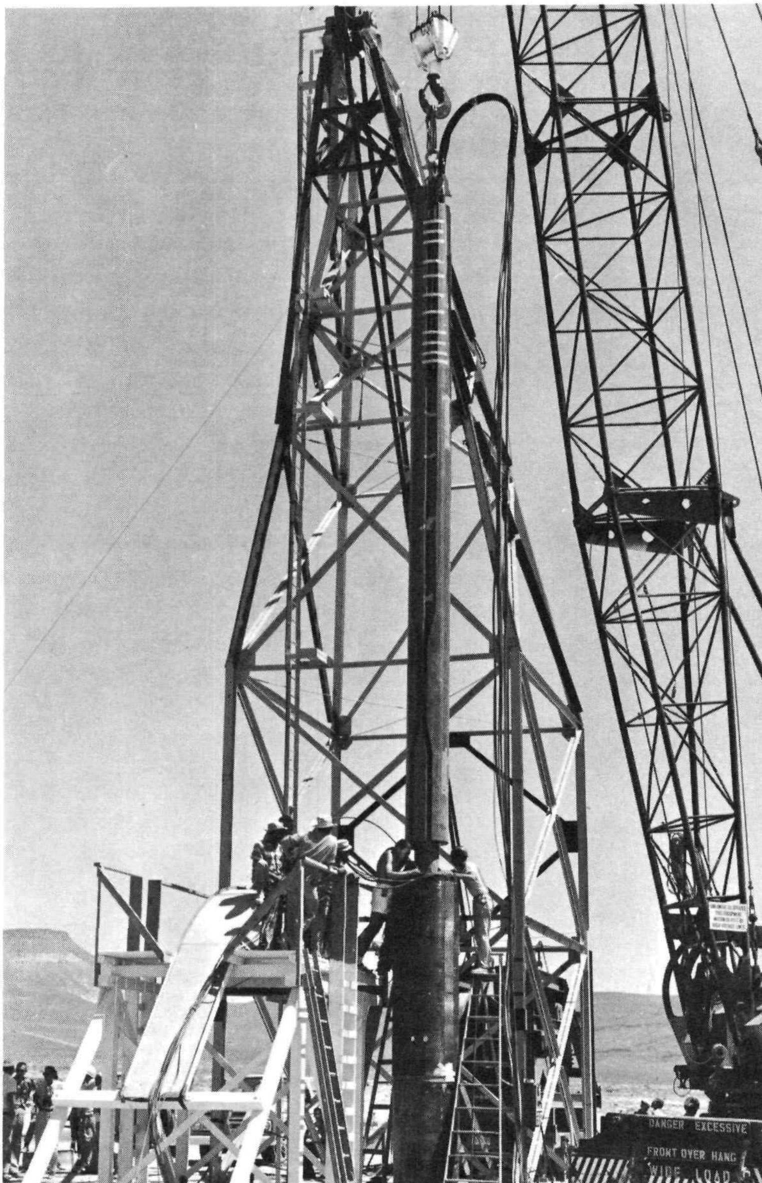
pressure. Samples that were subjected to higher pressures were mixed with the melted rock and rubble and could not be recovered. Greater pressures would be expected to produce more interesting changes, such as the possible shock production of diamonds. By placing the samples differently and making other changes in future underground explosions, it may be possible to recover samples subjected to shock pressures as high as 150,000 or 200,000 times atmospheric pressure.

Seismic instrumentation for GNOME was very extensive. The New Mexico site was interesting to seismologists because it lies close to the geological boundary between the Rocky Mountains and the Great Plains. The difference in travel times of the seismic waves moving in different directions to points at comparable distances from the site was found to be too great to be explained by variations in thickness of the earth's crust. It was therefore attributed to variations in the upper mantle of the earth, which lies deeper than the crust. This new information has contributed significantly to understanding the geological structure of the United States and probably will result in a reinterpretation of the properties of the earth's crust and mantle east of the Rocky Mountains. The seismic wave variations revealed by GNOME indicate that with similar coverage of detonations in other regions a clearer understanding of the earth's structure can be obtained.

Project SEDAN

Seven months after GNOME, on July 6, 1962, PLOWSHARE scientists had another project ready to go. This was a 100-kiloton cratering experiment given the name SEDAN. It was planned as the first of a series of nuclear explosions to develop techniques of nuclear excavation and to extend knowledge of cratering effects from explosions up into the 100-kiloton yield range.

Previous nuclear cratering experience had been limited to explosions of one kiloton yield or smaller, and the validity of using data from low-yield tests to predict results of much more powerful explosions was uncertain. SEDAN also was intended to provide safety data related to radioactivity, seismic effects, and air blast.



The 100-kiloton thermonuclear explosive and related experimental equipment for Project SEDAN being lowered into the drill hole.

The 100-kiloton SEDAN event formed the largest excavation ever produced by a single man-made explosion. Note the size of automobiles and structures near the crater rim.

The effect of the SEDAN explosion was awesome. The thermonuclear explosion occurred 635 feet below the surface and excavated a crater about 1200 feet in diameter and about 320 feet deep, with a volume of about 6.5 million cubic yards. The crater was slightly deeper than had been predicted on the basis of data from earlier work, and the radius was somewhat smaller.*

Examination of the fallout pattern from the explosion showed that most of the particulate radioactivity that escaped from the crater was deposited nearby. The fallout pattern is shown on page 19. Data from SEDAN confirmed a prediction that the close-in air-blast wave would be reduced to about one-fifth to one-tenth that to be expected from a surface burst of the same yield. Results from ground-motion stations indicated that the extent of the area of hazards from seismic effects for SEDAN was about 2.6 miles.

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*The apparent crater depth was about 5% larger than $W^{1/3.4}$ scaling predicted. The radius was about 15% smaller, thus approaching $W^{1/4}$ scaling. (See Appendix I for a discussion of scaling.)

Other Experiments

Experiments for the study of weapons effects conducted by the Department of Defense are always examined for information of value to the PLOWSHARE program. Two such experiments, which are described below, yielded data particularly significant to PLOWSHARE.

In the HARDHAT experiment, a 4.5 kiloton explosive was detonated 950 feet underground on February 15, 1962, at the Nevada Test Site. It was of particular interest to PLOWSHARE scientists because the test was made in a granite formation, typical of those encountered in many mining operations. The explosion formed a cavity about 126 feet in diameter, the roof of which collapsed about 11 hours after the detonation. Rock beyond the chimney also was fractured.

A PLOWSHARE mining experiment at the HARDHAT site provided information on the use of nuclear explosives to break and crush mineral deposits preparatory to extracting the ore by conventional techniques. A horizontal tunnel was driven through the rubble-filled chimney at a level 90 feet above the detonation point. More than 2700 tons of broken rock were withdrawn in a simulated mining operation. No hazardous amounts of radioactivity were encountered. The results from HARDHAT and the information obtained earlier from the RAINIER event are considered sufficient to allow undertaking an industrial-scale nuclear-mining project.

DANNY BOY, a low-yield nuclear cratering explosion in basalt, was set off at the Nevada Test Site on March 5, 1962. Instruments were installed to make measurements for the PLOWSHARE program. PLOWSHARE's objectives were to determine characteristics of crater formation in a hard, dry, inert medium, such as basalt, and to investigate the radioactivity released by a detonation in hard rock.

The explosion was set off 110 feet below the surface; the yield was about 400 tons. The resulting crater had a diameter of 214 feet and a depth of 62 feet. A base surge about 2900 feet in diameter and 1000 feet high was produced, and a cloud of dust diffused to a height of 2000 feet about 30 minutes after the detonation. Only a small portion—about

4%—of the radioactive particles was released as fallout and most of this was deposited within 2 miles of the blast. Information was obtained on variation of shock pressure with distance, seismic shock at various ranges, and air blast attenuation.

The HARDHAT, DANNY BOY, GNOME, and SEDAN investigations are cited only as examples of the overall research and development effort that is the PLOWSHARE program. For this program, ranging from laboratory bench, to the computer, to field tests, encompasses a wide variety of tasks—to develop and improve explosives, to develop a clearer understanding of crater and cavity formation, to obtain data on the effects of explosions in different types of rock, and to demonstrate specific applications of nuclear explosions.

THE FUTURE OF PLOWSHARE

The Approach

PLOWSHARE's chief task is learning to apply nuclear energy to specific uses, safely, economically, and with precision. This situation is little different from that of an apprentice carpenter's learning to use a saw. Properly applied, the saw can facilitate the building of a home, a boat or a beautiful piece of furniture. Improperly used, it can produce inferior work or harm its user.

Emphasis on safety is inherent in the PLOWSHARE program. Both the results of PLOWSHARE experiments and the record of the AEC in general have been excellent in safety matters. It is the AEC policy that no project be undertaken until there is assurance that there will be no undue risk to public health and safety.

In terms of economics, if the return does not justify the investment, nuclear explosives will find few users—either in government or industry—in the United States or elsewhere. The economy of nuclear explosives for large excavation projects has been demonstrated, and has been predicted by calculations for a number of other purposes. Other possible applications look less promising from an economic viewpoint, but should not be ruled out altogether, for economic factors are subject to change with time and technological advances.

In order to assist industry in evaluating possible uses of nuclear explosives, the AEC has announced projected charges of $350,000 for an explosive with a 10-kiloton yield and $600,000 for one with a 2-megaton yield. (Appendix II contains more information on these projected charges.) These charges indicate that the economic gain increases as the yield of the explosive increases. For example, increasing the yield from 10 to 2000 kilotons—a 200-fold increase—does not even double the charge.

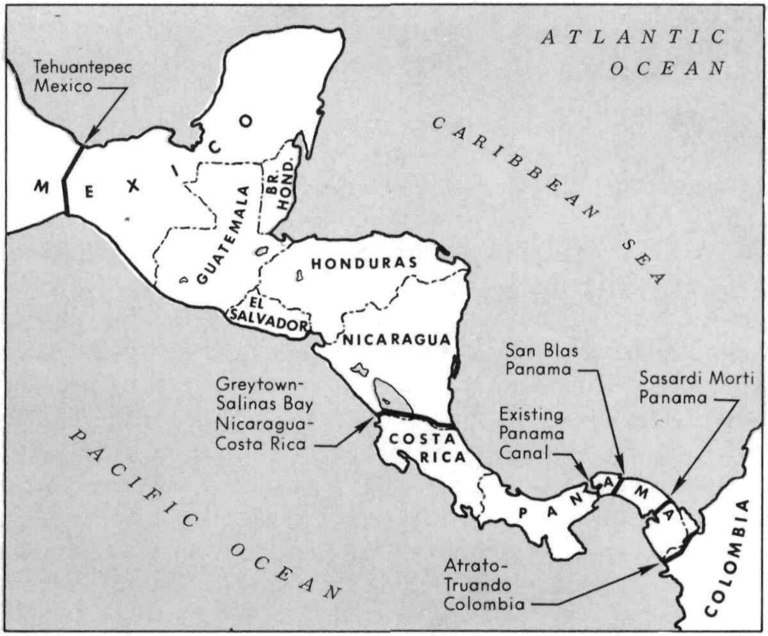
The feasibility of using nuclear explosives for peaceful purposes, however, will not be determined only by proven technology, safety, and economics. For in a program, such as PLOWSHARE, which involves a new source of enormous energy about which there is often misunderstanding and controversy, factors—political, sociological, and psychological—outside the scope of the AEC's technical program exert influence. These factors are complex and cannot be discussed adequately in a booklet of this length.

The Vision

The PLOWSHARE program was begun and has moved forward with an awareness of the important and beneficial things that can be done with nuclear explosives. Progressively the program is building toward specific applications. For example, the translation of chemical-explosive row-charge experience into nuclear terms is a step toward application of nuclear explosive engineering to the construction of canals. A planned series of cratering and cavity-making explosions in different rock and earth media is designed to enable engineers to construct—with precision and safety—harbors, dams, underground reservoirs, and mountain passes.

A sea-level canal across the Central American isthmus has been a dream since Balboa first saw the Pacific Ocean. In fact the present Panama Canal was originally begun by a French Company as a sea-level canal, but the overwhelming amount of rock to be excavated forced the company to redesign it as a lock canal. When the United States acquired

Nuclear explosives may be used to cut passes through mountainous regions. Such a project was studied by the AEC, the Atchison, Topeka and Santa Fe Railway Company, and the State of California Division of Highways. The study indicated that 22 nuclear explosions totaling 1730 kilotons could cut a pass, as shown in this photo of a model, through the Bristol Mountains about 11 miles north of Amboy, California.



The 5 routes shown on this map have been studied as possible sites for the construction, with nuclear explosives, of a sea-level canal across the Central American isthmus.

the concession, American engineers recommended a sea-level canal; but again the tremendous amount of money and time that would have been required forced adoption of a lock-canal design. Subsequent proposals for excavating a sea-level canal by conventional methods have faced the same prohibiting time and cost factors. Cost estimates have ranged from more than $2 billion to more than $13 billion for various routes; the biggest cost element—up to 85% of the total—has been the excavation.

A 1960 Panama Canal Company report indicated that digging a sea-level canal with nuclear explosives would be

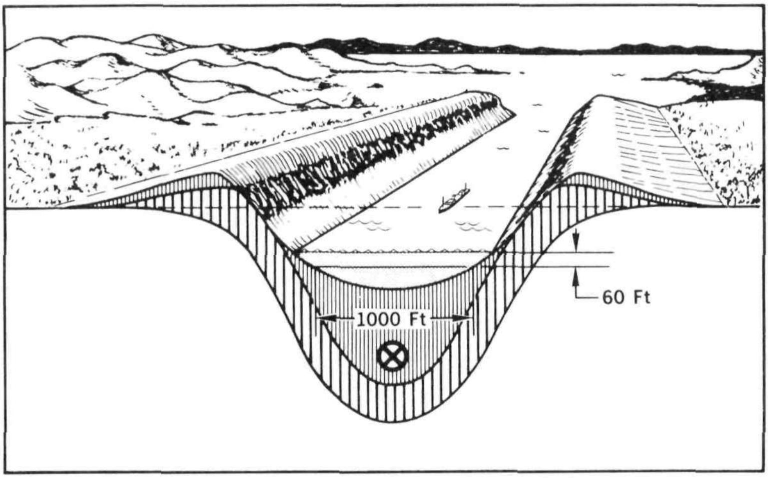
SALIENT FEATURES OF FIVE TRANS-ISTHMIAN ROUTES

Site	Length (miles)	Maximum elevation of divide (feet)	1947 Estimated* costs for conventional excavation (millions)	1960 Estimated† costs for nuclear excavation (millions)
Tehuantepec, Mexico	125	810	$13,000‡	$2,300
Greytown-Salinas Bay, Nicaragua	140	760	4,100	1,900
San Blas, Panama	37	1,000	6,200	620
Sasardi-Morti, Panama	46	1,100	5,132	700
Atrato-Truando, Colombia	102	950	5,261	1,200

*Estimates are based on a canal 600 feet wide and 60 feet deep.

†Estimates are based on a canal 1,000 feet wide, 250 feet deep at the center and include the construction costs of all operating facilities.

‡Estimate for lock canal only.



A sea-level canal, dug by nuclear explosives, as shown in this cross-section drawing, would be 1000 feet wide and at least 60 feet deep.

ESTIMATED COSTS FOR CONSTRUCTION OF A SEA-LEVEL CANAL ON TWO ROUTES ACROSS THE AMERICAN ISTHMUS*

	Route 17 (Sasardi-Morti) Panama	Route 25 (Atrato-Truando) Colombia
Phase I–Feasibility & Site Selection Surveys	$ 17,000,000	$ 17,000,000
Phase II–Engineering Surveys & Design	13,000,000	18,000,000
Phase III–Construction		
General construction:		
Construction for site access	90,000,000	130,000,000
Conventional excavation & embankments	70,000,000	470,000,000
Permanent facilities	60,000,000	80,000,000
Nuclear excavation:		
Emplacement drilling	60,000,000	70,000,000
Area excavation	30,000,000	30,000,000
Safety program	50,000,000	60,000,000
Explosives & firing services†	150,000,000	150,000,000
Engineering	30,000,000	75,000,000
Total	$570,000,000	$1,100,000,000
Contingency (15% of Phase III)	80,000,000	160,000,000
Total estimated cost of construction	$650,000,000	$1,260,000,000

*"Engineering With Nuclear Explosives: Proceedings of the Third Plowshare Symposium", TID-7695 (1964), p. 332.

†Estimate for engineering and production of a stockpile of a few hundred nuclear explosives for excavation, including services associated with firing them. This estimate is consistent with the 1964 charges announced by the Atomic Energy Commission.

feasible and safe. In addition, the company reported that the nuclear canal would be larger than one dug by conventional methods; thus it should be more useful, less vulnerable, and require less maintenance. Furthermore, to dig such a canal by nuclear excavation methods would cost only a fraction of the expense of conventional excavation. In 1959 and 1960 studies, five routes, shown on the map, were investigated. More recent (1964) studies* indicated that, because of technological advances, the cost may be as low as $650,000,000 for the Sasardi-Morti route and $1,250,000,000 for the Atrato-Truando route.

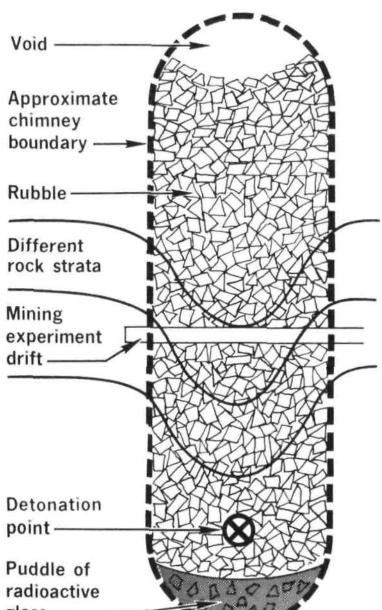
Petroleum recovery is another activity that has been subjected to considerable study. In particular, the Athabaska Tar Sands formation underlying 17,000 square miles of Alberta, Canada, has been investigated by the Richfield Oil Company for the possible use of nuclear explosives. The petroleum in these sands—an estimated 600 billion barrels of crude oil—is in the form of a gummy tar that

*For one such study see "Engineering with Nuclear Explosives: Proceedings of the Third Plowshare Symposium", TID-7695, 1964, p. 321.

does not flow freely enough to be pumped out by normal methods. Calculations indicate that a 9-kiloton nuclear explosive would release enough heat so that several hundred thousand barrels of oil could be recovered in a free-flowing state. While such a project would not pay for itself, it would provide a basis for further investigation and economic analysis.

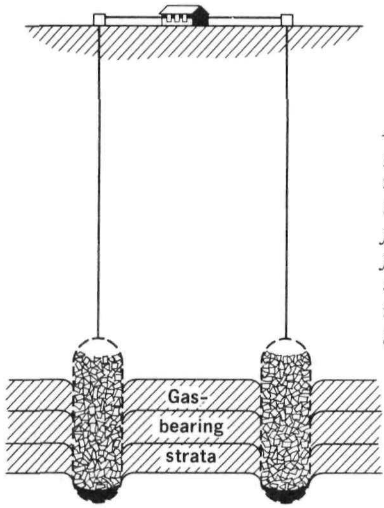
A similar proposal is to detonate a nuclear explosive in an oil shale formation. Only the fracturing energy of the nuclear explosive would be used—not the heat. The final recovery of oil might then be accomplished by "retorting", or heating, the broken shale with heat from other sources; it is proposed either to retort the shale while it is still in the ground and pump the crude oil to the surface, or to bring the broken shale to the surface and then retort it.

Mining of mineral deposits may be made easier by using nuclear explosives to aid in the removal of overburden or as a breaking agent to prepare ore bodies for mining or for leaching-in-place* of valuable minerals.



Ore may be recovered using standard mining techniques after the ore body has been broken by a nuclear explosion.

*Leaching is a process in which a liquid that will dissolve the mineral is pumped through the ore and emerges bearing metal; for example, sulfuric acid is used to leach copper ore.



A chimney of highly fractured, permeable material created by a nuclear explosion may increase the productivity of natural gas fields in which the gas does not flow freely. The nuclear explosion would produce a large "well" in which gas could collect and then be pumped to the surface.

Gas fields exist from which little or no gas can be produced due to the low permeability of the host rock. Preliminary studies* by the U. S. Bureau of Mines and several oil and gas companies indicate that increased production can be achieved in reluctant oil and gas fields by using nuclear explosives as fracturing tools. Detonation of nuclear explosives—below a host formation that is relatively thin, or in a host formation that is several hundreds or thousands of feet thick—would fracture large volumes of rock. Such fracturing would increase the permeability to the extent that economic recovery of gas might be possible.

Hydroelectric power development in the desert of North Africa awaits only the introduction of water from the Mediterranean Sea, no more than 35 miles away, into two below-sea-level depressions.† One is the 8000 square-mile Qattara Depression in Egypt's western desert, which is as much as 400 feet below sea level. The other is the 50,000-square-mile Chotts Depression, starting just 20 miles from Tunisia's coast. Studies have been made of the possibility of connecting these depressions to the sea by canals so that

*"Engineering with Nuclear Explosives: Proceedings of the Third Plowshare Symposium", TID-7695, 1964, p. 269.

†Sanders, "Project Plowshare", pp. 123-5.

large hydroelectric plants could be powered by the flow of salt water into the depressions to form shallow new inland seas. It is predicted that natural evaporation from the new seas would reduce their level rapidly enough to assure a continuous inflow from the sea for many years. It is also believed that canals into these depressions might open up vast, now unusable, areas to commerce and induce human migration to the vicinity. Nuclear explosives might make building these canals feasible.

New harbors, particularly in such areas as the west coasts of Africa, Australia, and South America,* would greatly assist economic development of these regions. These coasts adjoin areas of extensive mineral resources and some of the world's most fertile fishing grounds. Well-placed harbors can open these regions to development, but in some cases only nuclear explosives are powerful enough to do the required work.

In the control and conservation of water supplies, nuclear explosives have been suggested to alter watersheds, interconnect aquifers,† create or eliminate connections between surface and underground water supplies, and—where evaporation loss is high—create underground reservoirs. One of the most promising suggestions is the use of nuclear explosives to connect the surface with existing potential aquifers. This would be especially important in the arid regions where infrequent torrential downpours punctuate long, dry periods. In such areas, unless there is a way to impound rainwater quickly—preferably underground to minimize loss through evaporation—it is lost.

Other proposals to develop natural resources include the use of explosives to bring down canyon walls to form dams, or to aid in releasing natural geothermal heat to produce steam for desalting seawater or for electric power. Synthesis of chemicals in the ground also has been proposed, for example, calcium carbide might be produced from an explosion in a formation of coal and limestone; then by adding water, acetylene gas could be made.

For scientists, a nuclear explosion provides an intense source of many things needed in research: high pressure,

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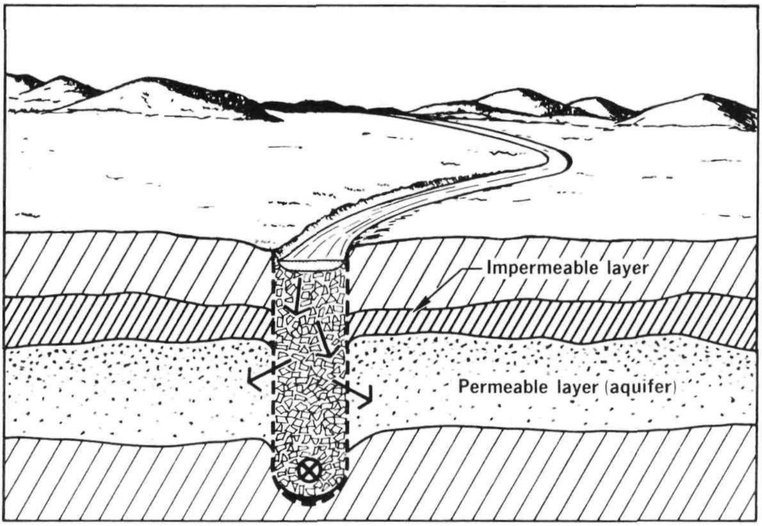
*Sanders, "Project Plowshare", p. 117.

†An aquifer is a water-carrying underground rock formation.

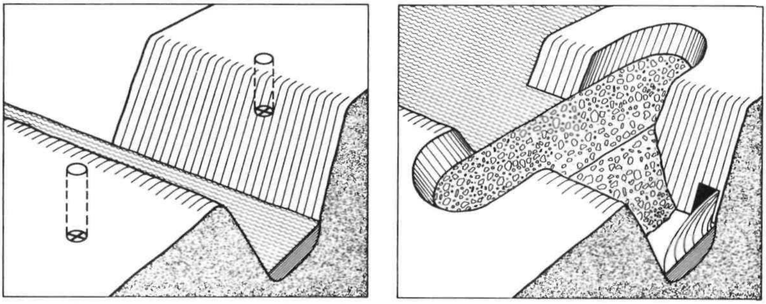


A nuclear explosion might be used to break through a barrier to permit run-off water to be used to recharge underground aquifers.

high temperature, fundamental particles such as neutrons and neutrinos, and most forms of electromagnetic radiation, such as gamma rays.

New elements have been created in nuclear explosions that do not occur naturally on earth. Einsteinium, element 99, and fermium, element 100, were first identified in the products of a thermonuclear explosion. Since then, several nuclear explosions designed specifically to produce heavy elements have been conducted. One of the most encouraging was the PAR experiment in October 1964, which produced the highest total neutron flux yet observed—about 4×10^{24} neutrons per square centimeter. Analysis of the PAR data shows that many transplutonium isotopes were created.

This method of making transplutonium elements involves exposing heavy-element target atoms to the intense neutron flux produced by the explosion. The resulting instantaneous capture of many neutrons in each of the nuclei of the target atoms creates unstable neutron-rich isotopes of the target material. These isotopes then undergo beta decay, in which electrons are ejected from the nuclei. Isotopes with higher atomic numbers and masses greater than that of target element result.



Mountain sides might be collapsed into valleys to make dams, with properly planned nuclear explosions.

In a nuclear explosion, target atoms undergo neutron exposures equivalent to several years of irradiation in one of the most powerful nuclear reactors. Moreover, some difficulties of reactor irradiation, caused by isotopes with short half-lives, are avoided. Thus nuclear explosives may be used in the scientific research field to produce significant quantities of scarce isotopes, new isotopes of heavy elements, or possibly new elements.

Under the extremely high pressures achieved in a nuclear explosion, the electron shells of the atomic structure are deformed, and matter acts in strange ways. For example, at 10 million atmospheres carbon can be compressed into a state denser than diamonds, and iodine, usually a nonconductor, becomes an electrical conductor.

As a source of neutrons, a nuclear explosion makes it possible to improve measurements of neutron capture and fission excitation values for numerous elements, and offers a possible means of measuring these values for highly radioactive isotopes that cannot be measured in the laboratory.

Study of these phenomena contributes to basic understanding of matter, and suggests that the research potential of nuclear explosions is as great as the potential for industrial applications.

Conclusion

The suggested applications for nuclear explosives are many; some, probably, are not yet imagined. The basic energy source, the nuclear explosive, is available, though modifications are often necessary, and improvements can be made. The PLOWSHARE program, which studies and develops peaceful applications for nuclear explosives, is well under way. Both promising and discouraging results are anticipated. The AEC is looking to industry for help in carrying out projects jointly, in order to evaluate and demonstrate specific applications, and for new ideas for using nuclear explosives constructively.

Some of the greatest benefits from PLOWSHARE applications may be the indirect ones. For instance, the ultimate limit on the size of ships now is the depth of harbors and canals. Consequently it is now possible to increase the size of ships only by increasing the length and width, and with such constraints the cost of larger ships becomes uneconomical. However, the use of nuclear explosives to create deeper harbors and canals than are now possible would remove this restriction and allow the building of deeper ships. This might reduce the cost of marine transportation.* This simple change, in addition to the saving in costs of building the harbors and canals with nuclear explosives, could have tremendous impact on the economy of ocean transport.

The imagination and effort devoted to the PLOWSHARE program must be great and relentless. For at stake is a source of tremendous energy, capable of doing great good for mankind. Surely as man discovered means to free nuclear energy, he is capable of finding ways to use it for his benefit.

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*"Engineering with Nuclear Explosives: Proceedings of the Third Plowshare Symposium", TID-7695, 1964, pp. 349-53.

APPENDIX I—CRATER SCALING LAWS

A scaling law is a simple mathematical rule that expresses the relationship between two variable quantities. Such a law is based on observable data and theoretical considerations and usually takes the form of an equation that can be used to predict the results of experiments. An example is the equation for the area of a square:

$$A = s^2$$

Thus, if you double the length of the side, the area is not doubled, it is quadrupled. In other words, the area scales as the square of the length of the side, and conversely, the side scales as the square root of the area.

Development of reliable scaling laws is a primary PLOWSHARE objective. Scaling laws are needed in order to predict the cratering effects of nuclear explosions in the hundred kiloton and megaton ranges from information obtained from explosions of lower yields. Scaling laws are necessary devices in the selection of explosive yields and in determining the correct depth-of-burial to produce a crater of desired dimensions. The laws must be applicable to many types of rocks and soils.

Theoretically, the yield of explosive energy to form a crater of given size scales approximately as the cube of the crater dimensions. Thus, if we want to double either the radius or the depth of a crater we would have to use a charge with eight ($2^3 = 8$) times as large a yield. Conversely, linear crater dimensions scale as the cube root of the explosive yield. These relationships are expressed in the three basic scaling law equations:

$$SCD = \frac{CD}{W^{1/a}}$$

$$SCR = \frac{CR}{W^{1/a}}$$

$$SDOB = \frac{DOB}{W^{1/a}}$$

where SCD = scaled crater depth
CD = crater depth
SCR = scaled crater radius
CR = crater radius
SDOB = scaled depth of burial
DOB = depth of burial
W = yield (weight of equivalent kilotons of TNT)
1/a = the scaling factor (where a = 2, 3, 3.4, or 4)
$W^{1/a} = \sqrt[a]{W}$, the a^{th} root of W.

Three different scaling factors, 1/3, 1/3.4, 1/4, have been considered at various times. However, even before the 100-kiloton SEDAN experiment, PLOWSHARE scientists suspected that the cube root (1/3) scaling would not hold for large explosions; in fact, they worked with 1/3.4 in the SEDAN test. This factor means that to double crater dimensions it is necessary to use a charge with a yield 10 times as large.

Maximum crater dimensions are obtained by using a specific scaled depth of burial, which is computed from the yield and actual depth of burial. Since the scaling factor used for depth of burial, 1/3.4, is the same as the scaling factor used for crater dimensions, if the yield is increased tenfold, the depth of burial must be doubled in order to keep the scaled depth of burial for maximum crater dimensions the same. That is,

$$SDOB = \frac{DOB}{W^{1/3.4}} = \frac{2\ DOB}{(10W)^{1/3.4}}$$

Pre-SEDAN calculations based on 1/3.4 scaling predicted a crater 300 feet deep and 1400 feet across. Based on 1/4 scaling, the predicted dimensions were 170 feet and 1200 feet, respectively. The actual SEDAN crater dimensions, 323 feet deep and 1216 feet across, approximated a depth scaling of 1/3.4, and a diameter scaling of 1/4.

The scaling factor for ditching, or detonation of simultaneous row charges, does not follow 1/3 scaling, even for small charges. Instead, the scaling factor approximates 1/2, or a square root relationship. When five or more cratering charges are placed in a straight line, at the proper depth, approximately one crater radius apart, and detonated simultaneously, they produce a ditch with smooth sides and bottom. The total excavated volume is about 20% greater than if an equal number of individual cratering charges were set off. Most of the ejected material is thrown out to the sides, with almost none at the ends. This last characteristic makes the technique especially appropriate for construction of canals.

Most ditching experience has been obtained with use of chemical explosive charges ranging in size from 256 pounds to 20 tons. Proposed large-scale projects will require nuclear explosives in the megaton range, and it may well be that at that level the 1/2 scaling factor will no longer apply.

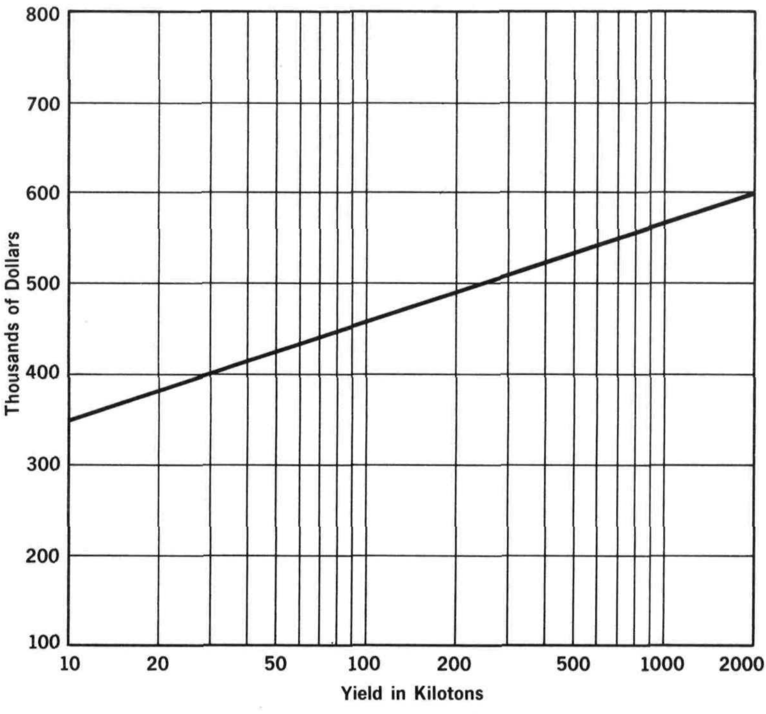
Development and understanding of scaling laws for nuclear excavation in various media and over a wide range of yields can only be gained through field experiments. It may turn out that the applicable scaling laws are more complex than it is now believed and additional factors, such as the depth and type of overburden, may have to be included.

APPENDIX II—POLICY STATEMENT ON PROJECTED CHARGES FOR PEACEFUL NUCLEAR EXPLOSIVES

As part of its PLOWSHARE program to investigate and develop peaceful uses for nuclear explosives, the AEC has encouraged industry and other groups to participate in the program by analyzing the possible uses of nuclear explosives in their specific fields. To allow such investigations the Commission, in 1958, released, within the limits permitted by the national defense and security, a schedule of cost estimates for nuclear explosives and related services, including safety studies.

Since that time, improvements have been made both in the design of nuclear explosives and in their emplacement, as well as in the technology of the explosion and its effects. One of the most significant technological advances has been in the development of thermonuclear explosives with very low fission yields. Also, costs of safety studies, which were included in the 1958 charges, can be accurately estimated only for each individual situation. These developments indicate that the charge for nuclear explosives ultimately developed for peaceful uses will cost less than predicted in 1958.

Consequently, the Atomic Energy Commission has revised its estimates and now projects a charge of $350,000 for a nuclear explosive with 10-kiloton yield and $600,000 for a nuclear explosive of 2-megaton yield. Interpolations may be made for other yields based on a straight line



drawn between these two charges on semi-logarithmic paper, as shown. These charges cover nuclear materials, fabrication and assembly, and arming and firing services. Significant related services that are not covered by these projected charges are safety studies, site preparation including construction of holes, transportation and emplacement of the devices, and support. For such of these related services as are supplied by the AEC, the user would be expected to pay full cost in accordance with the present

AEC policy. These costs depend significantly on the number of explosives detonated at one time.

These projected charges are released only for use in feasibility studies and evaluations and are based on a projection to a time when explosives will be produced in quantity for routine commercial utilization. Nevertheless, the Commission believes that these projected charges are sufficiently representative of the future situation to warrant their use in feasibility studies. At the present time, the Commission is not authorized to supply nuclear explosives and related services on a commercial basis, although the Commission may engage in research and development arrangements, including demonstrations of a particular peaceful application for nuclear explosives.

The Commission believes that more research and development is needed before any routine commercial applications are practical. Therefore, the Commission will continue to work with other groups in studying the contribution their proposals for projects could make to the research and development program. It is expected that technical and economic information can be derived from such projects to help develop and demonstrate peaceful uses for nuclear explosives. In such projects it can be expected that the Commission will negotiate the charge to be made for the nuclear explosives and related services based upon a number of factors, including the nature of the contribution by the other party, the economic value of the project to the other party, and the value of information to be received by the Commission. Although the projected charges discussed above might be used as a basis for discussion of costs to be assumed by the AEC in such projects, it should be recognized that the costs to be assumed by the AEC as finally negotiated might be significantly different from the projected charges.

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Project Sedan, 8 minutes, color, sound, 1962. Produced by the AEC's Lawrence Radiation Laboratory at the University of California. Describes the first of a series of experiments in the PLOWSHARE program to determine the feasibility of nuclear excavations.

Project Gnome, 29 minutes, color, sound, 1963. Produced by the AEC's Lawrence Radiation Laboratory at the University of California. Describes the first underground nuclear detonation in the PLOWSHARE program from its planning stage through the early months of the post-detonation period when scientists entered the man-created cavern.

PLOWSHARE, 28 minutes, color, sound, 1965. Produced by the AEC's San Francisco Operations Office. This film, on a popular level, introduces the PLOWSHARE program, presents the status of its development, and illustrates its research and development. The film explains the various potential uses of this enormous force of energy to perform tasks for the benefit of mankind, and explores the scope and range of possible applications in mining, petroleum recovery, massive earth-moving and excavations, and scientific research.

Safety in the Plowshare Program, 20 minutes, color, sound, 1965. Produced by the AEC's Nevada Operations Office in cooperation with the Divisions of Peaceful Nuclear Explosives and Public Information. This film discusses in detail the safety measures surrounding PLOWSHARE operations. Films made at the scene of several detonations as well as graphic art illustrating the environmental effects of the explosions are shown. Some of the beneficial uses of these peaceful nuclear explosives are also explained.

This booklet is one of the "Understanding the Atom" Series. Comments are invited on this booklet and others in the series; please send them to the Division of Technical Information, U. S. Atomic Energy Commission, Washington, D. C. 20545.

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