

EXCAVATION with NUCLEAR EXPLOSIVES

. . . promise and problems

By Gerald W. Johnson

THE Plowshare Program, devoted to exploring the potential constructive uses of nuclear explosions, was formally established in 1957 by the Atomic Energy Commission. Many of the ideas, thoughts, and suggestions for such applications had been put forth from the time it appeared possible to release energy from the nucleus in a controlled manner, using either reactors or explosions. In fact, in 1939, immediately after the publication of the discovery of the fission of uranium early in that year, many speculations appeared in the press concerning possible industrial uses of nuclear energy. Congress, in writing the Atomic Energy Act, noted, in the declaration of that Act, that "atomic energy is capable of application for peaceful as well as military purposes". In addition, the stated policy of the United States is that:

"a. the development, use, and control of atomic energy shall be directed so as to make the maximum contribution to the general welfare, subject at all times to the paramount objective of making the maximum contribution to the common defense and security; and

"b. the development, use, and control of atomic energy shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise."

As is always the case with a new technology, much of the research and development is partially justified and funds are appropriated on the basis of projected industrial and civil use. Atomic energy

has been no exception. However, a rather curious thing is happening in the United States: while national investments in research and development are increasing, the apparent return is not increasing nearly so rapidly—in fact, over the past twenty years the trend appears rather to be retrograde.

In the period 1947 to 1954, the average rate of growth of the economy was 3.7 percent; from 1954 to 1960 it was 3 percent. This took place in a period when our research and development expenditures tripled and the percentage of gross national product spent on research and development doubled (from 1.4 to 2.8 percent). Of the 2.8 percent, 2 percent is for space, defense, and atomic energy and 0.8 percent for all other purposes. Much of the justification of these enormous expenditures is based on the assumption that results will directly benefit industry and the economy. In commenting on this point recently, Mr. Holloman, Assistant Secretary of Commerce for Science and Technology,¹ had this to say: "These efforts to develop military equipment, atomic power plants, and space vehicles may well be providing the basis for a whole new technology of complex systems made up of highly reliable parts, but the translation of this technology to the economy through industry and commerce is neither direct nor cheap—nor inevitable. In fact, the translation requires specially trained people with a special point of view and an industry that understands and appreciates the possibilities of the new technology and can afford to use it. These people come from the same pool of scientists and engineers who provide the technology to meet the threat to our national security."

Gerald W. Johnson is associate director of the University of California's Lawrence Radiation Laboratory at Livermore. This article is based on a talk presented by Dr. Johnson on June 14 of this year at the University of California symposium on the Impact of Science, held in La Jolla, Calif. At that time the author was serving as assistant (for atomic energy) to the Secretary of Defense.

The Plowshare Program is an attempt to translate the technology of nuclear weaponry to the works of man. To accomplish this will require effort and will employ the same technology and people who have been responsible for the tremendous developments in weapons. While there are several goals of the program, I want to focus now on one which appears to be within reach if we want to use it—namely, the employment of nuclear explosions for excavation. My reason for selecting this area for discussion is that I believe the margin of potential cost advantage in using nuclear excavation on large projects is sufficient and that economic factors are not likely to be controversial. It also is an area in which major contributions to the public welfare can be made in the immediate future in terms of water-resource development and conservation, commerce (harbors and canals), and mining. In addition to attacking our own problems, through developing these methods and making them available on an international basis, important steps in international cooperation may also be taken.

The simple technical idea of nuclear excavation involves the detonation of nuclear charges, either singly or in an array, to provide a crater or a ditch for appropriate engineering purposes.

The principal problems appear to involve the development of techniques and the experimental demonstration that public health and safety are in fact assured so that public apprehensions centered around psychological-political factors may be overcome.

The bulk of the experimental program over the past few years has been directed toward developing suitable explosives, understanding the physical processes involved in cratering, and verifying theoretical models through full-scale experiments. Of most interest has been the determination of the sizes and characteristics of the craters formed, depending on the magnitude of the charge (scaling), the depth of placement, the nature of the medium, and, for multiple charges, the spacing between charges. Since 1957 a large part of the Plowshare Program has been devoted to carrying out experiments with charges of chemical explosives ranging from 256 pounds to 500 tons in a single event. These charges were spherical and centrally ignited to duplicate the characteristics of a nuclear explosion as closely as possible. This work established a scaling law for chemical explosives over the experimental range of yield used, which covers a factor of 4000 in energy. The derived relationships showed the crater diameter and depth to be proportioned to $W^{1/3.4}$, where W is the yield. In addition,

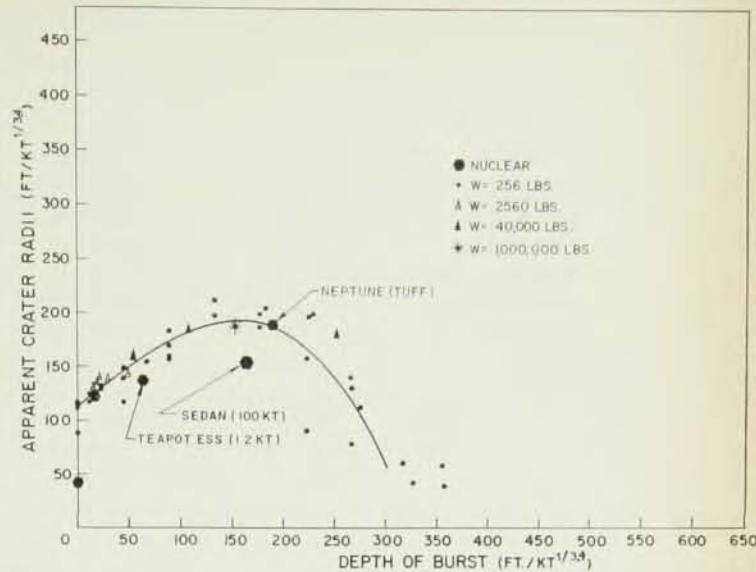


Fig. 1

tion, the dependence of crater dimensions on depth of burst was well established for Nevada desert alluvium (a lightly cemented sand and gravel). The results of this work are plotted in Fig. 1 and Fig. 2 (courtesy M. Nordyke²), where the data are all corrected to 1 kt using the empirical scaling law. Shown on the same graphs are the results obtained with nuclear explosions, which consisted of three nuclear experiments at 1.2 kt and one at 500 tons in the same medium fired for military-effects purposes (JOHNIE BOY, not plotted), one 115-ton nuclear weapons-development experiment in tuff (NEPTUNE), one 500-ton military experiment in basalt (DANNY BOY, not plotted), and one 100-

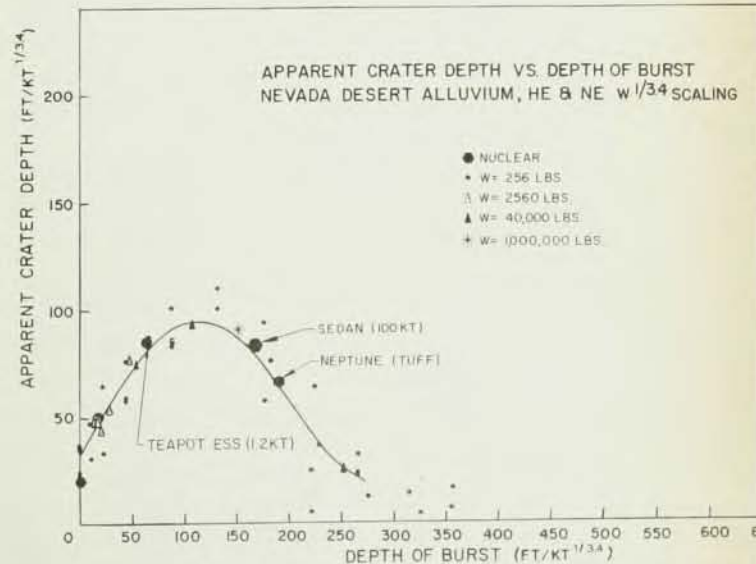


Fig. 2

Table 1. Nuclear Cratering Tests

<i>Event</i>	<i>Yield (kt)</i>	<i>Medium</i>	<i>Depth of burst (feet)</i>	<i>Crater radius (feet)</i>	<i>Crater depth (feet)</i>	<i>Crater volume (yd³)</i>
JANGLE S	1.2	Alluvium	-3.5 ^a	45	21	2470
JOHNIE BOY	0.5	Alluvium	2	62	30	6650
JANGLE U	1.2	Alluvium	17	130	53	3.7×10^4
TEAPOT ESS	1.2	Alluvium	67	146	90	9.6×10^4
DANNY BOY	0.42	Basalt	112	110	63	4.4×10^4
NEPTUNE	0.115	Tuff	100 ^b	100	35	2.2×10^4
SEDAN	100.00	Alluvium	635	600	320	6.7×10^6

^a The distance to the center of the explosive—above the surface.

^b NEPTUNE was detonated 100 feet beneath a 30° slope.

kt Plowshare cratering shot. The experiments together with the results are given in Table 1. Except for the 1.2-kt event slightly above the surface (3.5 feet), the agreement of the scaled nuclear data with the high-explosive results is striking. If the scaling law derived from the chemical-explosive experience is used, the observed crater depths for nuclear experiments lie on the empirical curves, but the radii are fifteen to twenty percent smaller.

When most of this work was considered together with some experimental work with chemical explosives using spaced charges, it was possible to make some estimates of sizes and costs of various excavation projects. Such estimates for single craters published in 1960³ are listed in Table 2. The costs were based on published estimates of costs of nuclear explosives developed for military systems and on the cratering data available at that time. Both the projected costs and dimensional characteristics must now be revised in the light of new results and developments. For example, all predicted volumes must be reduced by a factor of two. Economically, this makes slight difference although it will require an approximate doubling of yields since there will be little change in cost.

As a consequence of the large strides made in the technology of nuclear explosives in the last two years, it now appears that an explosive can be pro-

vided for Plowshare purposes in the near future with the following characteristics:

1. It can be lowered down a 36-inch hole;
2. It will weigh not more than 10 000 pounds;
3. It can provide an energy release at selected values from 100 kt to 1 Mt;
4. Its release of radioactivity will be greatly reduced in comparison with earlier systems.

Larger-yield and smaller-yield systems can be provided at some adjustment in cost and dimensions. However, for the present, most actual projects that have been examined can be approached successfully using explosives in the 100 kt to 1 Mt range of energy release.

Of major projects examined, the one most extensively studied is that for a sea-level canal across the American Isthmus. This has been under study for several years by the Corps of Engineers of the US Army and the Panama Canal Company in collaboration with the Atomic Energy Commission. The House Committee on Merchant Marine and Fisheries reported to the House of Representatives on June 23, 1960, that a sea-level canal probably would not be economically feasible in the foreseeable future unless nuclear methods can be used. The committee urged that development of such methods be vigorously pursued.⁴ Last year the AEC set a goal of approximately five years for the

Table 2. Estimated Costs of Crater Formation in Dry Desert Alluvium

<i>Yield (kt)</i>	<i>Placement Hole</i>		<i>Explosive Cost (\$)</i>	<i>Placement Cost (\$)</i>	<i>Operations (\$)</i>	<i>Total (\$)</i>	<i>Crater Dimensions</i>			
	<i>Diam (in)</i>	<i>Depth (ft)</i>					<i>Diam (ft)</i>	<i>Depth (ft)</i>	<i>Volume (yd³)</i>	<i>Cost (\$/yd³)</i>
1	36	160	500 000	100 000	500 000	1 100 000	400	90	210 000	5.25
10	36	325	500 000	150 000	750 000	1 400 000	800	175	1 600 000	0.88
100	70	620	750 000	300 000	1 000 000	2 050 000	1600	350	12 000 000	0.17
1000	70	1220	1 000 000	600 000	2 000 000	3 600 000	3200	690	96 000 000	0.04

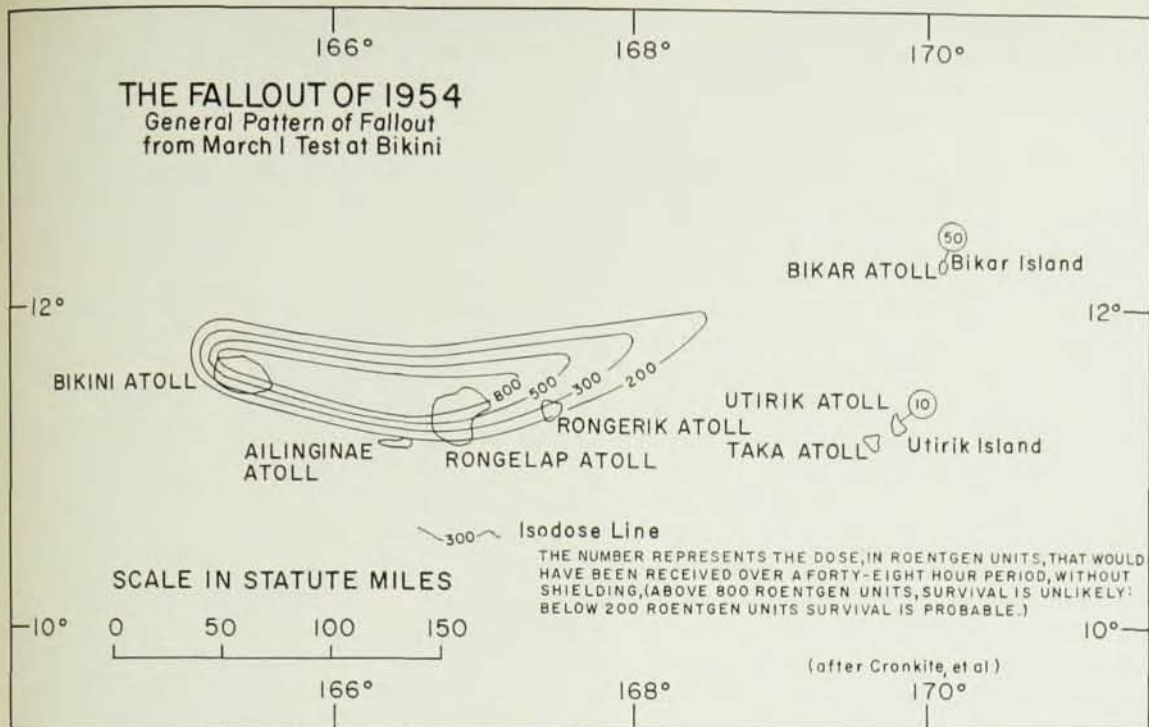


Fig. 3

development of a nuclear-excavation technology.⁵ However, before any project such as a major sea-level canal could be undertaken, many smaller projects probably would have to be carried out.

Thus, from an economic standpoint, there appears to be a clear advantage in the use of nuclear excavation techniques for appropriate projects. Using the immediate technology would require projects involving excavation of a few million yards for each single charge. With development and practical experience, the costs can be expected to be reduced to the point, perhaps, where explosions in the few-kiloton range will lead to profitable excavation. For the sea-level canal excavation, factors up to several-fold in cost advantage appear to be available. For simple jobs like river diversion, over-burden removal, or reservoir construction, the cost advantage of nuclear methods may be as high as 100-fold, depending on the size and function of the job.

While these considerations are all favorable, a large amount of work still is required to develop the detailed technology of excavation. It is clear, however, that whatever the developments show they cannot be expected to change the foregoing general conclusions. In view of this, why aren't projects under way now? The reasons have to do with radioactivity and its consequences, and with political-psychological factors.

Here, it is perhaps useful to refer to the large thermonuclear shot fired on the surface at Bikini

on March 1, 1954. This event was a 14.5-megaton nuclear weapons-development shot fired on the surface of a coral islet at Bikini. The cloud rose to a height in excess of 100 000 feet and, instead of moving northward as expected, moved eastward, depositing large fallout on the inhabited atolls of Rongelap, Ailinginae, and Rongerik 100 miles to the east. The general levels of fallout and the pattern in terms of possible 48-hour accumulation of gamma-radiation dosage are shown in Fig. 3 (courtesy of Neal O. Hines⁶). These levels were so high that the atolls had to be evacuated. The inhabitants of Rongelap (64 men, women, and children) who were evacuated 51 hours after the detonation had received the highest calculated dose of radiation, later estimated at 175 roentgens. The other 200 people, including 28 Americans on Rongerik, received less. The sources of food in the lagoon and on the land were all heavily contaminated by the fallout. As a consequence of this unhappy event, a major ecological study was initiated at Rongelap which has continued ever since. By June 29, 1957, the levels had decayed to such a point that the native residents could be repatriated, and they have been living there ever since.

The experience in the Pacific has been recently authoritatively documented in *Proving Ground* by Neal O. Hines of the Laboratory of Radiation Biology of the University of Washington.⁶ The following discussion is based on that book. During

the early years the radioactivities at Rongelap continued to be redistributed within the biological pattern but had reached equilibrium by about 1960 or 1961. Henceforth it is expected that in each organism the radioactivities will decay according to their radioactive half-lives rather than changing as a consequence of redistribution due to biological processes. Various generalizations regarding radioactivities are possible but I shall limit myself to two: (1) on land, fission products appeared to be most important; and (2) in the marine environment, induced activities seemed most relevant. The experience at Rongelap and Eniwetok-Bikini is the most valuable we have in understanding the processes at work following massive fallout on biological systems involving man and his environment (and, most important, in evaluating the possible biological impact of Plowshare excavation projects). This experience is valuable because it provides upper limits of the effects of radiation on the biosphere in one type of environment. It must be noted that the use of Plowshare explosives and burial techniques is expected to result in radioactivity levels, even in the crater, much below those observed at Rongelap, and many orders below those that existed at Bikini and Eniwetok from all shots.

In the Pacific atolls, the extraordinary healing powers of nature have been demonstrated. Islands devastated by radioactivity, heat, and blast and swept clean by water have revealed no evidence that normal growth is not occurring. The probabilities of remote radiation effects could not be denied, but no positive evidence of such effects was found in the test atolls or anywhere else in the Pacific.

One of the basic difficulties in interpreting the Pacific experience unambiguously is that prior to nuclear testing there had been no opportunity to establish natural backgrounds and ecological baselines. In recognition of the need to adequately document the effects, or lack of them, in Plowshare experiments, when the first large cratering experiment was proposed (the Chariot experiment in Alaska) it was decided as a basic part of the experiment to establish all backgrounds before the experiment was conducted. Included in the investigation were those studies also needed to assure that the experiment could be safely conducted. The work was carried out under the auspices of a biological-ecological panel led by John Wolfe of the Division of Biology and Medicine of the AEC. A highly competent and detailed job was done comprising three seasons beginning in the late spring of 1959 and at a cost of several millions of dollars. The conclusion of this group, published early

in 1963,⁷ was that the experiment as finally proposed "warrants the conclusion that if the detonation were carried out, the chance of biological cost at the ecological level, including jeopardy to the Eskimos or the plants and animals from which they derive their livelihood, appears exceedingly remote. There are necessarily some uncertainties involved in some predictions, however, that can be resolved only by experimentation."

The Chariot experiment has been shelved, not because of the possible biological impact but because it has been overtaken by events. From a technical standpoint, with the exception of the documentation of the explosion effects on the ecology, much of the experimental data have now been obtained or soon will be from experiments in Nevada. An important and perhaps key difficulty in the path of the Plowshare Program was demonstrated by the Chariot experience, namely, the relevance of public information. Fears concerning radioactivity were generated in the minds of the local population which were impossible to alleviate. This experience emphasizes what I believe to be the greatest problem in the Plowshare Program—that of establishing public confidence and acceptance.

This problem can perhaps best be approached through the recognition that development of explosives with much reduced radioactivity and refined methods of emplacement are expected to reduce fallout in the vicinity of craters to acceptable levels. By acceptable levels is meant that excavation projects might be accomplished without exceeding present tolerances for radiation exposure recommended by the Federal Radiation Council.

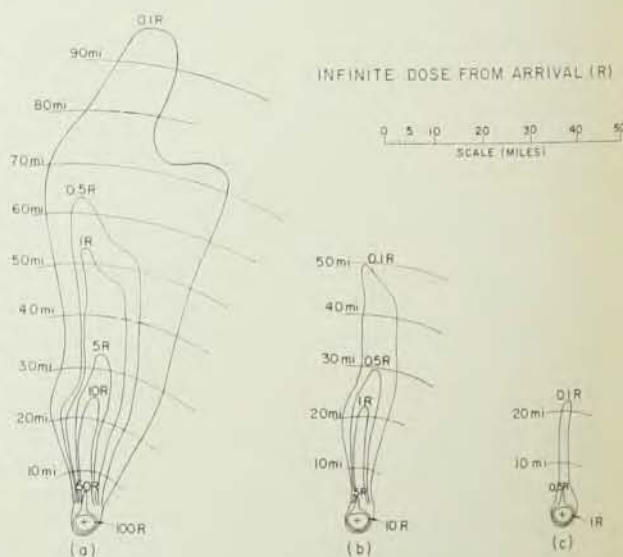


Fig. 4

However, to establish public confidence, care must be taken in any future experiments and demonstrations that all appropriate backgrounds are acquired before the experiments are conducted and that all appropriate bio-ecological work is encouraged. The preparatory work for the Chariot experiment provides a good example of such necessary exhaustive preparation.

To illustrate how advances in explosives technology and mode of emplacement can affect fallout in excavation projects I shall refer to recent results. In Figs. 4 and 5 (courtesy Lawrence Radiation Laboratory) are shown the fallout patterns for SEDAN, which was the first large-scale Plowshare excavation experiment, together with patterns to be expected with advanced explosives. It is noted that advanced nuclear explosives and the technology of emplacement will permit major reduction of fission activity deposited above the ground. Figure 6 (courtesy Lawrence Radiation Laboratory) illustrates the general effect of increasing depth of burial of the charge on fraction of radioactivity out to the surface. Concurrently, the induced radioactivities will be similarly reduced. The plot for SEDAN was the measured fallout pattern for a 100-kt shot (less than 30 percent fission) fired in Nevada on July 6, 1962. This explosion was set off at a depth such that maximum crater dimensions were to be expected. It was anticipated that about 6 percent of the radioactivity produced in the explosion would be released into the cloud formed by the explosion, with the remainder of the radioactivity remaining underground at the site of the explosion. The explosion provided some surprises

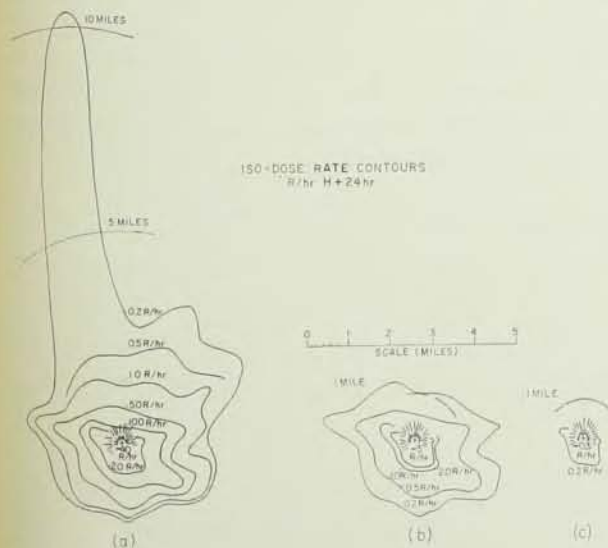


Fig. 5

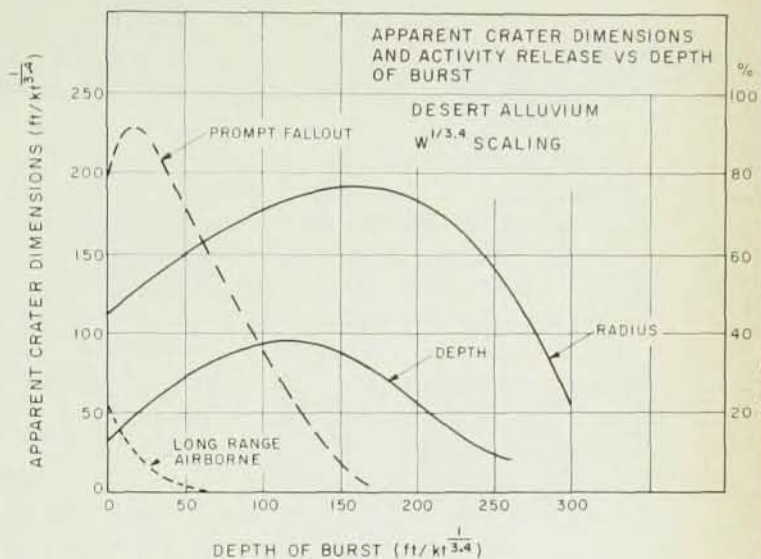


Fig. 6

and therefore new information. The cloud rose considerably higher than expected ($\sim 15\,000$ feet) because on emergence the gases were hotter than anticipated. The depth of the crater came out about as predicted but the diameter and volume were considerably less. In Table 3 the predicted results are compared with the observed behavior.

Table 3. The SEDAN shot was 100 kt placed at a depth of 635 feet down a 36-inch diameter drilled and cased hole

Crater Dimensions	Predicted Dimensions	Observed Dimensions
Depth (feet)	310	320
Radius (feet)	735	600
Volume (yards ³)	9 700 000	6 700 000
Cloud Height (feet)	~ 4000	$\sim 15\,000$
Fraction of radioactive fallout out of crater	6%	Slightly more

The crater volume for 100 kt is almost half that expected in 1960³ and 70 percent of that predicted just before the event. Considering that the predictions were based on an extrapolation from experience with 1-kt nuclear charges and on chemical-explosive experiments at lower yields, the results are encouraging. The two major surprises, namely, the greater height of the cloud and the smaller diameter of the crater, illustrate the value of experiments at full scale. Deeper burial by moderate amounts would be expected to reduce the height of

the cloud significantly without major change in crater dimension, but only additional experience with 100-kt to 1-Mt charges can provide quantitative answers.

One other nuclear event at low yield occurred in the last year. A shot yielding 420 tons in basalt at a depth of 112 feet was fired for military purposes, but the results are also of interest to Plowshare. This was the first nuclear shot in a hard, dry medium and there was some question as to how it would behave, particularly in comparison with chemical explosives. Previous chemical high-explosive tests in the same medium suggested that the explosion would produce a crater 116 feet in radius and 58 feet deep. The observed values for diameter and depth were 110 feet and 63 feet, respectively, indicating that the nuclear explosive behaved very much like the chemical explosive in hard rock. (It is important to note, however, that basic information for chemical explosives in basalt is not well established, so the close agreement may have been fortuitous. The Corps of Engineers is currently carrying out a program with chemical explosives to acquire the needed information.)

While there are differences in the fundamental mechanisms of chemical and nuclear explosives, the differences are well enough understood to permit effective use of chemical explosives to make predictions with respect to yields and placement of nuclear shots to achieve desired crater dimensions. It is noted that crater dimensions for nuclear shots in alluvium and hard rock appear to be the same for the same test conditions, suggesting that medium effects for nuclear explosions may not be very important. The scaled dimensions of nuclear explosions in (alluvium) and in (basalt) agree to better than 10 percent.

To round out the picture technically, large shots, 100 kt to 1 Mt, will be necessary in hard rock, carbonate rocks, and, although of less interest, soft, saturated material. Some of these results could be acquired as part of needed excavation projects and could also serve as demonstration experiments.

The future of excavation by nuclear methods will depend upon developing public confidence in the process through careful public information, backed up by well documented bio-ecological programs and appropriate pragmatic demonstration projects involving large-scale nuclear explosions and a continuing active program of nuclear-explosive development to reduce radioactivities and costs to a minimum.

A critical step in establishing confidence will be the declassification of relevant information, spe-

cifically information that will provide the detailed quantities, identification by isotopes, and distribution of radioactivities from advanced explosives. Since much of this information is now considered revealing in terms of the sensitive characteristics of nuclear weapons, it has not been released. Unless ways are found to provide for public scrutiny, debate, and assessment of all of the factors which may bear on the problem of possible radiological effects, I do not believe there is much chance for great progress in the program.

Whether the Plowshare excavation program can in fact be carried out must necessarily depend upon the national policy with respect to nuclear explosions for peaceful purposes. There is little doubt that the present state of the art makes feasible many projects, but, as development, experiment, and demonstration proceed, many additional projects can be seriously considered. In my opinion, this program, adequately supported and actively pursued, could in the near future begin to repay the American people for their investment in nuclear energy for peaceful purposes and could make important contributions to peace and international cooperation.

The author is indebted to the Plowshare staff of the Lawrence Radiation Laboratory, Livermore, California, for providing the basic technical information on nuclear explosives technology on which this paper is based. In addition, special gratitude is expressed to John Foster, Roger Batzel, Gary Higgins, Edward Teller, and Milo Nordyke for reading the manuscript and offering many valuable suggestions, as well as providing several graphs. The ecological information was derived from reports and discussions with Lauren Donaldson and Neal O. Hines of the Laboratory of Radiation Biology of the University of Washington, and John Wolfe of the Division of Biology and Medicine, Atomic Energy Commission.

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