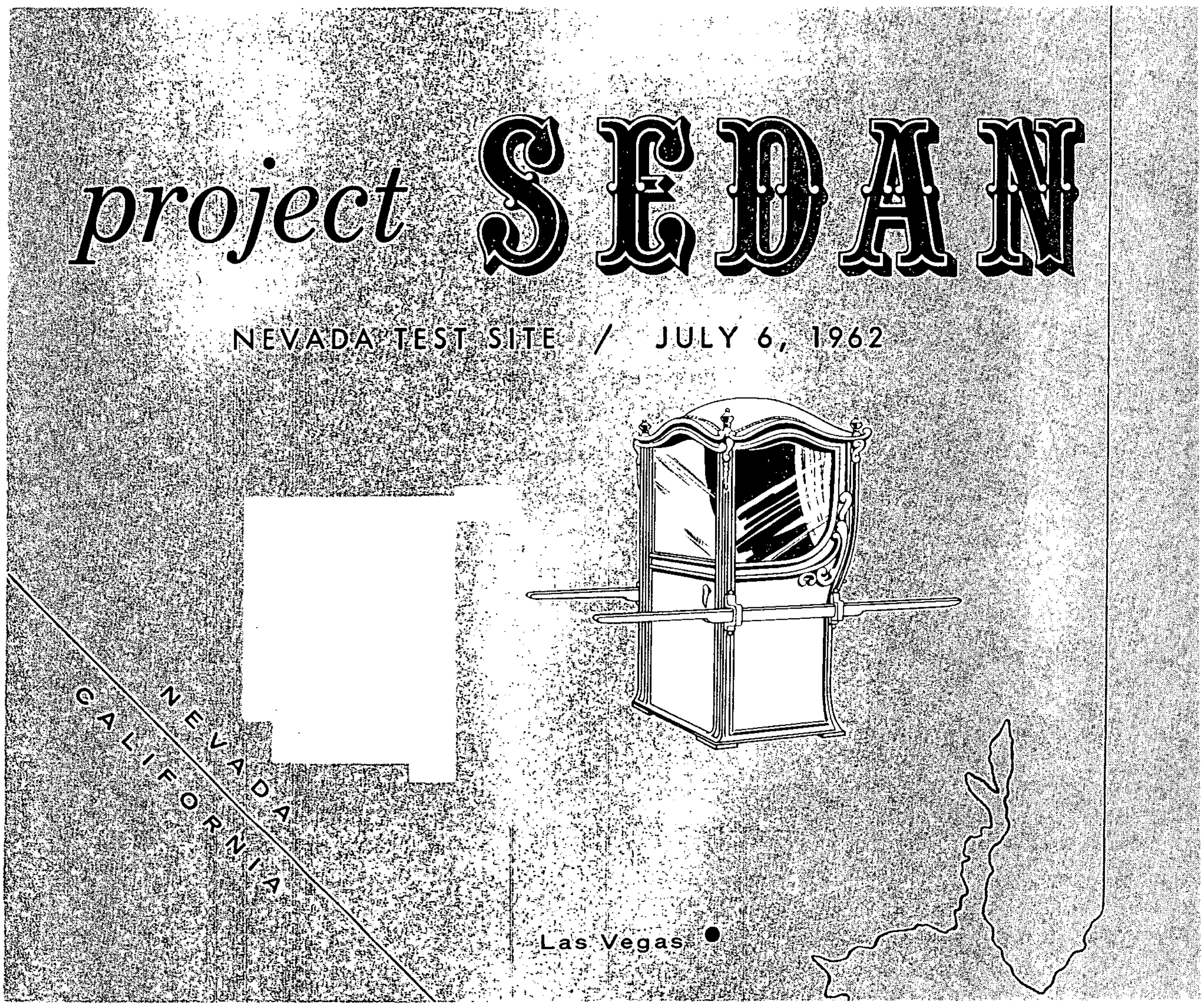
PNE-217P
PRELIMINARY REPORT

Plowshare / peaceful uses for nuclear explosives

UNITED STATES ATOMIC ENERGY COMMISSION / PLOWSHARE PROGRAM

project SEDAN

NEVADA TEST SITE / JULY 6, 1962



Ejecta Studies

W. A. Roberts / R. H. Carlson

THE BOEING COMPANY

ISSUED: APRIL 25, 1963

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PROJECT SEDAN

PNE-217P

EJECTA STUDIES

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The Boeing Company
Seattle, Washington

October 1962

ABSTRACT

This project included 146 ejecta measurement stations encircling ground zero at eight radial distances ranging from 373 to 1,707 meters. The twenty-four sampling lines were spaced at fifteen-degree intervals. Data presented were recovered from stations located at radial distances of 640, 853, 1,067, 1,280, and 1,707 meters. An attempt will be made to recover data at stations located closer to ground zero at a later time.

Preliminary analysis of ejecta data indicates that areal density varies inversely as distance raised to the 3.64 power. Circumferential variation of areal density is about a factor of 30 at the 1,707 meter radial distance, a factor of 10 at the 1,280 meter radial distance, and a factor of 7 at the 853 meter radial distance.

Cursory treatment is given to several related subjects, including outer limit of base surge dust deposit, volumetric ejecta densities, locations of natural missiles and impact craters, and the outer limit of ballistic debris. One case of missile damage to a reinforced concrete structure is documented. Raw data are included in the appendix.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

The primary objective of this project was to obtain quantitative data on distribution of ejecta on the ground surface surrounding a nuclear crater. Both areal density and thickness data were to be obtained and appropriate functional relationships developed.

Secondary objectives of this project were: (1) to determine the limits of the base surge deposit and ballistic ejecta, (2) to survey the area for significant natural geologic missiles; recording their size, weight, and location, (3) to determine particle size distribution and comminution (particle fracturing resulting from the explosive shock) existing at certain designated stations, (4) to determine particle size distribution relative to position within the ejecta profile, and (5) to map splash craters and determine their origin.

1.2 BACKGROUND

Determination of the extent and distribution of crater ejecta and associated radioactivity is a major problem that must be evaluated before peaceful projects for nuclear explosive harbor and canal excavation can be accomplished safely. From a military standpoint, crater ejecta may prove troublesome to such surface components of hardened underground structures as entrance hatchways, blast valves, and ventilators and to various weapons systems communication antennas.

Past nuclear cratering tests have not included experiments designed to measure crater ejecta distribution. Information that is available on the nuclear crater lip is taken from profiles drawn to determine apparent crater dimensions. Such cross-sectional profiles generally do not extend beyond a radial distance of two apparent crater radii. (The conventional crater lip is usually considered to extend a radial distance of two crater radii from ground zero).

Detailed examination of aerial photographs taken of both nuclear and high explosive craters show relatively large quantities of ejecta beyond the conventional crater lip. The ejecta is generally distributed in the region adjacent to the crater in a rayed pattern characterized by a relatively large amount of debris concentrated in longitudinal mounds radially oriented. These mounds are not necessarily continuous from their outer extremity inward to the conventional crater lip and may sometimes be tangential to the crater rather than radial.

Previous quantitative measurements of crater ejecta have been made on several high explosive cratering shots. The ejecta relationships resulting from these experiments are summarized in Table 1.1. The experiments described in the references listed in Table 1.1 (References 1 through 4) have consisted of physically sampling the debris to determine its distribution. Early experimental work of a similar nature was done by Engineering Research Associates (Reference 5). Existing ejecta data are not sufficient to derive empirical relationships whereby ejecta quantities can confidently be predicted for nuclear cratering shots regardless of burst depth, medium, or charge characteristics.

TABLE 1.1 HIGH EXPLOSIVE CRATER EJECTA RELATIONSHIPS

Event	Charge Weight	Burst Depth	Medium	Relationship*	Reference
	pounds	feet			
Stagecoach					
Shot II	40,000	17	Desert alluvium	$\delta = \frac{3.86 \times 10^4}{R^{2.03}}$	1
Shot III	40,000	34	Desert alluvium	$\delta = \frac{4.6 \times 10^4}{R^{1.97}}$	1
Scooter	1,000,000	125	Desert alluvium	$\delta = \frac{8.9 \times 10^6}{R^{2.6}}$	2
White Tribe (9 Shots)	11,560	0	Caliche	$\delta = \frac{8.7 \times 10^4}{R^{2.7}}$	3
Suffield					
100 Tons	200,000	0	Silt and clay mixture	$\delta = \frac{2.56 \times 10^8}{R^{3.65}}$	4
5 Tons	10,000	0	Silt and clay mixture	$\delta = \frac{4.5 \times 10^4}{R^{2.93}}$	4

* δ = Areal density in kg/m^2
  R = Distance from ground zero in meters

Most previous work done to determine shape and extent of the outer crater lip profile has been empirical. The crater lip profile has been reconstructed, recently, using data obtained from known positions of origin and termination of identifiable missiles artificially introduced into the anticipated crater region for a high explosive cratering shot (Reference 6).

CHAPTER 2

EXPERIMENTAL PROCEDURE

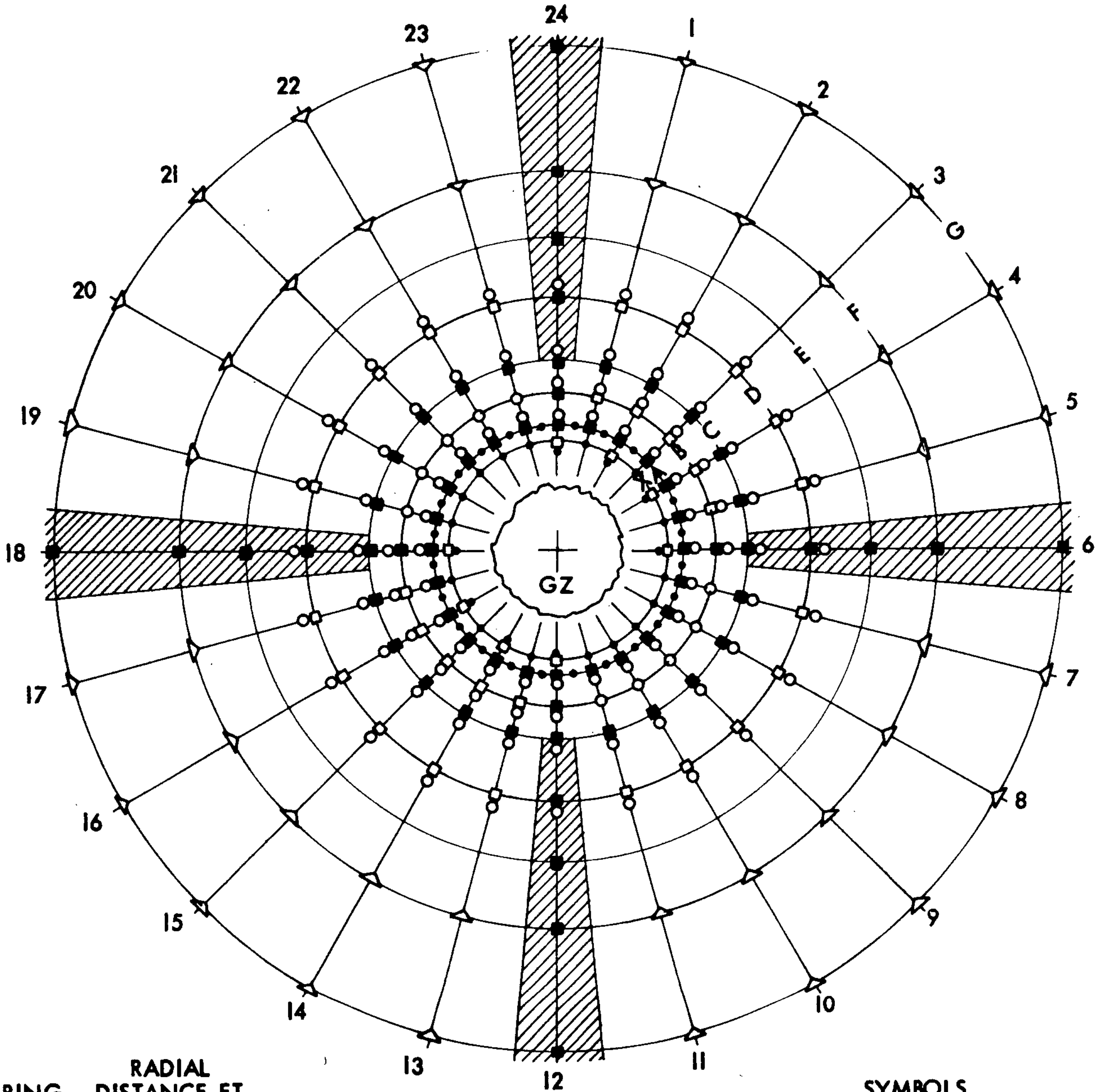
2.1 SHOT PARTICIPATION

The Sedan Shot was burst a a depth of 194 meters (635 ft) beneath the ground surface in Area 10 at the Nevada Test Site. The medium is desert alluvium. The shot detonated on July 6, 1962 resulted in a yield of 100 kt.

2.2 STATION LAYOUT

Ejecta station locations were based on a predicted crater radius of 213 meters (700 ft) (Reference 7). Sampling rings X, A, B, C, D, E, F, and G were located at distances from ground zero of 1 3/4, 2, 2 1/2, 3, 4, 5, 6, and 8 predicted crater radii, respectively. The range of radial distances over which stations were located was felt to be sufficient for the estimated range of yields. Radial sampling lines, spaced at fifteen-degree intervals, were numbered sequentially from 1 to 24 in a clockwise direction, Line 1 being coincident with the N 15°E bearing. The prevailing wind direction for July is directly from the south. All ejecta station locations relative to ground zero and the predicted crater boundary are shown in Figure 2.1. All stations were located by Holmes and Narver survey teams to an accuracy of ±30.5 cm (±1 ft).

All tarp stations were cleared of random debris and plastic trays were placed along F and G rings on the afternoon of D - 1 day.



RING	RADIAL DISTANCE, FT
X	1225
A	1400
B	1750
C	2100
D	2800
E	3500
F	4200
G	5600

SYMBOLS

- □ SECONDARY TARPS
- ■ PRIMARY TARPS
- ○ PIPE
- • FLEXIBLE ROD
- △ TRAYS
- ▨ MISSILE SURVEY AREA

Figure 2.1

2.3 DESCRIPTION OF STATIONS

Two methods were used to obtain data on mass distribution of crater ejecta. Areal density was determined by weighing ejecta samples obtained from tarp and tray stations. (A tarp station consists of a heavy canvas tarpaulin fastened to the ground surface.) Vertical pipes and rods were installed to gage ejecta thickness by marking the preshot position of the original ground surface and the postshot position of the ejecta surface on the same pipe. Spray paint of various colors was used to record ground surface and ejecta surface positions on rods and pipes.

The 68 primary tarp stations consisted of one or more 60 by 120 cm (2 by 4 ft) heavy canvas tarps oriented so that the shorter dimension was ccincident with the radial direction from ground zero. Tarp stations were located along the north, east, scuth, and west radial lines at the X, A, B, C, D, E, F, and G rings. Tarps were also placed at fifteen-degree intervals along the A and C rings. Radial stations were designed to sample approximately 0.2 percent and circumferential stations about 1.2 percent of the circumferences at their respective distances from ground zero. Tarps were fastened to the ground with steel spikes approximately 25 cm in length.

Thirty-eight secondary tarp stations, each consisting of a single 120-cm (4 ft by 4 ft) square tarp, were located so that twenty were on the D circle, ten on the B circle, and eight on the X circle.

Twenty-four vertical 1.3 cm (1/2 in.) steel pipes were located along each of the A, B, C, and D circles. The height of pipe protruding above the ground surface was approximately 150, 120, 120, and 60 cm

(5, 4, 4, and 2 ft) along the A, B, C, and D circles, respectively. All vertical pipe segments were fastened by a standard coupling to a 60-cm (2 ft) section driven into the ground. Pipe sections were metal, stamped with station locations for identification after recovery.

Twenty-four flexible steel rods were located along both the X and A rings. Each rod was 240 cm (8 ft) long with 90 cm (3 ft) driven into the ground. All rods and pipes were spray painted (to designate original ground surface) immediately after installation.

Twenty plastic trays, approximately 25 by 36 by 8 cm (10 x 13 x 3 in.) were located along both the F and G circles at intersections of all radial lines except 6, 12, 18, and 24. Each tray was held in place with light steel cable and four 20-cm (8 in.) steel spikes. Trays were positioned late on D - 1 day to avoid accumulation of preshot random debris.

The sampling array consisted of a total of 196 different stations that could yield 290 ejecta areal density and thickness measurements. Table 2.1 is a summary of all ejecta stations. Figure 2.2 shows typical preshot photographs of ejecta sampling stations.

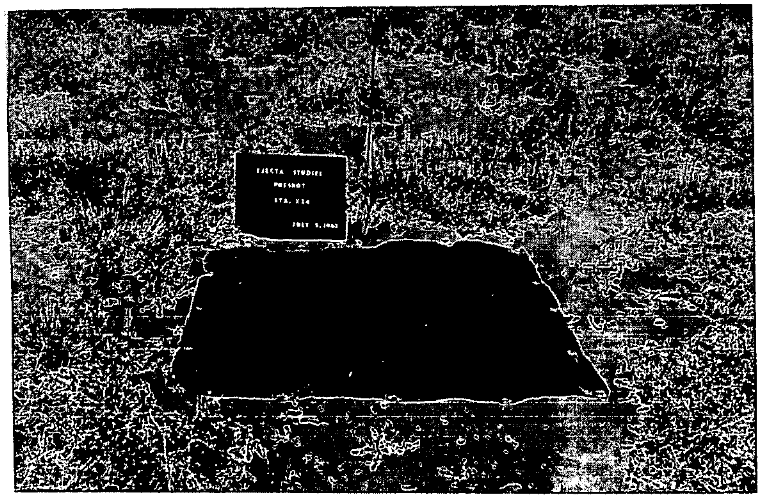
2.4 SAMPLING TECHNIQUES

The sampling procedures described herein were used for the recovery operation which has been completed. Additional recovery at A, B, and C stations will be attempted at a later time.

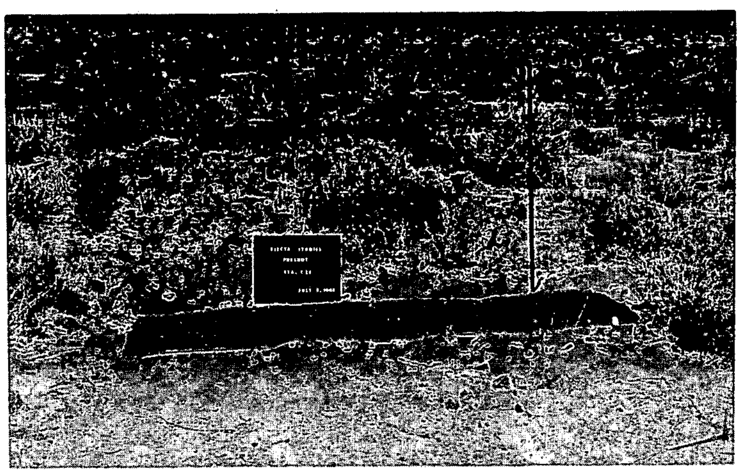
Areal density samples were taken in several ways. At all primary tarp stations with the exception of the C stations, the areal density was determined by weighing tarp and sample together and subtracting the tarp weight. Areal densities at F and G tray stations were determined in

TABLE 2.1 SUMMARY OF EJECTA SAMPLING STATIONS

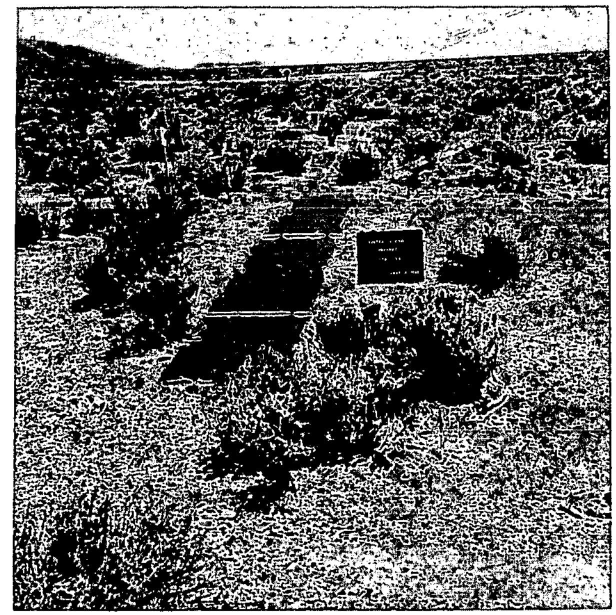
Ring	Distance from Ground Zero			Number of Stations				
				Primary Tarp	Secondary Tarp	Pipe	Flexible Rods	Tray
	meters	feet	increments of predicted crater radii					
X	373	1225	1 3/4		8		24	
A	427	1400	2	24		24	24	
B	533	1750	2 1/2	4	10	24		
C	640	2100	3	24		24		
D	853	2800	4	4	20	24		
E	1067	3500	5	4				
F	1280	4200	6	4				20
G	1707	5600	8	4				20
	TOTALS			68	38	96	48	40



Station X24 - 4 ft by 4 ft tarp same as those used along D circle.



Station C23



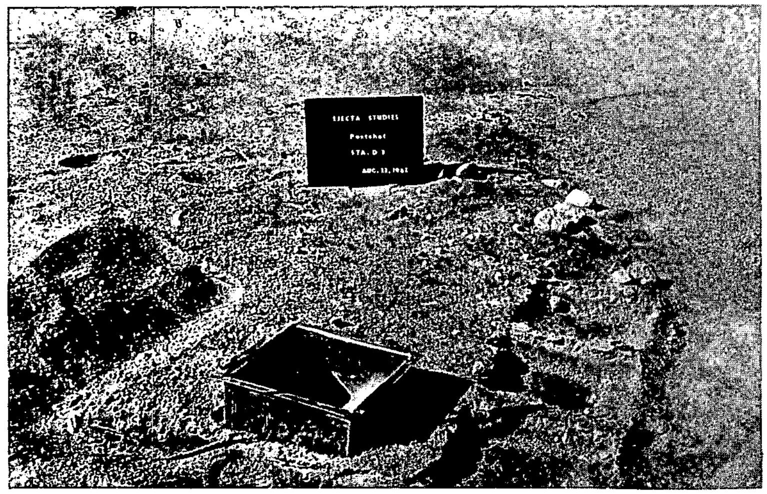
Station G24 - Note five 2 ft by 4 ft tarps required at this range (5,600 ft).

Figure 2.2

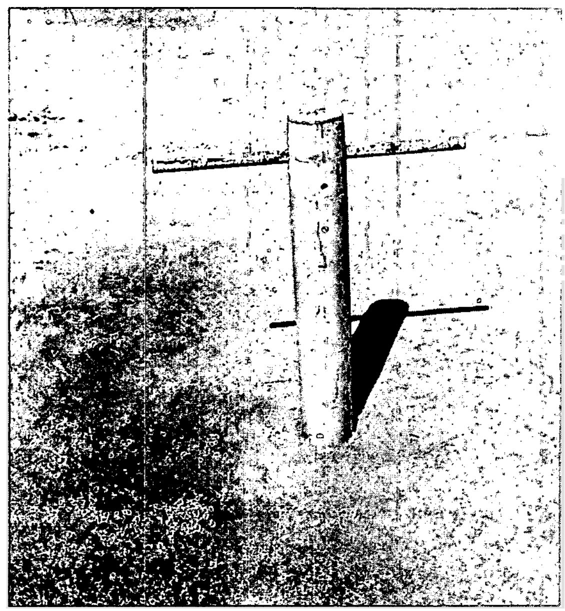
the same way.

At closer stations where the ejecta thickness was greater, other techniques were used to measure the areal density. Bottomless aluminum alloy boxes of known cross-sectional area (1 ft^2 and 2 ft^2) were used in obtaining samples on the D tarps. The box was forced down into the ejecta until its lower edge rested on the tarp. The material inside the aluminum form was then removed and weighed.

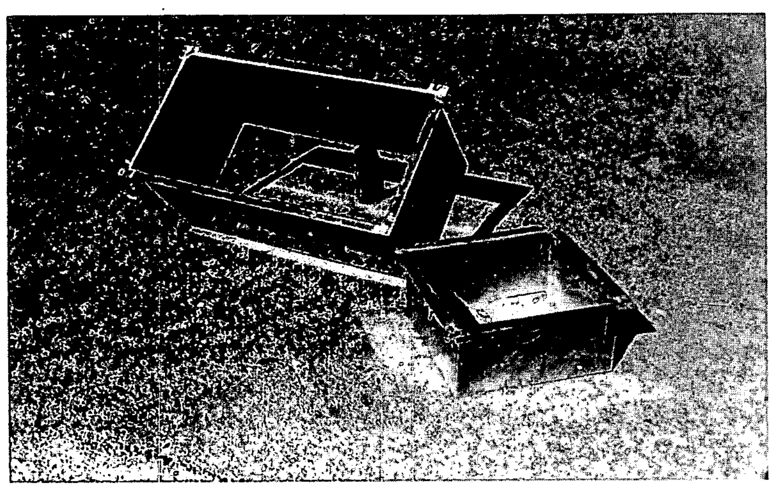
At several of the D stations where the original tarp was missing or badly damaged and at the four C stations for which data are herein reported, a thin-wall sampler having a cross-sectional area of 93 cm^2 (0.1 ft^2) was used. Tube barrels of 120 and 240 cm (2 and 4 ft) are available for use with this sampler. When using the thin-wall sampler, ejecta were excavated until the preshot ground surface was identified. A steel plate was then driven horizontally coincident with the preshot surface and used as the base to which the sample was taken. Recovery apparatus are shown in Figure 2.3.



One square foot sampler in place during recovery at Station D3.



Thin wall sampler.



One and two square foot samplers.

Figure 2.3

CHAPTER 3

RESULTS

3.1 AREAL DENSITY

Sample recovery has been completed for all G, F, E, and D stations (see Figure 2.1). Four samples were recovered along the C ring using the thin-wall sampler. High radiation levels and excessive ejecta thicknesses prevented recovery of all stations. Additional samples will be recovered at a later time. Photographs of several postshot stations are shown in Figure 3.1.

All original data are included in Tables A.1, A.2, and A.3 of the appendix. Areal densities for all recovered stations are summarized in Table 3.1. Ejecta thickness estimates are given in Table 3.1 using the average specific gravity of 1.5 determined by volumetric densities listed in Table A.6. Average areal densities are shown in Table 3.2.

Average areal densities for all samples recovered are plotted versus distance from ground zero in Figure 3.2. Also shown is the least squares straight line fit to these data. The equation of the straight line is:

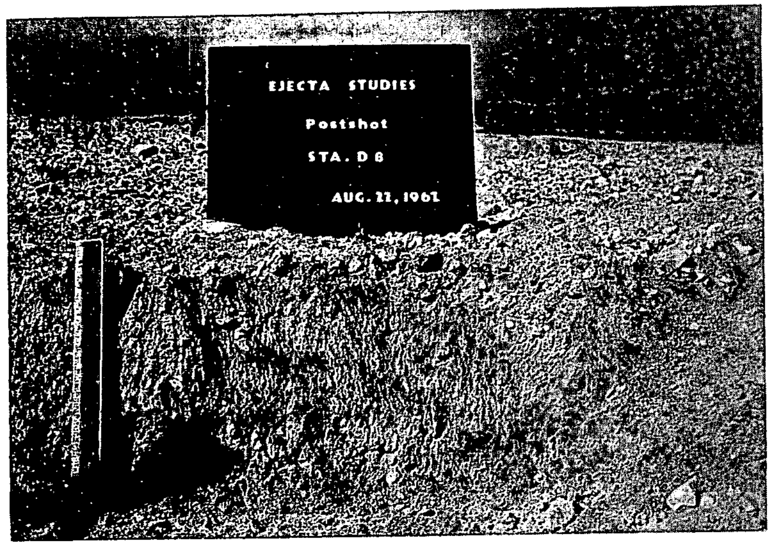
$$\delta = \frac{5.77 \times 10^{12}}{R^{3.64}}$$

Where: δ = areal density in kg/m^2

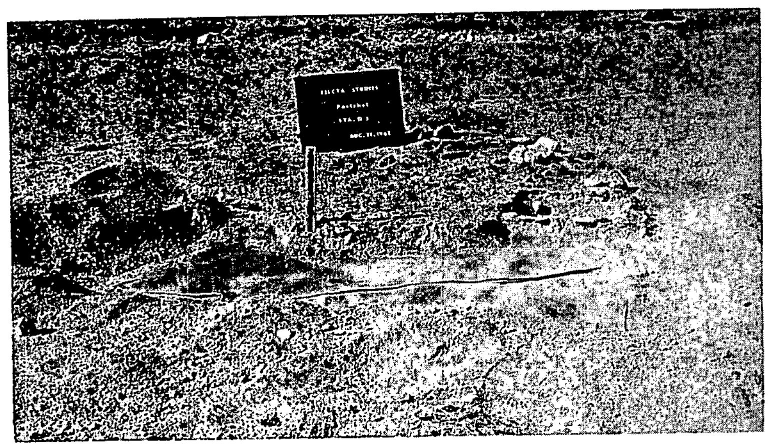
R = radial distance from ground zero in meters

Figure 3.3 shows the data and corresponding least squares best fitted straight lines for the primary radial lines. The equations of these fitted lines are as follows:

Station D8



Station D3



Station F9

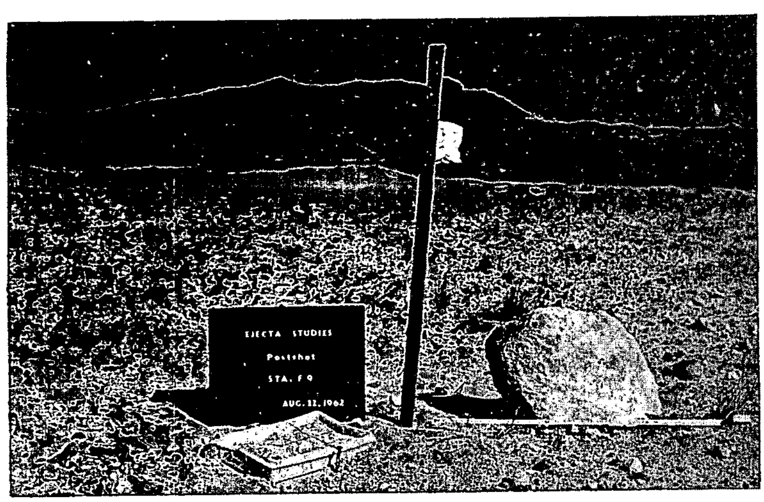


Figure 3.1

TABLE 3.1 AREAL DENSITY AT RECOVERED STATIONS

Station	Areal Density	Estimated Thickness*	Station	Areal Density	Estimated Thickness*
	kg/m^2	cm		kg/m^2	cm
G 1	8.10	0.54	F11	37.6	2.5
G 2	6.15	0.41	F12	25.1	1.7
G 3	8.93	0.60	F13	63.4	4.3
G 4	7.71	0.51	F14	58.5	3.9
G 5	16.9	1.1	F15	35.4	2.4
G 6	3.08	0.21	F16	39.5	2.6
G 7	6.54	0.44	F17	18.0	1.2
G 8	41.0	2.7	F18	7.62	0.50
G 9	30.3	2.0	F19	66.9	4.5
G10	4.59	0.31	F20	17.2	1.2
G11	3.76	0.25	F21	44.2	2.9
G12	3.08	0.21	F22	52.8	3.5
G13	4.59	0.31	F23	48.6	3.2
G14	10.9	0.73	F24	6.69	0.45
G15	11.3	0.75			
			E 6	62.1	4.1
G16	7.37	0.49	E12	21.9	1.5
G17	6.15	0.41	E18	23.1	1.5
G18	1.27	0.08	E24	19.5	1.3
G19	6.93	0.46			
G20	1.42	0.10	D 1	129	8.7
			D 2	91.2	6.1
G21	3.37	0.22	D 3	104	6.9
G22	9.33	0.62	D 4	125	8.4
G23	8.69	0.58	D 5	147	9.8
G24	1.86	0.12			
			D 6	89.3	6.0
F 1	19.6	1.3	D 7	191	13
F 2	37.0	2.5	D 8	262	19
F 3	24.0	1.6	D 9	118	7.9
F 4	52.5	3.5	D10	101	6.8
F 5	42.7	2.9			
			D11	53.6	3.6
F 6	10.2	0.68	D12	95.2	6.4
F 7	58.9	3.8	D13	87.6	5.8
F 8	---	---	D14	78.5	5.2
F 9	55.7	3.7	D15	177	12
F10	17.6	1.2			

TABLE 3.1 AREAL DENSITY AT RECOVERED STATIONS (Continued)

Station	Areal Density	Estimated Thickness*
	kg/m^2	cm
D16	124	8.3
D17	134	9.0
D18	42.0	2.8
D19	108	7.2
D20	---	---
D21	114	7.6
D22	78.0	5.2
D23	57.4	3.8
D24	38.2	2.6
C 6	323	22
C12	632	42
C18	229	15
C24	561	38

* Based on assumed density of 1.5 gm/cm^3.

TABLE 3.2 AVERAGE AREAL DENSITIES

Ring	Radial Distance from Ground Zero	Areal Density				
		Radius 6	Radius 12	Radius 18	Radius 24	All Radii
	meters	kg/m^2				
G	1707	3.08	3.08	1.27	1.86	8.89
F	1280	10.2	25.1	7.62	6.69	36.6
E	1067	62.1	21.9	23.1	19.5	31.6
D	853	89.3	95.2	42.0	38.2	111.0
C	640	323.0	632.0	229.0	561.0	436.0

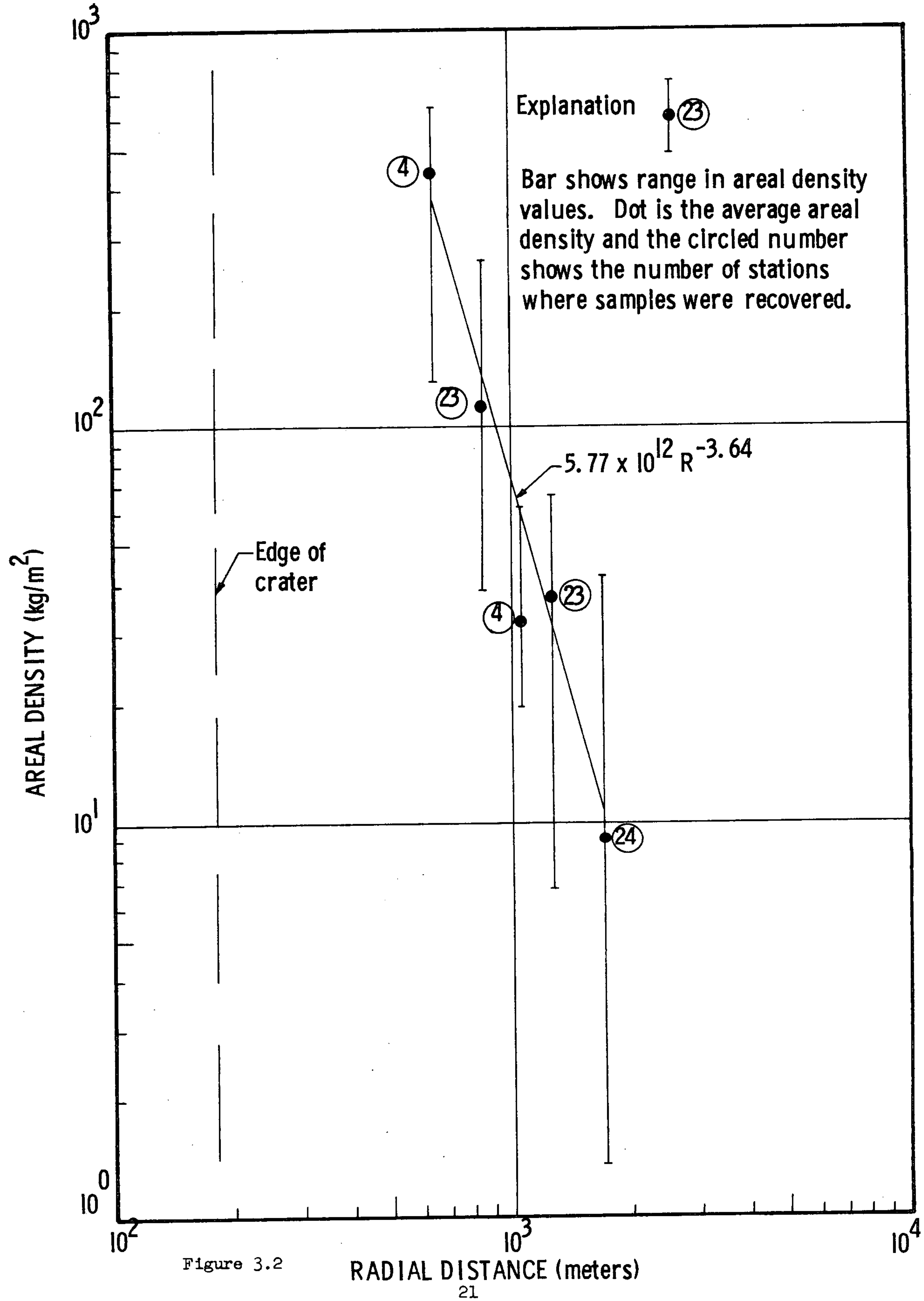
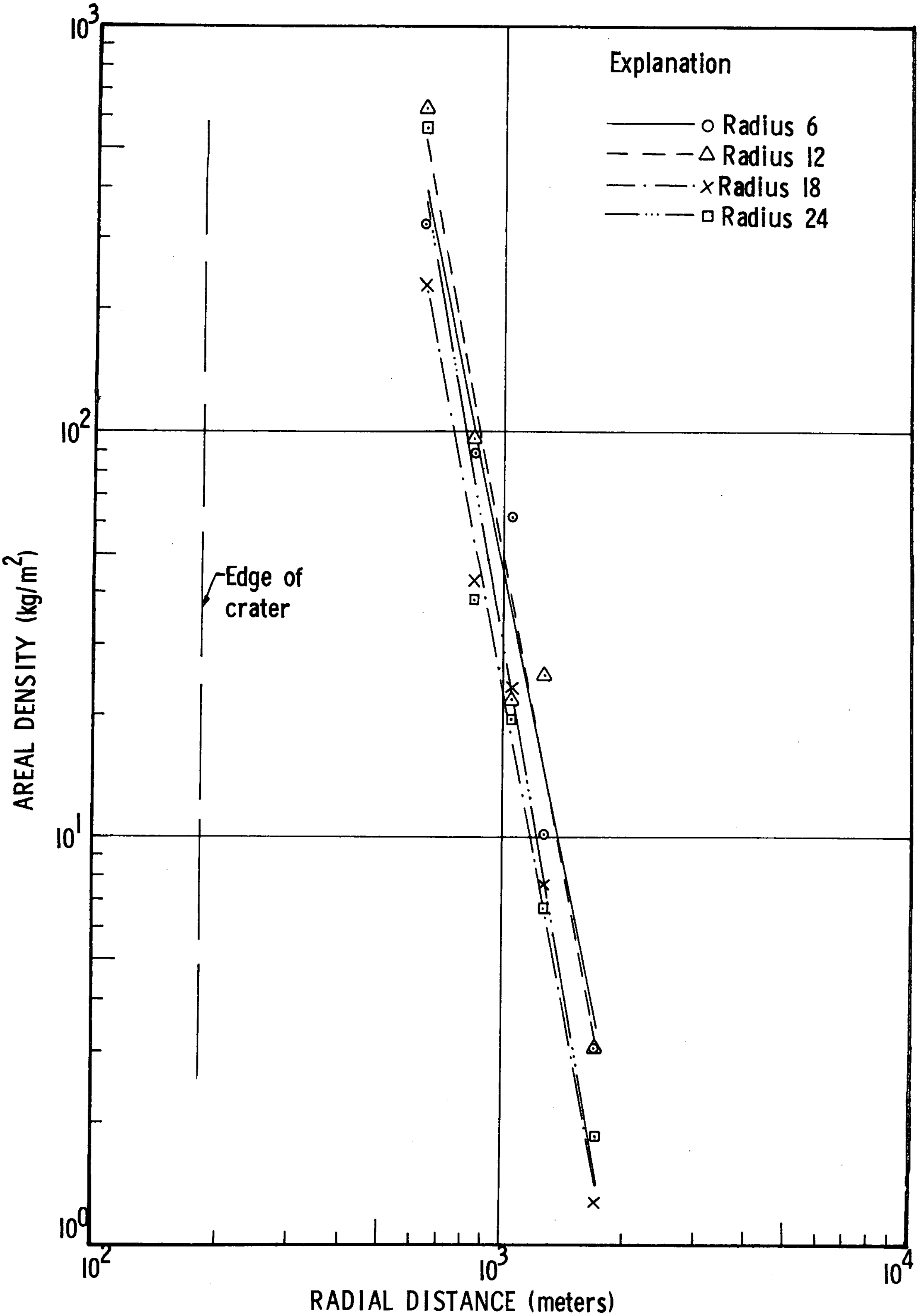

Explanation
23
Bar shows range in areal density values. Dot is the average areal density and the circled number shows the number of stations where samples were recovered.
4
23
4
23
24
$5.77 \times 10^{12} R^{-3.64}$
Edge of crater
AREAL DENSITY (kg/m^2)
10^3
10^2
10^1
10^0
10^2
10^3
10^4
RADIAL DISTANCE (meters)

Figure 3.2



Explanation
Radius 6
Radius 12
Radius 18
Radius 24
Edge of crater
AREAL DENSITY (kg/m2)
RADIAL DISTANCE (meters)

Figure 3.3

Radius 6 (East) $\delta = \frac{1.23 \times 10^{16}}{R^{4.81}}$

Radius 12 (South) $\delta = \frac{1.31 \times 10^{17}}{R^{5.14}}$

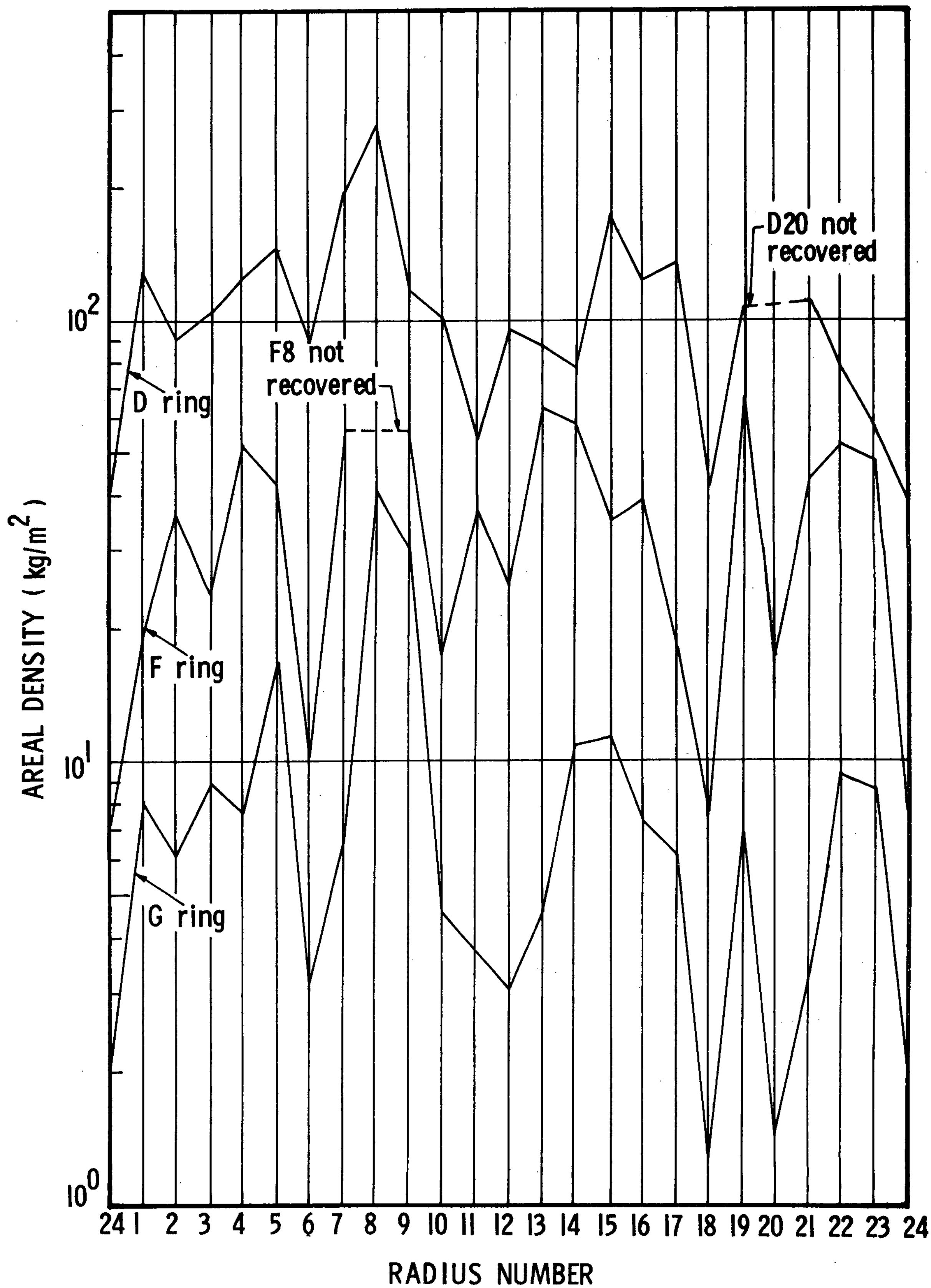
Radius 18 (West) $\delta = \frac{5.69 \times 10^{16}}{R^{5.13}}$

Radius 24 (North) $\delta = \frac{1.86 \times 10^{18}}{R^{5.60}}$

The variation of the amount of ejecta at a constant radial distance from gound zero is illustrated in Figure 3.4 for Rings D, F, and G. Areal densities vary by about a factor of 30 along the G ring, 10 along the F ring, and 7 along the D ring. The tray at F8 was not recovered but it was in an area of high areal density. The tarp at D20 was buried beneath the lip of a large splash crater.

Flexible rod stations have not been recovered. Samples from the outer ring of stations at which pipes were placed have been recovered. Only three of the 24 pipes installed along the D ring were found in a vertical position and is is doubtful if any of the pipes or rods at the inner stations will be found standing. The amount of debris falling on the surface at relatively low trajectory angles was apparently great enough to strike, and either bend or break, most of the pipes and probably all flexible rods located well within the D ring.

The thickness of ejecta at pipe locations recovered is listed in Table A.4 in the appendix. The gaged thicknesses at Stations D2, D11, and D22 were 8.2, 3.7, and 2.8 cm, respectively. The calculated thicknesses at these stations were 6.1, 3.6, and 5.2 cm, respectively. The average gaged thickness at these three stations was 4.9 cm, which is fortuitously close to the average calculated thickness of 5.0 cm for



AREAL DENSITY (kg/m²)
10²
10¹
10⁰
D ring
F ring
G ring
F8 not recovered
D20 not recovered
24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
RADIUS NUMBER

Figure 3.4

these same stations. Ejecta thickness at a pipe is, of course, for a single very small area while areal density measurements result in an average thickness for a much larger relative area.

3.2 VOLUMETRIC DENSITY

Twelve samples were taken to determine volumetric density of the ejecta. These data are given in Table A.6 of the appendix. The average density of the twelve samples was 1.5 gm/cm^3 (94 lb/ft^3). This is the 'in situ' density; however, moisture content determinations will be made at a later time. Ejecta thicknesses presented in Table 3.1 are based on this density.

3.3 BASE SURGE

The edge of the base surge deposit was taken from the aerial photographs made by the Naval Office of Radiological Defense Laboratories (NRDL) on D + 1 day. The upwind deposit is easily discernable. Crosswind and particularly downwind, the base surge deposit edge is gradational and diffuse and locally indeterminate. Figure 3.5 is a map showing this base surge deposit edge as determined from the NRDL aerial photographs.

3.4 MISSILE SURVEY

A missile survey was made along the four primary sampling radii. These data are listed in Table A.7 of the appendix. Locations of the missiles are shown in Figure A.1.

Splash, or impact, craters were generally associated with the remote missiles and result from missile impact with the ground surface.

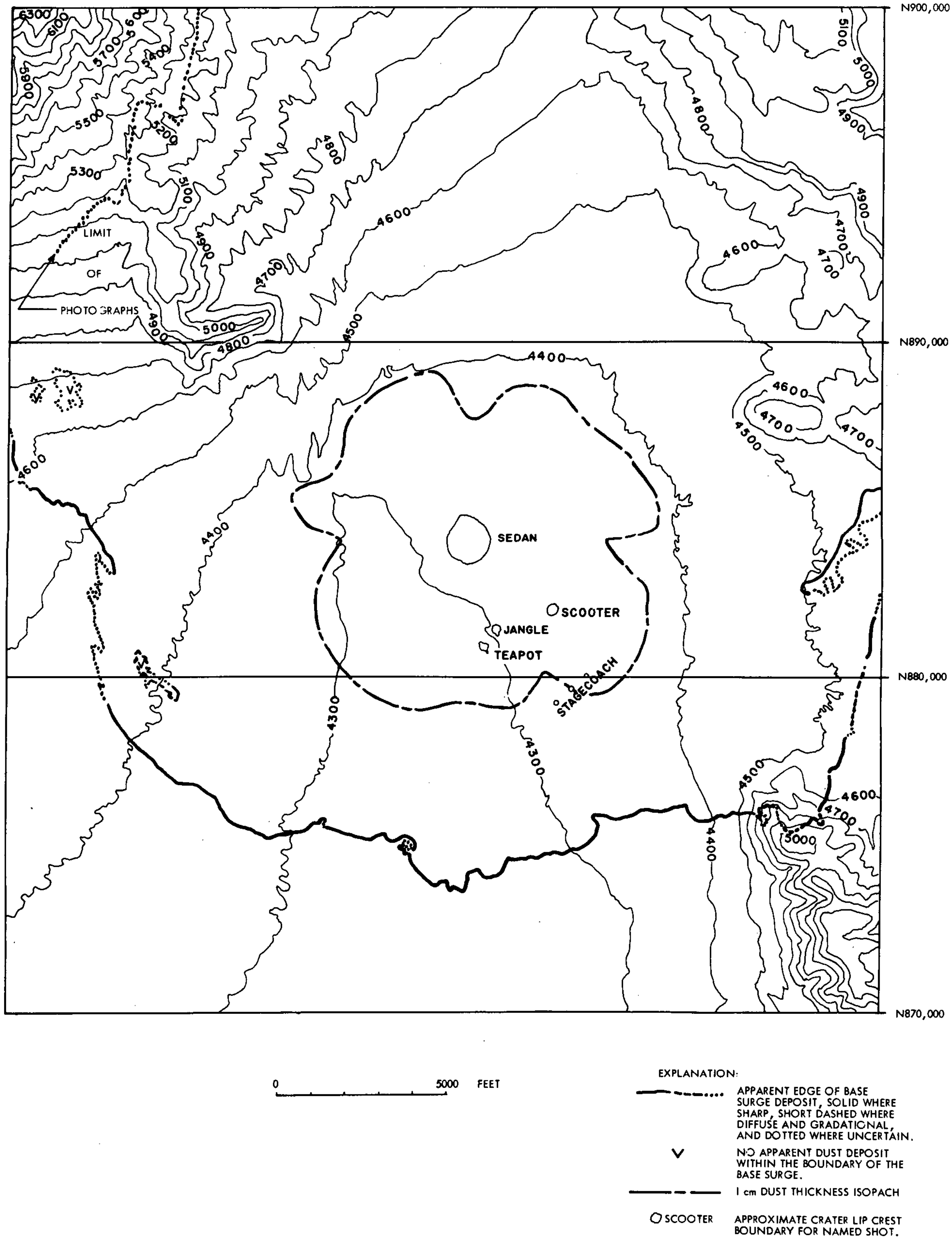

N900,000
N890,000
N880,000
N870,000
LIMIT
OF
PHOTO GRAPHS
SEDAN
SCOOTER
JANGLE
TEAPOT
STAGECOACH
6300
6100
5900
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
4500
4400
4300
0
5000 FEET
EXPLANATION:
APPARENT EDGE OF BASE SURGE DEPOSIT, SOLID WHERE SHARP, SHORT DASHED WHERE DIFFUSE AND GRADATIONAL, AND DOTTED WHERE UNCERTAIN.
V
NO APPARENT DUST DEPOSIT WITHIN THE BOUNDARY OF THE BASE SURGE.
I cm DUST THICKNESS ISOPACH
SCOOTER
APPROXIMATE CRATER LIP CREST BOUNDARY FOR NAMED SHOT.

Figure 3.5

Dimensions of splash craters surveyed are shown in Table A.7. Lip-to-lip diameters of smaller splash craters were about two to four times missile diameters. Large impact craters were relatively frequent within the D ring and were more common in the northwest quadrant. One crater measuring about 24 feet lip-to-lip was noted on the F ring, a distance of 1,280 meters from ground zero. It is estimated that the lip-to-lip diameters of these splash craters are as large as 20 meters. Additional exploratory work will be done on these splash craters at a later time.

3.5 LIMIT OF BALLISTIC EJECTA

The edge of ballistically ejected debris occurs at or beyond 2,140 meters from ground zero, this being the radial distance observed for the outermost missile and its splash crater. This particular missile was found along the bearing (S 60° E) coincident with a major ejecta concentration or ray extending outward from the crater.

3.6 RAYED EJECTA DISTRIBUTION

Rays are not clearly defined on the aerial photographs since aeolian dust was deposited by the base surge to approximately twice the radial distance estimated for ballistic debris. This base surge deposit was generally thick enough to color the region of deposition and obscure rays generally marked by lighter colored fragmented ejecta. Isolated mounds of ejecta a meter or so thicker than the adjacent debris are common inside the D ring, particularly south of the crater.

3.7 COMMINUTION AND SORTING

Ejecta samples recovered from stations located along primary radial sampling lines have been stored at the Nevada Test Site for later comminution analysis. (Comminution is defined as the reduction of soil particle size which results from the explosive shock.) Many of the tray samples from the F and G rings were also packaged and stored for later study.

Layering was observed at stations where significant ejecta thicknesses existed (See Figure 3.1, Station D8). The vertical sorting and stratigraphy of the ejecta profile will be recorded during future recovery operations.

CHAPTER 4

DISCUSSION

4.1 GENERAL

Recovery was delayed until D + 23 days because of the high radiation levels existing at the ejecta stations. An attempt will be made to obtain additional ejecta data at a later time. During the delay period, winds typical of the area eroded the fine dust layer deposited from the base surge cloud. A light rain on D + 21 days temporarily delayed and changed the wind erosion.

The tray at F8 could not be located. This station was located in a region of heavy ejecta concentration, a ray extending about S 60°E from the crater. Investigation of the F8 area indicated that ejecta were entirely eroded from ridges on the preshot ground surface. Drifted dust concentrations were 15 cm deep in depressions in the preshot ground surface; however, the average ejecta depth for this area was about 5 cm.

The tarp at Station D20 could not be located. Resurvey of this station established its location under the lip crest of a large splash crater. Probing in this region indicated that ejecta at this station was 100 to 150 cm in depth. The tarp at D7 also was not located; however, several thin-wall samples were recovered.

The primary tarp sample collectors appeared to be more subject to wind erosion than were trays located in the F and G rings. Analysis of data shows that areal density obtained from these primary stations was consistently less than that obtained from the trays. Figure 3.4

illustrates the lesser density recorded from the primary tarp stations.

Ejecta thicknesses presented in Table 3.1 are based on a density of 1.5 gm/cm^3 (94 lb/ft^3). This density is the average of twelve density samples taken at various locations in the crater lip (see Table A.6). These estimated ejecta thicknesses have been used to construct the ejecta isopach map shown in Figure 4.1. Inasmuch as detail is lacking for ejecta depth greater than 5 cm, a 1-cm contour line was constructed as shown in Figure 4.1. This 1-cm contour is also shown in Figure 3.5, the map showing the outer limit of the base surge deposit.

4.2 PREDICTED EJECTA DISTRIBUTION

The crater was predicted to have an apparent radius of 213 meters (700 ft) (Reference 7). The predicted ejecta thickness (made prior to the Sedan detonations) is based on a crater of this size using high explosive data. It should be noted, however, that differences in the basic phenomenology of high explosives and nuclear explosives (for example, the lack of a late-venting gaseous sphere for nuclear explosives) may greatly alter the distribution of ejecta for what otherwise might be considered comparable shots.

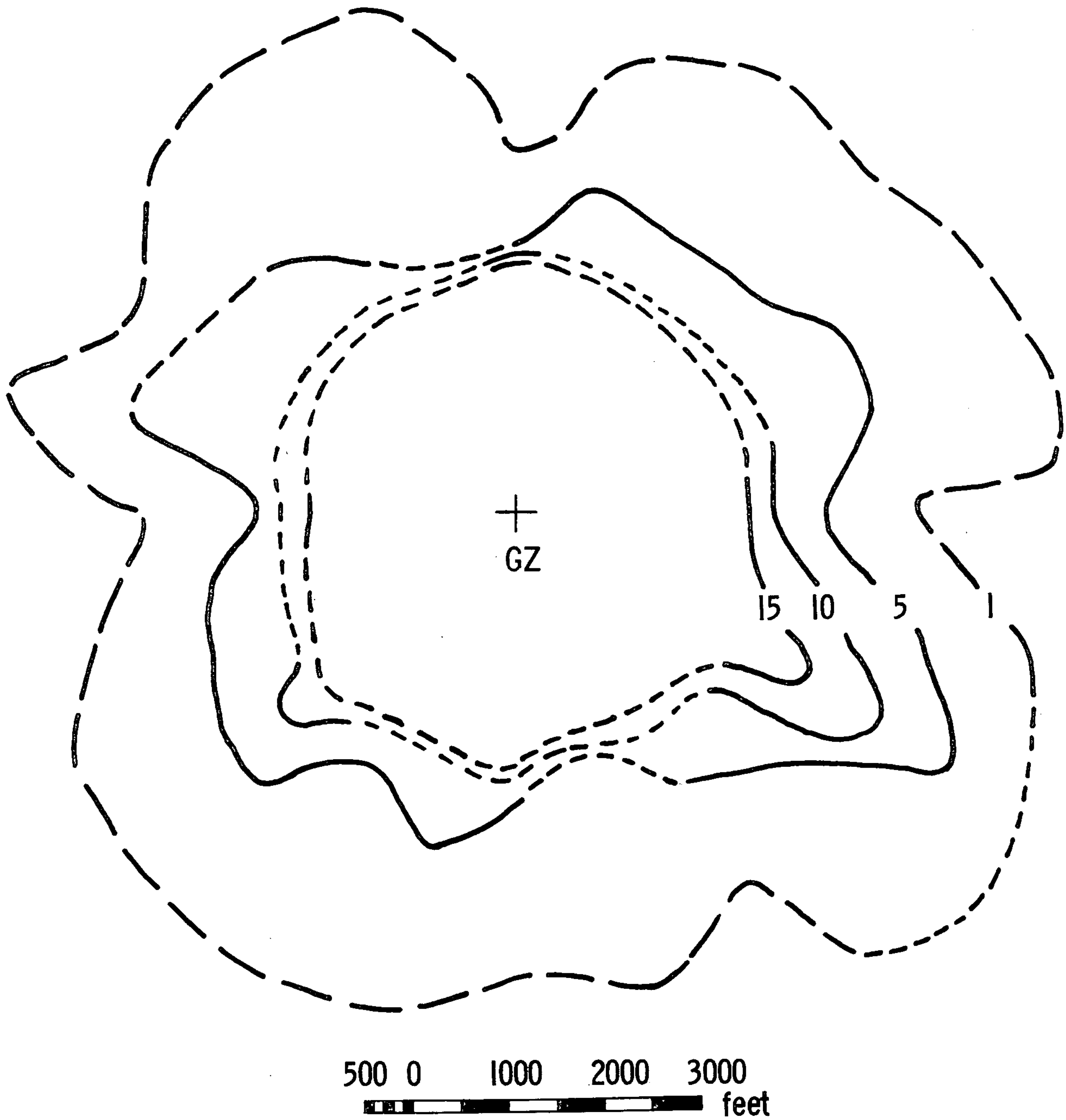
A simple power law similar to that used to correlate ejecta data resulting from high explosive experiments is assumed. It is of the form:

$$t = k/\alpha^n$$

Where: t = ejecta thickness

k = a proportionality constant

α = the distance from ground zero in increments of apparent crater radius



line of equal ejecta thickness in intervals of 5 cm, short dashed where no data

line of ejecta thickness equal to 1 cm

Thickness estimated assuming specific gravity of debris is 1.5

Figure 4.1

The Sedan shot was buried in desert alluvium at a depth of burst intended to be slightly greater than optimum for crater formation (Reference 7). Two chemical explosive shots, Stagecoach III burst at 34 ft and Scooter, burst at 125 ft, were detonated in Area 10. These are the only cratering shots at a burst depth equivalent to Sedan for which ejecta measurements are available. Charge and burst depth quantities for Stagecoach III, Scooter, and Sedan are listed in Table 4.1. The exponent n was about 4 near the crater lip and about 2 beyond about four crater radii for Stagecoach III (Reference 1). Ejecta data for the Scooter crater lip were obtained for the region beyond 9.6 crater radii. Assuming that debris thickness at the Scooter crater lip crest is 50 percent of the average lip crest height and that debris weighs about 1.2 gm/cm^3, then the exponent n for Scooter between the lip crest and the innermost ejecta areal density data is about 3.75. Since the Sedan shot was to be buried at slightly more than optimum, the exponent n may be slightly larger than for Scooter. A value of $n = 4$ was assumed.

The average lip crest height for Sedan was estimated to be 21.33 meters (70 ft) at 1.2 crater radii from ground zero. Half of the lip at the crest was assumed to be fallback. Using these assumptions, ejecta thickness for Sedan was predicted using the following equation:

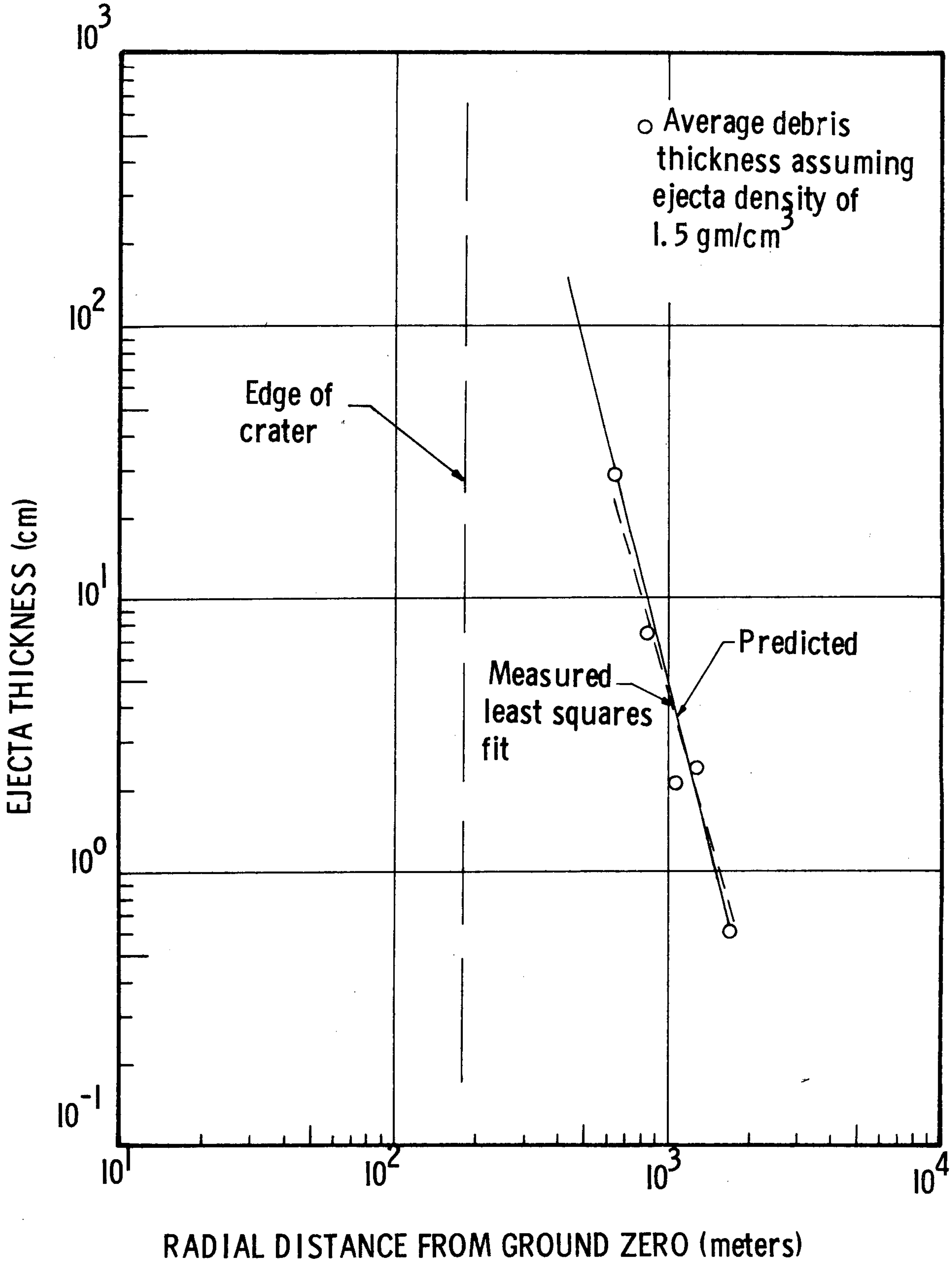
$$t = 2300 \, \ell^{-4} \text{ cm}$$

Predicted thicknesses are listed in Table 4.2.

Predicted and measured ejecta thickness as a function of distance is shown in Figure 4.2. The Sedan crater was smaller than predicted.

TABLE 4.1 SHOT DATA

Shot	Explosive	Yield	Medium	Actual Burst Depth	Scaled Burst Depth	
				FEET	$ft/(lb)^{0.3}$	$ft/(lb)^{1/3}$
Stagecoach III	TNT	20 tons	Desert Alluvium	34	1.42	1.00
Scooter	TNT	500 tons	Desert Alluvium	125	1.98	1.25
Sedan	Nuclear	100 kt	Desert Alluvium	635	2.05	1.08



Average debris thickness assuming ejecta density of 1.5 gm/cm^3
Edge of crater
Predicted
Measured least squares fit
EJECTA THICKNESS (cm)
10^3
10^2
10^1
10^0
10^{-1}
10^1
10^2
10^3
10^4
RADIAL DISTANCE FROM GROUND ZERO (meters)

Figure 4.2

TABLE 4.2 PRESHOT EJECTA THICKNESS* PREDICTIONS

Ring	Radial Distance			Ejecta Thickness	
	meters	feet	increments of predicted crater radii	cm	inches
A	427	1400	2	150	60
B	533	1750	2 1/2	61	24
C	640	2100	3	27	10.8
D	853	2800	4	9.1	3.6
E	1067	3500	5	3.0	1.2
F	1280	4200	6	1.5	0.6
G	1707	5600	8	0.6	0.2

* Based on an assumed ejecta density of 1.2 gm/cm^3 (75 lb/ft^3.)

The volume of the debris in the lip was smaller and the debris was spread over a larger area. This resulted in relatively close correlation of predicted and measured debris thickness in the region sampled.

4.3 IMPACT CRATERS AND SURFACE RUBBLE

Many impact craters with lip-to-lip diameters equal to about 10 meters or more occur approximately within the D ring. The nature of the missiles which formed these craters is unknown. The bulk of large impact craters were probably formed by discrete masses of poorly-sorted, unconsolidated alluvium; however, sections of casing from the device emplacement hole or large boulders could have caused some of the smaller impact craters. Comminuted alluvium near the device, compacted and partially cemented by the intense shock wave, is another possible missile source for the formation of large impact craters. Study of splash craters may indicate the type and relative abundance of the missiles which caused them. Impact or splash craters are illustrated by the photographs in Figure 4.3.

The rough, rubble-like nature of the ejecta surface is shown in Figure 4.4. This photograph was taken looking toward the crater from the D ring on a bearing of about S 30° W. An abundance of fused silicates was observed with their outermost extent being in the area adjacent to Station E6.

Small impact crater near G ring.

Large impact crater on D ring. (Note boulder in background which probably caused crater.)

Large impact crater on F ring. (Missile which caused crater is not evident).

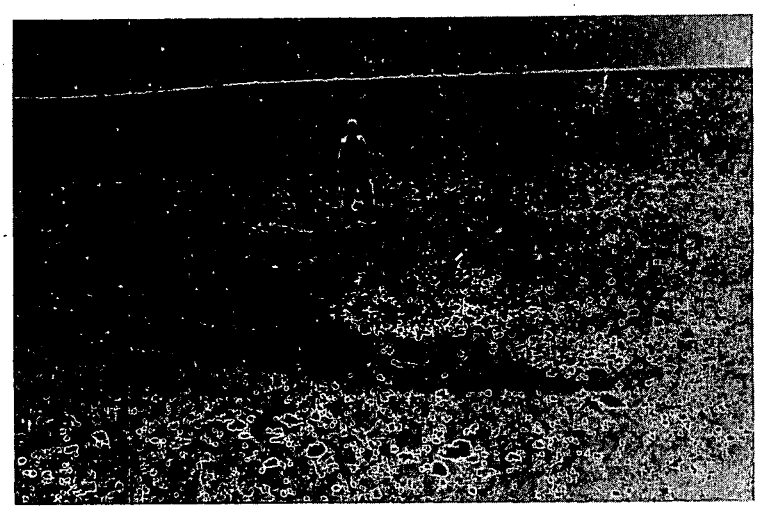
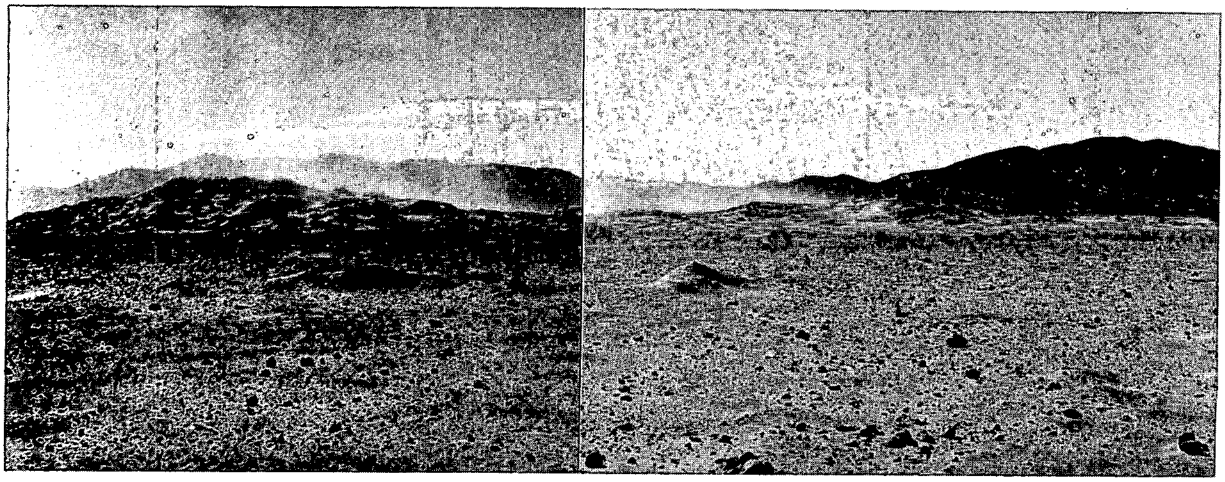
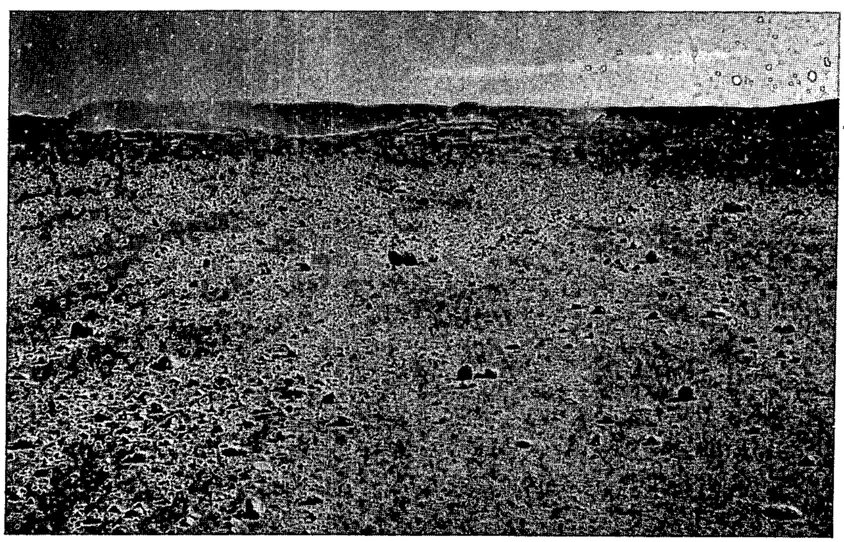


Figure 4.3



Composite view from Station D20 looking southeast.

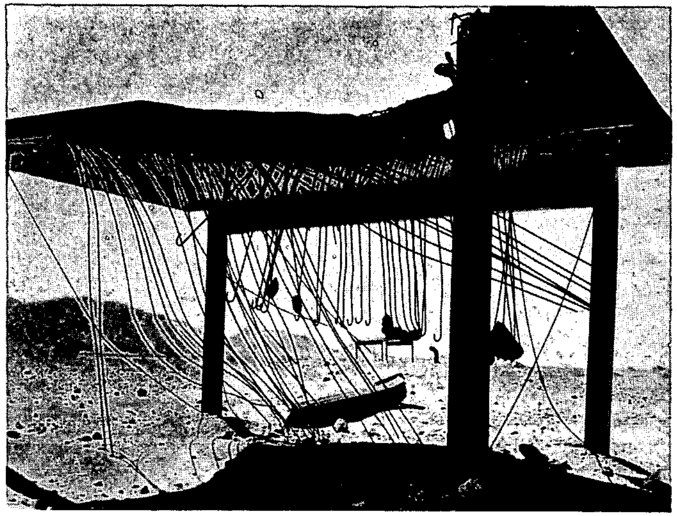


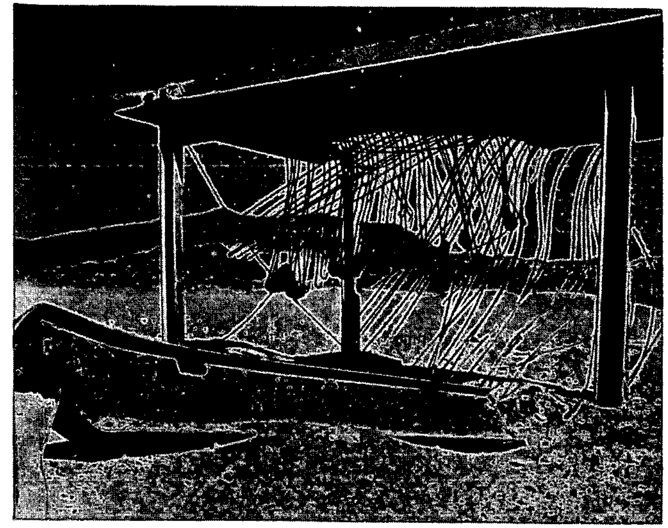
View from Station E14 looking northeast.

Figure 4.4

4.4 MISSILE STRUCTURAL DAMAGE

A significant case of missile damage to a structure was documented. A missile whose nature is unknown struck the Jangle 3.7 idealized structure causing severe damage to its roof. This structure was located approximately 900 meters (3,000 ft) from ground zero. Photographs of the resulting damage are shown in Figure 4.5.





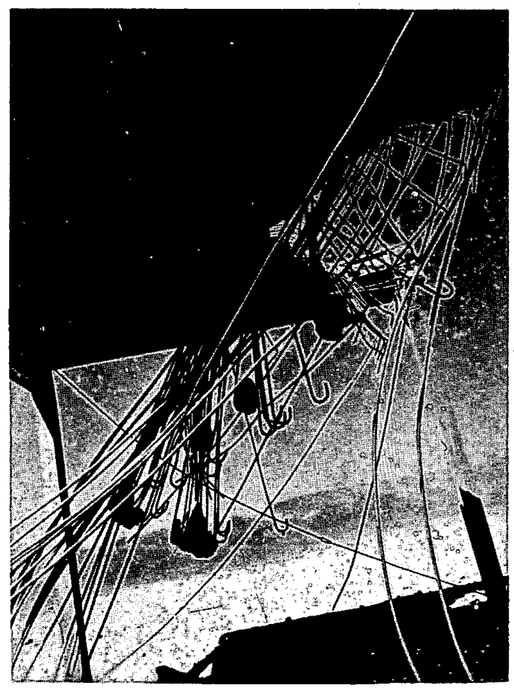


Figure 4.5

CHAPTER 5

CONCLUSIONS

The following conclusions are based on tentative data and are subject to change in the final report:

1. $\delta = 5.77 \times 10^{12} R^{-3.64}$ where δ is areal density of ejecta in kg/m^2 and R is radial distance from ground zero between 3.5 and 9.3 crater radii.

2. The areal density of ejecta varies significantly at a constant radial distance. The variation of areal density appears to increase with radial distance and was within a factor of about 30 at 1,707 meters, 10 at 1,280 meters, and 7 at 853 meters.

APPENDIX A

SUMMARY OF RAW DATA

TABLE A.1 EJECTA SAMPLES--PRIMARY RADIAL ARRAY

Station	Tarp	Weight of Sample Plus Tarp*	Weight of Sample	Areal Density
		pounds	pounds	lb/ft^2
G6	G6a	6.94	5.50	0.68
	G6b	4.63	3.19	0.395
	G6c	5.88	4.44	0.55
	G6d	9.19	7.75	0.96
	G6e	5.69	4.25	0.525
G12	G12a	7.00	5.56	0.69
	G12b	7.25	5.81	0.72
	G12c	5.19	3.75	0.465
	G12d	6.19	4.75	0.59
	G12e	7.13	5.69	0.705
G18	G18a	4.56	3.12	0.386
	G18b	3.38	1.94	0.24
	G18c	3.25	1.81	0.224
	G18d	3.25	1.81	0.224
	G18e	3.44	2.00	0.248
G24	G24a	5.19	3.75	0.465
	G24b	3.81	2.37	0.294
	G24c	4.00	2.56	0.317
	G24d	3.75	2.31	0.386
	G24e	4.94	3.50	0.434
F6	F6a	16.25	14.81	1.835
	F6b	16.25	14.81	1.835
	F6c	22.25	20.81	2.58
F12	F12a	12.94	11.50	1.42
	F12b	57.38	55.94	6.92
	F12c	58.31	56.87	7.04
F18	F18a	6.25	4.81	0.595
	F18b	22.81	21.37	2.64
	F18c	13.2	11.76	1.455
F24	F24a	12.38	10.94	1.35
	F24b	5.56	4.12	0.51
	F24c	19.75	18.31	2.26

TABLE A.1 EJECTA SAMPLES--PRIMARY RADIAL ARRAY (Continued)

Station	Tarp	Weight of Sample Plus Tarp*	Weight of Sample	Areal Density
		pounds	pounds	lb/ft^2
E6	E6a	-----	84.44	10.43
	E6b	-----	130.16	16.1
	E6c	-----	93.87	11.6
E12	E12a	34.06	32.62	4.05
	E12b	55.25	53.81	6.66
	E12c	23.38	21.94	2.72
E18	E18a	19.88	18.44	2.28
	E18b	30.75	29.31	3.63
	E18c	68.25	66.81	8.27
E24	E24a	38.25	36.81	4.56
	E24b	26.50	25.06	3.1
	E24c	36.25	34.81	4.31
D6	D6a	-----	133.66	16.55
	D6b	-----	161.88	20.0
D12	D12a	158.81	157.37	19.5
	D12b	158.88	157.44	19.5
D18	D18a	-----	76.94	9.52
	D18b	-----	62.26	7.7
D24	D24a	72.50	71.06	8.8
	D24b	56.75	55.31	6.85
C6			6.62**	66.20
	C6a			
	C6b			
C12			12.94**	129.4
	C12a			
	C12b			
			3.75**	37.50
C18			5.63**	56.30
	C18a			
	C18b			

TABLE A.1 EJECTA SAMPLES--PRIMARY RADIAL ARRAY (Continued)

Station	Tarp	Weight of Sample Plus Tarp*	Weight of Sample	Areal Density
		pounds	pounds	lb/ft^2
C24			11.50**	115.0
	C24a			
	C24b			

* Average tarp weight 1.44 pounds.
Average tarp area 8.08 ft^2. See Table A.5.

** Estimate, using thin-walled sampling tube and steel plate base at visually identified debris-preshot interface.

TABLE A.2 EJECTA SAMPLES--TRAYS

Station	Weight of Tray* Plus Sample	Weight of Sample	Areal Density
	pounds	pounds	lb/ft^2
G 1	1.75	1.28	1.66
G 2	1.44	0.97	1.26
G 3	1.88	1.41	1.83
G 4	1.69	1.22	1.58
G 5	3.13	2.66	3.46
G 7	1.50	1.03	1.34
G 8	6.94	6.47	8.4
G 9	5.25	4.78	6.2
G10	1.19	0.72	0.935
G11	1.06	0.59	0.765
G13	1.19	0.72	0.935
G14	2.19	1.72	2.24
G15	2.25	1.78	2.31
G16	1.63	1.16	1.51
G17	1.44	0.97	1.26
G19	1.56	1.09	1.42
G20	0.69	0.22	0.286
G21	1.00	0.53	0.69
G22	1.94	1.47	1.91
G23	1.81	1.37	1.78
F 1	3.56	3.09	4.01
F 2	6.31	5.84	7.58
F 3	4.25	3.78	4.91
F 4	8.75	8.28	10.75
F 5	7.19	6.72	8.74
F 7	9.44	8.97	11.65
F 8	lost	---	---
F 9	9.25	8.78	11.4
F10	3.25	2.78	3.61
F11	6.38	5.91	7.7
F13	11.25	10.78	14.0
F14	9.69	9.22	11.98
F15	6.06	5.59	7.25
F16	6.69	6.22	8.09
F17	3.31	2.84	3.69

TABLE A.2 EJECTA SAMPLES--TRAYS (Continued)

Station	Weight of Tray * Plus Sample	Weight of Sample	Areal Density
	pounds	pounds	lb/ft^2
F19	11.00	10.53	13.7
F20	3.19	2.72	3.53
F21	7.44	6.97	9.05
F22	8.81	8.34	10.81
F23	8.13	7.66	9.96

* Average tray weight 0.47 pounds and average tray area 0.77 ft^2. See Table A.5.

TABLE A.3 EJECTA SAMPLES--SECONDARY TARPS

Station	Weight of Sample	Collector Area	Areal Density	Sampling Technique*	Remarks
	pounds	ft^2	lb/ft^2		
D 1	2.19	0.1	21.90	B	Tarp destroyed.
	2.94	0.1	29.40		
	2.81	0.1	28.10		
D 2	41.75	2.0	20.88	A	Tarp intact.
	36.75	2.0	18.38		
	33.56	2.0	16.78		
D 3	20.13	1.0	20.13	A	Tarp intact.
	24.13	1.0	24.13		
	22.59	1.0	22.59		
	18.03	1.0	18.03		
D 4	26.66	1.0	26.66	A	Tarp partially destroyed.
	24.72	1.0	24.72		
D 5	30.09	1.0	30.09	A	Tarp partially destroyed.
D 7	11.75	0.3	39.17	B	Tarp not found.
D 8	50.78	1.0	50.78	A	Tarp intact.
	51.03	1.0	51.03		
	58.94	1.0	58.94		
D 9	28.28	1.0	28.28	A	Tarp partially destroyed.
	25.34	1.0	25.34		
	22.97	1.0	22.97		
	19.97	1.0	19.97		
D 10	2.07	0.1	20.7	C	Tarp badly damaged. Thickness estimates: 3.0 in., 2.75 in., 3.75 in.
D 11	22.69	2.0	11.34	A	Tarp intact.
	21.19	2.0	10.59		
D 13	15.09	1.0	15.09	A	Tarp intact.
	14.41	1.0	14.41		
	18.53	1.0	18.53		
	23.72	1.0	23.72		

TABLE A.3 EJECTA SAMPLES--SECONDARY TARPS (Continued)

Station	Weight of Sample	Collector Area	Areal Density	Sampling Technique*	Remarks
	pounds	ft^2	lb/ft^2		
D 14	19.78	1.0	19.78	A	Tarp intact.
	14.97	1.0	14.97		
	13.78	1.0	13.78		
	15.78	1.0	15.78		
D 15	36.85	1.0	36.85	A	Tarp intact
	36.66	1.0	36.66		
	34.85	1.0	34.85		
	36.91	1.0	36.91		
D 16	35.47	1.0	35.47	A	Tarp intact.
	30.72	1.0	30.72		
	16.03	1.0	16.03		
	19.09	1.0	19.09		
D 17	34.53	1.0	34.53	A	Tarp intact.
	23.28	1.0	23.28		
	21.97	1.0	21.97		
	30.03	1.0	30.03		
D 19	22.34	1.0	22.34	A	Tarp was folded where lightest sample taken.
	25.78	1.0	25.78		
	24.09	1.0	24.09		
	15.85	1.0	15.85		
D 20					Tarp location under splash crater and lip, Probe thickness: 32, 44, 54 in. Average 43 in.
D 21	20.41	1.0	20.41	A	Tarp intact.
	23.53	1.0	23.53		
	22.16	1.0	22.16		
	26.91	1.0	26.91		
D 22	258.16	16.20	15.98		Entire tarp picked up. Weight of tarp plus sample 260.94 lbs. and weight of tarp 2.58 lbs.

TABLE A.3 EJECTA SAMPLES--SECONDARY TARPS (Continued)

Station	Weight of Sample	Collector Area	Areal Density	Sampling Technique*	Remarks
	pounds	ft^2	lb/ft^2		
D 23	11.47	1.0	11.47	A	Tarp intact.
	9.16	1.0	9.16		
	16.72	1.0	16.72		
	9.59	1.0	9.59		

* Sample Techniques:

  A. Sample box inserted in debris until base rests on tarp. Sample removed and weighed.
  B. Debris excavated and original ground surface identified. A steel plate was inserted along the original ground surface and the thin-walled sampling tube was inserted until the base rested on the steel plate. Tube and plate removed and sample inside tube weighed.
  C. Thin-walled sampling tube inserted until base rests on tarp. Sample recovered and weighed.

TABLE A.4 EJECTA THICKNESS--PIPES

Station	Ejecta Thickness
	feet
D-2	0.27
	0.26
	0.27
	0.27
D-11	0.14
	0.15
	0.10
	0.09
D-22	0.10
	0.10
	0.08
	0.09

TABLE A.5 SAMPLE COLLECTOR DATA

Sampler Collector	Number of Collectors	Average Dimensions	Average Area	Average Weight
		feet	ft^2	pounds
Primary Tarps	18	2.05 x 3.94	8.08	1.44
Secondary Tarps	10	4.02 x 4.03	16.20	2.58
Trays	10	0.71 x 1.08	0.77	0.48
Thin-walled Sampling Tube	1		0.1	

TABLE A.6 DENSITY OF DEBRIS

Sample	Station	Moist Density	Remarks
		lb/ft^3	
1	E6	98	Sample taken at surface.
2	D6	100	Sample taken at surface.
3	C6	85	Sample taken at surface.
4	A6	95	Sample taken at surface.
5	X6	111	Sample taken at surface.
6	C12	87	Sample taken about 3 inches below surface.
7	A12	95	Sample taken about 4 to 5 inches below surface.
8	C24	90	Sample taken about 2 inches below surface.
9	B24	95	Ejecta very loose. Sample taken one inch below surface.
10	F8	87	Drifted dust.
11	C18	101	
12	B18	89	Sample taken 2 inches below surface.

TABLE A.7 MISSILE SURVEY DATA

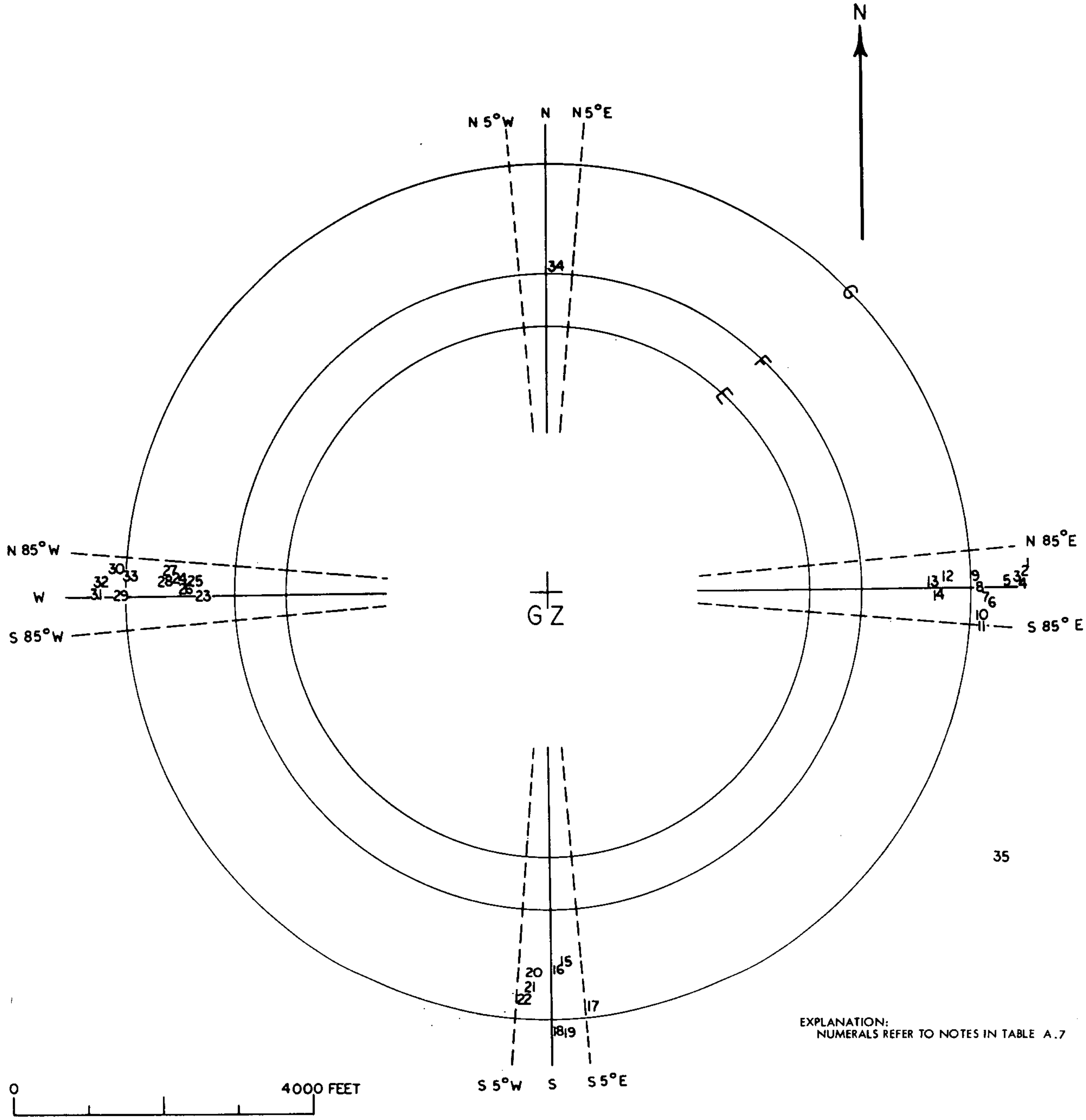
Radius	Note Number on Figure A.1	Lip-to-Lip Splash Crater Dimensions	Splash Crater Depth from Lip Crest	Weight of Missiles	Distance and Direction from Splash Crater	Remarks
		inches	inches	pounds	feet	
6	1	22 x 24	---	39.0	34 ft E	
				4.13	Adjacent	
6	2	30 x 30	---	2.38	1 ft S	Circular crater
				23.63	10 ft S	
				15.50	11 ft S	
				18.00	15 ft NW	
				2.88	Scattered	10 small fragments
6	3	54 x 54	---	29.50	60-70 ft E	Circular crater
				47.25	50 ft SE	
6	4	24 x 24	---	33.38	6 ft N	Circular crater in bush
6	5	24 x 30	6	0.31	6 ft N	
				11.13	10 ft E	
				27.25	12 ft NE	
				17.19	15 ft N	
6	6	30 x 40	6	300 est.		Missile ≈ 15 x 15 x 17 inches
6	7			14.31		No splash crater found
6	8	18 x 30	---	39.94	8 ft E	
6	9	24 x 24	---	22.69	6 ft E	Circular crater
6	10	30 x 48	---	24.88	up to 50 ft E	6 fragments
6	11	20 x 22	2	30.13	8 ft SE	
6	12	---	---	300 est.		3 fragments
6	13	Small				3 small splash craters. No missiles. Pile of poorly sorted rubble in one splash crater.
6	14	30 x 42	6-7	200 est.		4 fragments. Two about 10 pounds each and two totalling about 1.5 ft^3.

TABLE A. 7 MISSILE SURVEY DATA (Continued)

Radius	Note Number on Figure A.1	Lip-to-Lip Splash Crater Dimensions	Splash Crater Depth from Lip Crest	Weight of Missiles	Distance and Direction from Splash Crater	Remarks
		inches	inches	pounds	feet	
12	15	36 x 36	3	10.63	50 ft S	Circular crater
12	16	24 x 32	---	42.63	Adjacent	
12	17	24 x 36	3	9.81	Adjacent	
12	18	28 x 28	6	23.44	3 ft SW	Circular crater
12	19	24 x 24	5	23.19	Adjacent	Circular crater
12	20	26 x 26	---	15.50	In crater	Circular crater almost drifted full
12	21	24 x 28	3	15.88	18 ft S	
12	22	20 x 20	---	16.19	In crater	Circular crater almost drifted full
18	23	55 x 55	8-9	47.75 92.00 20.06 27.25 20.00 est		Circular crater Numerous small fragments
18	24	15 x 15	1	6.69		Almost drifted full
18	25	20 x 20	1	19.56		Almost drifted full
18	26	18 x 18	1	10.06		Almost drifted full

TABLE A.7 MISSILE SURVEY DATA (Continued)

Radius	Note Number on Figure A.1	Lip-to-Lip Splash Crater Dimensions	Splash Crater Depth from Lip Crest	Weight of Missiles	Distance and Direction from Splash Crater	Remarks
		inches	inches	pounds	feet	
18	27					11 missiles 15 to 40 pounds within an area about 150 ft. in diameter
18	28	35 x 43	3	43.00	Adjacent	
18	29	25 x 27	3	17.13		
18	30	26 x 47	3	59.75	75 ft W	Long crater dimensions oriented N of Sedan crater
18	31	30 x 40	4	17.56 24.00 9.75		 4 fragments 3 fragments
18	32	27 x 35	4-5	26.19 21.58 9.38	90 ft E	Long crater dimensions oriented toward Station D-24
18	33	20 x 20 20 x 20	--- ---	20.00	Adjacent	Two splash craters and one missile
24	34	12 x 12 8 x 8	--- ---	--- ---		No missiles two small possible splash craters



N
N 5°W
N
N 5°E
34
G
F
E
N 85°W
W
S 85°W
GZ
N 85°E
S 85° E
35
S 5°W
S
S 5°E
0
4000 FEET
EXPLANATION:
NUMERALS REFER TO NOTES IN TABLE A.7

Figure A.1

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STL	Space Technology Laboratories, Inc., Redondo Beach, Calif.
SC	Sandia Corporation, Sandia Base, Albuquerque, New Mexico
USC&GS	U. S. Coast and Geodetic Survey, San Francisco, California
LRL	Lawrence Radiation Laboratory, Livermore, California
LRL-N	Lawrence Radiation Laboratory, Mercury, Nevada
Boeing	The Boeing Company, Aero-Space Division, Seattle 24, Washington
USGS	Geological Survey, Denver, Colorado, Menlo Park, Calif., and Vicksburg, Mississippi
WES	USA Corps of Engineers, Waterways Experiment Station, Jackson, Mississippi
EGG	Edgerton, Germeshausen, and Grier, Inc., Las Vegas, Nevada, Santa Barbara, Calif., and Boston, Massachusetts
BYU	Brigham Young University, Provo, Utah
UCLA	UCLA School of Medicine, Dept. of Biophysics and Nuclear Medicine, Los Angeles, Calif.
NRDL	Naval Radiological Defense Laboratory, Hunters Point, Calif.
USPHS	U. S. Public Health Service, Las Vegas, Nevada
USWB	U. S. Weather Bureau, Las Vegas, Nevada
USBM	U. S. Bureau of Mines, Washington, D. C.
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