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FINAL REPORT PROJECT SCOOTER:
CLOSE-IN PRESSURE AND SHOCK
ARRIVAL TIME MEASUREMENTS

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UCRL-6605
Nuclear Explosions —
Peaceful Applications, UC-35
TID-4500 (16th Ed.)

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

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Printed in USA. Price \$ 0.75 . Available from the Office of
Technical Services, Department of Commerce,
Washington 25, D. C.

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ABSTRACT

Project Scooter, a part of Operation Plowshare, was a 500-ton chemical explosive shot fired at the AEC Nevada Test Site. Personnel of Lawrence Radiation Laboratory undertook a program of measuring pressure-time histories and shock wave arrival times. Tourmaline piezoelectric transducers were used for both purposes. Only one instrument, located 49.4 feet from the center of the detonation, gave usable information. At this distance the shock wave arrived 11.2 ± 0.4 msec after the X-unit signal, and the maximum pressure was 1.7 ± 0.5 kilobars.

ACKNOWLEDGMENTS

A number of people gave valuable assistance in carrying out this experiment. Myron Heusinkveld designed the transverse transducers and provided much useful information on the properties and use of tourmaline pressure transducers. Alfred Chesterman and Adolph Dietsch did the mechanical engineering and assisted in the field. Jack McKelvain and Barton Sellick made the crystal transducers and assembled the field packages. Dorner Schueler, Jr., supervised the construction and support at the Nevada Test Site. Russell Rossman and Harold Carstensen assembled and operated the electronic system. Milo Nordyke supplied theoretical calculations needed for setting the dynamic ranges on the instruments. All of the Sandia personnel, under the supervision of H. R. MacDougall, were very helpful and gave whatever assistance was needed.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

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1 INTRODUCTION

1.1 Background

Project Scooter of Operation Plowshare was a nominal 500-ton chemical explosive shot fired 125 feet deep in desert alluvium at the AEC Nevada Test Site. It was part of the Plowshare crater study series of chemical explosions basic to the design of excavations by nuclear explosives. The spherical charge was detonated approximately at its center at 0715 PST on 13 October 1960.

As part of a series of measurements by various groups, the Lawrence Radiation Laboratory (LRL) undertook a program of measuring pressure-time histories and shock wave arrival times. Tourmaline piezoelectric transducers were used for both purposes. The instruments were located 20.0, 23.6, 32.5, and 49.4 feet from the center of the spherical charge at a depth of 125 feet. A total of 12 transducers were used but only one gave any usable information.

1.2 Summary of Data

The data obtained from the single good transducer are summarized and compared with theoretical predictions below. The transducer was located 2.9° south of west at a distance of 49.4 feet from the center of the explosive, and at a depth of 125 feet. The preshot theoretical calculations were made by Milo Nordyke of the Lawrence Radiation Laboratory.

Quantity	Measured Value	Predicted Value
Arrival time*	11.2 ± 0.4 msec	9.5 ± 2 msec
Peak pressure	1.7 ± 0.5 kilobars	~ 1 kilobar
Total impulse generated by the explosive	$(9.4 \pm 3.3) \times 10^{14}$ dyne-sec	$\sim 5 \times 10^{14}$ dyne-sec

*Zero time = X-unit signal

The measured values of peak pressure and total impulse are substantially higher than those given in the preliminary report.¹ The reason for this is discussed in Sec. 4.2.2.

2 TOURMALINE PIEZOELECTRIC TRANSDUCERS

2.1 Transducer Design

Two different transducer designs were used, one for measuring pressures in a radial direction and one for pressures in the transverse direction. Both contained Z-cut gem-quality tourmaline crystals. These were chosen for reasons given elsewhere.²

2.1.1 Radial Transducers

The idea behind the radial design was to have, as nearly as possible, the bare crystal embedded in the medium. Of course one also must have the electrodes and cable to collect and relay the charge developed by the crystal. Thus, each transducer contained a sandwich of two crystals which electrically were in parallel, with the positive faces connected to the center electrode. The copper electrodes were soldered to the silver coating baked on the crystals by the supplier. After the electrodes had been soldered to the coaxial transmission cable the connections were potted in Adiprene.

In testing these assemblies with an air gun and a drop hammer it was found that the silver coating on the crystals could be stripped off fairly readily by a shock of a few hundred bars, thus breaking the electrical connection between the crystal and the electrodes. This was discovered too late to develop a better method of attaching the electrodes; it may be one reason why 11 of the 12 transducers gave no signals. In this connection it is interesting that the single good transducer was the only one completely potted in Adiprene; a layer about 1/16 in. thick covered the electrodes and crystal edges. The extra strength of this plastic coating may have prevented the assembly from coming apart before the signal was recorded.

¹ Jack Shearer, "Scooter Close-in Pressure Measurements — Preliminary Report," LRL document number UOPB 60-39 (Oct. 27, 1960).

² W. F. Lindsay, A. E. Villaire, M. Heusinkveld, and O. H. Krause, "Close-in Pressure Measurements with Tourmaline Crystals on Tamped Detonations," Project Cowboy Final Report, UCRL-6184 (Nov., 1960) p. 16 ff.

More recently we have found that Eastman 910 cement makes a stronger bond. It is a dielectric, but under pulsed conditions with a thin cement film there is enough capacitive coupling to avoid undue losses at the connections. The cement bond is more satisfactory if the crystal surfaces are first roughened by sand blasting.

2.1.2 Transverse Transducers

The transverse transducers, designed by Myron Heusinkveld, had to operate under more stringent conditions than the radial ones. Tourmaline responds to pressures in the X and Y as well as the Z directions.³ The expected tangential pressure was about one-half or one-third of the radial pressure. Thus it was necessary to shield the crystals so they would respond only to the tangential component. This was done by providing a steel rim around the edge of the crystal but separated slightly from it so no pressure could be transmitted. To avoid having the grouting medium flow into the space between the crystal and the rim, a thin steel cover was placed over the faces of the crystal so that the unit was encapsulated in much the same way as the inside of a watch is protected by its metallic case. The actual construction inside this case was quite similar to the radial crystals; copper leads were soldered to the silver coatings on the Z-cut faces.

2.1.3 Transducer Packaging and Insertion

The transducer container was a hollow plastic cylinder almost identical to that described by Lindsay et al.⁴ The principal differences were that the aluminum alloy top was not used and the diameter was 6 in. to allow insertion of two radial and two transverse transducers. After the transducers were positioned inside the cylinder it was filled with a mixture of 80% native sand and 20% cement. Measurements indicated that this mixture had approximately the same acoustic impedance as the native material at a depth of 125 feet. When the cement mixture hardened the cylinder bottom was covered with a plastic cap and all joints were sealed with Epon to make a water-tight unit.

³ W. P. Mason, Piezoelectric Crystals and Their Applications to Ultrasonics (Van Nostrand, New York, 1950), pp. 209-215.

⁴ Lindsay, Villaire, Heusinkveld, and Krause, op. cit., p. 23 ff.

In addition, the first 10 feet of cable extending from it was painted with a plastic-base waterproof paint. Figure 1 shows a completed unit ready to be installed.

In the field the individual packages were inserted and aligned by the same method used during Project Cowboy.⁵ After insertion and alignment each hole was backfilled about 5 feet with the sand-cement mixture described above. When this had hardened about a week the rest of the hole was completely filled with native sand. This last step was completed on July 8, 1960.

In the three-month interval before the shot was fired the resistance of the transducers dropped considerably. Most of this drop came within a week after a heavy rain and presumably was due to water seeping into the transducer units or cables, or both. Measured resistance values are listed in Appendix IV. If the crystal resistance drops too low the unit will not operate properly. This is another possible reason why many of the units failed.

2.2 Location of Transducers

Plans called for putting the transducer packages at four different locations. They were to be buried at the same depth as the center of detonation, 125 feet, and at radial distances from it of 20, 23, 32, and 50 feet. These plans were closely followed in the field. All packages were at a depth of 125 ± 0.5 feet and the radial distances, obtained from a survey, were 20.05, 23.58, 32.54, and 49.38 feet at the 125-foot mark. Results of the survey, carried out under the direction of J. D. Peterson, LRL, Nevada, are given in Table I; all measurements were made at a depth of 125 feet.

Hole A contained two radial transducers and an open-ended piece of cable for background measurements. The open end was potted in Epon. Holes B and C both contained two radial and two transverse transducers. Two radial transducers were placed in hole D.

⁵ Ibid., p. 32.

Fig. 1. Completed transducer package ready for installation. This unit contains two radial and two transverse detectors.

Table I. Coordinates of instrument holes.

Identification	North Coord.	EastCoord.	Distance to Center of Detonation(ft)
Hole A	881,997.61	683,480.29	20.05
Hole B	881,995.99	683,476.96	23.58
Hole C	881,995.63	683,467.95	32.54
Hole D	881,997.64	683,450.86	49.38
Ground Zero	882,000.12	683,500.18	—

2.3 Transducer Calibration

Calibration was attempted in two ways. First, the individual tourmaline crystals were calibrated as described in the Cowboy Final Report.⁶ Then an attempt was made to determine the sensitivity of the complete field package by submerging the whole unit in an oil-filled pressure vessel. This was not very successful. Even though all the joints of the unit were sealed with Epon, the oil was able to seep into it. A few numbers were obtained at low pressures, and they indicated that the calibration constants of the individual crystals were the same before and after fabrication of the field package. The numbers used in reducing the data are given below.

Radial crystals— 1.3×10^{-10} coulomb/bar,

Tangential crystals— 5.8×10^{-11} coulomb/bar.

The difference is due to the fact that the radial crystals were 0.750 inch in diameter while the tangential crystals were 0.500 inch in diameter.

3 ELECTRONIC SYSTEM

3.1 Transmission Lines

3.1.1 Cables

As noted above, all 12 piezoelectric transducers were located within 50 feet of the center of detonation, at a depth of 125 feet. The trailer containing the oscilloscopes and cameras was 3000 feet west of the zero site. The transducers were connected to the scopes by 12 runs of RG 7/U 97-ohm

⁶Ibid., p. 17 ff.

cable, one for each transducer. In addition there was an open-ended cable, with the end potted in Epon, placed in the hole nearest ground zero for background studies. As shown in Fig. 1, each transducer was assembled with 200 feet of cable attached to it. These cables were then attached to cathode followers for impedance matching. Since the instrument holes were 125 feet deep and the cables were 200 feet long, the cathode followers were placed on the surface of the ground about 75 feet farther away from ground zero than the holes. Details of the cathode follower construction and performance are given in the next section. On the output side of each cathode follower was attached a 3000-foot run of RG 7/U which ended at the oscilloscopes in the trailer. All cables were terminated with 100-ohm resistors to avoid ringing in the transmission lines.

3.1.2 Cathode Followers

The cathode followers were designed by Russell Rossman under the supervision of Otto Krause. They were needed to match the high impedance output of the piezoelectric transducers to the 100-ohm coaxial cable. Since the predicted signals were of 100-millisecond duration, long time constants were required in the input and output circuits. A circuit diagram is shown in Fig. 2. The input impedance was approximately 14 megohms which, in conjunction with the 2-microfarad capacitor, gave an internal input time constant of 28 sec. Capacitor C-3 provided a high frequency bypass to eliminate ringing in the 200-foot cable on the input side. Capacitor C-5 and the 100-ohm cable termination gave an output time constant of 0.2 sec. Use of the 7044 tube allowed the input and output follower circuits to be put in series, to avoid possible loading effects back on the crystals. In each assembly C-1 was adjusted so that the maximum predicted pressure would produce a signal of 25 volts.

3.1.3 Calibration of Cathode Followers and Transmission Lines

The net gain of each cathode follower-transmission line combination was measured with a precalibrated Hg pulser. The pulser was connected to the input side of the cathode followers in situ near ground zero. The output was read on an oscilloscope in the trailer. The pulses, of the same duration as the expected signal, were set at various voltage levels to cover

MUL-14860

Fig. 2. Circuit diagram of the cathode follower.

Fig. 3. Calibration of the cathode follower-transmission line combination used with transducer DR-11.

the predicted signal intensities. An example of the results is shown in Fig. 3. This is the calibration of the cathode follower-transmission line combination attached to the one good transducer.

3.2 Oscilloscope System

The transmission cable from each transducer was attached to two or more oscilloscopes in the trailer about 3000 feet west of ground zero. In all, 30 oscilloscopes were used, 15 Tektronix RM 45's and 15 Tektronix 545's. The signals were recorded on 35mm film. Figure 4 gives the one-line diagram showing how the oscilloscopes were connected. The code used in identifying the transducer is as follows. The first letter (A, B, C, or D) identifies the hole in which the transducer was placed. Holes A, B, C, and D were 20, 23, 32, and 50 feet from ground zero, respectively. The second letter (R or T) identifies the detector as being either a radial or transverse transducer. The number at the end (from 1 to 12) is a running serial identification used in distinguishing between similar units in the same package. Thus DR-11 means that number 11 transducer was a radial unit in hole D.

The voltage sensitivity, total sweep length, and sweep delay for each oscilloscope are shown on the one-line diagram.

4 RESULTS

4.1 Shock Wave Arrival Times

As stated above, only one transducer gave usable signals. This applies to the arrival time as well as the peak pressure data. The other transducer signals have been examined quite carefully, but there is no objective criterion one can use that will give a consistent set of results. Copies of all scope records are given in Appendix I. Scopes 20 and 21 were attached to the good transducer located 49.38 feet from the center of detonation. From these two one obtains an arrival time of

$$t = 11.2 \pm 0.4 \text{ msec.}$$

Zero time is the X-unit signal.

Fig. 4. Diagram showing how the oscilloscopes were connected. The numbers inside the circles are explained in the legend.

4.2 Peak Pressure and Total Impulse

4.2.1 Raw Data

From the system parameters given in Appendix II the vertical deflection calibrations for scopes 20 and 21 are 1.0 kbar/cm and 0.48 kbar/cm, respectively. Thus the peak pressure indicated on both scope traces is 0.9 kilobar. By graphically integrating the area under the pressure-time curve of scope 21, one obtains a specific impulse of 18×10^6 dyne-sec/cm². Therefore the explosive delivered a total of 5×10^{14} dyne-sec into 4π steradians. Both the peak pressure and total impulse are quite close to the theoretical values listed in Sec. 1.2. However, these experimental numbers are known to be in error.

4.2.2 Corrected Data

In the experimental setup, the crystals were attached to cathode followers by 200 ft of cable. The charge developed by the crystals was converted to a voltage by a shunt capacitor (C-1 in Fig. 2) on the input side of the cathode follower. Therefore the crystal formed part of an RC circuit with an inherent decay time. By the time Scooter was fired on Oct. 13 the resistance of most crystals had deteriorated considerably. The decay time of the good crystal was about 19 msec, which is less than the length of the signal (~30 msec). Thus the charge developed on the crystal at the beginning of the signal partially leaked off before the end of the signal could be recorded. As a result the scope deflection became progressively smaller than it should have been. This explains why, in scope trace 21, the pressure wave apparently becomes a tension wave at late times. The transducers could not have recorded a tension wave even if one had occurred. The way they were constructed, the copper tabs would have pulled loose from the crystal faces and broken the electrical connection.

A method for correcting this error has been developed and is outlined in Appendix III. The corrected results are

Peak pressure = 1.7 ± 0.5 kilobars,

Total impulse = $(9.3 \pm 3.3) \times 10^{14}$ dyne-sec.

The probable errors given arise primarily from an uncertainty in the crystal resistance at the time of the shot. The corrected pressure-time history is compared with the original trace from scope 21 in Fig. 5.

Fig. 5. Comparison of the original trace from scope 21 and the corrected pressure curve.

APPENDIX I

OSCILLOSCOPE TRACES

Traces of all oscilloscopes are shown here. In all cases the sweep (and therefore time) goes from left to right. Vertical deflection calibrations are listed in Appendix II. Sweep speeds and delays are given in the electronic diagram, Fig. 4. The number at the bottom of each trace is the scope identification number.

SC-1

SC-2

SC-3

SC-4

SC-5

SC-6

SC-7

SC-8

SC-9

SC-10

SC-11

SC-12

SC-13

SC-14

SC-15

SC-16

SC-17

SC-18

SC-19

SC-20

SC-21

SC-22

SC-23

SC-24

SC-25

SC-26

SC-27

SC-28

SC-29

SC-30

APPENDIX II SYSTEM PARAMETERS

Scope No.	Transducer	X-tal Sens. (coul/kbar)	Cable & C. F. Gain	Total Shunt Cap. (μf)	Scope Defl. (volts/cm)	Scope Sens. (kbar/cm)
1	AR-1	1.3×10^{-7}	0.32	0.20	2.0	9.6
2	AR-1	"	.37	.20	1.0	4.1
3	AR-2	"	.40	.12	0.50	1.1
4	AR-2	"	.34	.12	5.0	13.0
5	DR-12	"	.35	.0086	2.0	0.37
6	DR-12	"	.35	.0086	5.0	0.93
7	BR-4	"	.40	.12	2.0	4.8
8	BR-4	"	.34	.12	5.0	14.1
9	BR-4	"	.39	.12	2.0	4.9
10	BR-3	"	.46	.16	2.0	5.6
11	BR-3	"	.40	.16	0.50	1.6
12	BR-3	"	.34	.16	2.0	7.4
13	BT-5	5.8×10^{-8}	.34	.039	2.0	4.0
14	BT-5	"	.39	.039	0.50	0.87
15	BR-3	1.3×10^{-7}	.41	.16	2.0	6.2
16	CR-8	"	.39	.10	2.0	3.9
17	CR-8	"	.44	.10	1.0	1.7
18	CR-8	"	.43	.10	0.50	0.89
19	CR-7	"	.39	.13	0.50	1.3
20	DR-11	"	.38	.047	1.0	1.0
21	DR-11	"	.38	.047	0.50	0.48
22	CR-7	"	.36	.14	2.0	5.8
23	CR-7	"	0.44	0.14	1.0	2.4
24	CR-7	"	.39	.14	0.20	0.53
25	CT-9	5.8×10^{-8}	.36	.019	2.0	1.8
26	CT-9	"	.46	.019	1.0	0.69
27	BT-6	"	.36	.030	2.0	2.8
28	CT-10	"	.42	.019	2.0	1.6
29	CT-10	"	.41	.019	1.0	0.80
30	BT-6	"	0.40	0.030	0.50	0.64

APPENDIX III OUTLINE OF METHOD FOR CORRECTING THE DATA

Let $P(t)$ be the original pressure wave experienced by the tourmaline crystal and let $R(t)$ be the signal actually recorded on the scope. These two are related by an indefinite convolution integral⁷

$$R(t) = \int_0^t S(t - \tau) \frac{dP(\tau)}{d\tau} d\tau. \quad (1)$$

Here $S(t)$ is a function that describes the response of the system to a unit step function input. In the present case the system is an RC decay circuit, so

$$S(t) = \exp(-t/RC).$$

As stated above, the decay time is $RC = 19$ msec. The problem of correcting the experimental data is one of solving an indefinite convolution integral (i. e., a Volterra equation of the first kind). The scheme developed below is similar to one used for Volterra equations of the second kind.⁸ That is, the problem of solving (1) is reduced to that of solving a triangular set of simultaneous equations.

To do this, first generalize (1) into a Stieltjes integral:

$$R(t) = \int_0^t S(t - \tau) dP(\tau). \quad (2)$$

Now divide the integration interval $(0, t)$ into some arbitrary number of equal subintervals $(t_{\ell-2}, t_{\ell})$; $\ell = 2, 4, 6, 8, \dots, n$. Thus (2) can be written

$$R(t_n) = \sum_{\ell=2, 4, 6, \dots}^n \int_{t_{\ell-2}}^{t_{\ell}} S(t_n - \tau) dP(\tau). \quad (3)$$

Next, approximate the original $P(t)$ by a series of equally spaced step functions, each one occurring at a different time t_j and having an amplitude A_j ;

⁷ e. g., see F. M. Reza and S. Sealy, Modern Network Analysis (McGraw-Hill Book Co., Inc., New York, 1959), pp. 288-293.

⁸ R. A. Buckingham, Numerical Methods (Pitman Publishing Corp., New York, 1959), p. 362 ff.

$j = 1, 3, 5, \dots, k, \dots, n-1$. Let these be chosen in such a way that successive step functions occur in the middle of successive subintervals. Then, approximately,

$$P(t_k) \approx \sum_{j=1, 3, 5, \dots}^{\ell-1} A_j U(t_k - t_j), \quad k \leq \ell-1. \quad (4)$$

The amplitudes A_j are defined from the original function by

$$A_j = P(t_{j+1}) - P(t_{j-1}), \quad (5)$$

and U is the unit step function defined in the usual way:

$$U(t_k - t_j) = \begin{cases} 0, & t_k < t_j \\ 1/2, & t_k = t_j \\ 1, & t_k > t_j \end{cases}.$$

Substituting (4) into (3), and using the properties of the Stieltjes integral to carry out the integration,

$$R(t_n) = \sum_{\ell=2, 4, \dots}^n A_{\ell-1} S(t_n - t_{\ell-1}). \quad (6)$$

This set of triangular simultaneous equations can be solved successively for $A_1, A_3, A_5, \dots, A_{n-1}$. The approximate $P(t)$ is then calculated from (4).

The corrected data given in Sec. 4.2.2 and Fig. 5 were obtained by this method with the aid of an IBM 650 code written by Joseph Yeaton.

APPENDIX IV

RESISTANCE OF TRANSDUCERS AT VARIOUS TIMES AFTER INSERTION

Transducer	Date				
	6/30*	7/7	7/12	8/12	10/11
AR-1	3 MΩ	2 MΩ	2 MΩ	3 MΩ	120 KΩ
AR-2	20 "	18 "	10 "	10 "	170 "
BR-3	100 "	100 "	100 "	100 "	2 MΩ
BR-4	100 "	100 "	100 "	100 "	7 "
BT-5	100 "	100 "	100 "	100 "	7 "
BT-6	100 "	100 "	100 "	100 "	100 "
CR-7	100 "	100 "	100 "	100 "	13 "
CR-8	100 "	100 "	100 "	100 "	8 "
CT-9	100 "	100 "	100 "	100 "	6 "
CT-10	100 "	100 "	100 "	100 "	100 KΩ
DR-11	100 "	100 "	100 "	7 "	400 "
DR-12	6 "	9 "	10 "	10 "	150 "

* One day after insertion.

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-5626	Underground Nuclear Detonations.
UCRL-5709	Hydroclimatology and Surface Hydrology of San Clemente Island.
UCRL-5757	Geologic Studies of Underground Nuclear Explosions Rainier and Neptune.
UCRL-5766	The Neptune Event. A Nuclear Explosive Cratering Experiment.
UCRL-5840	Industrial and Scientific Applications of Nuclear Explosions.
UCRL-5882 Rev.	Chemical Reactions Induced by Underground Nuclear Explosions.
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UCRL-5928	Nuclear Explosives and Mining Costs.
UCRL-5932	The Soviet Program for Industrial Applications of Explosions.
UCRL-5949	An Application of Nuclear Explosives to Block Caving Mining.

<u>Report No.</u>	<u>Title</u>
UCRL-6008	Some Potential Uses of Nuclear Explosives in the Conservation and Development of Water Resources.
UCRL-6013	Probing the Earth with Nuclear Explosions.
UCRL-6030-T	Application of Nuclear Explosions as Seismic Sources.
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UCRL-6374	Results and Power Generation Implications from Drilling into the Kilauea Iki Lava Lake, Hawaii.
UCRL-6578	On Cratering. A Brief History, Analysis, and Theory of Cratering.
UCRL-6605	Final Report Project Scooter: Close-in Pressure and Shock Arrival Time Measurements.
UCRL-6636	Nuclear Explosives in Mining.

Report No.Title

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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