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THE NEPTUNE EVENT
A NUCLEAR EXPLOSIVE CRATERING EXPERIMENT

LIVERMORE SITE

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April 19, 1960

Frontispiece. Neptune crater and its position on slope of mesa.

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An important objective of the Plowshare Program for industrial and scientific application of nuclear explosives is the development of excavation techniques. These techniques are to be applied in the construction of canals, harbors, and in mining and water-resource development. Several of the nuclear devices tested at the Nevada Test Site (NTS) have resulted in craters which have provided such data as now exists on the problem. One such detonation was the Neptune event, fired at 10:00 a.m. Pacific Standard Time on 14 October 1958, with a yield of 115 ± 15 tons. This report describes the Neptune shot and its effects and indicates the major contributions of the data to the theory and prediction of cratering phenomenology.

SITE PROPERTIES

The Neptune device was detonated underground in a room approximately 12 ft $\times$ 17 ft $\times$ 10 ft high, at the end of a hooked drift designated as U12c.03 and shown in Fig. 1. Sandbag plugs, floor to ceiling, were placed prior to firing as indicated by the shaded areas. Zero point was 110 ft from the surface vertically and 100 ft from the mesa at its closest point. The mass of material in the device room was approximately 13,500 lb, of which 1500 lb was metal, 11,300 lb concrete floor, 500 lb wood, and 200 lb rubber. The coordinates of the zero point are: Latitude north $37^{\circ} 11' 38''$, longitude west $116^{\circ} 11' 59''$ at an elevation of 6712 ft. Figures 2 and 3 are vertical sections, normal to and along the mesa face through the zero point. The gross characteristics of the materials shown there are as follows:

TOS₇-2 (zero room):

Brown, cross-bedded, hard to slightly friable, fine-grained sandstone with some thin layers of lapilli tuff, claystone, and pumice fragments near the base.

TOS₆:

A hard, welded tuff and agglomerate with fragments of pumice.

TOS₅:

A very hard lapilli tuff, with fragments of pumice and obsidian and thin layers of coarse sandstone.

TOS_{7-3, 4, 5}:

Hard to slightly friable tuff.

TOS₇₋₆:

A hard to very hard sandy tuff.

TOS₇₋₇:

Slightly friable to friable tuff.

The average properties of the detonation medium are as follows:

Density <u>in situ</u> :	1.9 - 2.0 g/cm ³
Density dry:	1.7 g/cm ³
Percent moisture by weight:	15 - 35%
Porosity:	25 - 35%
Grain density:	2.29 g/cm ³
Bulk modulus:	3.5×10^{10} dynes/cm ²
Specific heat, dry, 25°C:	0.18 cal/g/°C
100°C:	0.21 "
200°C:	0.24 "
400°C:	0.27 "
600°C:	0.30 "
Specific heat, saturated,	
25°C:	0.30 cal/g/°C
100°C:	0.32 "

Chemical Analysis (Percent by dry weight):

SiO ₂	-	76%	K ₂ O	-	5.0%
Al ₂ O ₃	-	13%	MgO	-	0.5%
Fe ₂ O ₃	-	1.5%	CaO	-	1.0%
FeO	-	0.05%	CO ₂	-	0.2%
Na ₂ O	-	2.0%			
Compressive strength:			$3.5 - 7.0 \times 10^8$ dynes/cm ²		
Thermal conductivity, dry:			1.7×10^{-3} cal/sec/cm ² /°C		
saturated:			2.6×10^{-3} cal/sec/cm ² /°C		
Sound velocity:			2.4×10^5 cm/sec		

DETONATION RESULTS

The yield of the Neptune Event was 115 ± 15 tons, as measured by radiochemistry on samples taken from the crater surface and underground. Upon detonation, the surface bulged upward 25 - 35 ft, at which time it was disrupted by material and gas venting with sufficient force to throw very large rocks 80 - 100 ft in the air (Fig.4). The first 30 msec of motion are shown in Fig.5 for a point on the surface 35 ft uphill from the point of maximum rupture. The resultant dust plume rose to a height of about 1000 ft above the terrain. A large mass of rock and debris moved down the slope, carrying small amounts of radioactivity into gullies to distances downhill (upwind) of the order of 2000 ft.

The Crater

The shape of the crater formed by the Neptune detonation was influenced by the slope of the surface in that almost all of the debris formed a slide originating at the lower edge of the pit and terminating about 800 ft down. A contour map of the crater and slide is given in Fig.6. The mean diameter is 200 ft and the maximum depth is 35 ft. The vertical sections in Figs. 7 and 8 indicate the before and after surface shapes relative to the zero position. The crater volume is 22,000 cubic yards as compared to the measured volume in the slide area of 34,000 cubic yards. The bulk density in the slide area and in the broken zone beneath the crater is lower than in the preshot tuff. No traces of a crater lip exist along the upper section where sliding destroyed the conventional contours, but there is a well defined lip along the northeast and east edges and some trace on the southwestern side. Figures 9 and 10 illustrate the sizes of materials in the crater and in the slide area.

Subsurface Effects

A total of 11 holes, some of which were cored, have been drilled into the Neptune region, as designated by letters in Figs.7 and 8, to determine the physical state of the rock and to delineate the radioactive region. (These holes are also shown in Figs.2 and 3 for comparison purposes.) Preliminary studies, whose results are summarized in Figs.7 and 8, indicate that the several layers of tuff and sandstone have retained their continuity but have fallen into the cavity created by the detonation. The mixing which has occurred

has been minor, and the different lithologic types are easily identifiable.

Crushing of the tuff has occurred to a distance of 40 ft downward and 50 ft laterally except in the direction of the original drift where crushing extends to 80 ft. The extent of crushing was apparently influenced by bedding plane weaknesses.

Fracturing of the material (Figs. 7 and 8) extends to 70 ft in the hemisphere below the zero end, according to interpretations of cores. Above the original zero, fracturing extends to the surface, the boundary of fracturing lying on a cone whose top extends slightly beyond the surface cratered region. Note on Fig. 7 that the fracture limit to the SE (downhill) lays at the interface of the brittle TOS_6 and the more punky TOS_5 .

Radiation Logs

Gamma intensity logs were made of all eleven test holes during the same time period as for the temperature measurements.¹ A vertical section, Fig. 11, indicates a center of activity 16 ft below original zero.

The concentration of radioactive debris 16 ft below the zero point suggests that the original explosion cavity had a radius of 16 ft. The cavity radius calculated by cube-root scaling from the mean of Rainier, Logan, and Blanca would be 24 ft. Core analyses alone tend to support the larger number, but the radiation data are probably more definitive.

Temperatures

Temperature measurements have been made in five of the study holes (A, B, E, F, I) which serve to indicate the heat distribution in the rock during the period D+183 to D+296 days. Most of the data were taken during the period of July 7 to August 6, 1959. Figure 12 shows the temperature distribution in a vertical plane through zero for this period (average D+280 days). The isotherms are nonsymmetrical, extending further toward the portal and exhibiting the effect of the cratering and fall-back of material on the region above zero. The hottest area is displaced from zero 15 ft downward and 6 ft into the mesa. If the density and specific heat of the material are assumed to be 2 g/cm^3 and $0.2 \text{ cal/g/}^\circ\text{C}$, respectively; the total energy represented as heat is 9×10^{10} cal, or 8% of the 115-ton yield.

Air Shock

Two bits of data are available on the air shock from Neptune: One at about 3500 ft and one at 120 mi. The peak-to-peak overpressure at 3500 ft

was 672 microbars (0.007 psi). At 120 mi, the pressure was 9.6 microbars which arrived via the ozonosphere. No calibration data were obtained so that these shocks could be quantitatively related to those which would have been received from a surface shot of the same yield, but standard curves of pressure versus distance would predict a pressure at 3500 ft of 0.7 psi, indicating a blast reduction of the order of 100 caused by charge burial. The air shock at 120 mi is estimated to be lower by a factor of 10 than would have been recorded from a surface shot of the same yield. This estimate is derived from the climatological average of ozonosphere sound transport at Nevada; no calibration shot was made. It is to be expected that the distant signal will be attenuated less than the near sound for buried charges, because most of the energy exchange between the earth and the air for such shots results in sound directed at high angles to the surface. Any sound return from such high angle generation will be beyond 80 to 100 miles.

Fallout

Figures 13 and 14 are of the above-ground surface activity distributions in the crater and downwind to a range of several miles. The crater measurements were made at D+11 days. Indicated H+1 hour contours have been calculated from these measurements using $t^{-1.2}$ decay. A small bit of data at 5 mi from zero shows a decay much slower than $t^{-1.2}$, and it is possible that intensities in the crater were not as high as 1000 R/hr at 1 hr. Integration of the total fallout patterns on the surface gives 1 - 2% of the total fission activity produced by the explosion.

Radiochemical analyses were made on a series of underground samples obtained from the recovery drift and on two samples of the escaping debris --activity picked up by the crater rocks and at the tunnel portal. The fused material found near ground zero had less than 10% of the normal amount of Sr^{90} and Cs^{137} . This corresponds to that quantity of these nuclides formed directly in fission. The balance is produced from decay of other fission products. Pockets of activity at 2 - 3 cavity radii had larger fractions up to normal amounts of these nuclides. The close-in fused samples also had the order of 10% of the expected Ru^{106} . Local fallout from the escaping debris seems to be enriched in fission species with volatile precursors. The crater surface sample had five times the normal Sr^{90} and ten times the Sr^{89} and Ce^{141} . The portal fallout sample was enriched sixfold in Ba^{140} . It is not

possible to make a material balance on the Sr and Cs from present data.

The airborne debris from Blanca was enriched in Sr^{90} to the same order as that in the Neptune crater, which suggests that the total release to the atmosphere of Sr^{90} , Sr^{89} and Cs^{137} was of the order of 5 - 10% in Neptune. It is likely that the bulk of these products is contained in the rubble from zero depth to the surface. Current radiochemical investigations of the rubble zone are expected to clarify this question.

THEORETICAL MODEL OF DETONATION AND CRATER FORMATION

Based on a postshot geological study of the regions surrounding the detonation point,² core holes drilled into the active region, and machine calculations of the expected behavior of underground detonations, it has been possible to reconstruct a history of the Neptune event, including the mechanisms that led to formation of the crater.

A few microseconds after the detonation of the device, all of the material surrounding the device was vaporized and the mixture of hot air and vaporized material had filled the shot room. Since the volume of the room was approximately $5.8 \times 10^7 \text{ cm}^3$ and there was about 10^6 g of material in the room (assuming the concrete floor was one face of the room) the gas would be at a temperature of about $150,000^\circ \text{ K}$ and a pressure of 25,000 atmospheres (bars). At these temperatures, the gas would be only partially ionized and the above temperatures and pressures are estimated on the basis of a Thomas-Fermi-Dirac equation of state for the material in the room. The radiation pressure is completely negligible. These temperatures and pressures are significantly lower than the corresponding temperatures and pressures described in Reference 3 for the Rainier event due to the much smaller energy release, and the larger volume of the room. The 25-kilobar pressure in the room would not generate a shock strong enough to melt or vaporize the surrounding rock, but the shock would crush and fracture the tuff, permanently displacing the material near the room allowing the cavity to expand. The high temperature gas in the cavity would vaporize and melt the inner surface of the spherical cavity by conduction and produce a thin molten lining. Such a picture is confirmed by samples of the fused material recovered from the Neptune area which show that it occurs only as thin layers, a fraction of an inch thick, in contrast to the fused material from Rainier, which was several inches thick.

As the shock wave traveled outward, it decreased in strength, ultimately propagating as an elastic wave. The shock wave reached the sloping face of the mesa, which is 100 ft from the device, at about 12 milliseconds after the detonation. The rarefaction from the free surface, traveling back to the cavity at close to sonic speed, reached the liquid-lined sphere at about 25 milliseconds.

The rarefaction from the surface, combined with the tail of the outward moving shock wave set up tensile stresses within the rock near the surface which exceeded the tensile strength of the medium. Under these conditions the rock fractured, the broken pieces flying off the surface with velocities corresponding to the momentum of the shock wave that is trapped within them. This phenomena, known as "spalling", will occur at each new free surface that is produced until the tensile stresses experienced by the rock is less than the tensile strength of the rock. Thus, the initial mechanism in creating the surface crater consists of fracturing of the rock near the surface by spalling and the ejection of this rock into the air.

The initial velocity of the surface material as measured on Neptune near the region of maximum rupture was 30 - 40 feet/sec (See Fig. 5).⁴ If it is assumed that these pieces moved in "free fall" paths under the influence of gravity, they would go only 15 - 25 ft in the air. Since large rocks were observed going much higher, it is clear that the cavity started to vent upon arrival of the rarefaction from the surface. The outward rush of hot gases from the gas bubble accelerated the upward flight of the broken rock fragments, blowing them out of the crater. However, this venting must have occurred through cracks in the overlying strata with no general upheaval or mixing of the strata above the cavity as evidenced by the clear delineation of the preshot geologic structure shown in Figs. 7 and 8. These show that the regions above ground zero must have been pushed upward as the gas-filled cavity expanded; they then collapsed when the cavity vented, but with no mixing of the layered structure.

Due to the low overburden pressure in the region of the Neptune detonation and the large gradient in the overburden pressure horizontally in the direction of the face of the mesa, the cavity expanded asymmetrically, with fractures extending large distances from the cavity. Hot gases penetrating these cracks produced fused layers of rock on the surface of the cracks which

resulted in evidences of radioactivity throughout the region surrounding the cavity. Such widespread distribution of the radioactivity and heat from the detonation have made determination of the final cavity radii very difficult. Significant amounts of radioactivity have been found up to 30 ft from the detonation in the direction away from the face of the mesa and up to 50 ft toward the face. In general, the zones of maximum radioactivity define a maximum radius for the cavity of 15 - 20 ft. The large amount of radioactivity found up to 50 ft away toward the portal is probably due to early venting of the cavity along bedding planes in that direction. This is indicated by films that show venting from the surface occurring at a point about halfway between the point of maximum rupture and the portal area, before the venting at the point of maximum rupture is visible.

The venting of the cavity at about 25 - 30 milliseconds would result in solidification of the liquid lining the cavity by decompression. If the $50 W^{1/3}$ formula for cavity size derived from Rainier, Blanca, and Logan is used, correcting for the much smaller overburden pressure, it predicts approximately a 50-ft-radius cavity for Neptune. However, the venting of the cavity would rapidly stop the expansion of the cavity and result in a maximum size much smaller than that expected had the cavity adiabatically expanded to overburden pressure. Preliminary computing machine calculations similar to those reported in Reference 3 for Rainier predict a maximum radius of approximately 20 ft. At this time 40% of the energy was in the kinetic energy of the spalled-off rock and 31% in the gas contained in the cavity. Therefore, it is calculated that 70% of the energy was lost to the atmosphere on the rock blown out of the crater. Thus, only 30% of the energy of the detonation would be expected to be found in the region surrounding the detonation point. Due to the large porosity of the region resulting from the extreme fracturing, it would be expected that there would be a high degree of heat transfer by air and rain water, which could spread this thermal energy over a large region as a fractional temperature rise.

Following the venting and collapse of the cavity, a chimney or subsidence was formed which propagated to the surface. If all of the volume of the cavity had been transmitted to the surface by the chimney, it would have contributed approximately 640 cubic yards to the volume of the crater.

Thus, the crater was the result of three processes, (1) the breakage

of the rock between the cavity and the detonation point by spalling of the free surfaces into the air, (2) acceleration of these pieces by the gases venting from the cavity so they are blown out of the crater, and (3) collapse of the cavity resulting in some portion of the cavity volume appearing as a surface subsidence.

THE SIGNIFICANCE OF NEPTUNE TO NUCLEAR EXCAVATION

The crater formed by the Neptune Event was located on a 30° slope on the side of the Rainier mesa in an outcropping of bedded tuff known as TOS₇. While it was on a sloping surface and the results are hence somewhat difficult to interpret, some rather important conclusions are indicated. To understand the full implications of Neptune, it is well to review some of the history of nuclear and high explosive excavation.

Summary of High Explosive (HE) and Nuclear Explosive (NE) Experience

All of the useful experience to date with nuclear cratering explosions have been in desert alluvium at the Nevada Test Site. In conjunction with these cratering explosions, there have been several high explosive programs conducted at NTS with charge weights ranging from 256 lb to 20 tons of TNT. To correlate results from cratering explosions with different charge weights, dimensional analysis indicates that a basic scaling law of $W^{1/3}$ is correct, where W is the weight of the explosive. Consideration of gravity effects indicates that a scaling law with an exponent closer to $1/4$ would be expected for large charges. A scaling law of $W^{1/3.4}$ has been found empirically to give a much more consistent form to the high explosive data. Accordingly, scaled radii and depths of the crater from the high explosive programs in Nevada desert alluvium have been plotted in Figs. 15 and 16 versus scaled depth-of-burst, with all the dimensions scaled by $W^{1/3.4}$, where W is the charge weight in kilotons of TNT.

The two underground nuclear detonations which resulted in craters, Jangle U and Teapot ESS, which also were shot in Area 10 at NTS, are shown in Figs. 15 and 16. Both detonations had a TNT equivalent yield of 1.2 kilotons. Jangle U which was fired at a depth of 17 ft, produced a crater 258 ft in diameter and 53 ft deep; Teapot ESS was fired at a depth of 67 ft, producing a crater 294 ft in diameter and 90 ft deep.

The Neptune Crater

While Neptune was detonated on a hillside in bedded tuff and not in alluvial fill, it has been included in Figs. 15 and 16 for comparison purposes. It is interesting to note that prior to the Neptune event, there were no published nuclear data below a scaled depth of 60 ft nor H. E. data below 120 ft. Based on these data it was believed that the depth-of-burst curves for alluvium peaked around a scaled depth-of-burst of 60 ft and dropped to zero at about 250 ft.⁵ The indications given by Neptune that much larger craters were possible with deeper depths-of-burst were confirmed by subsequent high explosive studies in the region between scaled depths-of-burst of 126 ft and 400 ft.^{6, 7}

A limited high explosive program has been conducted in a level bedded tuff formation similar to that in which the Neptune crater was formed using spherical charges of 256 lb.⁷ These data, scaled by $W^{1/3}$,⁴ are shown in Fig. 17. There were eight 256-lb detonations at scaled depth-of-burst greater than 185 ft but in every case a mound was formed instead of a crater. If we include points corresponding to Neptune (fired under a 1:3 slope) in this figure we can see that they appear to be inconsistent with the 256-lb high-explosive data.

The reasons for this inconsistency may be seen from a consideration of the particle sizes of the rubble remaining in the crater relative to the dimensions of the crater. Variations in the rubble-size distribution with charge size would not be expected to be anywhere as large as the variation in crater dimensions. For example, if the particle distribution function for a 256-lb charge peaked at a size which was 1/10 the crater size, it would peak at a size which was roughly 1/100 the crater size for a 90-ton charge. Therefore, for small charges, the chunks of rock tend to form arches in the crater, resulting in a high porosity of the rubble for large depth-of-burst. For large craters characteristic of nuclear detonations or in a medium where small particles are produced, like alluvium or sand, such effects would be minimized. A high explosive program with 20-ton charges in the tuff medium has been proposed in the near future to investigate this phenomenon.

Thus Neptune led to the conclusion that it was possible to produce much larger craters for the same size charge than had been previously thought possible. In addition, comparison of the Neptune data and high explosive data

in tuff indicates that small high explosive charges probably are not completely reliable for predicting the results of nuclear cratering explosions in some media.

Other Considerations

Perhaps more important to nuclear excavation than the above conclusions relative to the cratering capabilities of nuclear explosives was the fact that in the Neptune event less than 1 - 2% of the gross radioactivity of the explosion escaped to the atmosphere even though almost maximum crater dimensions were realized as seen in Fig.18. Thus, it is indicated that nuclear excavation can be performed using megaton explosives, in which only 5% of the energy comes from fission, and have only 2% of this activity escape to the atmosphere, i.e., with less than 0.1% of the nuclear energy source contributing radioactivity to the atmosphere. Moreover, almost all of the radioactivity that does escape from the crater is deposited on large particles which fall out in very short distances so that essentially no radioactivity is contributed to world-wide fallout. The direction and shape of the fallout pattern are determined by low altitude wind direction and velocity and the dust cloud height. The detonation time for an excavation project could be selected so that the fallout occurs in the most desirable areas.

As previously noted, the Neptune event indicated that close-in air blast is reduced by a factor of 100 for deeply buried cratering explosions. Applying this factor to the air pressure versus distance curves in Reference 8, page 109, assuming the maximum allowable overpressure to be 0.1 psi, it can be estimated that a 1-megaton excavation could be performed within 2 mi of permanent structures with minimal damage occurring due to air blast.

Data on air blast from surface nuclear detonations transmitted by ozonosphere shows that detonations up to 10 megatons may be performed with no major damage occurring downwind. If a factor of 10 reduction in the long range blast is realized, as indicated by Neptune data, yields as high as 1000 megatons would give no long range blast damage.

REFERENCES

1. Peterson, J. D. and Bennett, W. P., Radiation and Temperature Measurements of the Neptune Event. Final Report, Jan. 1960, internal laboratory report.
2. Thompson, T. L. and Misz, J. B., Geologic Studies of Underground Nuclear Explosions, Rainier and Neptune. Final Report, UCRL-5757, Oct. 1959.
3. Johnson, G. W., Higgins, G. H. and Violet, C. E., Underground Nuclear Detonations, J. Geophys. Res. 64, 1457-1470 (Oct. 1959).
4. Morris, R. H. and Schneiderhan, R. C., Earth Motion Studies, Operation Hardtack, Phase II, Edgerton, Germeshausen and Grier, Inc., ITR-1706, Feb. 1959.
5. Bacigalupi, C. M., Large Scale Excavation with Nuclear Explosives, UCRL-5457, Jan. 1959.
6. Murphey, B. F. and MacDougall, H. R., Crater Studies in Desert Alluvium, Sandia Corporation, SCTM 117-59 (51), May 1959.
7. Murphey, B. F., Sandia Corporation, private communication, Dec. 1959.
8. Glasstone, S., ed., The Effects of Nuclear Weapons, USAEC (1957), Gov. Printing Off., Washington 25, D. C.

NEPTUNE ZERO ROOM AND ACCESS DRIFT

Fig. 1. Preshot tunnel and zero room configurations as built for U12c.03 tunnel.

Fig.2. Preshot vertical section (B-B', Fig.6) normal to the mesa slope contours (also showing postshot drill holes).

MUL-9335

Fig.3. Preshot vertical section (A-A', Fig.6) roughly along mesa contours (also showing postshot drill holes).

Fig.4. Disrupted material at time of venting.

Fig.5. Surface motion prior to venting (from Ref.4).

Fig. 6. Contour chart of crater and slide area, showing sections A-A', B-B', C-C' and D-D' which are illustrated in Figs. 8, 7 and 18 respectively.

Fig.8. Postshot vertical section (A-A', Fig.6) roughly along mesa slope contours, showing postshot drill holes.

Fig.9. View of rubble in slide area.

Fig.10. View of rubble in crater area.

Fig.11. Radioactivity distribution in relative units on a vertical section (B-B', Fig.6) normal to slope contours.

TEMPERATURE DISTRIBUTION

UI2c.03

"NEPTUNE"

SCALE IN FEET

MUL-9341

Fig.12. Temperature distribution in °C at 280 days on vertical section (B-B', Fig.6) normal to slope contours.

Fig.14. Fallout contours as gamma intensities in mr/hr at 12 hours.

MUL-9170

Fig. 15. Crater radius versus depth-of-burst, Nevada desert alluvium.

MUL-9171

Fig.16. Crater depth versus depth-of-burst, Nevada desert alluvium.

Fig. 17. Crater radius and depth for bedded tuff versus depth-of-burst.

MUL-9345

Fig.18. Crater profile. (a) Section C-C' (Fig.6) along slope contours. (b) Section D-D' (Fig.6) normal to slope contours.

LIST OF PREVIOUS PLOWSHARE AND/OR RELATED REPORTS

<u>Report No.</u>	<u>Title</u>
UCRL-4659	Deep Underground Test Shots.
UCRL-5026	Non-Military Uses of Nuclear Explosions.
UCRL-5124 Rev. I	Phenomenology of Contained Nuclear Explosions
UCRL-5253	Industrial Uses of Nuclear Explosives.
UCRL-5257 Rev.	Peaceful Uses of Fusion.
UCRL-5281	Temperatures and Pressures Associated with the Cavity Produced by the Rainier Event.
UCRL-5457	Large Scale Excavation with Nuclear Explosives.
UCRL-5458	Mineral Resource Development by the Use of Nuclear Explosives.
UCRL-5538	Evaluation of the Ground Water Contamination Hazard from Underground Nuclear Explosions.
UCRL-5542 Rev.	Properties of the Environment of Underground Nuclear Detonations at Nevada Test Site. Rainier Event.
UCRL-5623	Radioactivity Associated with Underground Nuclear Explosions.
UCRL-5709	Hydroclimatology and Surface Hydrology of San Clemente Island.
UCRL-5757	Geologic Studies of Underground Nuclear Explosions Rainier and Neptune

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LIST OF PREVIOUS PLOWSHARE AND/OR RELATED REPORTS

<u>Report No.</u>	<u>Title</u>
	Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium (Held at San Francisco May 13-15, 1959):
UCRL-5675	Part I : Phenomenology of Underground Nuclear Explosions.
UCRL-5676	Part II : Excavation.
UCRL-5677	Part III: Recovery of Power and Isotopes from Contained Underground Nuclear Explosions.
UCRL-5678	Part IV: Industrial Uses of Nuclear Explosives in the Fields of Water Resources, Mining, Chemical Production, and Petroleum Recovery.
UCRL-5679	Part V : Scientific Applications of Nuclear Explosives in the Fields of Nuclear Physics, Seismology, Meteorology and Space.

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