SCOOTER

FINAL REPORT
OCTOBER 1963

PLOWSHARE PROGRAM

NEVADA TEST SITE
OCT 1960

Sandia Corporation
CONTRACTOR FOR U. S. ATOMIC ENERGY COMMISSION
PROJECT SCOOTER

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October 1963
ACKNOWLEDGMENTS

Project Scooter, as a part of the Plowshare Program, was assigned for planning and accomplishment to Sandia Laboratory. However, throughout all phases of the project cooperation of the Lawrence Radiation Laboratory, Livermore and support of the San Francisco Operations Office and the then Office of Test Operations of the Albuquerque Operations Office of the United States Atomic Energy Commission were of great help and are appreciated.

Sandia Corporation Field Test personnel who made major contributions to Project Scooter included H. R. MacDougall, Test Group Director, F. B. Collins, Experiment Coordinator, R. J. Burton and F. Shoemaker, Arming and Firing, R. C. Bass and R. B. Abbott, Underground Instrumentation. Data reduction was performed by C. R. Eisenhour, R. J. Beyatte and F. R. Millsap. L. M. Schofield and D. B. Hayes assisted in the analysis of data from some of the projects reported herein.
ABSTRACT

Project Scooter was a cratering experiment devised as a part of the Plowshare study of large scale explosions as excavation tools. The Scooter explosive was approximately one million pounds of TNT stacked in a spherical cavity centered at a depth of 125 feet in desert alluvium at Area 10 of the AEC Nevada Test Site.

This report includes results of studies of crater dimension, throwout material distribution, ground motion, dust cloud growth, and long-range air blast. The crater produced by Scooter was 75 feet deep, had an average diameter of 307 feet, and a volume of nearly 100,000 cubic yards. Crater dimensions for chemical explosions up to a million pounds of TNT were found to fit overburden approximate scaling best.

Fine particulate material ejected from the crater verified the empirical scaling law for ejecta derived from the Stagecoach experiments.

Particle motion studies indicated a shock transmitted at a velocity of 4260 feet per second through desert alluvium. All measurements were at distances between 50 and 300 feet from the charge center and were shown to be within the region of nonlinear response of the soil.

Surface particle velocities derived from photographic records served to derive expressions for crater radius stresses. Ground surface accelerations show a double peak, implying reaction first to ground shock and then to gas pressure.

Maximum cloud height appears to scale as the fourth root of yield. Base surge propagated at an average velocity more than double the rate of base surge growth observed for the two shallower Stagecoach events.

Long distance air-blast studies show that signals are ducted through the ozonosphere with higher transmission factors for larger yields. A high-speed jet stream affected strongly the signals ducted through the troposphere.
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CHAPTER 1 -- PURPOSE AND BACKGROUND

1.1 PURPOSE AND SCOPE OF THE EXPERIMENT

Project Scooter was a cratering experiment devised to provide technical and scientific information concerning the mechanics of crater formation by large underground chemical explosions. This project was one of a series of chemical-explosive cratering studies undertaken by Sandia Laboratory as a part of the Plowshare Program and planned in cooperation with Lawrence Radiation Laboratory (LRL), Livermore. Data from observations of mechanical effects of the explosion made within the earth and at the ground surface and measurements of the resultant crater were required to provide some of the basis for adequate and realistic design of major excavation projects employing nuclear explosives which are to be included in the Plowshare Program.

Project Scooter climaxed a long series of high-explosive charges detonated in the desert alluvium of Area 10 at the Nevada Test Site. Earlier experiments included charges of TNT weighing 256 pounds,\(^1\), 2650 pounds,\(^3,4\) and 40,000 pounds.\(^3,4,5\) The earlier experiments had suggested a departure from cube-root scaling of crater dimensions which was confirmed by Project Stagecoach and was to be further tested by Project Scooter.

The major purposes of the Project Scooter experiment were to improve knowledge of the craters produced by chemical explosions and to relate craters produced by chemical and nuclear explosives. More specifically, the objectives were (a) to study the mechanisms of crater formation by means of transient and passive observation of ground motion, crater dimensions, and throwout distribution, and (b) to relate crater dimensions from numerous smaller charges to corresponding data from a very large charge and clarify scaling laws.

The Scooter explosive comprised 987,410 pounds of TNT stacked to approximate a sphere centered 125 feet below the surface of Yucca Flat in Area 10 of the AEC Nevada Test Site. Detonation was originally scheduled for 0645 PDT on July 14, 1960, but a misfire requiring installation of new detonators at the charge center caused a delay of about three months. Scooter was detonated at 0715 PST on October 13, 1960.

Specifically, information sought concerning the transient phenomena produced by Scooter included transit times for shock within the explosive, pressures generated within the soil very near the explosion, particle motion within the crater region and at burst level within the earth near the charge, air-blast overpressure at ground level and up to about 500 feet outward from near surface zero to about 2500 feet, surface motion by photography of a group of targets near surface zero, three-component surface motion at ranges to about 15,000 feet, and long-distance...
air-blast observations to ranges of 135 miles. In addition to these observations of transient effects, several types of passive measurements were made, including topographic surveys of the crater and lip, distribution of throwout material, and trajectory end-point locations for tagged pellets.

Several organizations participated in the various measurement programs, and each will report the results of its work. Pressures in the soil near the explosive were observed by LRL, shock transit times within the explosive and particle motion in the earth and at the surface by Sandia and LRL, air-blast overpressure near surface zero by Naval Ordnance Laboratory (NOL) and Sandia, surface-motion and dust-cloud photography by Edgerton, Germeshausen, and Grier (EG&G), three-component surface motion by U.S. Coast and Geodetic Survey (C&GS), long-distance air blast by Sandia, and passive crater measurements by Sandia.

1.2 SCOPE

This report is concerned with results of all observations made by Sandia Laboratory in connection with the Scooter detonation. It is divided into chapters dealing with (a) crater size, (b) distribution of throwout, (c) particle motion, (d) surface motion and cloud growth, (e) long-distance air pressures. Each chapter is the responsibility of the scientific advisor for the measurement project reported. Sandia air-blast observations were limited to data from two gages, and these have been submitted to NOL for inclusion in the report on air-blast overpressures. The surface motion and cloud-growth analysis in this report use data reported by Edgerton, Germeshausen, and Grier, as well as additional information derived from film exposed by Sandia.

1.3 ENVIRONMENT

The site chosen for the Scooter experiment was in Area 10 of the AEC Nevada Test Site. This area had been the site of two nuclear cratering shots, Jangle U and Teapot ESS, and of numerous smaller chemical explosion cratering tests, including the Stagecoach series and part of the Sandia 256-pound TNT series and the Mole series.

Area 10 is in the northern part of the Yucca Flat basin about 13 miles north of the Yucca Playa. In the area chosen for Scooter, the terrain slopes gently in a south-southwesterly direction at about 63 feet per mile. The material is normal basin fill derived from arid region weathering of the surrounding mountain ranges, which are composed principally of bedded and massive rhyolytic tuffs, dolomites, and some granite. It ranges in size from cobbles of 1- to 2-foot maximum dimension through gravel and sand sizes to very fine rock flour.

This material is not highly consolidated, as is shown by the accompanying table of dry densities and water content. However, very extensive cementation has occurred by the caliche process, at least to depths of 140 feet. This cementation
introduces a considerable dry strength to the material, most of which vanishes in the presence of water because of high solubility of the cementing agency.

**TABLE 1.1 PROFILE OF SOIL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Wet Density (lb/ft(^3))</th>
<th>Dry Density (lb/ft(^3))</th>
<th>Water Content (% of dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>98</td>
<td>94</td>
<td>4.3</td>
</tr>
<tr>
<td>25</td>
<td>89</td>
<td>83</td>
<td>7.2</td>
</tr>
<tr>
<td>50</td>
<td>90.8</td>
<td>85.7</td>
<td>6.0</td>
</tr>
<tr>
<td>75</td>
<td>95</td>
<td>88</td>
<td>8.0</td>
</tr>
<tr>
<td>100</td>
<td>94.3</td>
<td>84.3</td>
<td>11.9</td>
</tr>
<tr>
<td>Averages</td>
<td>93.4</td>
<td>87.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>
CHAPTER 2 -- CRATERING

2.1 CRATER DIMENSIONS

2.1.1 Apparent Crater Dimensions

The depth of the Scooter crater was 75 feet, and the diameter at the original ground level was 307 feet; precise dimensions are given in Table 2.1. The dimensions were obtained from preshot and postshot aerial topography (Figures 2.1 and 2.2). Figures 2.3 through 2.6 are views of the Scooter crater. In the background of Figure 2.5 can be seen the three Stagecoach craters, and in the background of Figure 2.6, the Jangle U (J-U) and Teapot ESS (T-S) craters.

TABLE 2.1 SCOOTER CRATER DIMENSIONS

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius ((\text{Area}/\pi)^{1/2})</td>
<td>153.78 ft</td>
</tr>
<tr>
<td>Radius ((D_1 + D_2 + D_3 + D_4)/8)</td>
<td>153.37 ft</td>
</tr>
<tr>
<td>Depth (at center)</td>
<td>74.5 ft</td>
</tr>
<tr>
<td>Depth (maximum)</td>
<td>76.4 ft</td>
</tr>
<tr>
<td>Volume (Planimetry of contour map)</td>
<td>2.66 x 10^6 ft^3</td>
</tr>
<tr>
<td>Volume ((2\pi \int_0^R r(r)dr), where (r(r)) is average crater cross section)</td>
<td>2.642 x 10^6 ft^3</td>
</tr>
<tr>
<td>Lip volume (total based on profile at oil strips to 400 ft)</td>
<td>1.612 x 10^6 ft^3 (a)</td>
</tr>
<tr>
<td>Lip volume (upthrust only)</td>
<td>6.96 x 10^4 ft^3</td>
</tr>
<tr>
<td>Lip volume (Planimetry of map to 325 ft)</td>
<td>1.357 x 10^6 ft^3 (b)</td>
</tr>
<tr>
<td>Fallback volume (325 to 700 ft)</td>
<td>0.170 x 10^6 ft^3 (c)</td>
</tr>
<tr>
<td>Fallback mass (collectors)</td>
<td>1.291 x 10^{10} gm</td>
</tr>
<tr>
<td>Fallback volume (beyond 700 ft)</td>
<td>2.843 x 10^5 ft^3 (d)</td>
</tr>
<tr>
<td>Lip height (average)</td>
<td>8.54 ft (map)</td>
</tr>
<tr>
<td>Radius to maximum lip height</td>
<td>9.72 ft (oil strip)</td>
</tr>
<tr>
<td>Distance from point of maximum depth to center</td>
<td>38.8 ft</td>
</tr>
<tr>
<td>Bearing from center to maximum depth point</td>
<td>S16°E</td>
</tr>
<tr>
<td>True crater radius</td>
<td>153.24 ft at 356.62°</td>
</tr>
</tbody>
</table>

NOTE: a and b are volume of throwout and upthrust to ranges noted. Total throwout and upthrust are sum of items b, c, and d.

2.1.2 Crater Lip

Figures 2.4 through 2.6 give some impression of the size of the crater lip, which was unusually small, its average height of 8.5 feet being only slightly more than 10 percent of the crater depth. For comparison, the crater lip for smaller
craters in desert alluvium is about one-third the crater depth at comparable scaled depths of burst, while the lip of the Buckboard Shot 12 crater in basalt at the same scaled burst depth (cube-root scaling) was 20 percent of the crater depth.

Two oil-stabilized strips, 20 x 300 feet long, were constructed along north and east radii from surface zero. These strips extended between 100 and 400 feet from surface zero. From observation of preshot and postshot elevations of these strips, it was possible to determine the permanent vertical displacement of the original ground surface. Figure 2.7 shows the vertical positions of the original ground surface before and after the shot. The maximum upheaval (permanent vertical displacement) of the ground surface was only 2 feet, which is no greater than the upheaval produced by the 40,000-pound Stagecoach shot buried at a depth of 34.2 feet. It can be seen from Table 2.1 that the upheaval contributes only about 5 percent of the crater lip volume.

Crater lip height is plotted against the burst depth in Figure 2.8 (0.3-power scaling) and in Figure 2.9 (overburden scaling). In spite of large scatter, both figures indicate a slight increase in scaled lip height with increased scaled burst depth. They also show that, compared with other craters, the Scooter crater lip was among the lowest. In all cases, lip height was obtained by averaging the lip height at a number of uniformly spaced points along the crater rim.

The ratio of crater depth to lip height is shown versus scaled burst depth in Figures 2.10 and 2.11 by the two scaling methods used above. Except for very deep scaled burst depths, crater depth is ordinarily three to seven times lip height. However, the Scooter depth was nearly nine times lip height, which further emphasizes that Scooter lip height was considerably less than expected.

Figures 2.12 and 2.13 use 0.3-power and overburden scaling methods, respectively, to show scaled radius to the maximum of the crater lip versus scaled burst depth. Since scaled crater radius (see Figure 2.22) increases with increased scaled burst depth, it is not surprising that the radius to the lip peak also increases. Figures 2.14 and 2.15 show ratio of

\[
\frac{\text{radius to crater lip maximum}}{\text{crater radius}}
\]

versus scaled burst depth—again by the same two scaling methods. These figures indicate that the ratio is relatively constant for all but the deepest scaled burst depths. Jangle U data for radius to crater lip maximum are not available and were consequently omitted from this analysis.

The scaled volume of the crater lip is plotted for 0.3-power and overburden scaling against scaled burst depth in Figures 2.16 and 2.17. Although scatter is unusually large, it appears that scaled lip volume varies about as the first power of the scaled burst depth. This is as would be expected.

Ratios of apparent crater volume to the volume of the crater lip plotted versus scaled burst depth (Figures 2.18 and 2.19) show similarly large scatter. Although both the Jangle U and Scooter ratios appear high, there is no discernible trend with yield.
Figure 2.1 Pretest topography - Scooter site
Figure 2.2 Post-test topography - Scooter site
Figure 2.3 Aerial view - Scooter crater - toward west

Figure 2.4 Aerial view - Scooter crater - toward northeast
Figure 2.5 Aerial view - Scooter crater - toward southeast

Figure 2.6 Aerial view - Scooter crater - toward southwest
Figure 2.7  Crater lip uplift - oil-stabilized strip

Figure 2.8  Scaled lip height versus depth of burst - 0.3-scaling
Figure 2.9  Scaled lip height versus depth of burst - gravity scaling.
Figure 2.10 Crater depth-lip height ratio versus 0.3-scaled depth of burst
Figure 2.11 Crater depth-lip height ratio versus gravity-scaled depth of burst
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Figure 2.15 Radius of lip-radius of crater ratio versus gravity-scaled depth of burst.
Figure 2.16 Scaled lip volume versus 0.3-scaled depth of burst
Figure 2.17 Scaled lip volume versus gravity-scaled depth of burst
Figure 2.18 Ratio apparent crater volume-lip volume versus 0.3-scaled depth of burst
Figure 2.19 Ratio apparent crater volume-lip volume versus gravity-scaled depth of burst
2.1.3 True Crater Radius

True crater radii were observed at three points: (a) along the north oil-stabilized strip, (b) along the east oil-stabilized strip, and (c) in the north-west quadrant of the crater. Along the north stabilized strip, the true crater radius (to the postshot position of the end of the strip rather than at the level of the original ground surface) was 169 feet; along the east stabilized strip, it was about 160 feet. At an azimuth of 356.6 degrees, an outcrop of undisturbed material was identifiable in the wall of the crater near the level of the original surface. This outcrop permitted the true crater radius along that one radius to be determined as 153 feet. These observations indicate that there is little difference between the true and apparent Scooter crater radius.

Figure 2.20 Crater profile comparison

Comparison of the Scooter crater profile (Figure 2.20) with the profile of a 256-pound charge crater scaled to Scooter yield by cube-root scaling shows not only that the Scooter crater is relatively smaller but also that its shape is somewhat different. The relatively flat bottom of the Scooter crater can be explained by the large amount of very fine material which filled the crater bottom. Because this fine material has almost no shear strength, it tends to flow as a liquid. This explanation, together with observations of the true crater radius, suggests the Scooter crater was initially both deeper and narrower. Also, some material lying beyond the momentary radius of the true crater was ruptured and, lacking shear strength, sloughed off the crater wall into the bottom of the crater, where it sank beneath the large amount of fluid-like dust. The profile of the crater lip (Figure 2.21) illustrates this hypothesis. This explanation accounts for the negligible difference between the radii of the true and the apparent craters.
2.2 DISCUSSION

2.2.1 Scaling

Empirical scaling of crater radius, depth, and burst depth by the 0.3 power of charge weight, \( W^* \) (volume by the 0.9 power) has been considered earlier by others.\(^1\)\(^{11}, \)\(^{12} \) These earlier considerations, however, neglected the effects of gravity. Later contributors,\(^11, \)\(^{12} \) took into account gravity effects on the scaling of crater dimensions and also emphasized that true similarity does not exist in field experiments unless medium strength properties and viscosity are scaled. Hence, rigorous scaling cannot be applied. Nonetheless, an approximate scaling method was proposed\(^12 \) in which the effects of departures from similarity are small. This "overburden" method can best be described as a sliding scale from cube-root scaling for surface bursts and for small charges, where atmospheric pressure greatly exceeds lithostatic pressure, to fourth-root scaling for large deep bursts, where lithostatic pressure is much greater than atmospheric pressure.

The results of overburden scaling of crater dimensions in desert alluvium are shown in Figures 2.22 (radius), 2.23 (depth), and 2.24 (volume). Log-log plots of scaled crater dimensions show an approximately linear relationship with burst depth from shallow bursts to those near the peak of the depth-of-burst\(^t \) curves.

That scaling method is judged best in which the deviation from a fit to the data is least. The standard deviation of \( \log \lambda \) from least-squares fits were calculated from

\[
\sigma = \left[ \frac{\sum_{i=1}^{n} (\log_{10} \lambda_i - \log_{10} \lambda_{ci})^2 / (n-1)}{n} \right]^{1/2}
\]

where there are \( n \) data, \( \lambda_i \) is the observed dimension, and \( \lambda_{ci} \) is the calculated dimension, and the deviation is expressed as a logarithm.

\*Throughout this report \( W \) will represent TNT charge weight in pounds. Distances are in feet and volume is in cubic feet unless otherwise identified.

\( ^t \)Depth of burst is represented by \( D \).
Figure 2.22 Gravity-scaled crater radius versus gravity-scaled depth of burst
Figure 2.23 Gravity-scaled crater depth versus gravity-scaled depth of burst
The deviations of all HE data from a least-squares fit to a straight line on a log-log plot for each of two scaling methods are:\(^{10}\)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Charge Weight (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>216</td>
</tr>
<tr>
<td>o</td>
<td>256</td>
</tr>
<tr>
<td>△</td>
<td>2,560</td>
</tr>
<tr>
<td>▽</td>
<td>40,000</td>
</tr>
<tr>
<td>□</td>
<td>1.0 \times 10^6 (SCOOTER)</td>
</tr>
<tr>
<td>✡</td>
<td>2.4 \times 10^6 (J-U THRU T-S)</td>
</tr>
<tr>
<td>×</td>
<td>3,000</td>
</tr>
<tr>
<td>√</td>
<td>5,000</td>
</tr>
</tbody>
</table>

\[ W_{0.3} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( W_{0.3} )</th>
<th>Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>0.036</td>
<td>0.041</td>
</tr>
<tr>
<td>Depth</td>
<td>0.066</td>
<td>0.064</td>
</tr>
<tr>
<td>Volume</td>
<td>0.087</td>
<td>0.100</td>
</tr>
</tbody>
</table>

Figure 2.24 Gravity-scaled crater volume versus gravity-scaled depth of burst
Since a straight line does not fit the data precisely, the standard deviations from a quadratic relation, fitted to the data by least squares, were calculated to be:

<table>
<thead>
<tr>
<th></th>
<th>$W^{0.3}$</th>
<th>Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>0.032</td>
<td>0.031</td>
</tr>
<tr>
<td>Depth</td>
<td>0.066</td>
<td>0.064</td>
</tr>
<tr>
<td>Volume</td>
<td>0.085</td>
<td>0.085</td>
</tr>
</tbody>
</table>

It is generally accepted that the scatter in crater dimensions decreases as charge size is increased relative to the inhomogeneities of the medium. For this reason, it is interesting to explore deviations from a linear fit using only the four charges over 10,000 pounds. The results are:

<table>
<thead>
<tr>
<th></th>
<th>$W^{0.3}$</th>
<th>Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>Depth</td>
<td>0.028</td>
<td>0.008</td>
</tr>
<tr>
<td>Volume</td>
<td>0.039</td>
<td>0.032</td>
</tr>
</tbody>
</table>

Deviations from a second-order least-squares fit to the same data are:

<table>
<thead>
<tr>
<th></th>
<th>$W^{0.3}$</th>
<th>Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>0.008</td>
<td>0.002</td>
</tr>
<tr>
<td>Depth</td>
<td>0.013</td>
<td>0.002</td>
</tr>
<tr>
<td>Volume</td>
<td>0.030</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The preceding tables are generally in the order of decreasing standard deviations. When the effects of the scatter of small charge data are removed, overburden scaling appears the better method.

Increased scatter observed in small charge data may be attributed to lack of similarity among experiments as well as to inhomogeneities in the medium. Justification for omitting small charge data from a standard deviation analysis stems primarily from the belief that these small charge experiments are much less similar than the large charge experiments. By comparing standard deviations in data from only the more similar experiments of large charges, a better evaluation of scaling rules may be made since scaling has meaning only so long as similarity exists among experiments.

A further comparison has been made. Cartesian plots of crater dimensions versus burst depth were made for both $W^{0.3}$ and overburden scaling. Only data on the rising portions of the curves were considered, for there are indications of a change in the mechanism of crater formation beyond the peak of the depth-of-burst curves, and there is no assurance that the two mechanisms scale in precisely the same way. Fractional deviations from best-fit curves given by first- through sixth-order polynomials were computed. The fractional deviation was calculated by
\[ \delta = \left[ \frac{1}{(n-1)} \sum_{i=1}^{n} \left( \lambda_i - \lambda \right)^2 \right]^{1/2} \]

where \( \lambda_i \) is the observed dimension, \( \lambda \) is the calculated dimension, \( \bar{\lambda} = \frac{1}{n} \sum_{i} \lambda_i \) is the mean observation, and \( n \) is the number of observations. The results are summarized in Table 2.2.

<table>
<thead>
<tr>
<th>Scaling Method</th>
<th>Radius</th>
<th>Depth</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order of polynomial</td>
<td>( W^{0.3} ) Overburden</td>
<td>( W^{0.3} ) Overburden</td>
<td>( W^{0.3} ) Overburden</td>
</tr>
<tr>
<td>1st</td>
<td>0.0837</td>
<td>0.1656</td>
<td>0.1989</td>
</tr>
<tr>
<td>2nd</td>
<td>0.0826</td>
<td>0.1281</td>
<td>0.1986</td>
</tr>
<tr>
<td>3rd</td>
<td>0.0826</td>
<td>0.1280</td>
<td>0.1951</td>
</tr>
<tr>
<td>4th</td>
<td>0.0766</td>
<td>0.1278</td>
<td>0.1820</td>
</tr>
<tr>
<td>5th</td>
<td>0.0718</td>
<td>0.1226</td>
<td>0.1523</td>
</tr>
<tr>
<td>6th</td>
<td>0.0705</td>
<td>0.1160</td>
<td>0.1504</td>
</tr>
</tbody>
</table>

Several observations may be made as a result of these analyses. Overburden scaling has a smaller fractional deviation for all dimensions except the radius with fifth- and sixth-order equations. A significant improvement is made, as one would expect, by going from a first-order to a second-order equation, but improvements thereafter are small. Because of the unusual curvature that results, the sixth-order polynomial should not be considered. From the standpoint of both improvements in results and ease of use, no more than a third-order polynomial is warranted for most practical considerations. The results of third-order fit for \( W^{0.3} \) scaling are shown in Figures 2.25 through 2.27, and of third-order fit for overburden scaling in Figures 2.28 through 2.30. One must bear in mind that the equations shown in the figures are for the purpose of evaluating scaling methods on the rising portion of the curve. Because data beyond the peak were ignored, the curves are not intended to define the peaks of the depth-of-burst curves.

The earlier portion of this section indicated that because of scatter in small charge data a considerable improvement was obtained by considering only large-charge data.* Presumably scatter in the small charge results from lack of similarity among small charge experiments as well as to the relatively greater

*While this report was in preparation, the Sedan 100-kiloton nuclear explosion was fired in alluvium at a depth of 635 feet. This experiment confirmed the inadequacy of cube-root scaling for comparison of craters from large explosions. The Sedan crater radius was too small to satisfy \( W^{0.3} \) scaling to the Scooter crater radius; it more nearly satisfied \( W^{1/4} \) scaling. On the other hand, the Sedan crater depth was too small to satisfy \( W^{1/2} \) scaling and too large to permit \( W^{1/4} \) scaling to the Scooter crater depth. Both of these statements assume that craters from chemical and nuclear explosions correspond. If they do not, the results of the Sedan-Scooter scaling comparison must be inconclusive until HE-NE relative efficiencies are known.
Figure 2.25 Curve fitting of 0.3-scaled radius versus 0.3-scaled depth of burst
Figure 2.26 Curve fitting of 0.3-scaled depth versus 0.3-scaled depth of burst
Figure 2.27 Curve fitting of 0.3-scaled volume versus 0.3-scaled depth of burst
Figure 2.28 Curve fitting of gravity-scaled radius versus gravity-scaled depth of burst
\[
y_d = 12.87 + 1.068x - 0.101x^2 + 3.6 \times 10^5 x^3
\]
where 
\[
p = 100 \text{ lb/ft}^3
\]

SYMBOLS

<table>
<thead>
<tr>
<th>CHARGE WEIGHT (lb)</th>
<th>SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>216</td>
<td>+</td>
</tr>
<tr>
<td>256</td>
<td>O</td>
</tr>
<tr>
<td>2,560</td>
<td>△</td>
</tr>
<tr>
<td>40,000</td>
<td>▽</td>
</tr>
<tr>
<td>1.0 \times 10^6</td>
<td>(SCOOTER)</td>
</tr>
<tr>
<td>2.4 \times 10^6</td>
<td>(J-U THRU T-S)</td>
</tr>
<tr>
<td>3,000</td>
<td>x</td>
</tr>
<tr>
<td>5,000</td>
<td>x</td>
</tr>
</tbody>
</table>

Figure 2.29 Curve fitting of gravity-scaled depth versus gravity-scaled depth of burst
Figure 2.30 Curve fitting of gravity-scaled volume versus gravity-scaled depth of burst
effect of inhomogeneities in soil. Such an appraisal is adequate where only first- or second-order fits are required. To obtain higher order fits, the small-charge data can hardly be ignored. However, a better result is obtained if the data are weighted to give greater importance to the dimensions of large-charge craters. One method, although not necessarily the best, is to weight according to the cube-root of charge weight. This gives nearly equal emphasis to 256-, 40,000-, and 1 million-pound charge craters, as shown below:

<table>
<thead>
<tr>
<th>Charge Weight</th>
<th>Cube-Root $W^{1/3}$</th>
<th>Number of Charges $h$</th>
<th>Weighting $hW^{1/3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>216</td>
<td>6.00</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>256</td>
<td>6.35</td>
<td>17</td>
<td>108</td>
</tr>
<tr>
<td>2,560</td>
<td>13.7</td>
<td>5</td>
<td>69</td>
</tr>
<tr>
<td>5,000</td>
<td>17.0</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>40,000</td>
<td>34.2</td>
<td>3</td>
<td>103</td>
</tr>
<tr>
<td>1,000,000</td>
<td>100.0</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

When this weighting method is used, the fractional deviations computed gave the results shown in Table 2.3. In every case, the percentage deviations are smaller than for the unweighted situation. Overburden scaling again shows smaller deviations than $W^{0.3}$ scaling. Also, improvements beyond second-order were small. Figures 2.31 through 2.33 give the results of the weighted third-order fit to $W^{1.3}$ scaling, and Figures 2.34 through 2.36 those for overburden scaling.

<table>
<thead>
<tr>
<th>Scaling Method</th>
<th>Order of polynomial</th>
<th>Radius $W^{0.3}$ Overburden</th>
<th>Depth $W^{0.3}$ Overburden</th>
<th>Volume $W^{1.3}$ Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td></td>
<td>0.0781</td>
<td>0.0604</td>
<td>0.1614</td>
</tr>
<tr>
<td>2nd</td>
<td></td>
<td>0.0618</td>
<td>0.0510</td>
<td>0.0881</td>
</tr>
<tr>
<td>3rd</td>
<td></td>
<td>0.0605</td>
<td>0.0510</td>
<td>0.0878</td>
</tr>
<tr>
<td>4th</td>
<td></td>
<td>0.0568</td>
<td>0.0493</td>
<td>0.0876</td>
</tr>
<tr>
<td>5th</td>
<td></td>
<td>0.0511</td>
<td>0.0486</td>
<td>0.0833</td>
</tr>
<tr>
<td>6th</td>
<td></td>
<td>0.0491</td>
<td>0.0482</td>
<td>0.0764</td>
</tr>
</tbody>
</table>

From the foregoing it may be concluded that overburden scaling has only a slight advantage over $W^{0.3}$ scaling over the range of charge weights involved. It may be further concluded that larger charge craters will be required to indicate decisively which of the two methods of scaling will permit the most confident extrapolation to larger yields, or whether still another method will be necessary.

2.2.2 **Crater Shape**

The flat bottom of the Scooter crater has already been noted. Also, the crater profile of the Scooter crater was compared (using cube-root scaling) with
Figure 2.31 Weighted curve fitting of 0.3-scaled radius versus 0.3-scaled depth of burst.

The equation for the curve is:

\[ y = 1.492 + 7.30X + 0.15X^2 - 0.137X^3 \]

Where:

- \( y \) is the scaled radius (\( \text{in} / \text{lb}^{0.3} \))
- \( X \) is the scaled depth of burst (\( \text{ft} / \text{lb}^{0.3} \))
Figure 2.32 Weighted curve fitting of 0.3-scaled depth versus 0.3-scaled depth of burst
Figure 2.33 Weighted curve fitting of 0.3-scaled volume versus 0.3-scaled depth of burst
Figure 2.34 Weighted curve fitting of gravity-scaled radius versus gravity-scaled depth of burst
Figure 2.35 Weighted curve fitting of gravity-scaled depth versus gravity-scaled depth of burst.

Graph showing the relationship between gravity-scaled burst depth and weighted data, with various symbols representing different charge weights (in lb) and a fitted line indicating the trend.

Mathematical expressions are also included:

- \( y = 12.16 + 1.125X - 0.011X^2 + 4.7 \times 10^8X^3 \)
- \( \rho = 100 \) lb/ft

Symbols correspond to charge weights:
- \( + \) 216
- \( O \) 256
- \( \Delta \) 2,560
- \( V \) 40,000
- \( \square \) \( 1 \times 10^6 \) (SCOOTER)
- \( * \) \( 2.4 \times 10^6 \) (J-U THRU T-S)
- \( X \) 3,000
- \( \times \) 5,000

Scalings and units are noted:
- Weighted data
- Scaled burst depth
- Depth versus gravity-scaled depth of burst
- Units: lb/ft
- Mathematical constants: \( 10^8 \), \( 10^6 \), \( 10^3 \)
Figure 2.36 Weighted curve fitting of gravity-scaled volume versus gravity-scaled depth of burst

\[ y = 10^3(3.53 + 0.571x + 0.0076x^2 - 9 \times 10^{-6}x^3) \]

\[ \rho = 100 \text{ lb/ft}^3 \]

**Symbols**

- +: 216
- o: 256
- △: 2,000
- ▽: 40,000
- □: 10 \( \times 10^6 \) (Scooter)
- ★: 2.4 \( \times 10^6 \) (J-U Thru T-S)
- X: 3,000
- X: 5,000
the crater profile from a small charge to point up the inadequacy of cube-root scaling. It is difficult to make a similar comparison using overburden scaling. When the crater dimensions of a crater such as Buckboard Shot 12 (which, by cube-root scaling has the same scaled burst depth as Scooter) are scaled to Scooter yield by overburden scaling, the burst depth is shallower by comparison. The Buckboard Shot 12 crater would appear as the crater of a 500-ton charge buried only 98 feet in basalt. Even so, it is interesting to compare such a crater with the Scooter crater (see Figure 2.37). Except for the flat bottom and low lip of the Scooter crater, the profiles are remarkably similar.

Figure 2.37 Scooter-Buckboard crater profile comparison
3.1 INTRODUCTION

Experiments conducted to investigate the distribution of ejecta from the Scooter explosion are part of a continuing effort\textsuperscript{5,13} to obtain data which will be useful in the design of future Plowshare nuclear cratering events. The purpose of experiments in ejecta distribution is to obtain quantitative information on the ejecta pattern as influenced by winds, on the surface area covered by ejecta, on the concentration of ejecta as a function of radial distance from the explosion epicenter, and on the total mass of ejecta deposited by the explosion.

A distinction is made here between earth material which is deposited ballistically by the explosion and earth material or fine particulate which is not so deposited. Ballistic material is characterized by large size, high terminal velocity, short range, and by dominance of gravitational body forces (Figure 3.1). Fine particulate matter is characterized by small size, low velocity, long range, and by dominance of wind forces. Fine particulate was measured by means of ejecta collectors placed at relatively great distances from the explosion. Ballistic ejecta was investigated by placing radioactive tracers in the region about the explosion which eventually became the crater void.

Figure 3.1 Ejecta from an underground explosion
3.2 DISTRIBUTION OF FINE PARTICULATE EJECTA

Fine particulate collectors for the Scooter explosion were placed at the intersections of a radial-circular array as indicated in Figure 3.2. The experimental procedure used for Scooter was identical to that for the Stagecoach\textsuperscript{5} and Buckboard\textsuperscript{12} experiments.

Figure 3.2 Ejecta collector array

The mass of fine particulate collected at each station is given in Table 3.1. The isodensity contour shown in Figure 3.3 was constructed from the particulate collector data by use of the following procedure. Areal density of fine particulate, or fallback density (mass of material collected divided by area of collector pan), at collector stations was plotted on log-log paper as a function of radial distance of collectors from ground zero for each of the twelve radial lines on which collectors were placed. Radial distances for the particular density values used on these contours were then interpolated from the log-log plots.
### TABLE 3.1 DISTRIBUTION OF FINE PARTICULATE FALLOUT COLLECTED AT VARIOUS STATIONS

<table>
<thead>
<tr>
<th></th>
<th>A (gm)</th>
<th>B (gm)</th>
<th>C (gm)</th>
<th>D (gm)</th>
<th>E (gm)</th>
<th>F (gm)</th>
<th>G (gm)</th>
<th>H (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3649.324</td>
<td>24.099</td>
<td>33.301</td>
<td>0.0111</td>
<td>0.0068</td>
<td>0.0083</td>
<td>0.0157</td>
<td>0.0124</td>
</tr>
<tr>
<td>2</td>
<td>2111.169</td>
<td>185.562</td>
<td>16.802</td>
<td>70.697</td>
<td>0.0015</td>
<td>0.6704</td>
<td>0.0022</td>
<td>0.0132</td>
</tr>
<tr>
<td>3</td>
<td>2174.325</td>
<td>62.313</td>
<td>3.046</td>
<td>56.692</td>
<td>19.177</td>
<td>0.0006</td>
<td>0.0032</td>
<td>0.0026</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>133.164</td>
<td>17.407</td>
<td>56.162</td>
<td>5.717</td>
<td>0.0041</td>
<td>0.0008</td>
<td>0.0077</td>
</tr>
<tr>
<td>5</td>
<td>1984.424</td>
<td>565.517</td>
<td>13.055</td>
<td>40.440</td>
<td>17.373</td>
<td>0.5047</td>
<td>0.0005</td>
<td>0.0007</td>
</tr>
<tr>
<td>7</td>
<td>0.0064</td>
<td>355.056</td>
<td>69.96</td>
<td>38.521</td>
<td>7.903</td>
<td>4.067</td>
<td>1.483</td>
<td>0.3782</td>
</tr>
<tr>
<td>8</td>
<td>0.0040</td>
<td>757.373</td>
<td>5.661</td>
<td>69.972</td>
<td>17.517</td>
<td>8.920</td>
<td>0.0008</td>
<td>0.0075</td>
</tr>
<tr>
<td>9</td>
<td>0.0068</td>
<td>77.738</td>
<td>12.776</td>
<td>219.801</td>
<td>32.159</td>
<td>10.714</td>
<td>10.146</td>
<td>0.0018</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>248.979</td>
<td>44.062</td>
<td>32.192</td>
<td>0.6119</td>
<td>0.0086</td>
<td>0.0285</td>
<td>0.0155</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>529.496</td>
<td>22.649</td>
<td>19.939</td>
<td>0.0170</td>
<td>0.0710</td>
<td>0.0199</td>
<td>0.0213</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>241.606</td>
<td>184.854</td>
<td>14.041</td>
<td>64.081</td>
<td>0.0038</td>
<td>0.0019</td>
<td>0.0044</td>
</tr>
</tbody>
</table>

X indicates a station at which the collector was destroyed and no sample obtained. Two numbers indicate duplicate sampling.

**APPARENT CRATER MEASUREMENTS:**
- **Radius:** 153.8 ft
- **Depth:** 76.4 ft
- **Volume:** $2.642 \times 10^6$ ft$^3$
The mass, $8.1 \times 10^{10}$ grams, of fine particulate deposited by the Scooter explosion plotted against apparent crater volume is shown in Figure 3.4 together with other alluvium data\(^1,3,4,5,14\) and data for dry sand,\(^15\) dry clay,\(^15\) sandstone,\(^16\) and basalt.\(^13\) The mass of fine particulate is defined and calculated in the following way. The average fallback density was obtained for each of the array circles, A to H, by taking the densities of the twelve stations on each circle and calculating the arithmetic mean. This quantity was then used as an average fallback density at a radial distance equal to the radius of the circle for which it was computed. On a log-log plot of average density versus radial distance from ground zero, a straight line was drawn through the data, the equation for which is given by $\rho(r) = Cr^m$ (see Figure 3.5). The mass of fine particulate was then obtained by means of the formula

$$M_F = M_O + 2\pi \int_{r_O}^{\infty} \rho(r)dr,$$

(3.1)
Figure 3.4 Mass of fine particulate deposited versus apparent crater volume
Figure 3.5 Ejecta density versus radial distance
where \( M_o \) is the mass of fine particulate deposited within the circle of radius, \( r_o = 7W^{1/3} \), (r in feet and \( W \) in pounds), the mass having a constant density equal to \( C_0 m \). All data in Figure 3.4 were obtained by this procedure.

The distance \( r_o \) is the radius of circle A for the Scooter experiment within which it is difficult to collect fallback deposits, since collectors are destroyed by missiles and air blast or are buried by ejecta. A constant fallback density for \( r < 7W^{1/3} \) is assumed in order to avoid the difficulty of extrapolating data from \( r = 7W^{1/3} \) to \( r = 0 \), where no collector data are available. Under this assumption, the mass calculated by Eq. 3.1 gives a lower limit for the total mass of earth, including missiles, which is ejected by an explosion. However, since one interest here is to obtain a measure of the mass of fine particulate deposited by winds, particularly at distant positions from the explosion, the mass figure arrived at by means of Eq. 3.1 is thought to be reasonable for fallback mass or total mass of fine particulate. This method for calculating fallback mass is simple and direct and compares favorably in accuracy with calculations by other methods; see for example the method used by Stetson, et al.\(^4\) The error in the mass of fine particulate deposited is estimated to be less than 25 percent.

The area covered by a given level (or greater) of fallback density may be estimated to within a factor of 2 by taking from Figure 3.5 that radius (\( r \)) at which the given density level occurs and by letting the area equal \( \pi r^2 \).

The best fit to the data plotted in Figure 3.4 is given by the empirical relationship

\[
M_F = 2.71 \times 10^4 V^{0.652},
\]

(3.2)

where \( M_F \) is the mass of fine particulate in grams and \( V \) is the apparent crater volume in cubic feet. Data from explosions in soil, as well as those from explosions in rock, are fairly well described by Eq. 3.2 and the dependence of fallback mass on burial depth is to some extent removed by a plot such as shown in Figure 3.4. With Eq. 3.2 and a knowledge of crater volume as a function of explosive energy release and depth of burial, the dependence of fallback mass on burial depth and yield may be inferred, as was done in Reference 5.

\[
\frac{M_F}{W^{0.64}} = 4.4 \times 10^8 \left( \frac{D}{W^{1/4}} \right)^{0.628}, \quad 0.2 \frac{D}{W^{1/4}} < 4
\]

(3.3)

\[
\frac{M_F}{W^{0.64}} = 1.28 \times 10^8 \left( \frac{D}{W^{1/4}} \right)^{-4.64}, \quad \frac{D}{W^{1/4}} \geq 4,
\]

(3.4)

where \( W \) is in pounds, \( D \) is depth of burial in feet, and \( M_F \) is mass in grams.

The total mass of fine particulate (\( M_F \)) deposited by the Scooter explosion agrees, within a factor of 2, with the total mass calculated by the empirical
scaling law of Eq. 3.3; $M_F$ calculated by Eq. 3.3 for the Sedan explosion (100 kt, D = 635 ft) also agrees well with the $M_F$ determined from preliminary data\textsuperscript{17} for Sedan.

3.3 DISTRIBUTION OF BALLISTIC EJECTA

To investigate the manner in which earth is ejected ballistically by underground explosions, radioactive pellets of antimony 124 were buried near the explosive charge in the region which ultimately became the crater void. From knowledge of the initial and final positions of the radioactive pellets, the approximate trajectories of crater ejecta can be obtained and an estimate made of the effective initial velocity field of earth particles in the crater void region. In addition, data are obtained on the areal density of the earth material ballistically deposited radially outward from the edge of the crater and on the total mass of each (including fine particulate) ejected by the explosion.

Twenty pellets, each initially containing 600 millicuries of antimony 124, which were used in two Stagecoach experiments were also used for the Scooter experiment. Each pellet was a stainless-steel cylinder 3/8 inch in diameter and 3/8 inch long, with a wall thickness of 1/16 inch. Each pellet was inscribed with an identifying number. A stainless-steel cap was welded to the cylinder to retain the antimony. Density of the pellets was about 6.5 grams per cubic centimeter.

Initial locations of antimony pellets for the Scooter explosion are shown in Figure 3.6. The pellets were buried in vertical holes 3 inches in diameter at the depths shown. Moistened earth was inserted in each hole tamped to the depth at which the next shallower pellet was to be buried. Previous investigations had shown that firmly tamped moistened earth in the holes adequately restored the original density of the soil and made the drill hole an insignificant perturbation to the explosive disturbance. This precaution and the small size of the pellets ensured that a pellet would represent a soil particle and that its ejection from the crater region would be essentially identical to that of a similarly located soil particle.

The final positions of the pellets are shown in Figure 3.6 and are tabulated in Table 3.2. Of twenty pellets used in the Scooter explosion, all but three were recovered.

In Figure 3.7 are shown those volume segments of soil originally surrounding the charge which were ejected to the same epicentral distances. These contours were constructed by noting the epicentral distance of ejection of a particle at its initial burial position and then drawing lines representing equal distances of ejection through the data so as to produce a consistent picture. Although the lines of constant range in Figure 3.7 are not unique, it was found that those variations which still give a consistent or meaningful picture did not greatly influence results derived from the contours. Figure 3.7 shows that a fairly large volume of earth in the region of the crater is not ejected beyond the crater's edge, but is retained within the crater where it partially fills the true crater void.
Figure 3.6 Tracer pellet positions pre- and postshot
<table>
<thead>
<tr>
<th>Pellet No.</th>
<th>Preshot location</th>
<th>Postshot location</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance from epicentral axis (ft)</td>
<td>Depth below surface (ft)</td>
<td>Distance from epicenter (ft)</td>
</tr>
<tr>
<td>1</td>
<td>75</td>
<td>55</td>
<td>66</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>40</td>
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<td>3</td>
<td>75</td>
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<td>4</td>
<td>100</td>
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<td>264</td>
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<tr>
<td>5</td>
<td>75</td>
<td>10</td>
<td>462</td>
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<td>32.6</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>55</td>
<td>370</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>20</td>
<td>246</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>40</td>
<td>Not recovered</td>
</tr>
<tr>
<td>11</td>
<td>125</td>
<td>10</td>
<td>133</td>
</tr>
<tr>
<td>12</td>
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<td>10</td>
<td>656</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>80</td>
<td>Not recovered</td>
</tr>
<tr>
<td>15</td>
<td>125</td>
<td>20</td>
<td>Not recovered</td>
</tr>
<tr>
<td>16</td>
<td>30</td>
<td>65</td>
<td>238</td>
</tr>
<tr>
<td>17</td>
<td>30</td>
<td>50</td>
<td>371</td>
</tr>
<tr>
<td>18</td>
<td>30</td>
<td>35</td>
<td>367</td>
</tr>
<tr>
<td>19</td>
<td>30</td>
<td>20</td>
<td>542</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>5</td>
<td>483</td>
</tr>
</tbody>
</table>

*Ranges of pellets 1 and 7 are too small to give a meaningful initial velocity from Eq. 3.5.*
The areal density of ejecta was determined from Figure 3.7 in the following manner. At the distance \((S_k + S_{k+1})/2\), shown in Figure 3.8, the mass of earth per unit area is

\[
\sigma = \rho \left( V_k - V_{k+1} \right) / \left( \pi \left( S_{k+1}^2 - S_k^2 \right) \right),
\]

where \(\rho\) is the soil density, and \(V_k\) is the volume of soil enclosed by the contour, \(S_k\), rotated about the vertical epicentral axis. The volumes \(V_k\) may be found from the integrals

\[
V_k = \int_{\theta_k}^{\theta_{k+1}} \int_{r_k}^{r_{k+1}} r \, dr \, dz = 2\pi \int_{r_k}^{r_{k+1}} r \, d(r) \, dr
\]

by means of numerical integration, using the contours of Figure 3.7 as the functions \(d(r)\). The results of these calculations are shown in Figures 3.9 and 3.10. The cylindrical volume of radius 20 feet unidentified in Figure 3.7 is not included in the calculation to obtain density versus distance, simply because it has been found from previous attempts that tracer pellets cannot be recovered from this region. Apparently this mass of earth undergoes violent or turbulent
Figure 3.8 Tracer pellet trajectory analysis

Figure 3.9 Scaled ejecta density versus scaled range
Figure 3.10 Ejecta density versus distance

\[ \rho_0 = 100 \text{ lb/ft}^3 \]

\[ \text{TOTAL MASS OF EJECTA} (M_e) = 8.4 \times 10^{10} \text{ gm.} \]

\[ \text{DISTANCE FROM EPICENTER (ft)} \]

\[ \text{EJECTA DENSITY (g/ft}^2 \]
motion and is ejected to great heights in a nearly vertical direction. It is likely that the major portion of this mass of earth eventually forms the dust cloud of buried explosions and is deposited as fine particulate.

In Figure 3.9, scaled areal density of ejecta (as determined from radioactive pellet data) is shown as a function of scaled distance from the charge epicenter. Also shown are the data obtained from pellets for the two Stagecoach shots (20 tons at 17- and 34-foot depths of burial). No empirical relationship between areal density of ejecta, depth of burst, and yield, such as that suggested by Sakharov\textsuperscript{16} for loess and clay, is evident from Figure 3.9 for explosions in desert alluvium.

In Figure 3.10 are presented all data obtained on ejecta density from the Scooter experiment. Crater lip profiles, \( h(r) \), are converted to areal density by taking \( \sigma(r) = \rho_0 h(r) \), \( \rho_0 = 100 \text{ lb/ft}^2 \). Lip profile data, antimony tracer data, and fine particulate data together determine a fairly continuous curve for ejecta density as a function of distance. Density values obtained from particulate collectors at positions closest to the charge may be low, since some of these collectors were destroyed by the air blast and missiles. The fine particulate data in Figure 3.10 are the averages of Lines 2 and 3 of the array shown in Figure 3.2; the radius (see Figure 3.6) under which antimony pellets were buried bisected the angle formed by Lines 2 and 3.

Estimates of the total mass of ejecta may be made from antimony tracer data, from particulate data, and from true and apparent lip profiles. The total mass of ejecta is defined as \( M_T = M_m + M_P - M_{TL} \), where \( M_P \) is the value of the integral,

\[
2\pi \int_{r_o}^{\infty} \rho(r)r \, dr
\]
given in Eq. 3.1; \( M_{TL} \) is the mass of the true lip obtained by multiplying true lip volume (Table 2.1 and Figure 2.7) by density, \( \rho_o = 100 \text{ lb/ft}^2 \); and \( M_m \) is the value of the integral

\[
2\pi \int_{R}^{r_0} \rho(r)r \, dr,
\]

where \( \rho(r) \) is the function shown in Figure 3.10 between \( R \) and \( r_o \). \( R \) is crater radius and \( r_o \) is the radius of circle A of the particulate collector array. Magnitudes of the various mass quantities described are listed in Table 3.3 for the Scooter experiment as well as for the HE-2, Stagecoach, Teapot ESS, and Sedan experiments. The total ejecta mass \( (M_T) \) and mass of fine particulate \( (M_P) \) deposited at distances greater than \( 7W^{1/3} \) are shown as functions of apparent crater volume in Figure 3.11. Mass \( M_c \), associated with apparent crater volume, is shown for comparison. It is obtained by multiplying the density \( (\rho_o = 100 \text{ lb/ft}^2) \) by the apparent crater volume.
<table>
<thead>
<tr>
<th></th>
<th>20 tons D = 5 ft</th>
<th>20 tons D = 17.1 ft</th>
<th>20 tons D = 34.2 ft</th>
<th>500 tons D = 125 ft</th>
<th>1.2 kt D = 67 ft</th>
<th>100 kt D = 635 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho = \frac{C \rho^m}{\sqrt[3]{r}} ) ( r \geq 7 \text{ft} )</td>
<td>1.13 \times 10^{0.87} \rho</td>
<td>2.34 \times 10^{0.22} \rho</td>
<td>2.27 \times 10^{1.5} \rho</td>
<td>1.67 \times 10^{4.07} \rho</td>
<td>4.57 \times 10^{4.07} \rho</td>
<td>4 \times 10^{6.3} \rho^{0.64}</td>
</tr>
<tr>
<td>( M_O = \rho (r_0) \pi r_0^2 )</td>
<td>0.47 \times 10^6</td>
<td>0.87 \times 10^8</td>
<td>0.51 \times 10^6</td>
<td>0.65 \times 10^{10}</td>
<td>0.15 \times 10^{10}</td>
<td>1.5 \times 10^{11} *</td>
</tr>
<tr>
<td>( M_P = 2 \pi \int_{r_0}^{\infty} \rho(r) r dr )</td>
<td>2.6 \times 10^5</td>
<td>4.7 \times 10^9</td>
<td>0.83 \times 10^6</td>
<td>0.64 \times 10^{10}</td>
<td>0.25 \times 10^{10}</td>
<td>1.8 \times 10^{11} *</td>
</tr>
<tr>
<td>( M_F = M_O + M_P )</td>
<td>3.1 \times 10^6</td>
<td>5.6 \times 10^9</td>
<td>1.3 \times 10^6</td>
<td>1.3 \times 10^{10}</td>
<td>0.40 \times 10^{10}</td>
<td>3.3 \times 10^{11} *</td>
</tr>
<tr>
<td>( M_l = \pi \int_{R}^{r_0} \rho(r) r dr )</td>
<td>1.9 \times 10^6</td>
<td>4.3 \times 10^9</td>
<td>0.67 \times 10^6</td>
<td>0.72 \times 10^{10}</td>
<td>0.74 \times 10^{10}</td>
<td>2.6 \times 10^{11}</td>
</tr>
<tr>
<td>( M_T = M_m + M_p - M_{TL} )</td>
<td>--</td>
<td>3.8 \times 10^9</td>
<td>5.5 \times 10^9</td>
<td>8.1 \times 10^{11}</td>
<td>6.7 \times 10^{11}</td>
<td>--</td>
</tr>
<tr>
<td>( M_C )</td>
<td>--</td>
<td>9.3 \times 10^9</td>
<td>1.5 \times 10^9</td>
<td>0.32 \times 10^{10}</td>
<td>2.2 \times 10^{10}</td>
<td>--</td>
</tr>
<tr>
<td>( M_T/M_C )</td>
<td>--</td>
<td>0.87</td>
<td>0.73</td>
<td>0.70</td>
<td>0.40</td>
<td>--</td>
</tr>
</tbody>
</table>

\( \rho \) in gm/ft², \( r \) in ft  
*Average of all data to date (Ref. 9)  
**Average of primary tarp data only (Ref. 9)
Figure 3.11 Comparison of crater volume mass and ejecta mass

Photography of the motion of targets placed on the earth surface above the explosive charge (see Chapter 5) allows values of surface particle velocity to be calculated. The measurements indicate that surface motion occurs in essentially radial directions along lines through the charge center. The observed velocities probably result from expansion of high pressure explosive gases released by the charge. If this is correct, it might be expected that the particle velocity field in the soil about the upper hemisphere of the charge would be nearly radial, in spite of the fact that a compressive wave and a tensile wave reflected from the surface have passed through this region. From the postshot location of the antimony pellets shown in Figure 3.6, it is evident that particle trajectories are not strictly along radial lines. Deviation from truly radial trajectories is similar to that observed for the two Stagecoach events on which antimony pellet trajectories were observed. These deviations were generally down wind, but it is not considered that wind action on the pellet trajectories was sufficient to account for the deviations observed. Possibly the nonradial motion may have resulted from geological inhomogeneities in the medium. Assuming that the velocity field is radial, that it results from expansion of explosion gases, and that it determines the trajectories of soil particles, an estimate of the field may be obtained from the observed ranges of antimony tracers.
Neglecting air drag, the initial velocity \( V_{o,j} \) of the \( j \)th tracer or soil particle is given by the ballistic formula

\[
V_{o,j} = R_j g^{1/2} \left( \frac{R_j \sin \theta_j - 2y_j \cos^2 \theta_j}{\sin^2 \theta_j - 2y_j \cos \theta_j} \right)^{1/2},
\]

(3.5)

where \( R_j \) is the range, \( y_j \) is the initial depth below surface, \( \theta_j \) is the angle between a radial line through charge center and the horizontal for the \( j \)th tracer, and \( g \) is the acceleration of gravity. Since the motion about the charge is assumed to be radial, the angles \( \theta_j \) are known; from knowledge of initial positions \( y_j \) and observed ranges \( R_j \), initial velocity \( V_{o,j} \) is found.

Values of effective initial velocities as determined by ballistic formula are shown in Figure 3.12 and listed in Table 3.2. Also shown in Figure 3.12 are surface velocities obtained from photography of surface targets. The order of magnitude of ejecta velocity determined from motion picture photography (Chapter 5) compares well with velocities calculated from tracer data. The radial velocity field of Figure 3.12, calculated from Eq. 3.5, is different from that assumed for the Scooter explosion by Hess and Nordyke.\(^{18}\) For comparison with the Scooter velocity field of Figure 3.12 the velocity fields for two Stagecoach explosions are shown in Figure 3.13a and b. In Figure 3.14 the velocity fields of a 20-ton and a 500-ton explosion at nearly the same cube-root-scaled depths are compared.

3.4 SUMMARY

The distribution of ejecta from an underground explosion is described very generally by the expression

\[
\rho = A f(r, \theta, D, W),
\]

(3.6)

where \( \rho \) is mass of ejecta per unit area, \( r \) and \( \theta \) are polar coordinates with the explosion epicenter as origin, \( W \) is explosive weight detonated at depth \( D \); and \( A \) is a constant dependent on properties of the medium in which the explosion occurs. Azimuthal variation in the ejecta density of the fine particulate deposited from an explosion is determined primarily by meteorological conditions and can be computed fairly well by fallout models, if wind speed and direction are known to the altitudes reached by the explosion cloud. For ballistic ejecta, the azimuthal variation in \( \rho \), produced by \( \theta \)--which must describe, for example, the fingers or rays of debris common to cratering explosions--is probably accounted for by non-uniformities in the geology of the medium about the explosion such as stratification, planes of weakness, and gross inhomogeneities. By sampling ejecta for a number of values of \( \theta \) from 0 to \( 2\pi \) at each fixed distance \( r \) and averaging the results, the influence of \( \theta \) on the ejecta density is to some extent removed and \( \theta \) is then considered an average density at distance \( r \).
Figure 3.12 Effective velocity field derived from Scooter pellet trajectories
Figure 3.13 Effective velocity fields for Stagecoach
Figure 3.14 Comparison of Stagecoach and Scooter effective velocity fields
The exact dependence of \( \rho \) on \( W \) and \( d \) has not been established from experiments to date. The empirical scaling law (Eq. 3.3) for the mass of fine particulate suggests that \( \rho \) is proportional to \( W^{1/3} \) and to \( d^{0.6} \). In Table 3.3 experimental results for \( \rho \) from six explosions in desert alluvium are expressed in the form \( \rho = C r^m \), where \( m \) has values ranging from -2 to -5. We may assume for the form of Eq. 3.6

\[
\rho = AC(W,D)r^m(W,D),
\]

(3.7)

where the quantities \( C \) and \( m \) are in general functions of \( W \) and \( D \). Data from Table 3.3 indicate that \( m \) is not strongly, if at all, dependent on \( W \), but is primarily a function of \( d \) alone.

The relation

\[
m = -1.35 (d + 7.6)^{0.2}
\]

(3.8)

fits the data of Table 3.3 reasonably well. From Eqs. 3.3, 3.7, and 3.8 and

\[
M_F = 2\pi \int_{r_0}^{\infty} \rho r \, dr,
\]

one can deduce a dependence of \( C \) on \( W \) and \( D \). This result, however, is not consistent with the values of \( C \) listed in Table 3.3. Hopefully, data from future experiments will allow the functional dependence of \( C \) on \( W \) and \( D \) to be established. It should be pointed out that the nature of ejecta deposition from buried explosion is extremely complex, and consequently data on ejecta densities will be characterized by gross statistical variations. The quantity \( C \) is extremely sensitive to these variations in data, and any relationship \( C = C(W,D) \) which gives values of \( C \) that differ by only an order of magnitude from experimental values can be considered good.

3.5 CONCLUSIONS

The extremely simple experiments of the Scooter explosion have provided reliable data on the distribution and quantity of earth material ejected by the explosion. By means of the radioactive tracer technique, measurements have been made of the areal density of ballistic ejecta from the crater radius outward. The tracer method also leads to an estimate of the effective velocity field about the explosive charge and a determination of those regions of earth about the charge from which particular ejecta originated. At distances from the explosion epicenter beyond which ballistic ejecta are not deposited, dust from the explosion cloud or fine particulate was measured with collector pans. From these data average areal density as a function of distance is determined, and that fraction of crater volume material which is deposited as fine particulate is established. An empirical scaling law (Eq. 3.5) for the mass of ejecta deposited as fine
particulate, obtained from data of the Stagecoach experiments, has been verified by the 500-ton Scooter experiment and also by available data from the recent 100-kt Sedan cratering experiment. This scaling law appears to give results for the mass of earth material deposited as fine particulate which are correct to within a factor of about two.

Data from tracer and fine particulate experiments are sufficient to determine the total mass of ejecta deposited by an explosion. From Figure 3.11, which shows total ejecta mass as a function of apparent crater volume, a scaling law for total ejecta mass may be obtained for desert alluvium as was done (Eq. 3.5) for mass of fine particulate. That part of crater volume mass which can be accounted for as ejecta is 70 to 90 percent for chemical explosions at cube-root scaled depths of 1/2 to 1. Data from the Teapot ESS nuclear explosion (scaled depth of 1/2) reveal that 40 percent of the crater volume mass was ejected. This fraction is about a factor of 2 less than that for a chemical explosion at the same scaled burst depth (20-tons at 17-feet). It would thus appear from ejecta data that chemical explosives are more energetic than nuclear explosives in ejecting earth material from the crater void region.

In addition to the array of throwout collector pans, seven canvas pads 10 feet square were placed on a line running north-south through surface zero to collect all types of ejecta. This study of particles large enough to act as missiles was intended to furnish data for empirical missile distribution equations. The collection pads were at ranges of 1500, 2175, and 3180 feet both north and south of surface zero and at 4650 feet south.

Quantities of material collected on these pads ranged from nothing to 17.2 pounds and included only 1.5 pounds of material greater than 0.33 inch in diameter. The latter material was all on the pad 1500 feet south of surface zero.

No data suitable for a missile distribution analysis were derived because the only material comprising missile sizes was on a single collection pad.
CHAPTER 4 -- PARTICLE MOTION

4.1 EXPERIMENT PLAN

Interest in explosion craters for design of major excavation projects generated by the Plowshare Program emphasized the paucity of quantitative information concerning crater mechanics, with the exception of apparent crater dimensions. Some particle acceleration observations and a few earth pressure measurements were made during the Corps of Engineers Underground Explosion Tests at Dugway Proving Grounds, Utah; the Project Mole explosion series at Dugway and Nevada Test Site; and the underground nuclear and chemical explosions, Jangle U, Jangle HE-2, Teapot ESS, and Rainier. The last-named explosion did not produce a crater, but some measurements made close to it are pertinent to very early phases of crater formation.

Studies of particle motion produced by the Scooter explosion were planned to include four measurements of early vertical velocities within the crater volume, measurements of radial acceleration and velocity on a horizontal radius at shot depth and at five ranges between 50 and 300 feet, and surface radial displacements at ranges of 275 and 1000 feet. Gage positions are represented schematically in Figure 4.1. Radial ranges to gages and other pertinent information are included in Table 4.1. Two additional surface motion stations at 225- and 275-foot ranges were made available to Stanford Research Institute (SRI) for field tests of a newly developed displacement gage. Data from these gages were recorded on the same tapes as were those from Sandia gages but will not be reported here since they are properly a part of an SRI gage development project.

Figure 4.1 Plan and elevation - Scooter ground-motion gages
### TABLE 4.1 INSTRUMENTATION

<table>
<thead>
<tr>
<th>Station</th>
<th>Range (ft)</th>
<th>Depth (ft)</th>
<th>Gages</th>
<th>Status (H-1 hours)</th>
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</thead>
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<td>BR1</td>
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<td>125</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>BR2</td>
<td>8</td>
<td>125</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
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<td>125</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>BR4</td>
<td>4</td>
<td>125</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>BR5</td>
<td>8</td>
<td>125</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>BR6</td>
<td>12</td>
<td>125</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>BR7</td>
<td>4</td>
<td>125</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>BR8</td>
<td>8</td>
<td>125</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>BR9</td>
<td>12</td>
<td>125</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>TOA 1</td>
<td>0</td>
<td>95</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>TOA 2</td>
<td>0</td>
<td>80</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>TOA 3</td>
<td>0</td>
<td>60</td>
<td>Pressure switch</td>
<td>Unused</td>
</tr>
<tr>
<td>TOA 4</td>
<td>0</td>
<td>20</td>
<td>Pressure switch</td>
<td>Operable</td>
</tr>
<tr>
<td>SZ-1</td>
<td>0</td>
<td>2 (high)</td>
<td>Wiancko pressure</td>
<td>Operable</td>
</tr>
<tr>
<td>SZ-2</td>
<td>0</td>
<td>10 (high)</td>
<td>Wiancko pressure</td>
<td>Operable</td>
</tr>
<tr>
<td>P-1</td>
<td>140</td>
<td>0</td>
<td>Ultradyne pressure</td>
<td>Operable</td>
</tr>
<tr>
<td>P-2</td>
<td>235</td>
<td>0</td>
<td>Ultradyne pressure</td>
<td>Operable</td>
</tr>
<tr>
<td>P-3</td>
<td>420</td>
<td>0</td>
<td>Ultradyne pressure</td>
<td>Failed</td>
</tr>
<tr>
<td>P-4</td>
<td>730</td>
<td>0</td>
<td>Ultradyne pressure</td>
<td>Failed</td>
</tr>
<tr>
<td>P-5</td>
<td>1260</td>
<td>0</td>
<td>Ultradyne pressure</td>
<td>Failed</td>
</tr>
<tr>
<td>U-15</td>
<td>15</td>
<td>20</td>
<td>( u_r )</td>
<td>Failed</td>
</tr>
<tr>
<td>U-30</td>
<td>30</td>
<td>20</td>
<td>( u_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>U-50</td>
<td>50</td>
<td>125</td>
<td>( a_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>U-100</td>
<td>100</td>
<td>125</td>
<td>( a_r u_r \sigma_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>U-150</td>
<td>150</td>
<td>125</td>
<td>( a_r u_r \sigma_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>U-200</td>
<td>200</td>
<td>125</td>
<td>( a_r u_r \sigma_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>U-300</td>
<td>300</td>
<td>150</td>
<td>( a_r u_r \sigma_r )</td>
<td>Operable</td>
</tr>
<tr>
<td>S-275</td>
<td>275</td>
<td>0</td>
<td>( \delta \sigma_\nu T )</td>
<td>Operable</td>
</tr>
<tr>
<td>S-1000</td>
<td>1000</td>
<td>0</td>
<td>( \delta \sigma_\nu T )</td>
<td>Operable</td>
</tr>
</tbody>
</table>

Five ground baffle stations were prepared between ranges of 140 and 1200 feet for measuring surface air-blast overpressure before it became certain that NOL could implement its more sophisticated program of overpressure measurements. Air-blast gages were also installed at 2 and 10 feet above surface zero to indicate overpressure magnitude and wave shape of ground-shock-induced air blast and, if possible, of gas-bubble pressure.

Time-of-arrival instrumentation was installed at nine points on three radii of the equatorial plane within the charge, at 4, 8, and 12 feet from the center, and at four points in the soil above the charge. These instruments were intended to indicate rate and symmetry of burning within the charge and shock velocity immediately above the charge.
4.2 INSTRUMENTATION

End instruments for vertical velocity and for horizontal acceleration and velocity were mounted in canisters molded of equal parts of epoxy resin and mica filler. These canisters accommodated the gages and cabling in 6-inch-diameter cylinders matched to the bulk density of Area 10 soil. Photographs of a canister with gages in place and ready for assembly are shown in Figure 4.2.

![Underground gage canister before final assembly](image)

Accelerometers were of two types. The instrument at 50-foot range was a high-range Statham accelerometer in which the transducer element included unbonded, resistive wire strain gages. All other accelerometers were variable reluctance Wiancko gages.

Particle velocity gages were of SRI design. The vertical type is composed of two parts: (1) the transducer element, a linear differential transformer the core of which falls vertically through a tube containing a viscous fluid, and (2) the cocking mechanism, a solenoid which retrieves and holds the core in a position above the transformer and releases it on signal for free fall during passage of earth shock. Horizontal velocity gages included a pendulum damped to about 100
times critical by a viscous fluid and developing a signal proportional to the case velocity through a variable reluctance transducer.

Soil pressure gages were barium titanate crystals enclosed in polyethylene sacks filled with sand. The sacks were attached above the instrument canisters.

All gage canisters were placed in borings at appropriate positions, using placement rods in 10-foot sections to lower and orient the canisters (Figure 4.3). Remotely operated disconnects released the placement rods when the instruments were properly oriented in place. A special grout, designed to approximate the density and strength of the soil at shot depth, was used to hold each canister in place. Each gage boring was filled with grout.

Air overpressure gages in the ground baffles were variable reluctance, diaphragm-type instruments made by Ultradyne. Wiancko air-pressure gages were used at the two stations above the surface zero.

Radial displacements at ground surface were derived from measurement of tangential strain by long-base strain gages similar to those designed for use during Operation Hardtack II. These gages were placed with transducer ends adjacent to the Sandia blast line in trenches about 2 feet deep dug perpendicular to radii from surface zero through mid-points of the gage spans. The gage at 275 feet spanned 76 feet and that at 1000 feet spanned 156 feet. Gage trenches were backfilled with loose soil after gage ends were attached to anchors grouted into shallow borings.

Time-of-arrival end instruments were small crush switches. Each of these switches actuated a multivibrator in series with an 80-kilocycle oscillator. Two switches and a zero-time fiducial signal were served by each oscillator channel and multivibrators were arranged to double the oscillator-output amplitude for three pulses of 6-, 12-, or 18-cycle duration. The 80-kilocycle signal was recorded continuously on magnetic tape. The 6-cycle-long pulse in each case was actuated by the
zero-time fiducial signal produced by the firing unit. Thus, each channel included a zero-time signal and arrival-time signals of 12- or 18-cycle pulses from the two switches at different positions.

Transistorized cathode followers were included in each canister adjacent to the piezoelectric pressure gages. Outputs of the cathode followers were frequency modulated and were recorded on magnetic tape.

All other gages included variable resistance or reluctance transducers. They were operated as parts of 3-kcps carrier-amplifier system, the DC output of which was converted from an amplitude-modulated to a frequency-modulated signal and recorded on magnetic tape.

All tapes were returned to Sandia Laboratory for playback and analysis.

4.3 DATA

The delay in detonation of Scooter from July 14 to October 13 included several periods of serious flooding by rains and an early snow in Area 10. At one time early in October, all instrumentation circuits were rendered inoperable by the flooding. As a result of this damage and other mechanical failures, three of the surface overpressure stations were lost through gage corrosion, three vertical velocity gages failed mechanically, and several time-of-arrival channels were inoperable.

Some attrition of data resulted from causes other than those attributable directly to weather. All earth pressure channels failed to produce data records, but the cause of failure could not be fixed. Circuitry above ground was operative, but it was not possible to determine whether failure occurred in the cathode followers, in the crystal gages, or was the result of negligible loading because of the method of placement.

Loss of data from all time-of-arrival circuits resulted in complete absence of information on rate and symmetry of explosive burning. This loss appears to have been caused solely by an electrical transient at zero time which loaded the 80-kilocycle carrier to essentially zero output. All channels from this portion of the project showed normal carrier amplitude to zero time, when amplitude dropped irregularly to noise level. The carrier recovered normal amplitude by about 2 milliseconds after detonation and several 6-, 12-, or 18-cycle pulses of doubled amplitude occurred during the remainder of the record, suggesting that the circuits were performing properly at these later times when collapsing coaxial cables produced short circuits at progressively shallower depths. Unfortunately, these were spurious data, since there was no way of knowing at what points the short circuits occurred.

Pertinent data for all Scooter recording channels which operated satisfactorily are compiled in Table 4.2. Data derived from the five horizontal radial stations are presented as functions of time in Figures 4.4 through 4.8. These curves include directly observed accelerations and velocities as well as particle
Figure 4.4 Particle motion records - 50-foot range

Figure 4.5 Particle motion records - 100-foot range
Figure 4.6 Particle motion records - 150-foot range
Figure 4.7 Particle motion records - 200-foot range
Figure 4.8 Particle motion records - 300-foot range
velocities and displacements derived by integration of observed data. Data from two additional gages, VV-2S, the vertical velocity gage about 105 feet above the burst point, and SRD-275, the surface tangential strain gage at 275 feet from surface zero, are presented in Figures 4.9 and 4.10.

TABLE 4.2 PARTICLE MOTION

<table>
<thead>
<tr>
<th>Gage number</th>
<th>Radial range (ft)</th>
<th>Time of arrival (msec)</th>
<th>Acceleration out (g)</th>
<th>Acceleration in (g)</th>
<th>Velocity out (ft/sec)</th>
<th>Velocity in (ft/sec)</th>
<th>Displacement out (in.)</th>
<th>Displacement in (in.)</th>
<th>Set range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-50</td>
<td>50</td>
<td>12.0</td>
<td>18,187</td>
<td>--</td>
<td>&gt;1200</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>10⁴ g</td>
</tr>
<tr>
<td>A-100</td>
<td>100</td>
<td>23.7</td>
<td>491</td>
<td>21.6</td>
<td>53.0</td>
<td>--</td>
<td>&gt;41.7</td>
<td>--</td>
<td>500 g</td>
</tr>
<tr>
<td>HV-100</td>
<td>100</td>
<td>23</td>
<td>--</td>
<td>--</td>
<td>&gt;40</td>
<td>--</td>
<td>---</td>
<td>--</td>
<td>32 ft/sec</td>
</tr>
<tr>
<td>A-150</td>
<td>150</td>
<td>34.9</td>
<td>27.1</td>
<td>6.2</td>
<td>19.2</td>
<td>4.15</td>
<td>21.7</td>
<td>--</td>
<td>30 g</td>
</tr>
<tr>
<td>HV-150</td>
<td>150</td>
<td>34.6</td>
<td>--</td>
<td>--</td>
<td>22.9</td>
<td>--</td>
<td>28.2</td>
<td>--</td>
<td>30 ft/sec</td>
</tr>
<tr>
<td>A-200</td>
<td>200</td>
<td>46.0</td>
<td>4.92</td>
<td>2.97</td>
<td>8.55</td>
<td>2.68</td>
<td>11.7</td>
<td>--</td>
<td>5 g</td>
</tr>
<tr>
<td>HV-200</td>
<td>200</td>
<td>46.4</td>
<td>--</td>
<td>--</td>
<td>8.24</td>
<td>1.74</td>
<td>12.1</td>
<td>--</td>
<td>10 ft/sec</td>
</tr>
<tr>
<td>A-300</td>
<td>300</td>
<td>71.9</td>
<td>0.80</td>
<td>0.88</td>
<td>2.53</td>
<td>0.84</td>
<td>4.28</td>
<td>--</td>
<td>1 g</td>
</tr>
<tr>
<td>HV-300</td>
<td>300</td>
<td>72</td>
<td>--</td>
<td>--</td>
<td>3.44</td>
<td>1.06</td>
<td>5.81</td>
<td>0.30</td>
<td>3 ft/sec</td>
</tr>
<tr>
<td>VV-2S</td>
<td>110</td>
<td>34</td>
<td>--</td>
<td>--</td>
<td>&gt;40</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>32 ft/sec</td>
</tr>
<tr>
<td>SRD-275</td>
<td>275</td>
<td>177</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>19.5</td>
<td>--</td>
<td>18 in.</td>
</tr>
</tbody>
</table>

Gages are designated by the following code: A represents an accelerometer always horizontal radial at shot depth, HV represents a horizontal velocity gage at shot depth, VV represents a vertical velocity gage, numbers following A or HV designate the nominal horizontal range in feet from charge center to the gage, and numbers following VV indicate by 1 the nearer boring within the crater area (15 feet offset from vertical charge axis) and by 2 the farther boring (30 feet offset). S and D following the numbers 1 and 2 indicate the shallow or deep gage.

Curves for HV-100 and VV-2S indicate that only the initial part of the motion was within the effective range of the gage. It is noteworthy that although the recorded signal from VV-2S reached the limit of gage response about 36 milliseconds after the first arrival, the circuit apparently operated normally for about 126 milliseconds longer before cable damage caused failure of the channel.
Figure 4.9  Initial particle velocity within crater volume

Figure 4.10  Surface motion at 275-foot range
4.4 ANALYSIS OF DATA

Arrival times at the five subsurface stations show general agreement between accelerometer and velocity gage data. Propagation velocities have been derived from these data by two methods: (1) by calculating velocities across intervals between gages, and (2) by computing velocities from the source to each gage. Table 4.3 includes the derived velocities, mean values, and average deviations for each method of computation.

**TABLE 4.3 PROPAGATION VELOCITIES**

<table>
<thead>
<tr>
<th>Gage</th>
<th>Range (ft)</th>
<th>Time of arrival (msec)</th>
<th>Velocity (intervals) (ft/sec)</th>
<th>Velocity (from source) (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-50</td>
<td>50</td>
<td>12.0</td>
<td>4166.7</td>
<td>4166.7</td>
</tr>
<tr>
<td>A-100</td>
<td>100</td>
<td>23.7</td>
<td>4273.5</td>
<td>4219.4</td>
</tr>
<tr>
<td>HV-100</td>
<td>100</td>
<td>23.0</td>
<td>4545.5</td>
<td>4347.8</td>
</tr>
<tr>
<td>A-150</td>
<td>150</td>
<td>34.9</td>
<td>4464.3</td>
<td>4298.0</td>
</tr>
<tr>
<td>HV-150</td>
<td>150</td>
<td>34.6</td>
<td>4310.0</td>
<td>4335.3</td>
</tr>
<tr>
<td>A-200</td>
<td>200</td>
<td>46.0</td>
<td>4504.5</td>
<td>4347.8</td>
</tr>
<tr>
<td>HV-200</td>
<td>200</td>
<td>46.4</td>
<td>4237.3</td>
<td>4310.3</td>
</tr>
<tr>
<td>A-300</td>
<td>300</td>
<td>71.9</td>
<td>3861.0</td>
<td>4172.4</td>
</tr>
<tr>
<td>HV-300</td>
<td>300</td>
<td>72.0</td>
<td>3906.3</td>
<td>4166.7</td>
</tr>
</tbody>
</table>

Mean Propagation Velocity 4252.1 4262.7
Average Deviation 186.0 (4.4%) 72.4 (1.7%)

There appears to be a region of higher velocity (see Figure 4.11) between the gage at 50 feet and those at 200 feet from the detonation. That velocity is about 4400 feet per second and is indicative perhaps of a lenticular mass of caliche including the gages at 100, 150, and 200 feet. The best average velocity is about 4260 feet per second, from which the average deviation is 72 feet per second or about 1.7 percent.

The velocity with which pressure or particle velocity peaks are propagated will be less than that derived from initial signal arrivals in a dispersive medium. Data from Scooter particle velocity records indicate that peaks are transmitted at about 2100 feet per second, a little less than half the initial signal velocity.

Data in Table 4.2 represent results of all measurements for this project. Reliability of these data may be judged by comparing particle velocity peaks at three stations where this quantity was observed directly with the velocities derived from integration of acceleration records. In addition, the initial portion of the velocity curve derived from A-100 compares favorably with that portion of the record from HV-100 which was within the limits of gage response, Figure 4.5.
Plots of peak acceleration, particle velocity, and displacement as functions of radial range are shown in Figure 4.12. The acceleration plot indicates that between 50 and 300 feet attenuation follows the inverse 5.75-power of range represented by the solid line. This line is a least-squares fit to the data and is expressed by the equation

\[ a = 1.14 \times 10^{14} R^{-5.75 \pm 0.18}, \]

where \( a \) is acceleration in g-units and \( R \) is range in feet.

![Figure 4.11 Interval propagation velocity on horizontal radius](image)

Peak particle velocities as plotted in Figure 4.12 suggest attenuation as the inverse 2.68-power of radial range between 100 and 300 feet. There is also an implied faster rate of attenuation between 50 and 100 feet, but the integrated data from A-50 do not define a peak velocity well enough to support its use in analysis. The line drawn on the velocity plot representing a least-squares fit to the data between 100 and 300 feet is expressed by

\[ u = 1.26 \times 10^7 R^{-2.68 \pm 0.12}, \]

where particle velocity, \( u \), is in feet per second and range, \( R \), in feet.
Figure 4.12 Peak particle motion versus range

Similarly, the line drawn through the displacement data in Figure 4.12 represents a least-squares fit which indicates that attenuation in the region between 100 and 300 feet occurs as the inverse 2.3-power of range. The equation for the displacement curve is

$$\delta = 2.43 \times 10^6 \ R^{-2.3 \pm 0.17},$$

where $\delta$ is displacement in inches, and $R$, range, in feet.

Attenuation exponents are given standard deviation limits which furnish a measure of reliability for the data. These limits imply that of all regression fits made to acceleration data derived under Scooter conditions, 67 percent of the
exponents will fall within ±3.1 percent of the inverse 5.75 power. Similarly, for particle velocity the range is ±4.5 percent and for displacements it is ±7.4 percent.

There is nothing in these data to indicate that a transition from nonlinear to linear response of the soil occurred within the range of instrument distances. The lowest velocity, at 300 feet, is about 2.5 feet per second. Propagation velocity between the 200- and 300-foot stations was about 3900 feet per second for initial motion, and phase velocity for peak particle velocity between these stations was about 2060 feet per second. If soil density is taken to be 1.5, then peak pressure at 300 feet can be estimated at about 104 psi—probably greater than the compressive elastic limit of the soil. This verifies the fact that the gage line did not extend out into the region of linear or elastic response.

It is of interest to compare results of the Scooter measurements with similar ones made during three comparable explosions in Area 10. Acceleration data were derived from the Jangle U²⁰ and Teapot ESS²² nuclear cratering experiments and from Jangle HE-2,²¹ a 40,000-pound TNT cratering experiment. These explosions differed from Scooter in energy yield, depth of burst and, in two cases, in type of explosive. Instrumentation was all below the ground surface but not always at shot depth, as in the case of Scooter. Comparison of peak radial accelerations and particle velocities and displacements derived from those accelerations during the four events is feasible if motion observations and radial range are scaled to a common datum. This may be accomplished on the basis of scaling to the cube root of explosive energy,* where equivalent weights of TNT are used as an energy parameter. Scaling relations for the various motion parameters have the form

\[ a \cdot W^{1/3} = (R/W^{1/3})^\ell \]
\[ u = (R/W^{1/3})^m \]
\[ \delta/W^{1/3} = (R/W^{1/3})^n \]

where \( a \) represents particle acceleration, \( u \) particle velocity, \( \delta \) particle displacement, \( R \) radial range, and \( W \) equivalent TNT charge weight in pounds. For our purpose, \( \ell \), \( m \), and \( n \) are empirically derived exponents and usually have negative values.

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*It should be noted that free-field particle motion scales as the cube root of charge energy, and that under the conditions of this test there is no reason to expect body-force or free-surface influences to act as they evidently do in scaling crater dimensions. It is possible that at much greater depths departures from cube-root scaling of motion parameters might become observable.
Plots of the scaled data are presented in Figures 4.13a, 4.14a, and 4.15a. These plots show reasonably good agreement between Scooter and Jangle HE-2 data, wherein the latter extend information from Scooter outward to considerably greater scaled ranges. It is also apparent from plots that data from the nuclear explosions follow a pattern of attenuation with distance similar to those from the chemical explosions, but that nuclear data at the same scaled range are generally of lower magnitude than the chemical data.

The latter situation suggest that nuclear explosions may have a lower efficiency for producing ground motion than is indicated by radiochemical energy yield. The fact that actual and scaled depths of burst differ considerably between Scooter and the Jangle U and Teapot ESS events should not influence this efficiency, because in any of these events there seems little likelihood that the influence of venting could have occurred early enough to have affected the acceleration or particle velocity peaks notably. It seems interesting, then, to discover whether a simple apparent reduction of equivalent energy can cause scaled ground motion data from two types of explosive to correspond. Several efficiencies were tried and it was found that the assumption of 50-percent efficiency for Teapot ESS (or a yield equivalent to 0.6 kiloton of TNT) and 20 percent (or 0.24 kiloton of TNT) for Jangle U give the results illustrated in Figures 4.13b, 4.14b, and 4.15b. These efficiencies are not in any way unique, and the analysis is evidently not very sensitive. However, results demonstrated by the fit of nuclear to chemical explosive data indicate that, insofar as this analysis is valid, the efficiencies are good within 10 percent; i.e., the efficiency of Teapot ESS in terms of ground motion is not greater than 60 percent nor less than 40 percent.

It is also of interest to note that the change in slope of the curve for particle velocity in Area 10 soil from that characterizing nonlinear response ($R^{-2.88}$) to that which implies linear or quasi-linear response ($R^{-1.5}$) occurs at about 0.8 foot per second. This corresponds to a pressure of about 33 psi, which is a reasonable value for the dynamic elastic limit of caliche-cemented sand and gravel under dynamic load.
Figure 4.13 Scaled acceleration versus scaled range, comparison of nuclear and chemical explosions
Figure 4.14  Particle velocity versus scaled range, comparison of nuclear and chemical explosions
Figure 4.15 Scaled displacement versus scaled range, comparison of nuclear and chemical explosions
CHAPTER 5 -- SURFACE MOTION AND CLOUD GROWTH

5.1 BACKGROUND

Surface motion of the ground over buried detonations has been determined for high-explosive shots in NTS desert alluvium with 256-pound charges and 40,000-pound charges, in tuff with 256-pound charges, and in basalt with 40,000-pound charges. Similar motions were observed above nuclear charges in alluvium and tuff.

Growth of the cloud over cratering explosions was also observed for 256-pound charges, 2560-pound, and 40,000-pound charges in desert alluvium, for 40,000-pound charges in basalt, and for a range of charge weights in dry clay.

5.2 SURFACE MOTION

5.2.1 Surface Displacement

A record of the displacement of the ground surface caused by the Scooter shot was obtained from motion picture photography. The films were re-read by Sandia Corporation and the results used in this analysis. Photographic targets were placed at surface zero and at 30, 60, and 120 feet along a radius perpendicular to the camera line of sight and along another radius oriented 18 degrees from the line of sight (Figure 5.1). The target numbers, radial distances, and orientations were:

<table>
<thead>
<tr>
<th>Target No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from surface zero (ft)</td>
<td>120</td>
<td>60</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Orientation with respect to camera line of sight (degrees)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Figure 5.2 shows the vertical displacement of the surface at ground zero as the mound rose.

The vertical motion of Target 4 is essentially the same as that of the ground zero surface. The vertical motions (displacement-time) of the other targets are shown in Figures 5.3, 5.4, and 5.5. After the charge was in place, a hole cased with steel pipe was drilled at surface zero to permit access to the charge. This charge-access steel pipe was located near Target 4 at surface zero. Its vertical displacement as a result of the detonation was more rapid than that of Target 4 (Figure 5.6). The horizontal displacements of Targets 5, 6, and 7 (Figure 5.7) together with their vertical displacements permit trajectories of the three targets to be constructed (Figures 5.8 and 5.9). Only one dimension of the trajectories of Targets 1, 2, and 3 is shown because of their position with respect to the camera line of sight (Figure 5.1). It may be assumed that the trajectories of Targets 1, 2, and 3 were similar to those of Targets 5, 6, and 7.
Figure 5.1 Vertical displacement at surface zero

Figure 5.2 Phototarget plan
Figure 5.3 Vertical displacement 30 feet from surface zero

Figure 5.4 Vertical displacement 60 feet from surface zero
Figure 5.5 Vertical displacement 120 feet from surface zero

Figure 5.6 Vertical displacement of pipe at surface zero
Figure 5.7 Horizontal displacement at 30, 60, and 120 feet from surface zero

Figure 5.8 Hodographs of phototargets
Figure 5.9 Hodographs of phototargets
5.2.2 **Surface Velocity**

Differentiation of the surface displacement-time curves has given velocity-time curves for the Scooter event (Figures 5.10, 5.11, 5.12, 5.13, and 5.14). Vertical velocities of comparable targets are in good agreement (Figures 5.10, 5.11, and 5.12). The velocity of the pipe emerging from the ground at surface zero was, as noted, considerably greater than the motion of Target 4.

![Figure 5.10](image1.png) **Figure 5.10** Vertical velocity 30 feet from surface zero

![Figure 5.11](image2.png) **Figure 5.11** Vertical velocity 60 feet from surface zero
Figure 5.12  Vertical velocity 120 feet from surface zero

Figure 5.13  Vertical velocity above surface zero
Figure 5.14 Horizontal velocity at 30, 60, and 120 feet from surface zero

Comparison of the initial (first peak) velocity of Scooter surface zero with the corresponding velocities of Stagecoach shots and the 256-pound charges in alluvium (Figure 5.15) shows that initial surface velocities from charges buried in alluvium are consistent. Examination of peak vertical velocities of the ground surface and Target 4 (Figure 5.13) and peak radial velocities from Targets 5 and 6 (obtained from Figures 5.10, 5.11, and 5.14) shows that Targets 4, 5, and 6 had velocities slightly higher than those for Stagecoach. The radial velocities from Target 7 agree with Stagecoach data (Figure 5.16), so it is not unreasonable to conclude that the peak velocities given by Targets 4, 5, and 6 are slightly high. The peak resultant velocities of Targets 5 and 7 indicate that at the time of the peak they are radial with respect to the charge center, whereas that of Target 6 indicates an origin at a 45-foot shallower depth. Reference to Figure 5.9 shows this to be a transient condition at about 175 msec. It is clear from Figure 5.9 that initial velocities of each target (except Target 4) are not radial, but instead are more nearly vertical at early times. By the time peak initial velocity is reached, the direction is very nearly radial. The horizontal component increases thereafter more rapidly than the vertical.

Incident vertical particle velocities at surface zero, which are estimated to be half the observed surface velocities, are in excellent agreement with velocities reported by Perret (Figure 4.14). Stresses \( P_r \) computed from free surface particle velocities \( u_{fs} \), by \( P_r = \frac{1}{2} \rho_o c u_{fs} \), are shown in Table 5.1. A density
Figure 5.15 Initial vertical velocity versus scaled depth of burst

\[ v_v = 119.5 \left( \frac{D}{15^{1/3}} \right)^{-2.28} \]
Figure 5.16 Radial stress versus scaled radial distance
\( \rho_0 = 1.6 \text{ gm/cm}^3 \) and a sonic velocity \( c = 2600 \text{ ft/sec} \) have been used. If these values of \( \rho \) and \( c \) are inexact, the resultant stresses are proportionally inexact.

TABLE 5.1 STRESSES COMPUTED FROM FREE SURFACE PARTICLE VELOCITIES

<table>
<thead>
<tr>
<th>Ground range to target (ft)</th>
<th>Radial distance from charge center (ft)</th>
<th>Radial velocity at ground surface (ft/sec)</th>
<th>Particle velocity (ft/sec)</th>
<th>Radial stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>125</td>
<td>80</td>
<td>40</td>
<td>2242</td>
</tr>
<tr>
<td>30</td>
<td>128.5</td>
<td>78</td>
<td>39</td>
<td>2185</td>
</tr>
<tr>
<td>60</td>
<td>138.6</td>
<td>72</td>
<td>36</td>
<td>2020</td>
</tr>
<tr>
<td>120</td>
<td>173.3</td>
<td>33</td>
<td>16.5</td>
<td>925</td>
</tr>
</tbody>
</table>

Combining the Scooter data with the motion of surface zero for the three Stagecoach shots indicates (Figure 5.16) that radial stress \( (P_r) \) as a function of radial distance \( (r) \) is approximately

\[
P_r = 3350(r/W^{1/3})^{-2.26}, \tag{5.1}
\]

where \( r \) is the radial distance in feet. If the distance from charge center to crater edge is determined for each crater (on the basis of burst depth and crater radius), the stress at the crater edge can be obtained for each crater from the above equation and then related to the scaled burst depth of the charge. The true and apparent crater radii are about equal for Stagecoach and Scooter. No attempt was made to make a similar observation for the smaller craters, and we can only presume equality of their true and apparent craters.

Figure 5.17 is a plot of the radial stresses at the crater edge \( (P_{cr}) \) versus the scaled burst depth \( (D/W^{1/3}) \). First the stresses at the edge of the four 40,000-pound charge craters were plotted, and the curve was drawn through the data points. Next, at a scaled burst depth of 1.25 ft/lb\(^{1/3}\), the corresponding values for Scooter (1,000,000 pounds) and an interpolated value between six 256-pound shots (four at 1 ft/lb\(^{1/3}\) and two at 1.5 ft/lb\(^{1/3}\) were plotted. Since these points are in order (the smallest charge having the smallest \( P_{cr} \)), a yield dependence is suggested. The yield dependence was evaluated by plotting radial stress for this one burst depth (the only one for which data exists for a 1,000,000-pound charge) against charge weight. The yield dependence was thus shown to be about as the 0.06 power of the charge weight \( (W) \). Since particle

*Arrival times of first motion at Scooter surface zero give a velocity of about 2600 ft/sec. This is only slightly lower than the velocities reported by Rugg (2750 to 3300 ft/sec) for the first 100 feet in alluvium in about the same area. No differences in velocity are indicated between the surface and about the 100-foot depth. An overall average is not precise, but it is a good approximation.\]
velocity (Figure 5.15) and radial stress ($P_r$) (Figure 5.16) show no yield dependence, it is at first surprising to find a yield dependence on radial stress at the crater edge, ($P_{cr}$).

![Figure 5.17](image)

**Figure 5.17** Radial stress at crater edge versus scaled depth of burst

A plot of $P_{cr}/W^{0.06}$ versus scaled burst depth (ft/lb$^{1/3}$) is shown in Figure 5.18. The slope of the deeper portion of the curve is about minus one. The shallower portion of the curve, however, has a lesser slope. Clearly the slope must change, or an infinite stress at the edge of a surface-burst crater would be indicated. However, the mechanism causing the change is not clear.

The following expression was found to fit the high explosive data fairly well:

$$P_{cr}/W^{0.06} = 300 \exp(-0.2875 \frac{D}{W^{1/3}}) + 1200 \exp(-2.05 \frac{D}{W^{1/3}})$$  \hspace{1cm} (5.2)
Figure 5.18  Scaled radial stress at crater edge versus scaled depth of burst

\[ P_{rW}^{-0.08} = 370 \exp(-0.28 D/W^{1/3}) + 1485 \exp(-2.05 D/W^{1/3}) \]

\[ P_{rWc}^{-0.06} = 300 \exp(-0.28 D/Wc^{1/3}) + 1200 \exp(-2.05 D/Wc^{1/3}) \]
Assuming an upward shift in the curve to fit the data from the only two nuclear cratering shots, a corresponding expression for nuclear cratering events is:

\[ P_{cr}/W^{0.66} = 370 \exp(-0.2875 \ D/W^{1/3}) + 1485 \exp(-2.05 \ D/W^{2/3}). \tag{5.3} \]

The crater radius \( R \) and burst depth \( D \) are two sides of a triangle whose hypotenuse is the radial distance \( r \) from the charge center to the crater edge. Equating \( P_r \) in Eq. 5.1 and \( P_{cr} \) in Eq. 5.2, substituting \((R^2 + D^2)^{1/2}\) for \( r \), and solving for \( R \) gives the following expression for crater radius \( R \) in terms of only the burst depth \( D \) and charge weight \( W \):

\[ R = \left[ \left( \frac{W^{2/3}}{W^{0.66}} \left( \frac{3350}{\exp[0.2875 \ (D/W^{1/3})]} + \frac{1200}{\exp[2.05 \ (D/W^{1/3})]} \right) \right)^{1/1.14} - D^2 \right]^{1/2} \tag{5.4} \]

This expression is applicable to high-explosive cratering shots in NTS desert alluvium. A similar expression for nuclear cratering shots is apparent from Eq. 5.3. These expressions are interesting because they permit estimates of crater radius to be obtained from a knowledge of stress decay with distance in a medium and a knowledge of critical stress at the crater edge. Equation 5.4, derived from consideration of radial stress at the crater edge, permits the calculation of crater radius in desert alluvium so long as the charge weight and burst depth are known. This is believed to be the first indication that stress at a given scaled radial distance is not constant for all yields but increases slightly as the yield is increased. Equation 5.4 together with the similar equation for nuclear shots indicates that the radius of high explosive craters will be larger than that for nuclear craters. The high explosive crater radii will be about 10 percent larger for surface bursts ranging to about 15 percent larger for the deep burst depths (~2 ft/lb^{1/3}).

Consideration of the two scaling methods discussed in Chapter 2 leads one to suspect that the \( W^{0.66} \) yield dependence noted above is merely another manifestation of the failure of cube-root scaling. Noncube-root scalings can be expressed as \( W^s \), where \( s \) is 0.3 in one approximation or varies between 1/3 and 1/4 in overburden scaling.

Let us assume temporarily that the pressure-distance relationships for pressure are still cube-root scaled, that is, \( P = KW^{n/3}/r^n \), but that the crater dimensions are scaled as \( W^s \). Then the pressure at the crater edge will be

\[ P_{cr} = KW^{n/3}/R_o^n W^{ns} \tag{5.5} \]

\[ = KW^{n(\frac{2}{3} - s)}/R_o^n \]

\(^3\)Project Sedan (approximately 100 kt at 635 feet) was conducted while this report was in preparation. The radius at the Sedan crater is in agreement with that given in Eq. 5.3.
By Eq. 5.1, where $R_0$ is the radial distance from charge center to crater edge, $n = 2.28$, in which case if $s = 0.3$, the pressure scaling should be

$$2.28(\sqrt[3]{3} - 0.3) = 0.076,$$

which is probably within the range of uncertainty of determination of the 0.06.

When the same data as in Figure 5.17 are plotted using overburden scaling rather than cube-root scaling for the scaled burst depth, it is clear from Figure 5.19 that a different group of 256-pound charges must be used for comparison with Scooter at nearly the same scaled burst depth. Clearly the dependence of stress at the crater edge on charge weight remains.

If, in Eq. 5.5, $s$ is taken to represent overburden scaling, then stress at the crater edge is scaled as

$$\frac{P_{cr}}{W^{(\frac{1}{3} - s)}}$$

(5.6)

$W^s$ has been evaluated by

$$s = \frac{D + 18.3}{4D + 3\times18.3}$$

(5.7)

and the scaled radial stress at the crater edge calculated for each alluvium shot. Figure 5.20 shows the overburden scaled stress at the crater edge against the overburden scaled burst depth.

No attempt at regression analysis was made to determine which of the two forms (Figure 5.18 or 5.20) best represents the data. The form of Figure 5.20 has little to recommend it other than that it is consistent with the scaling results presented in Chapter 2.

5.2.3 Surface Acceleration

Differentiation of the velocity-time records gave the acceleration-time plots shown in Figures 5.21, 5.22, 5.23, 5.24, and 5.25. The second acceleration peak attributable to the expanding gas pressure is evidenced only on the records from Targets 4, 5, and 6, which were normal to the camera line of sight. Failure to record the second peak at Targets 1, 2, and 3 is due to inability to read the small increments of target displacement against the moving background of the mound.

Peak accelerations of the center of the Scooter mound are compared in Figure 5.26 with those of Project Stagecoach scaled to the Scooter yield by cube-root scaling. The first peak of Scooter appears low by a factor of about three, while the second or gas-pressure-induced peak agrees well. Peak accelerations in NTS desert alluvium are described by the following expressions:
Figure 5.19 Radial stress versus overburden-scaled depth of burst
Figure 5.20 Scaled radial stress at crater edge versus scaled depth of burst
Figure 5.21 Vertical acceleration 30 feet from surface zero

Figure 5.22 Vertical acceleration 60 feet from surface zero
Figure 5.23 Vertical acceleration 120 feet from surface zero

Figure 5.24 Vertical acceleration at surface zero
Figure 5.25  Horizontal acceleration at 30, 60, and 120 feet from surface zero

Figure 5.26  Comparison vertical acceleration versus depth of burst, Scooter and Stagecoach
First (ground shock) peak

\[ a = 27,000 \, D^{-4.3} \, W^{1.1} \]  \hspace{1cm} (5.8)

Second (gas-pressure-induced) peak

\[ a = 3.5 \, D^{-4} \, W, \] \hspace{1cm} (5.9)

where \( a \) is acceleration in g's, \( W \) refers to charge weight, and \( D \) is burst depth in feet.

After an initial shock acceleration, it would be expected that the material would slow down and reach a minus 1-g acceleration. However, each acceleration-time plot shows negative acceleration greater than 1 g; sometimes as much as minus 4 or 6 g. Such large negative accelerations can only be attributed to inaccuracies introduced by double differentiation of the displacement-time data.

5.3 CLOUD GROWTH

5.3.1 Displacements

Figure 5.27 shows displacements versus time for Scooter. The following displacements are presented where they are applicable:

1. **Mound height** is measured along the vertical axis of the charge. (See Figure 5.28 in connection with this and the following definitions.)

2. **Smoke crown height**. Height of the smoke crown of venting gases is measured along the vertical axis of the charge.

3. **Jets** break through the smoke crown and reach the greatest heights. Included in the figures are the vertical height of the highest or center jet and the height of a jet on one side. The fact that the highest jet is in the center can be attributed to failure of stemming material; since it may therefore be atypical, the height of an adjacent jet was also determined.

4. **Column height** measured to the intersection of the column and the smoke crown.

5. **Column horizontal diameter** is measured both at a point near the base and a point just below the intersection of the column with the smoke crown.

6. **Smoke crown and jet diameter**. Horizontal diameter of the smoke crown is measured at its widest point regardless of height and without reference to surface zero.
Figure 5.27 Displacement-time plot of mound, cloud, and base surge

Figure 5.28 Sequence photographs of Scooter explosion
7. **Base-surge horizontal radius.** The horizontal radius of the base surge is measured at the widest point both to the right and left of surface zero.

5.3.2 Velocities

Figure 5.29 shows vertical velocities as a function of time for mound, column, smoke crown, jet, and base-surge radius.

![Figure 5.29 Vertical velocity of mound, cloud, and base surge](image)

Project Scooter was at the same scaled burst depth (by cube-root scaling) as Project Buckboard Shot 12. Therefore, it is of interest to compare velocity-time profiles in the two media simply by scaling the times of Scooter cloud growth to those of Buckboard (Figure 5.30). The most notable differences are these. The mound velocity in basalt increases more rapidly and is more than twice the value in alluvium. The smoke crown velocities were approximately the same, but in the case of Scooter there was not much evidence of the jets breaking through the smoke crown (at 2 seconds) as they did on Buckboard Shot 12.
5.3.3 Height of Smoke Crown

The smoke crown originated from the initial venting of gases through the raised mound. Except at the very top, the smoke crown disappeared as jets of ejected material pierced its outer boundary and obscured it. The center jet never reached the height of the smoke crown. To the north of center (Figure 5.27), however, one jet rose higher than the center jet and for a time exceeded the height of the smoke crown. One major portion of the smoke crown remained until very late times.

The mound vented at about 997 msec giving a scaled venting time in agreement (Figure 5.31) with that reported earlier\textsuperscript{13} for desert alluvium. The mound height at venting, however, was greater than would have been predicted from Stagecoach results (Figure 5.32).

5.3.4 Jet

The term jet is used here to describe the high-velocity ejected materials (soil and rocks) which pierce through the periphery of the turbulent black smoke crown after it has begun to slow down. As can be seen from Figure 5.29, there is little change in the decrease of the velocity of the smoke crown diameter as it

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_30}
\caption{Comparison of vertical cloud velocity, Scooter and Buckboard 12}
\end{figure}
Figure 5.31 Scaled venting times versus scaled depth of burst
transits into the jet diameter when jets break through at between 2 and 3 seconds. Thus, the distinction between the two phases in Scooter is not as pronounced as in the case of shallower shots. For this reason it is not reasonable to relate the time of jet breakthrough for Scooter to the expression derived earlier\textsuperscript{13} for alluvium.

![Scaled height of mound at venting versus scaled depth of burst](image)

Figure 5.32 Scaled height of mound at venting versus scaled depth of burst

The maximum height of the smoke from the Scooter shot was about 950 feet. The maximum height of the ejected jet was a little less than 1000 feet. For high explosives, maximum height is determined by maximum jet height, with some increase in height due to wake over-ride. For nuclear explosives, the maximum ejecta-cloud height is dependent on the rise of the sphere of hot gas.

Earlier work\textsuperscript{13} showed the maximum scaled height of the cloud from underground high-explosive shots (scaled by cube-root scaling) versus comparable scaled burst depths for those cratering shots in which such observations had been made. The addition of the Scooter datum emphasized that cube-root scaling does not properly describe maximum cloud height.

One might assume that, since initial mound velocities are constant where scaled burst depth is the same in a given medium, the maximum height ($S_{\text{max}}$) might be derived from
\[ S_{\text{max}} = \frac{V_0^2}{2g} \text{ (in vacuum)} \quad (5.10) \]

or

\[ S_{\text{max}} = \frac{V_0^2}{(2g + a_d)} \text{ in air}, \quad (5.11) \]

where \( V_0 \) is an initial velocity and \( a_d \) is deceleration due to air drag. Where the particle or mass of desert alluvium is a sphere, this becomes:

\[ S_{\text{max}} = \frac{V_0^2 C_d}{(2g + 0.00014 \frac{V_0^2}{d})} \quad (5.12) \]

Thus, the initial velocity and the diameter of the particle or fragment of earth ejected to the greatest height being known, the maximum height could be determined.

Two things preclude this approach. First, it is difficult to determine or to approximate the dimensions of the fragment of earth which will have the highest trajectory. The throwout patterns show discrete masses of earth lying about the crater, attesting to the fact that they maintain considerable integrity throughout their entire trajectory. That the dimensions of these fragments from Scooter are large can be inferred from the masses of earth. The largest of these are of sufficient size to make air drag negligible.

Second, although the initial velocity of the mound is constant for a given (cube-root) scaled burst depth, the velocity of jetting material which influences the maximum height of the ejecta does not appear to be. The pressure of venting gases continues to accelerate ejecta for a considerable time after venting and jet breakthrough. Thus the initial velocity with which one is concerned here is that at which the acceleration is minus 1 g. As nearly as can be determined from the data available (Stagecoach, Scooter, and Buckboard), this occurs at times and heights which are, at present, unpredictable. For Scooter the acceleration is very close to minus 1 g from 6.15 seconds to about 8 seconds (Figure 5.33), indicating that the drag component of the equation above is, as one would expect for a large diameter mass, of little significance. The velocity at the beginning of the minus 1 g is only 60 ft/sec, while the height is 816 feet. Prior to 5.5 seconds, the material which is being decelerated rapidly is smoke in the smoke crown.

Fourth-root scaling of maximum cloud height appears to be better than cube-root scaling if cube-root scaling is retained for burst depth (Figure 5.34). Data from Buckboard basalt indicate that the ratio of maximum cloud heights in basalt to those in alluvium is about the ratio of their densities. Maximum heights appear to occur where scaled burst depth is about 0.5 ft/lb\(^{1/3}\).

5.3.5 Column

Column heights of the Scooter cloud were not clearly identifiable. Column base and top diameters as a function of time are given in Figure 5.35.
Figure 5.33 Smoke crown and center jet velocity
Figure 5.34  Scaled maximum cloud height versus scaled depth of burst
Figure 5.35 Cloud diameter growth
5.3.6 Smoke Crown and Jet Diameter

Diameters of the smoke crown and jet measured at their widest points are given as a function of time in Figure 5.36. Diameter exceeded the height by nearly 100 feet between 1 and 5 seconds. Because of uncertainties in scaling, no effort has been made to compare diameters of the Scooter cloud with diameters of smaller detonations.

![Figure 5.36 Smoke crown and jet diameter](image)

5.3.7 Base Surge

The horizontal growth of the base surge is shown in Figure 5.37. Because the growth was measured perpendicular to the camera line of sight, the propagation designated north is actually N10°E and that designated south is S10°W. Shot time surface winds were 040 degrees, 4 mph or about 5 ft/sec normal to the camera line of sight. Consequently, the surge moved more rapidly southward than northward.
Figure 5.37  Base surge radius at early time
The average velocities (from Figure 5.38) differed by about 26 ft/sec, indicating an average effective wind velocity of 13 ft/sec normal to the camera line of sight or about 10 mph along the direction of flow. Observed wind speeds were nearly half this value, with peak gusts approaching it.

The peak velocity at 20 to 21 seconds, followed by the low at 26 seconds, indicates a pulsing caused by major collapses from the crater walls or late escape of explosive gases. Similar velocity discontinuities were observed on the Stagecoach shots, but no consistent pattern is apparent.

The average propagation velocity of the Scooter base surge was about 41 ft/sec. This is more than double the average velocity for the Stagecoach 17- and 34-foot-deep shots, both of which had a base-surge horizontal velocity of only about 18 ft/sec. The fact that the average velocities for both Stagecoach shots were approximately the same may indicate that base-surge horizontal velocity is not a function of burst depth, but rather of yield. In spite of medium difference, the results of Project Buckboard tend to bear out this conclusion. Their average apparent base-surge velocities were 19, 11, and 15 ft/sec, respectively, for the shots at 26-, 43-, and 59-foot depths.

The base-surge displacements and velocities at late times are shown in Figures 5.39, 5.40, and 5.41.
Figure 5.38 Base-surge horizontal velocity
Figure 5.39 Base-surge radius at late time
Figure 5.40 South base-surge radius velocity at late time

Figure 5.41 North base-surge radius velocity at late time
CHAPTER 6 -- LONG-RANGE AIR BLAST

6.1 INTRODUCTION

The Scooter air-blast wave was recorded by microbarographs at ranges from 2 to 135 miles (a) to establish muffling or attenuation and yield scaling factors for cratering bursts in desert alluvium, and (b) to compare observed air-blast patterns with calculated values from ray tracing through the high-altitude ozonosphere sound duct. These studies are necessary to planning and to assure public safety at long distances in future large-scale excavation projects such as those described at the Second Plowshare Symposium.\(^{34}\)

A few bits of data on air blast propagated from 256-pound high-explosive (HE) buried charges were obtained at Nevada Test Site (NTS) in 1959,\(^{35}\) but windy conditions caused considerable scatter in results. Measurements on Project Stagecoach\(^5\) in the spring of 1960 confirmed the observation made for Shot ESS of Operation Teapot\(^{36}\) (1955) that air blast at large off-site distances, to 135 miles, was attenuated much less by charge burial than close-in, ground-level, high-pressure gage measurements indicated. Microbarograph data from Project Buckboard\(^{13}\) showed less air-blast attenuation from equivalent burial depths in hard basalt than did Project Stagecoach in the desert alluvium.

Measurements were made, but no controlled experiment was attempted, on distant air blast propagated from the Rainier shot of Operation Plumbbob (1957) and the several underground tests in Phase II of Operation Hardtack (1958). Recordings showed that large (relative to our HE experience) underground nuclear bursts in volcanic tuff propagated more air blast than would be extrapolated from HE data.\(^{37}\) Project Scooter provided an opportunity to obtain data for comparison with smaller-yield data at similar scaled depths in a similar medium. Yield dependence, hinted by previous measurements, could be directly determined.

Blast propagated to and beyond about 80 miles is usually carried by an ozonosphere sound duct generated by high temperatures and winds between 100,000- and 180,000-foot altitudes. During past full-scale nuclear tests, there was no operational system for measuring atmospheric conditions above 100,000 feet. Predictions for long-range sound propagation were made by yield scaling from microbarograph records of 1.2-ton HE shots fired 1 or 2 hours before each full-scale event. These few point microbarograph measurements were usually adequate to assure off-site safety because the yields of shots made at NTS were limited. Experience had shown that chances of causing damage at ranges greater than 100 miles were small. For larger yields or more confident assurance of no off-site damage, a more complete calculation of sound propagation patterns is required. This requires either many more recording stations or upper atmosphere measurements to permit sound-ray calculations for complete patterns of ozonosphere ducting.
A rocket program to spread radar reflecting chaff for high-altitude wind measurements was developed and used in high-altitude tests of Operation Hardtack at Johnston Island in 1958. Since that time many more measurements have been made at Tonopah Test Range (TTR), Nevada, and operational data acquisition for ozonosphere winds has become available. In association with Plowshare Projects Stagecoach and Buckboard, wind rocket firings were used for the first time to make sound-ray calculations and predictions for ozonosphere ducting similar to those made for several years in lower tropospheric layers within reach of rawinsonde weather balloons.

At the time of the Scooter shot there was no operational rocket temperature system for ozonosphere measurements. However, Stagecoach had shown that sound-ray calculations, using an ARDC-1959 Model Atmosphere temperature-height curve, agreed fairly well with observed propagations. Higher temperatures obtained in many studies of sound ranging from explosions give less accurate propagation pattern calculations and are now believed to be wrong. Data accumulated by the Meteorological Rocket Network also show that ARDC-atmosphere temperatures are probably adequate for sound-ray calculations. Only minor changes with latitude and season were observed. Wind structure is, after all, the most important and variable factor in atmospheric sound refraction. In ozonosphere layers, directed wind components vary by hundreds of feet per second in an annual cycle as shown by Webb, while changes in sound speed caused by temperature ranges are only 10 or 20 percent as large. Furthermore, errors in assuming a constant sound speed structure are smaller than errors in rocket wind measurements.

Sound-ray calculations of wave arrival times and incidence angles gave generally good predictions at 100- to 150-mile ranges for Stagecoach and Buckboard. Recorded amplitudes were, however, only one-fourth as large as predicted from geometrical divergence considerations. Classical sound attenuation described by Schrödinger may be shown in a first approximation to reduce wave amplitudes by as much as 50 percent for a 1-ton HE yield propagated over ozonosphere paths. This only partially corrects the observed discrepancy. Further experimental data are needed to help resolve this difficulty. Additional research into further attenuation by atmospheric turbulence and internal reflections from atmospheric stratifications is also being attempted. Results will affect yield-scaling techniques and values for burial attenuation coefficients being sought in various Plowshare studies.

Future excavation projects may well pose distant off-site blast safety problems far more serious than those for NTS operations. By the time such projects are attempted, predictions must be much more accurate and confident than those obtained by present techniques. Every opportunity must be exploited to refine our understanding of and procedure for predicting distant blast propagation so that reasonable yield limitations and feasible excavation designs can be made. Construction can then be accomplished with safety and without international incident. Toward these ends, the Scooter microbarograph project has contributed a few valuable data points.
6.2 EXPERIMENT PLAN

Originally Scooter shot was scheduled for firing in summer, a season in which ozonosphere winds blow from east to west and duct sound into California. The delay until October allowed seasonal upper flow reversal to take place, so that winds were blowing in the west-to-east winter pattern. Upper airflow charts showing this seasonal wind reversal are reproduced from Meteorological Rocket Network data in Figure 6.1a and 6.1b. Off-site recording stations, originally planned for Bishop and Inyokern, California, and Beatty, Nevada, were moved to St. George, Utah, and Lund and Boulder City, Nevada, when prior Project Buckboard pressure observations and Tonopah wind rocket firings confirmed that winter had arrived at ozonosphere levels.

Figure 6.1

Microbarographs were also operated on-site south from surface zero at ranges of about 2, 8, and 15 miles to help connect off-site data with pressure-distance measurements made by the U.S. Naval Ordnance Laboratory at close ranges. Points of interest at NTS and off-site are mapped in Figures 6.2 and 6.3, respectively. Shot and microbarograph locations are given in Table 6.1 together with distances and direction bearings from shots to stations.
Figure 6.2 Microbarograph station plan, Yucca Flat

Figure 6.3 Microbarograph station plan, off-site
Microbarograph sensors were Wiancko devices which have been used satisfactorily for many years. They were designed to Sandia Laboratory specifications and functioned properly according to performance tests. New transistorized signal amplifiers and time mark generators were obtained early in 1960. Recent calibration tests have shown that pressure waves between 0.02 and 15 cps frequency and between 3 μb (microbars or dynes per square centimeter) and 9 mb (millibars) amplitude are recorded accurately within ±20 percent for 85 percent of the test points.

An airburst reference explosion was fired 10 minutes before Scooter to show pressure amplitudes propagated from a known yield under the existing meteorological ducting condition. The calibration shot consisted of 2400 pounds of TNT (four U.S. Navy, WW II surplus depth charges) burst 15 feet above ground on a light wooden platform. This height-of-burst (HOB) acts to increase wave amplitudes above surface burst values for more accurate readings at long ranges where

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<th>Shot Points</th>
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<td>E 667,692.81 ft</td>
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<td>W-2</td>
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|            | 146°18'36" | 197°36'09"
| W-1        | 30,424.25 ft | 39,777.66 ft |
|            | 179°04'50" | 187°41'04"
| Lund - Close | 69,625.46 ft | 76,760.02 ft |
|            | 179°04'50" | 183°30'11"
| Lund - Far | 691,648 ft  | 680,984 ft  |
|            | 26°01'39" | 25°56'25"
| St. George - Close | 715,753 ft | 710,222 ft |
|            | 92°16'55" | 93°01'22"
| St. George - Far | 719,233 ft | 713,715 ft |
|            | 92°16'36" | 93°00'54"
| Boulder City - Close | 563,734 ft | 559,194 ft |
|            | 140°37'32" | 141°39'34"
| Boulder City - Far | 570,987 ft | 566,449 ft |
|            | 140°36'37" | 141°37'54"
signal-to-noise ratios may be small. Close-in records also show better signal source repeatability for such shots than for surface bursts, where early ground reflections, cratering, late burn, etc., give nonideal waveshapes such as are shown in Figure 6.4. Later experiments made at Albuquerque in 1961 with 6400-pound HE spheres showed that HOB pressure magnification effects determined by Vortman and Shreve at the 2-psi isobar were propagated to 107 and 129 miles. Curves of effective yield versus scaled height of burst are reproduced in Figure 6.5.

![Figure 6.4 Close-in waveshapes for various high-explosives burst conditions](image-url)
Figure 6.5 Height-of-burst effects at 20 feet from 1-lb HE
Pressure recordings from both calibration and Scooter shots were compared to a reference standard blast overpressure-distance curve. IBM Problem-M values, calculated at Los Alamos, are used for reference rather than an empirical curve, such as one recommended by The Effects of Nuclear Weapons. It is the author's opinion that many empirical atomic test data at low overpressures are biased toward low values by refraction under nonhomogeneous meteorological conditions. The IBM-M curve, shown in Figure 6.6, has been extended beyond its end at 9000 feet (from a 1-kiloton nuclear burst) according to \( \Delta p R^{-1/2} \). This proportionality was found valid to 500 feet by 1-pound HE shots at Sandia's Coyote Canyon test field in May 1961. It was further verified to 80,000 feet by 500-pound HE shots in DASA Project Banshee at White Sands Missile Range in July-August 1961. In each of these tests, bursts were fired vertically above ground level gages to minimize atmospheric refractive bending and wave distortion. Atmospheric refraction has affected nearly all low-pressure measurements made at large horizontal distances from nuclear blasts. Data from the vertically oriented experiments have unfortunately not yet been published, but some preliminary data points are shown in Figure 6.6 to support the curve.

Microbarograph wave amplitude from Scooter divided by wave amplitude recorded from the calibration shot, with appropriate corrections for yield and HOB, gives an air-blast transmission coefficient. This factor, together with its variation with distance and propagation duct (i.e., surface inversion, troposphere, or ozonosphere), has been compared with results from Projects Stagecoach and Buckboard.

Shot-time weather data for sound-ray calculations below 100,000 feet and for other project applications were obtained by the U.S. Weather Bureau Research Station, c/o AEC-Nevada Operations Office. Winds above 100,000 feet were measured from the drift of radar reflecting chaff ejected from a Deacon-Arrow rocket launched at TTR. A second rocket was fired several hours after Scooter to show wind variability with time.

Sound-ray calculations from upper air data were made on Raypac, an analogue computer used for off-site blast safety prediction in full-scale NTS tests. Final ray calculations, which also provide wave arrival times and relative wave divergence values, were made on a high-speed digital computer, the CDC-1604, at Sandia Laboratory.

6.3 RESULTS

6.3.1 Weather Data

Weather Bureau observations of Area 10 conditions at and after shot time are shown in Table 6.2. Rawinsonde balloon upper-air measurements of air pressure, temperature, relative humidity, and wind at altitudes to 95,000 feet MSL are shown in Table 6.3. This balloon was launched from Jackass Flats, about 30 miles southwest of Scooter and Area 10. In the upper atmosphere, however, this amount of position difference is of little practical consequence in calculating sound propagations out to 150 miles.
Figure 6.6 Standard explosive overpressure-distance curve
TABLE 6.2 METEOROLOGICAL DATA
Area 10, NOL Trailer: Ambient Pressure 868 mb

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Average Hourly Recorded Winds

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<td>32</td>
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<td>86</td>
<td>272/13</td>
<td>21</td>
<td>-50.6</td>
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</tr>
<tr>
<td>88</td>
<td>266/15</td>
<td>19</td>
<td>-49.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>263/16</td>
<td>18</td>
<td>-49.0</td>
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<tr>
<td>90</td>
<td>264/17</td>
<td>18</td>
<td>-48.6</td>
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<td>93</td>
<td>271/17</td>
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</tr>
<tr>
<td>95</td>
<td>272/16</td>
<td>14</td>
<td>-49.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tropopause height: 49,000 ft msl  
Temperature -63.4°C
Rocket wind run RW-180 was fired from TTR at 0640 PST. The chaff cloud was picked up by radar as it fell through 190,000 feet msl. Good radar return was temporarily lost as the chaff fell from 108,000 to 98,000 feet. Near 75,000 feet the chaff cloud had become too diffuse for reasonably smooth tracking. Wind measurements, selected to show the main character of ozonosphere flow from this rocket flight, are shown in Table 6.4. A second wind rocket (RW-181) was launched at 1200 PST, to determine the wind flow changes taking place. This chaff cloud was radar-tracked as it fell from 182,000 feet down to 125,000 feet, where it became too diffuse for good tracking. Significant wind data from this flight are also shown in Table 6.4. For each recorded wind level, an entry has been made of temperature according to the ARDC-1959 Model Atmosphere for use in sound-ray calculations.

Table 6.4 Ozonosphere Meteorological Data

<table>
<thead>
<tr>
<th>Altitude (Kilofeet, MSL)</th>
<th>Wind Direction/Speed (Deg/Knots)</th>
<th>Standard Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>274/32</td>
<td>-31</td>
</tr>
<tr>
<td>115</td>
<td>267/18</td>
<td>-27</td>
</tr>
<tr>
<td>130</td>
<td>235/34</td>
<td>-12</td>
</tr>
<tr>
<td>145</td>
<td>266/73</td>
<td>-12</td>
</tr>
<tr>
<td>155</td>
<td>269/83</td>
<td>0</td>
</tr>
<tr>
<td>168</td>
<td>264/95</td>
<td>+10</td>
</tr>
<tr>
<td>190</td>
<td>259/112</td>
<td>-10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude (Kilofeet, MSL)</th>
<th>Wind Direction/Speed (Deg/Knots)</th>
<th>Standard Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>127</td>
<td>272/80</td>
<td>-15</td>
</tr>
<tr>
<td>147</td>
<td>260/61</td>
<td>+3</td>
</tr>
<tr>
<td>157</td>
<td>255/119</td>
<td>+10</td>
</tr>
<tr>
<td>165</td>
<td>256/74</td>
<td>+10</td>
</tr>
<tr>
<td>178</td>
<td>244/95</td>
<td>+7</td>
</tr>
<tr>
<td>182</td>
<td>250/109</td>
<td>+3</td>
</tr>
</tbody>
</table>

6.3.2 Blast Pressures

Height-of-burst effects for the 1.2-ton HE calibration shot at 15 feet above ground (see Figure 6.5) cause its blast to appear as if it were from a $1.76 \times 2400 = 4220$-pound HE yield burst in a free air environment. If we assume that nuclear blast yield is half of HE blast yield, then a 1-kt nuclear burst calculated in IBM Problem M is equivalent in blast production to $10^6$ pounds of HE. Sachs scaling then gives a pressure-distance curve for the 1.2-ton HE calibration shot similar to the curve in Figure 6.6 but with ranges shortened by a factor $(4220 \times 10^2/10^6 \times 868)^{1/3} = 0.170$. Ambient pressure scaling from IBM-M at 1000-mb sea level to NTS Area 10 at 868-mb is included. Overpressures are reduced by $868/1000 = 0.868$.

Pressure-distance values for a 500-ton HE ($10^6$ pounds) free airburst are likewise obtained by reducing IBM-M overpressures by 0.868 and increasing ranges by $(1000/868)^{1/3} = 1.048$. These two standard curves for the calibration shot and an airburst of Scooter yield are shown for reference in Figure 6.7.
Figure 6.7 Scooter and calibration shot pressure-distance data
At long ranges, where $\Delta p \propto R^{-1.2}$, $\Delta p \propto W^{0.4}$ at fixed distance from various yields $W$. A 500-ton HE free airburst would give pressures larger than recorded pressures from the calibration shot, $\Delta p_c$, by a factor $(10^6/4220)^{0.4} = 8.9$. Thus, the air-blast transmission factor, $f$, from observations, $\Delta p_s$, of underground Scooter, when related to free airburst pressures from the same yield, becomes

$$f = \frac{\Delta p_s}{8.9 \Delta p_c} = 0.112 \frac{\Delta p_s}{\Delta p_c}.$$ 

Pressure measurements from Scooter and the HE calibration shot are plotted in Figure 6.7. Check-gage data points for the calibration shot show that at 300-foot range, yield and HOB effects gave pressures very nearly as expected. Waveform recordings are shown in Figure 6.8; no significant anomalies can be seen. There is some gage ringing, which is not exactly repeatable on the two gages and is ignored.

![Figure 6.8 Calibration shot pressure-time records at 300-foot range](image)

On-site microbarograph records show that an overpressure-distance curve for the first positive pulse changes slope at 6 to 8 miles range, while a multiple cycle wave is forming. This is typical of propagation under a surface inversion, as shown theoretically by Byatt and DeVault.5 The ratio of peak-to-peak pressure to positive overpressure also closely follows a 1.4 ratio, as calculated in IBM Problem M.

Signals recorded from Scooter and the calibration shot are reproduced in Figures 6.9 and 6.10, respectively. Amplitude readings are listed in Table 6.5 together with calculated transmission factors ($f$) for each comparable signal pair. Logarithmic averages of $f$ were calculated for similarly propagated signals at distant stations. When measurements and error scatter are nearly equal, a logarithmic distribution of errors is usually found.
### Table 6.5 Microbarograph Pressures and Blast Transmission Factors

<table>
<thead>
<tr>
<th>Station</th>
<th>Overpressures</th>
<th>Peak-to-Peak Pressures</th>
<th>Duct Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta P_{cal} )</td>
<td>( \Delta P_s )</td>
<td>( \Delta P_{cal} )</td>
</tr>
<tr>
<td>M-11</td>
<td>3040</td>
<td>505</td>
<td>4055</td>
</tr>
<tr>
<td>W-2</td>
<td>879</td>
<td>215</td>
<td>1218</td>
</tr>
<tr>
<td>W-1</td>
<td>72.1</td>
<td>40.3</td>
<td>254</td>
</tr>
<tr>
<td>BLC</td>
<td>&lt;6**</td>
<td>8.4</td>
<td>&lt;10**</td>
</tr>
<tr>
<td>SGU-C</td>
<td>4.32</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.65</td>
<td>27.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.62</td>
<td>35.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19.72</td>
<td>49.95</td>
<td></td>
</tr>
<tr>
<td>SGU-F</td>
<td>2.03</td>
<td>3.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.37</td>
<td>18.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.72</td>
<td>20.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.45</td>
<td>40.95</td>
<td></td>
</tr>
<tr>
<td>LND-C</td>
<td>3.00</td>
<td>11.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.06</td>
<td>24.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.88</td>
<td>4.76</td>
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<tr>
<td>LND-F</td>
<td>7.36</td>
<td>38.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>52.15</td>
<td>70.72</td>
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</tr>
<tr>
<td></td>
<td>14.31</td>
<td>15.07</td>
<td></td>
</tr>
</tbody>
</table>

**Logarithmic Averages**

- Surface Duct Average, SGU (a)
  - 0.120 SFC
- Troposphere Jet Duct Average, SGU (b), LND (a)
  - 0.465 TR
- Ozonosphere Duct Average, SGU (c,d), LND (b,c)
  - 0.185 OZ

* At ranges interpolated between calibration shot data points.
** No signal distinguished above ambient noise level indicated.

In Table 6.6, NOL pressure data are compared to values expected at the same slant ranges from a 500-ton HE free airburst. Here \( f \) values are calculated directly by dividing observed overpressure by free airburst overpressure. At short ranges meteorological structure and refraction do not appreciably distort a blast-wave front; an airburst calibration shot is not necessary for reference.

Transmission factors calculated from Scooter pressure data are plotted in Figure 6.11. Previously determined curves from Stagecoach and Buckboard are dashed in for reference. Transmission factor values are different from those reported for the previous projects, but this difference is a constant factor, since underground burst propagations are now referenced to free airburst propagations rather than to surface-burst waves. As shown previously in Figure 6.5, an HE surface-burst blast wave has lower amplitude than a free airburst of the same weight or yield. There is further an appreciable difference between surface-burst nuclear and HE apparent yield factors. Since free airburst nuclear and HE
Figure 6.9 Microbarograph traces, Scooter shot
Figure 6.10 Microbarograph traces, calibration shot
blasts are so easily related and since details of the HE-nuclear difference for surface bursts are so complicated, our procedure is being changed at this time before the less satisfactory surface-burst reference method becomes standardized. When data from underground nuclear tests become available, a new blast yield relation between HE and nuclear will be needed, since the factor of two for free air-bursts loses its physical justification, but that is a problem of no concern here.

TABLE 6.6 CLOSE-IN OBSERVED PRESSURES (NOL) AND BLAST TRANSMISSION FACTORS

<table>
<thead>
<tr>
<th>Station</th>
<th>Slant range (ft)</th>
<th>Observed (Ap mb)</th>
<th>500-ton free airburst (Ap mb)</th>
<th>f</th>
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<tr>
<td>11</td>
<td>325</td>
<td>34.5</td>
<td>4800</td>
<td>0.00719</td>
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<tr>
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<td>4800</td>
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<td>414</td>
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<td>2750</td>
<td>0.0118</td>
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<td>14</td>
<td>536</td>
<td>39.3</td>
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<td>0.0241</td>
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<td>15</td>
<td>675</td>
<td>30.5</td>
<td>1020</td>
<td>0.0299</td>
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<td>516</td>
<td>24.8</td>
<td>1740</td>
<td>0.0143</td>
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<td>516</td>
<td>22.6</td>
<td>1740</td>
<td>0.0130</td>
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<td>23</td>
<td>575</td>
<td>21.9</td>
<td>1400</td>
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<td>470</td>
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<td>1006</td>
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<td>470</td>
<td>0.0253</td>
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<td>365</td>
<td>0.0276</td>
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<td>1506</td>
<td>8.90</td>
<td>241</td>
<td>0.0369</td>
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<td>8.55</td>
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<td>0.0355</td>
</tr>
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<td>1524</td>
<td>8.55</td>
<td>237</td>
<td>0.0361</td>
</tr>
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<td>230</td>
<td>0.0321</td>
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<td>45</td>
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<td>0.0436</td>
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<tr>
<td>52</td>
<td>2500</td>
<td>5.86</td>
<td>120</td>
<td>0.0489</td>
</tr>
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</table>

Within 1 mile from Scooter, f rises rapidly with distance, as found in previous tests. An approximately constant value then prevails to ranges of 15 miles. Off-site at Boulder City, values could only be given lower limits because ambient wind gust noises obscured the calibration shot signal.

At 135 miles range, both Lund and St. George stations obtained clear recordings from the ozonosphere duct. Transmission in this channel is very nearly the same as from the Stagecoach shot at 1.0 ft/\text{W}^{1/3} in alluvium and the Buckboard shot at 1.25 ft/\text{W}^{1/3} in basalt. Comparison with Stagecoach shows that a larger yield burst in similar material at a constant scaled depth-of-burst will show a larger transmission factor. If this relation continues into megaton yields, large shots may not be appreciably muffled by burial for optimum cratering. This effect would greatly restrict the use of large yields for excavation projects near inhabited regions.

Weak signals were carried to St. George, Utah, and Boulder City, Nevada, apparently in a surface inversion sound duct. This duct is seldom, if ever, of consequence in long-range safety considerations. Low f values for these signals are higher than values found on-site, yet they should have followed the same duct
Figure 6.11 Scooter air-blast transmission factors
and maintained constant $f$ at distance. The difference in direction may, however, be responsible for this discrepancy, since on-site recordings were south and off-site recordings were southeast and east from the shots. Moreover, there were winds, however light, which contributed to the inversion duct structure.

A most disturbing observation is the high $f$ value calculated from tropospheric duct signals recorded at Lund and St. George. This duct was generated by high-speed jet stream winds in the troposphere. Wave portions caught by this duct would be expected to have lower initial elevation angles at the explosion source than for ozonosphere signals. They would therefore have less relative intensity if the model shown in Figure 6.12 is correct. This model proposes strong blast propagated above an underground source and much weaker signals spread out horizontally over the crater lip. In considering signal attenuation by air, higher frequencies from the smaller calibration shot should be relatively more damped along an ozonosphere, low-ambient-density path and should tend to give higher computed transmissions for ozonosphere signals than for troposphere-ducted waves. The only explanation apparent is that this high tropospheric transmission factor was a random fluctuation caused by wind focusing. Experience in January 1960 with waves focused by a jet stream out to 30 to 50 miles range showed that patterns may shift drastically in 15-minute intervals, particularly around foci. Strong horizontal signal gradients (as great as 100) in a few miles may exist. It is therefore not unlikely that, with tropospheric ducting and focusing at work, Scooter signals happened to be more focused than calibration shot signals traveling nearly the same paths only a few minutes earlier.

![Figure 6.12 Crater shot air-blast source model](image-url)
Close-in overpressure measurements made by NOL were studied to see if they agreed with the air-blast source model shown in Figure 6.12. Of their data points shown in Figures 6.7 and 6.11, two are significantly above the line through the others. Their measurements plan is shown in cross section in Figure 6.13. Gages were hung on lines from balloons at 480, 320, and 160 feet above ground and at ground surface, tied lines were positioned at distances of 300, 500, 1000, and 1500 feet from surface zero. A ground level measurement was also made at 2500 feet. Scatter in reported data was smoothed by first assuming that the so-called "porch" wave, which came before the crater blew out, was uniform and decayed regularly with distance. Actual "porch" overpressures were smoothed to fit this assumption, since measurement errors were probably larger than true wave variations. Blow-out wave overpressures were then adjusted by applying these same smoothing factors to their respective gage records. A mean pressure-distance curve was plotted through these smoothed data, and ratios to this mean were calculated for each data point and entered on Figure 6.13. As ratio isopleths show, the resultant field is very flat except for two top gage points under the balloon nearest to surface zero. This pattern shows that high pressures are more narrowly confined above ground zero than would be expected from extension of the true crater slope. The 320-foot gage gave a 3-percent higher relative pressure than the 480-foot gage, but this is not disturbing. More important, the figure shows that more high-angle data points are needed to verify the source model of Figure 6.12.

6.3.3 Ray Calculations

Weather data in Tables 6.2, 6.3, and 6.4 were used to calculate sound velocity-height curves for each shot-to-station bearing direction in Table 6.1. Separate calculations were made for each of the two rocket wind reports in Table 6.4. A CDC-1604 computer program then calculated paths and travel times through the atmosphere and back to ground level for sound rays emitted at 1-degree intervals of initial elevation angle from zero degree up to the angle at which the ray penetrated the top of the observed atmosphere. Intermediate rays, which turned over at weather data point altitudes, were also traced to show refracted sound pattern limits at ground level.

Calculations for bearings on-site stations show the influence of a weak surface temperature inversion left over from nighttime cooling and a sound duct modification caused by light, low-level winds. There was no ducting from Scooter toward Station M-11, but at the different bearing from F-5 to M-11 an almost homogeneous layer (constant sound velocity) extended to a 700-foot height. Thus, propagation to M-11 from the calibration shot should have been relatively stronger than that of the diffracted signal recorded from Scooter. This apparently caused the relatively low overpressure transmission factor at M-11 shown in Figure 6.11.

Bearing differences between calibration and Scooter shots toward W-1 and W-2 were smaller. Also, no ducted propagation was calculated for any of these paths. This indicates that all four recorded signals were diffracted into a silent zone. However, reference to Figure 6.7 shows amplitudes for the calibration shot which equal or exceed a homogeneous atmosphere pressure-distance curve. Since the
computed sound velocity decreases only slightly with height in the lowest layer, there probably was some small error in wind measurement or representativeness, so that weak surface ducting was really in effect.

![Graph](image)

Figure 6.13 Scooter NOL data, cross-section, smoothed relative overpressures

Ray calculations toward Boulder City show a weak surface inversion sound duct and another weak duct caused by winds at 15,000 feet msl. Surface ducting probably could not carry significant sound energy out of Yucca Flat. A troposphere signal recorded at Boulder City traveled at 1089 ft/sec; the calculated speed for the 15,000-foot duct signal was 1091 to 1095 ft/sec. It is concluded that rays emitted from Scooter at elevation angles of 2 to 4 degrees were ducted below 15,000 feet msl, were reflected twice by the ground, and gave small signals at Boulder City. Ozonosphere signals were calculated to land beyond Boulder City at ranges of between $6.7 \times 10^5$ and $13.4 \times 10^5$ feet. Rays initially between 4 and 22 degrees were ducted by the ozonosphere. Mean travel speeds were computed to vary from 963 to 1064 ft/sec, with only the farthest landing ray traveling faster than 1000 ft/sec. Boulder City's ozonosphere signal showed a 956 ft/sec speed and relatively weak and unfocused amplitude. It most probably resulted from refraction by fine structure of ozonosphere winds which was not observable by chaff wind measurement techniques. Calculations from winds observed 6 hours later do not show duct pattern changes which could account for the Boulder City signal.

St. George-directed calculations were used to construct curves for mean speed of wave arrivals and relative amplitudes (referred to homogeneous atmosphere propagation) shown in Figure 6.14. Scooter signal times and calibration shot times and pressures were used to get observed points on this graph for comparison with the calculations. Observed signals arrived about 16 ft/sec faster than expected from calculation. Recorded amplitudes are in good agreement with calculated curves, without the attenuation factors discussed with reference to Stagecoach results.
If viscous and turbulent atmospheric attenuation is appreciable, then recorded signal amplitudes resulted from considerably more focusing than was calculated. It is possible that strong signals calculated to land near 6.35 x 10^5 feet drifted to longer ranges. Calculations from the later wind run show even higher wave speeds, and the strongest focusing moved in to 5.7 x 10^5 feet range.

![Diagram]

Figure 6.14 Comparison of data with ray calculations at St. George

In the Lund direction, calculated ozonosphere rays all land well beyond Lund range. Extrapolation of calculated velocity curves into Lund range shows that observed arrivals were again 15 to 20 ft/sec fast, as shown in Figure 6.15. Lund fell short of the sound ring and in the silent zone, so no pressures would have been predicted. Ray calculations from noon rocket winds gave an appreciably different pattern of pressures but little change in wave speed. Observed pressures from the calibration shot bracketed the calculated pressure-distance curve; however, the calculation predicted one wave, while two waves were observed.

In summary, while prediction calculations show some similarities to observed conditions, there are many facets of observed recordings which can only be attributed to detailed fine structure of high atmosphere winds beyond the resolving of power current measurements. A larger statistical sample of comparative data is required to assess the accuracy and error ranges of calculated predictions adequately.
Figure 6.15 Comparison of data with ray calculations at Lund
CHAPTER 7 -- CONCLUSIONS

Detonation of the Scooter event of the Plowshare program on October 13, 1960, created a considerable fund of data concerning cratering and associated phenomena. Analysis of these data in the several categories differentiated by the chapters of this report have led to conclusions which follow.

7.1 CRATER

The apparent crater developed by Scooter was 75 feet deep and had an average diameter of 307 feet. Its volume was nearly 100,000 cubic yards.

The bottom of the Scooter crater was unusually flat and its lips were relatively low with very sharp inner edges. Material which fell back into the crater was extremely fine and behaved much like a liquid to form the relatively flat crater floor. It is postulated that the initial apparent crater diameter was smaller than that quoted above. But material falling back on the crater lip loaded that ruptured material beyond its shear strength and caused portions of the wall to slough with a resultant increase in diameter and leaving very sharp inner edges. Consequently, radii of the true and apparent craters from Scooter are essentially the same.

Regression analysis shows that correlation of chemical explosion crater dimensions for charges up to and including a million pounds is best described by the method of overburden approximate scaling. However, this method fits the data very little better than the empirical \( W^{0.3} \) method. It appears that considerably larger charges than Scooter will be required to establish which of these scaling methods will permit the more confident extrapolation to larger yields, or whether still another method will be required.

7.2 THROWOUT

The simple experiments employed to study throwout distribution from the Scooter event have provided reliable data on quantity and distribution of earth material ejected by the explosion. Measurement of the areal density of ballistic ejecta from the crater edge outward was possible using the radioactive tracer pellet technique. This technique also led to an estimate of the effective particle velocity field about the explosive charge and to establishment of those regions of earth surrounding the charge within which specific ejecta originated.

Fine particulate matter or dust from the explosion cloud was collected in a pan array and measured at distances from the explosion greater than those at which ballistic ejecta were found. These data established average areal density of fine
particulate throwout as a function of distance as well as that fraction of the crater volume material which was deposited as fine particulate.

The empirical scaling law, Eq. 3.5, for the mass of ejecta deposited as fine particulate matter which was derived from the Stagecoach experiments has been verified by the Scooter experiment, and very recently by the available preliminary data from the 100-kt nuclear cratering experiment, Sedan. This scaling law indicates correctly within a factor of about two, the mass of earth material deposited as fine particulate.

Data from the tracer and fine particulate experiments are sufficient to determine the total mass of ejecta deposited by an explosion. A scaling law for the total mass of ejecta may be derived for desert alluvium from the plot of total ejecta mass as a function of apparent crater volume shown in Figure 3.11, by following the procedure used in deriving Eq. 3.5 for the total mass of fine particulate matter.

Between 70 and 90 percent of the crater volume mass can be accounted for as ejecta from chemical explosions at cube-root-scaled depths of from 0.5 to 1. Data from the Teapot ESS nuclear explosion buried at a scaled depth of 0.5 imply that 40 percent of the apparent crater volume mass was ejected. This fraction is about half that derived for a chemical explosion at the same scaled depth (20 tons of TNT 17 feet deep). It appears from presently available ejecta data that chemical explosions may be more energetic than nuclear ones in ejecting earth from the crater void region.

7.3 PARTICLE MOTION

Measurements of particle motion along a horizontal radius through the center of gravity of the Scooter explosion were successful.

Arrival time data indicate an average seismic velocity over the radial range covered by instrumentation of 4260 ± 72 feet per second. There is indication of a lens of higher velocity material between 50 and 200 feet from the explosion. This is probably a caliche lens of greater density or rigidity than the surrounding material. It indicates local propagation of about 4400 feet per second. Propagation velocity of peak particle velocities is about 2100 feet per second.

Peak accelerations from all five particle motion stations indicate attenuation according to Eq. 4.1,

$$a = 1.14 \times 10^{14} R^{-5.75\pm0.10}$$

where acceleration, a, is in gravity units, g, and radial range, R, is in feet.

Peak particle velocities derived from both velocity gages and integrated acceleration records are attenuated with range in accordance with Eq. 4.2,
\[ u = 1.26 \times 10^7 R^{-2.65 \pm 0.12} \]

where particle velocity, \( u \), is in feet per second and range, \( R \), in feet.

Peak displacements derived by integration of particle velocity gages are attenuated, as shown by Eq. 4.1, according to

\[ \delta = 2.43 \times 10^6 R^{-2.30 \pm 0.17} \]

where displacement, \( \delta \), is in inches and range, \( R \), in feet.

Analysis of Scooter particle motion data shows no evidence that the instrumentation extended beyond the region of nonlinear response into that of elastic response.

Comparison of these data with similar data from two nuclear explosions, Jangle U and Teapot ESS, which formed craters in Area 10 at NTS and with data from Jangle HE-2, a chemical-explosive cratering event fired near Area 10 indicate (1) that Jangle U produced ground motion comparable to that of a chemical explosion of 20 percent (0.24 kiloton of TNT) of its radiochemical energy yield, (2) the Teapot ESS produced ground motion comparable to that of a chemical explosion of 50 percent (0.6 kiloton of TNT) of its radiochemical energy yield. It may be said then that Jangle U had a 20-percent efficiency for ground motion and that Teapot ESS had a corresponding 50-percent efficiency. But it must be understood that this efficiency applies only to ground motion.

The Jangle HE-2 data imply a transition to elastic response at a peak particle velocity of 0.8 foot per second corresponding to a peak pressure of about 33 psi.

7.4 SURFACE MOTION

Surface particle velocities derived by differentiation of surface displacements observed photographically show that at peak these velocities are essentially radial. Stresses computed from these radial velocities were found to decrease as the inverse 2.28 power of scaled radial distance. Radial stress at the crater edge, \( P_{cr} \), derived from the foregoing relationship exhibits a yield dependence which is approximately \( W^{0.06} \). A plot of \( P_{cr}/W^{0.06} \) versus \( (D/W^{1/3}) \) yielded an expression to fit chemical explosion data as follows:

\[ P_{cr}/W^{0.06} = 300 \exp[-0.2875(D/W^{1/3})] + 1200 \exp[-2.05(D/W^{1/3})] \]

The analogous equation for nuclear craters differs only in the numerical coefficients. Finally, an equation can be derived from the relationships given for crater radius and for \( P_{cr} \) which yields the crater radius, \( R \), in terms of energy yield and depth of burst.
Ground surface accelerations in the vicinity of surface zero derived by double differentiation of the photographic displacement data indicate a double peak, the first evidently caused by ground shock, the second attributable to gas pressure.

Development and venting of the mound were in agreement with previously developed expressions except that the mound surface velocities were only about half those observed for explosions in basalt.

7.5 CLOUD GROWTH

Maximum height of the cloud appears to scale as the fourth root of yield rather than as the cube root as formerly considered correct. For either analysis, the depth of burst is scaled as the cube root of yield.

Base surge moved southward most rapidly; its southward velocity being about 26 feet per second greater than toward the north. Late accelerations and decelerations in horizontal growth of base surge are attributable either to major collapses of crater walls or to late escape of explosive gases. The average propagation velocity of the Scooter base surge was about 41 feet per second, more than double that for the two shallow Stagecoach events. The question of whether base surge horizontal velocity is a function of yield or depth of burst remains to be answered by the explosion of larger charges.

7.6 LONG-DISTANCE AIR BLAST

Atmospheric signals generated by Scooter and by the preceding calibration explosion of 2400 pounds of TNT indicated generally larger signals from Scooter than anticipated from experience with Stagecoach cratering events.

Signals ducted through the ozonosphere indicate that the transmission factor at long distances is higher for larger yields. If this trend continues into the megaton yield range, there may be no appreciable muffling derived from burial of very large yield explosions such as those planned for major excavation projects.

Signals ducted through the troposphere appear to have been affected strongly by a high-speed jet stream. The high tropospheric-ducted transmission factor may have resulted from wind focusing and may have been radically altered by changes in the jet stream pattern over the 15-minute period between the calibration explosion and Scooter detonation.

High pressures generated by a cratering explosion are evidently confined to a narrower cone above the source implied by projection of the true crater slope.

Predictions show similarities to the observed data, but records include many facets which can best be attributed to fine structure of the high atmosphere beyond the resolving power of present measurements.
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