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LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Fuel Element and Support Element
Fragment Study -
Kiwi Transient Nuclear Test

(Title Unclassified)

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

AEC RESEARCH AND DEVELOPMENT REPORT

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LA-3445-MS
C-91, NUCLEAR REACTORS FOR ROCKET PROPULSION
M-3679 (46th Ed.)

LOS ALAMOS SCIENTIFIC LABORATORY
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University of California
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Report written: December 1965

Report distributed: January 10, 1967

Fuel Element and Support Element Fragment Study - Kiwi Transient Nuclear Test

(Title Unclassified)

Work performed by:

C. J. Boasso
C. L. Cuntz
P. W. McWilliams

Report written by:

Robert V. Fultyn
Clifford J. Boasso

UNITED STATES
ATOMIC ENERGY COMMISSION
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ABSTRACT

The size distribution by count and location of reactor core fragments (i.e., uranium-loaded fuel elements and associated core support elements only) resulting from the Kiwi Transient Nuclear Test (TNT) was obtained. Several size classes, 1/4 to 1/2, 1/2 to 1, 1 to 2, 2 to 4, 4 to 8, 8 to 16, and 16 to 32 inches, were used to determine the size distribution. For collection purposes, the TNT area was divided into 50-foot, 45-degree annular sectors from the test pad to 500 feet and 250-foot, 45-degree annular sectors from 500 to 1,000 feet.

The total core fragment count distribution was a reasonable approximation to a normal distribution with a mean value of 0.90 inch and a standard deviation of 1.15 inches. The wind at the time of the experiment affected the geographical distribution of both small and large fragments.

The fragment study accounted for approximately 28 percent of the reactor core material. However, this core material included 74 percent of the reactor center elements.

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ACKNOWLEDGMENTS

Group H-8 would like to express appreciation to the following for their efforts in making this report possible: The Radiation Services Department of Pan American World Airways, Inc. for the recovery of the TNT fragments, American Car and Foundary Incorporated and Group J-9 of the Los Alamos Scientific Laboratory for the fragment sizing at Nevada, and Group CMB-14 of the Los Alamos Scientific Laboratory for the sizing of fragments shipped to Los Alamos.

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INTRODUCTION

On January 12, 1965, at 10:57 a.m. PST, the Los Alamos Scientific Laboratory conducted the Kiwi Transient Nuclear Test (TNT) at the Nuclear Rocket Development Station (NRDS) of the Nevada Test Site. This test consisted of inducing a nuclear transient in a slightly modified Kiwi nuclear rocket reactor (Fig. 1) by rotating the control drums ~4000 degrees per second (approximately 100 times faster than normal).

Since there was no gaseous hydrogen flow through the reactor, the propellant-coolant system and nozzle were omitted for the TNT event. A large mirror assembly was mounted at the upward pointing nozzle end of the reactor so pictures could be obtained of the core during the transient. The transient produced $3.1 \pm 0.3 \times 10^{20}$ fissions[1] in a few milliseconds, completely destroying the reactor (Fig. 2).

One of the experimental programs conducted by Group H-8, Field Studies Group of the Health Division of the Los Alamos Scientific Laboratory, was an attempt to document by numerical count and geographical location the size distribution of the larger reactor core fragments, i.e., fragments from 1/4 to 32 inches in any one dimension. For purposes of this study, the core materials were defined to include only the uranium-loaded fuel elements and their associated support elements.

METHODS

The plan for the recovery of core fragments consisted of dividing the TNT area (Fig. 3) out to 1,000 feet into 12 annular sections, two with widths of 150 feet each, and 10 with widths of 50 feet each (Fig. 4).

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Each annular section was further divided into 45-degree segments. Some deviation from this plan was caused by rough terrain and the confinement of the Test Cell C complex area approximately 300 feet southeast of the TNT test pad (partially shown by fenced area in Fig. 3). The areas of typical sectors are listed in Table I.

Personnel from the Radiological Safety Department of Pan American Airways at NRDS were responsible for the ground pickup of the TNT fragments. Fragments were collected by several teams of three men each: a monitor equipped with an E-112-B survey meter, and two collectors equipped with tongs (~2 feet in length) and collection containers. Each section was radiologically surveyed by scanning the desert surface with the probe approximately 3 inches above ground level. A long handle (~3 to 4 feet) was attached to the probe to facilitate the scanning and reduce the dose rate to the monitor. Each increase in meter response above background was visually investigated, and usually lead to the location of a reactor fragment. Fragments were picked up with tongs and placed in collection containers marked as to the sector in which they were recovered. The monitor frequently checked the dose rate from the material in the collection containers, and if it exceeded tolerable levels, the collector obtained a new container before proceeding with the fragment collection.

This procedure placed a lower limit of ~1/4 inch on the fragment recovery since this was the smallest fragment that could easily be seen in the field. All fragments from each sector were divided by the collector in the field into two groups according to their security classification, namely "classified" (primarily uranium-loaded graphite fuel elements and unloaded graphite center or support elements) and

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"unclassified" (pressure vessel fragments, bolts, wire, etc.), and placed in separate containers. The "classified" material was sent to the Reactor Maintenance, Assembly, and Disassembly (R-MAD) building at NRDS for sizing, while the "unclassified" material, which was not sized, was stored in the NRDS contaminated waste dump. Because of the manner of collection and the large number of fragments collected, a total of 1400 manhours over a period of 3 months was required to complete the ground pickup of the TNT fragments.

The high radiation dose rate from the TNT material necessitated sizing this material in a hot cell of the R-MAD building. Only an approximation of fragment size could be obtained since a very large number of fragments had to be sized individually in a reasonable length of time. The size of a fragment was determined by simply estimating its longest single dimension. This procedure defined the sizing parameter of a fragment and could be easily duplicated. The fragment size classes employed to determine the size distribution pattern were 1/4 to 1/2, 1/2 to 1, 1 to 2, 2 to 4, 4 to 8, 8 to 16, and 16 to 32 inches.

Two categories of fragments were sized: fuel elements (Fig. 5) and center elements (Fig. 6). Reflector graphite, excluded from the size analysis, was distinguished from fuel and center element graphite by shape factors characteristic of the core elements. Table II lists the sizes and categories of graphite fragments collected from 75 sectors. The notation F + C represents the sum of fuel elements and center elements for each sector.

As shown in Fig. 4, there were some areas from which material was collected but mistakenly discarded before being analyzed. Estimates were made of the total number of fragments from these areas. The values of these estimates and the method of estimation are listed in Table III.

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Approximately one-half of the recovered fragments were sized in the R-MAD building. The remaining fragments were shipped to Los Alamos where the sizing was completed in a hot cell of the Chemical and Metallurgical Research building by Group CMB-14 using the same sizing procedure. In addition, the fuel elements and center elements in each size class from three 50-foot downwind sectors (180 - 225 degrees, 200 to 150 feet, 150 to 100 feet, and 100 to 50 feet) were weighed to obtain an average weight per fragment as shown in Table IV. Since no fragment larger than 4 inches was present in the three downwind sectors, values of weight per fragment for the size classes 4 to 8, 8 to 16, and 16 to 32 inches were obtained by weighing a 3-inch center element (40 grams) and using the theoretical weight (pretransient) per inch for fuel elements (13. 08 grams per inch). Because of the time required to weight each size class individually, only a gross weight (fuel elements + center elements) was obtained for the remaining sectors examined by CMB-14. The total gross weight of these fragments is shown in Table V.

RESULTS

The fragment size-distribution data collected during the study were subjected to several statistical analyses. A linear-linear histogram of the numbers of fragments per size class vs. size, as typified by Figure 7, clearly showed the fragment distributions to be skewed. This skewness appeared to be typical of particle or fragment size distributions created by mechanically or explosively destroying a parent material.[2] Some distortion of the distribution may be attributed to the fact that the study included only fragments ≥ 1/4 inch in largest dimension. Also, it is conceivable that a large number of fragments in the size classes 1/4 to

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1/2 and 1/2 to 1 inch were concealed by the sandy terrain of the TNT test area, resulting in incomplete data.

Because of the apparently typical skewness of the distribution, the independent variable of fragment size was subjected to a logarithmic transformation, and a nonlinear least squares computer program was used to obtain a fit of the data to a log normal distribution.[3] Using this technique, the mean value of the distribution and the standard deviation were computed for these distributions, i.e. fuel elements, center elements, and total of fuel plus center elements. These values and the deviation values of the fitted curves from collected data are listed in Table VI.

A second analysis consisted of constructing logarithmic probability plots of fragment size vs. percentage of fragments less than stated size for the distributions, and selecting the median size as that occurring at the fiftieth percentile and the standard deviation as the ratio of sizes at the 84th percentile to the 50th percentile, or 50th percentile to 16th percentile. This method is frequently employed to describe particle size distributions.[2] These plots are shown in Figures 8 to 10. Owing to the small number of fragments in the size intervals 8 to 16 and 16 to 32 inches, these points were not included in the graphs. The values of the parameters thus obtained are given in Table VII.

A third analysis consisted of merely calculating the mean size and standard deviation of each distribution according to the standard statistical definitions of these parameters, the mean being merely the arithmetic average size, and the standard deviation the square root of the sum of the squares of the individual deviations. In this case, rules for grouped data were used; the size of each interval was taken as the

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midpoint of the interval. The values of the parameters obtained in this fashion are also given in Table VII.

Plots of the number of fragments versus azimuth were made for each of the annular sections. Typical examples of these plots are shown in Figs. 11 and 12. All plots indicated that the fragment size distribution had a maximum concentration at an azimuth of ~200 degrees. This was a direct result of a strong, 15- to 20-knot, northeast wind at the time of the TNT experiment.

A second maximum of fragments at ~70 degrees is shown in Fig. 11. A possible explanation for this is the manner in which the pressure vessel fractured. Two areas of great fragmentation corresponding to ~70 and 225 degrees are indicated by A and B, respectively, in Fig. 13. The section of the vessel indicated by C in Fig. 13 was recovered but was not available when the fragments were photographed. This piece did not show gross fragmentation. Blowout of fragments from areas A and B contributed to high fragment concentrations in the ~70- and 225-degree directions. Blowout effects at 225 degrees were obscured by the increased concentration of fragments caused by the prevailing wind.

DISCUSSION OF THE RESULTS

It can be concluded from the analysis of the 29,364 fragments collected that the count fragment size distribution is a reasonable approximation to a logarithmic normal distribution. Sufficient information was obtained to determine the geographical distribution pattern for fragments ranging from 1/4 to 32 inches in any one dimension.

The plots of fragment size versus azimuth and the fragment concentration plot (Fig. 14) indicate that the wind was the predominant influence upon the distribution of both small and large fragments. The

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high concentration of fragments at ~200 degrees was a direct result of the strong northeast wind.

The total weight of recovered core material, using the weight per fragment values listed in Table IV, was 232 kilograms (119 kilograms of fuel elements and 113 kilograms of center elements). The total weight of fuel elements and center elements from the unanalyzed sectors, based on an average theoretical weight of 13.2 grams per inch and the estimates in Table III, is 13 kilograms. The reactor core contained a total of 1054 kilograms of fuel elements and 178 kilograms of center elements. Hence, of the total 1232 kilograms, only 19 percent were collected.

From examination of the photograph of the reactor base support plate after the excursion (Fig. 15), it was estimated that the average length of the fuel elements and center elements remaining on the support plate was 4 inches. Assuming an average theoretical weight of 13.2 grams per inch and considering that the reactor core contained 1542 fuel elements and 236 center elements, the weight of the material on the support plate was approximately 100 kilograms. As previously mentioned, 232 kilograms of material was collected and analyzed, and an additional estimate of 13 kilograms was made for the material not analyzed. Hence, one can account for a total of ~345 kilograms of reactor fuel elements and center elements. A summary of the accountability of the reactor core as fuel and center element material is given in Table VIII.

It is difficult to give a definite account of the remaining 887 kilograms of reactor fuel elements and center elements not recovered. It is certain that an unknown percentage of the reactor core burned from the thermal energy generated in the excursion (~10^{10} joules). A con-

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siderable amount of core material was deposited in the vicinity of the TNT area as particulates <1/4 inch.[4] Also, some material in the fragment size ranges studied was not recovered from the field.

Using the average weight per fragment values in Table IV, the total weight of the 14,990 fragments sized by Group CMB-14 was 54.3 kilograms. Compared to the actual gross weight of 59.2 kilograms for these fragments, the error in the weight values of Table IV is only 8.3 percent. This is also the error in the 232-kilogram weight value obtained for the total 29,364 fragments sized.

The reactor core contained 236 center elements weighing a total of 178 kilograms. Using the previously mentioned length and weight values, ~12 kilograms of center elements remained on the reactor base support plate after the excursion. A total of 113 kilograms of center elements were collected and sized. Because of poor statistics and the methods of estimation, no individual estimates of the number of center elements and fuel elements were made for the unanalyzed sectors. However, if we assume that half of the total number of particles estimated for the unanalyzed sectors were center elements, then ~6 kilograms of center elements were present in these sectors. Hence, ~131 kilograms or 74 percent of the center elements were shattered into fragments ≥1/4 inch in any one dimension. A similar calculation for fuel elements yields 119 kilograms collected and sized, ~7 kilograms collected but not analyzed, and 88 kilograms assumed remaining on the support plate. Therefore, ~214 kilograms of the 1054 kilograms originally present, or 20 percent of the fuel elements, were accounted for as fragments ≥1/4 inch in any one dimension. One might expect this, considering that the center elements were not uranium loaded, thus requiring any gain in thermal energy to be an external

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conductive process. The uranium loaded fuel elements were heated internally to very high temperatures by the fission process, vaporizing some of the fuel element material.

One must also consider the structures of center and fuel elements to explain the degree of breakup. A center element (Fig. 16) is hexagonal in cross section (1.91 centimeters across flats) and consists primarily of graphite. A hole 0.930-centimeter in diameter in the center of the center element extends the full 52-inch length of the element. A graphite sleeve (inside diameter = 0.632 centimeter, outside diameter = 0.907 centimeter) is used as a liner for the 0.930-centimeter hole. A stainless steel rod 0.254-centimeter in diameter extends the full length of the center element, adding to the structural strength. A fuel element (Fig. 17) has the same hexagonal cross section and also consists primarily of graphite. However, 19 coolant channels, each 0.254-centimeter in diameter, extend the full 52-inch length of the element.

From the above description it is reasonable to conclude that more center elements than fuel elements will exist as large fragments after an excursion.

One might ask if it would be reasonable, considering that the field collection alone required 1400 manhours, to determine the count fragment size distribution by extrapolation from a much smaller area. To answer this, sectors in the downwind (180- to 225-degree) and upwind (0- to 45-degree) regions out to 1,000 feet were considered in an extrapolation experiment. These sectors were used since the count fragment size distribution was obviously biased by the wind vector. Table IX lists the number of fragments in the downwind and upwind sectors.

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The total number of fragments in the high concentration region between 135 and 270 degrees was obtained by multiplying the total number of fragments in each size class in the 180-225 degree area by a factor of 3 (to represent three 45-degree areas: 135-180 degrees, 180-225 degrees, and 225-270 degrees). Similarly, the total number of fragments in the low concentration region, 270-135 degrees, was obtained by multiplying the total number of fragments in each size class in the 0-45 degree area by a factor of 5 (to represent five 45-degree areas: 270-315 degrees, 315-360 degrees, 0-45 degrees, 45-90 degrees, and 90-135 degrees). The extrapolation results are shown in Table X.

The large percentage-difference values for the size classes 8-16 and 16-32 inches are tolerable considering that these classes accounted for only 0. 06 percent of the total number of TNT fragments sized. Hence, for the TNT experiment, the above extrapolation would produce data with maximum and minimum errors of 28 and 11 percent, respectively.

REFERENCES

1. Bryant, E. A., et al., "Radiochemical Measurements on Kiwi-TNT," Los Alamos Scientific Laboratory Report LA-3290, May 1965 (Confidential).
2. Drinker, P., and T. Hatch, "Industrial Dust," Second Edition, McGraw Hill Book Company, Inc., 1954.
3. Moore, R. H. and R. K. Zeigler, "The Solution of the General Least Squares Problem with Special Reference to High-Speed Computers," Los Alamos Scientific Laboratory Report LA-2367, October 1959.
4. Campbell, E. E., et al., "Kiwi TNT Particle Study," Los Alamos Scientific Laboratory Report LA-3337-MS, June 1966.

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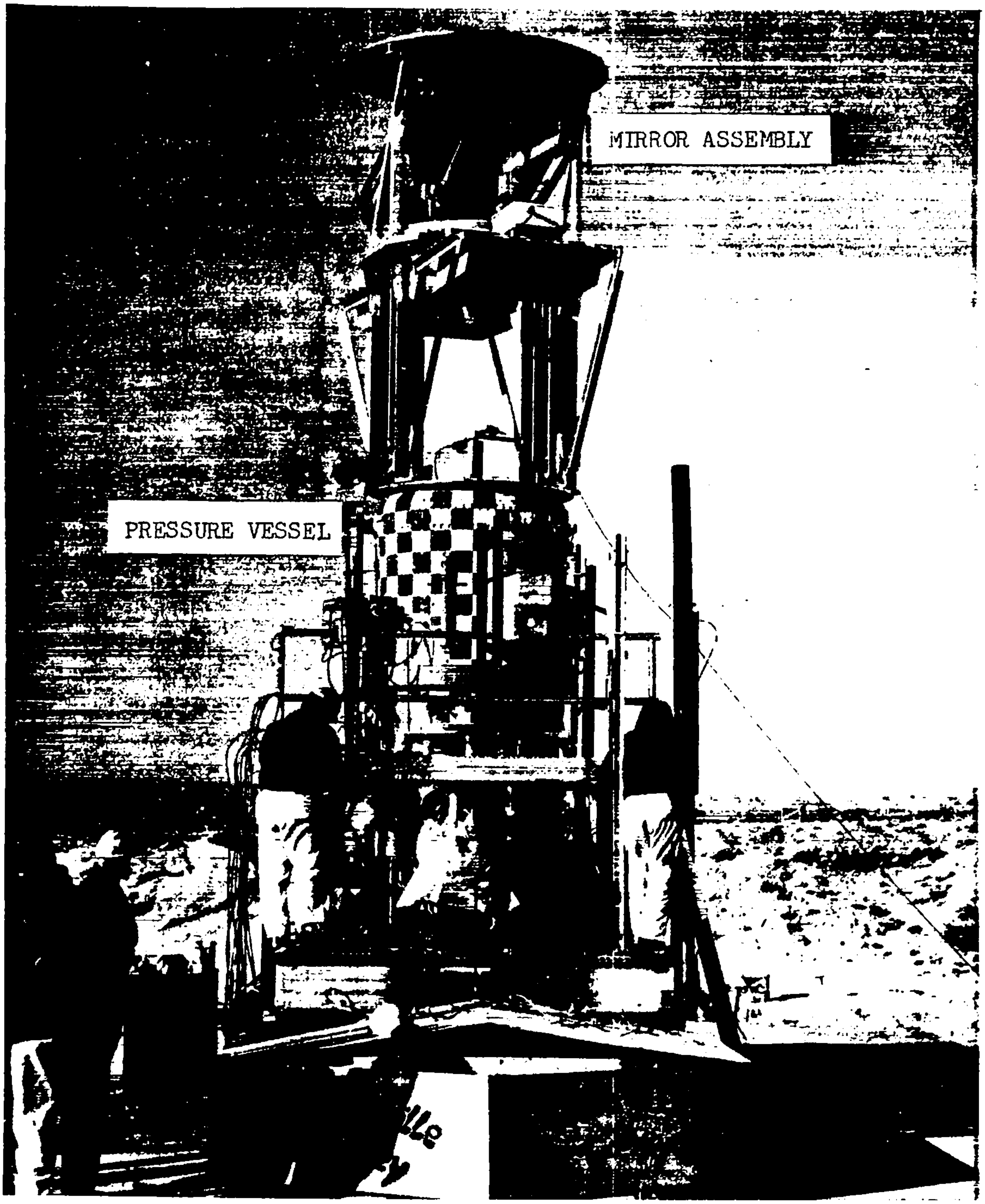

Fig. 1. Kiwi TNT reactor on the test pad prior to excursion.

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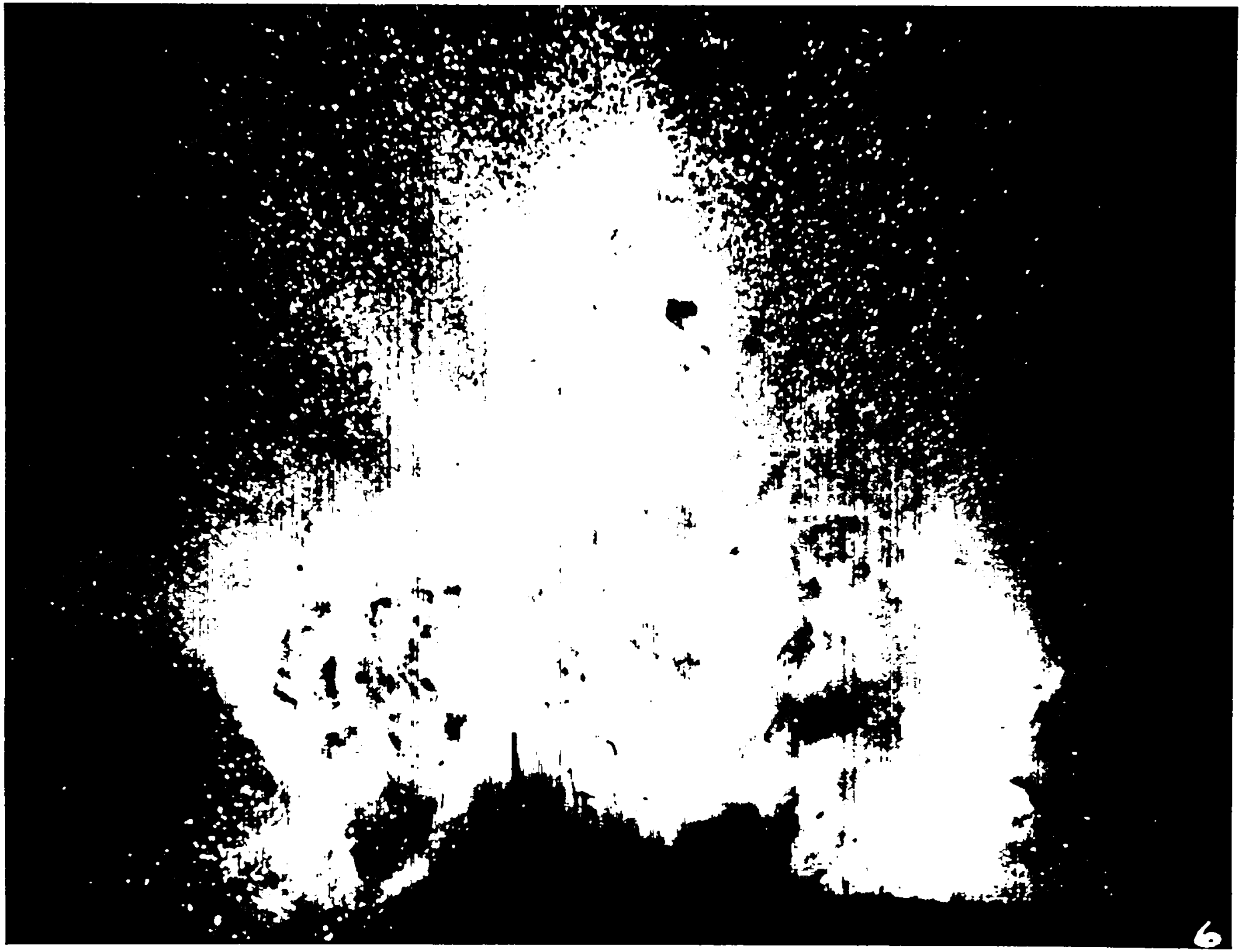

Fig. 2. High-speed photograph of the TNT reactor 1.2 seconds after the excursion was initiated.

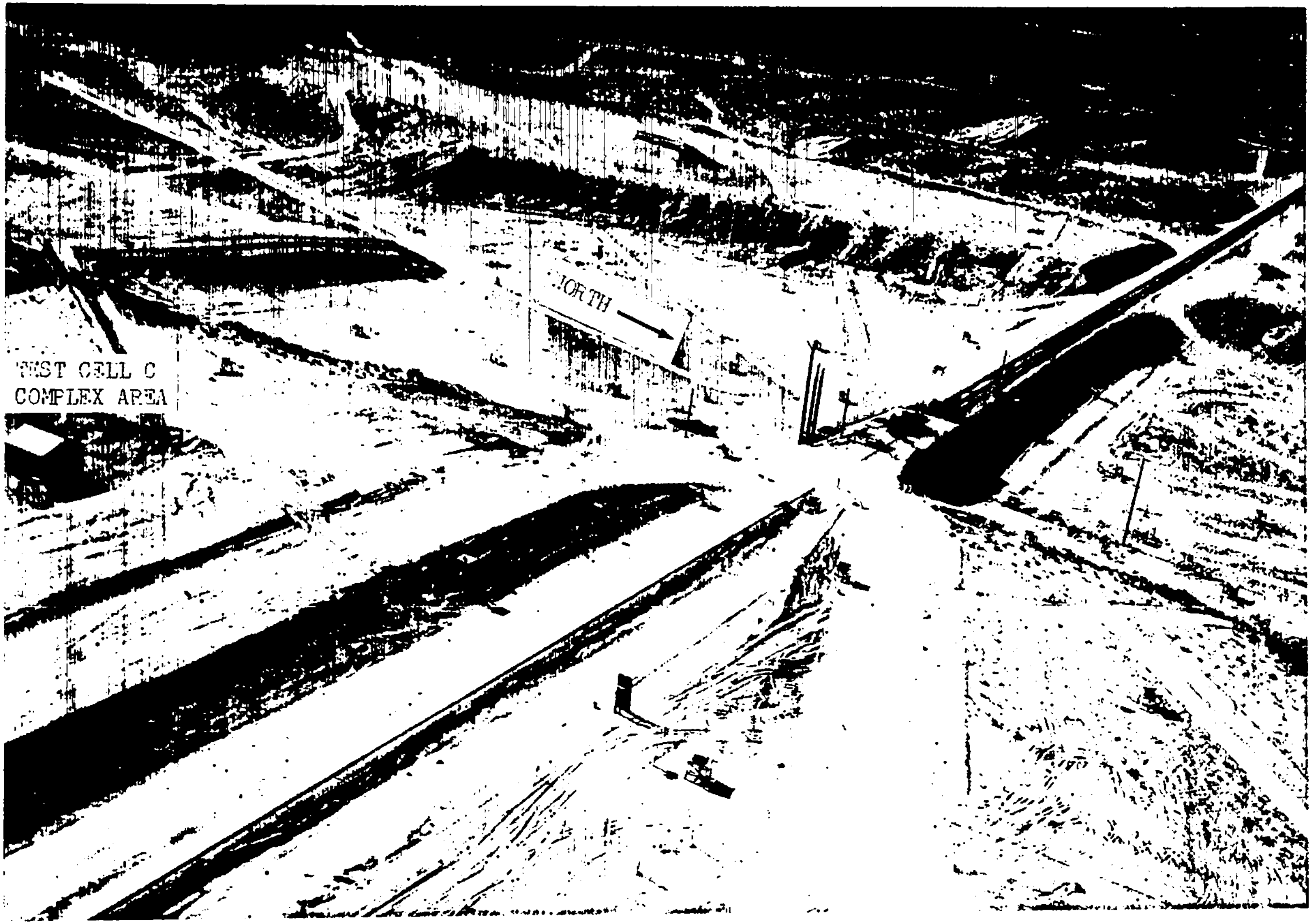

Fig. 3. TNT area.

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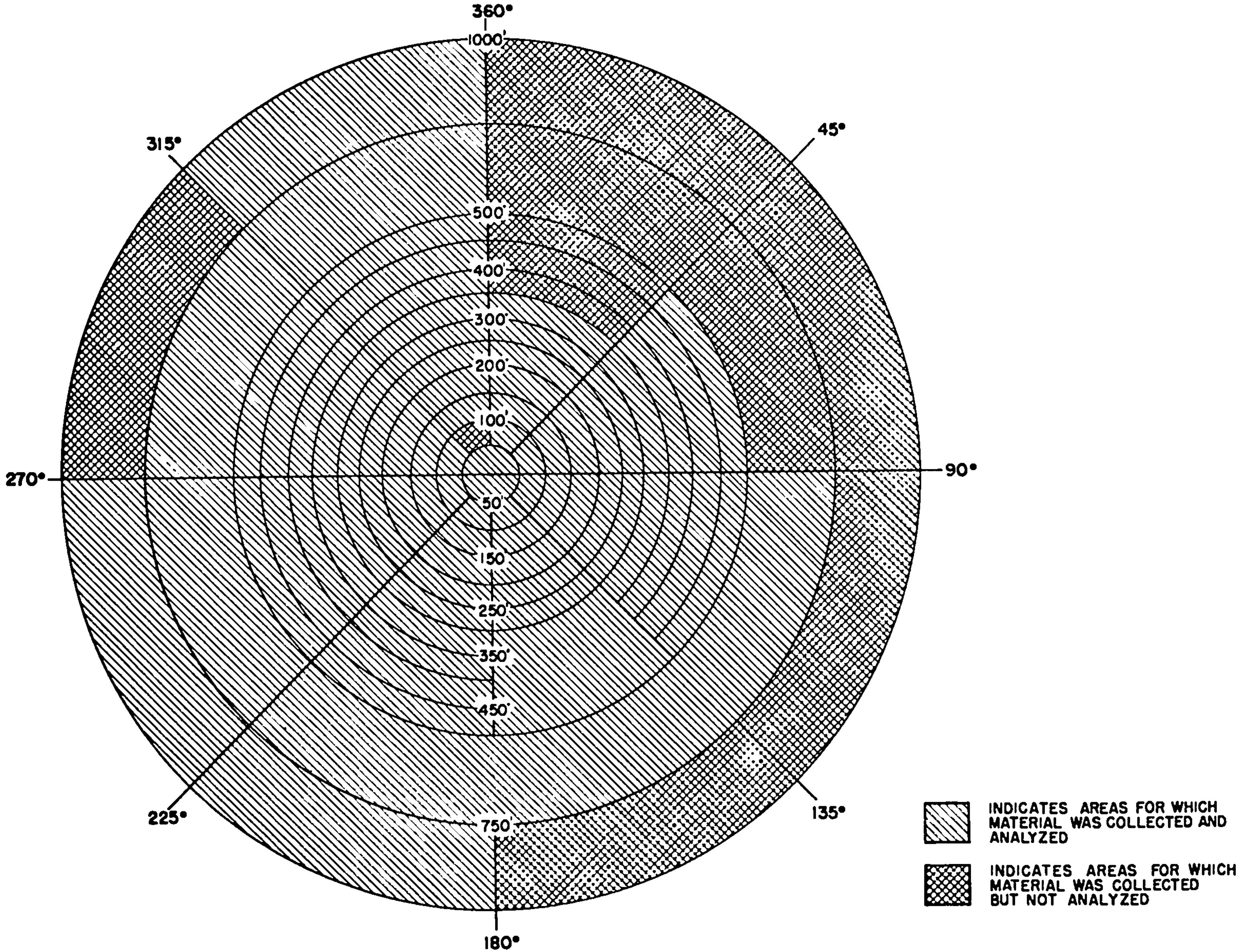

Fig. 4. Division of the TNT area from test pad to 1,000 feet.

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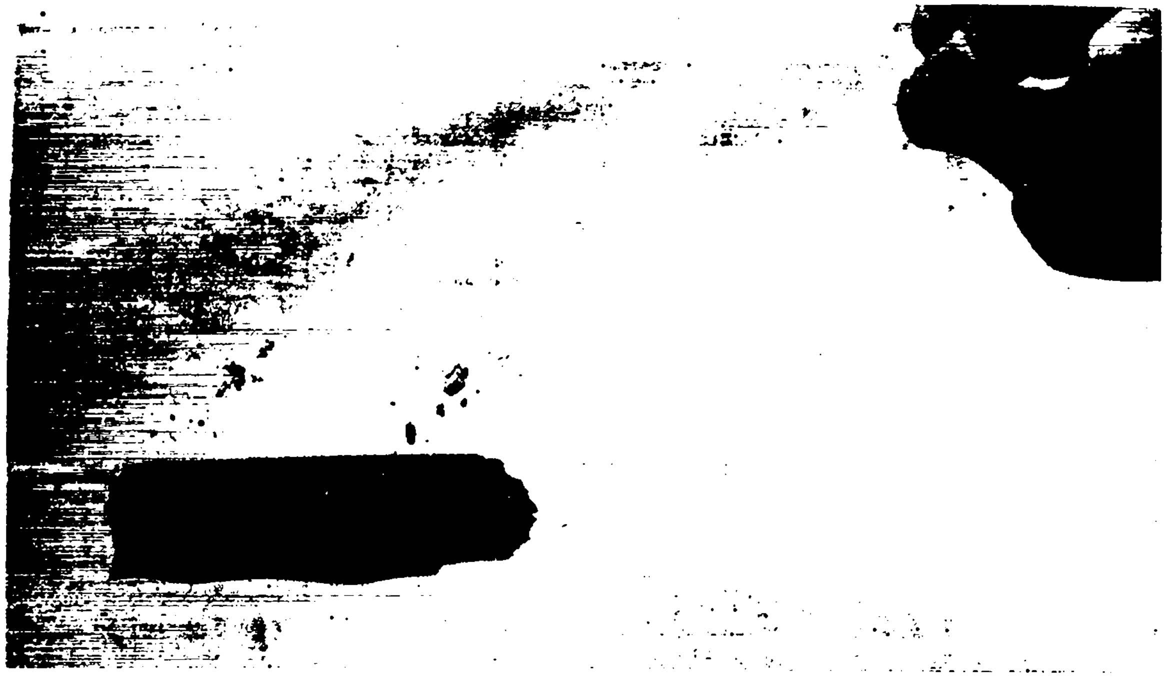

Fig. 5. Kiwi TNT fuel element fragment.

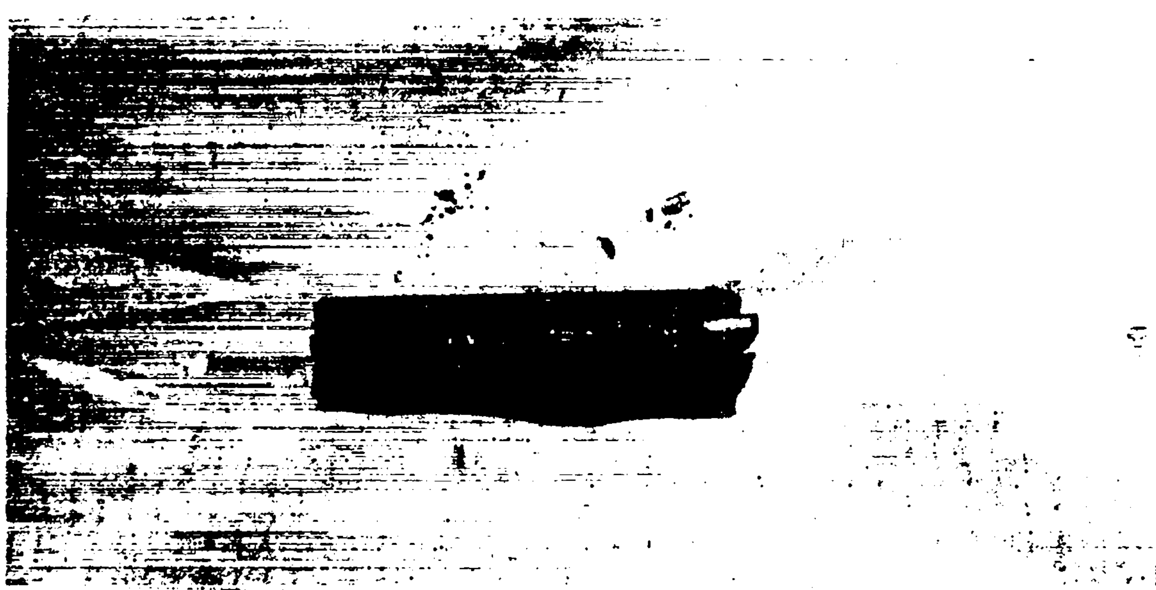

Fig. 6. Kiwi TNT center element fragment.

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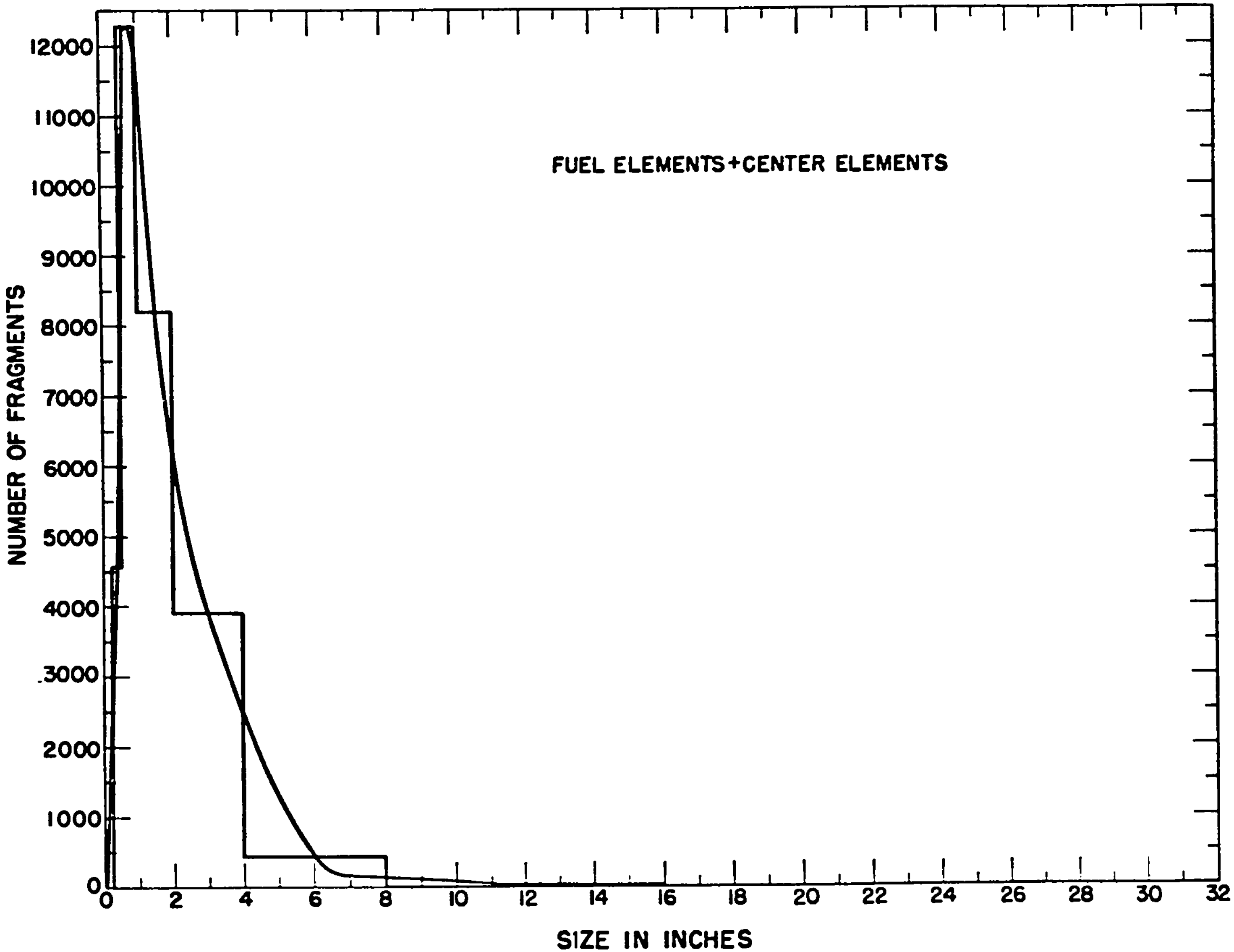

Fig. 7. Linear-linear histogram plot for fuel elements + center elements. The smooth curve is drawn through the midpoints of the size classes.

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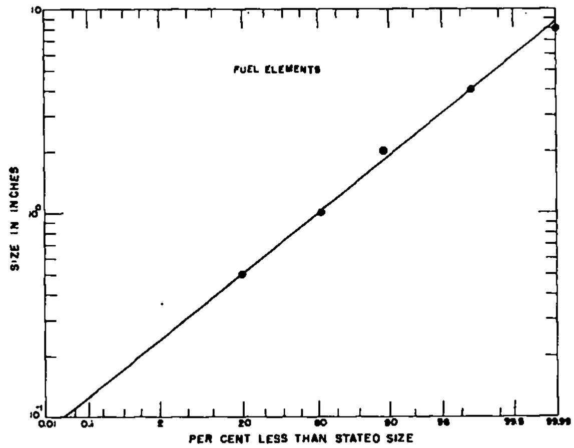

Fig. 8. Logarithmic-probability plot for fuel elements.

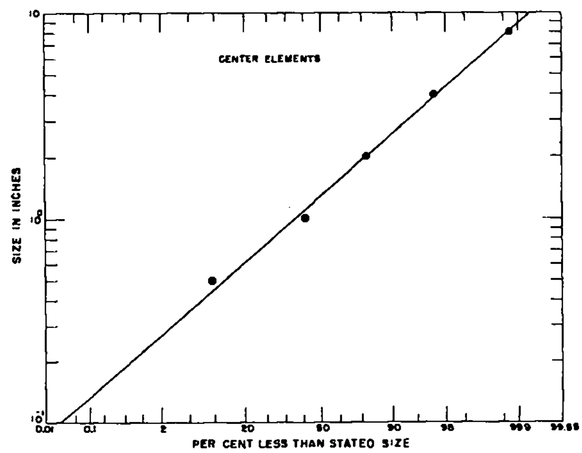

Fig. 9. Logarithmic-probability plot for center elements.

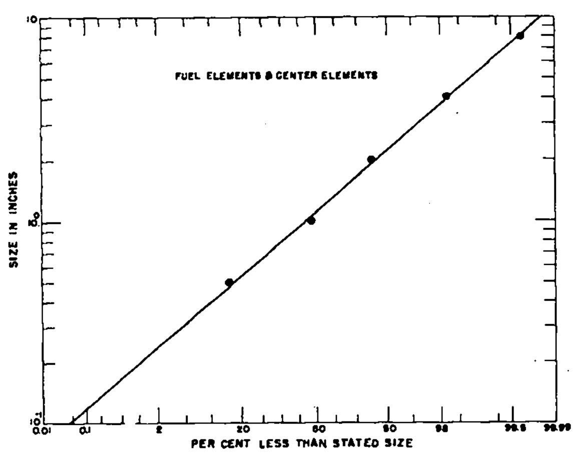

Fig. 10. Logarithmic-probability plot for fuel elements + center elements.

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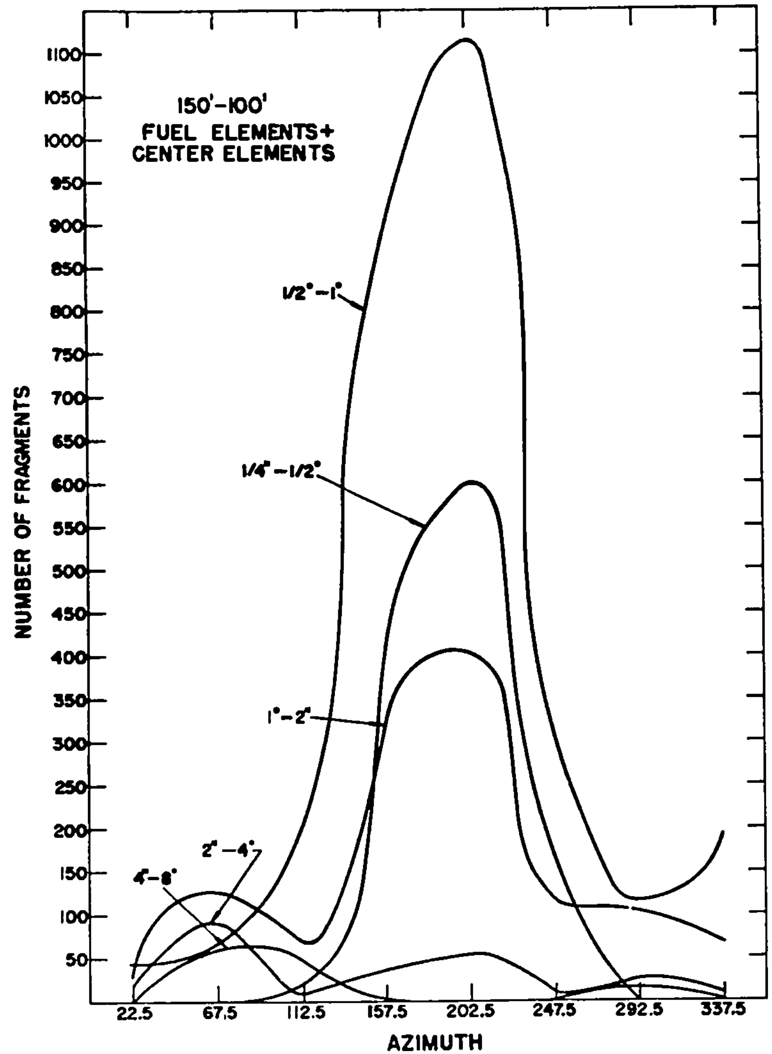

Fig. 11. Fragment size distribution by count for the annular section 150-100 ft.

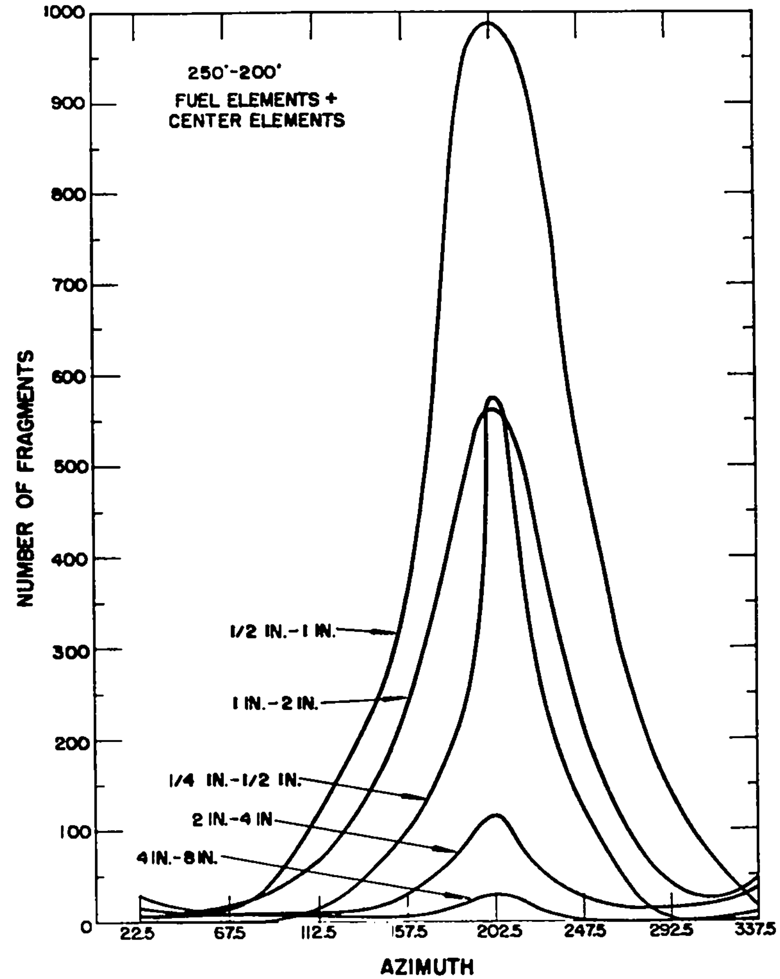

Fig. 12. Fragment size distribution by count for the annular section 250-200 ft.

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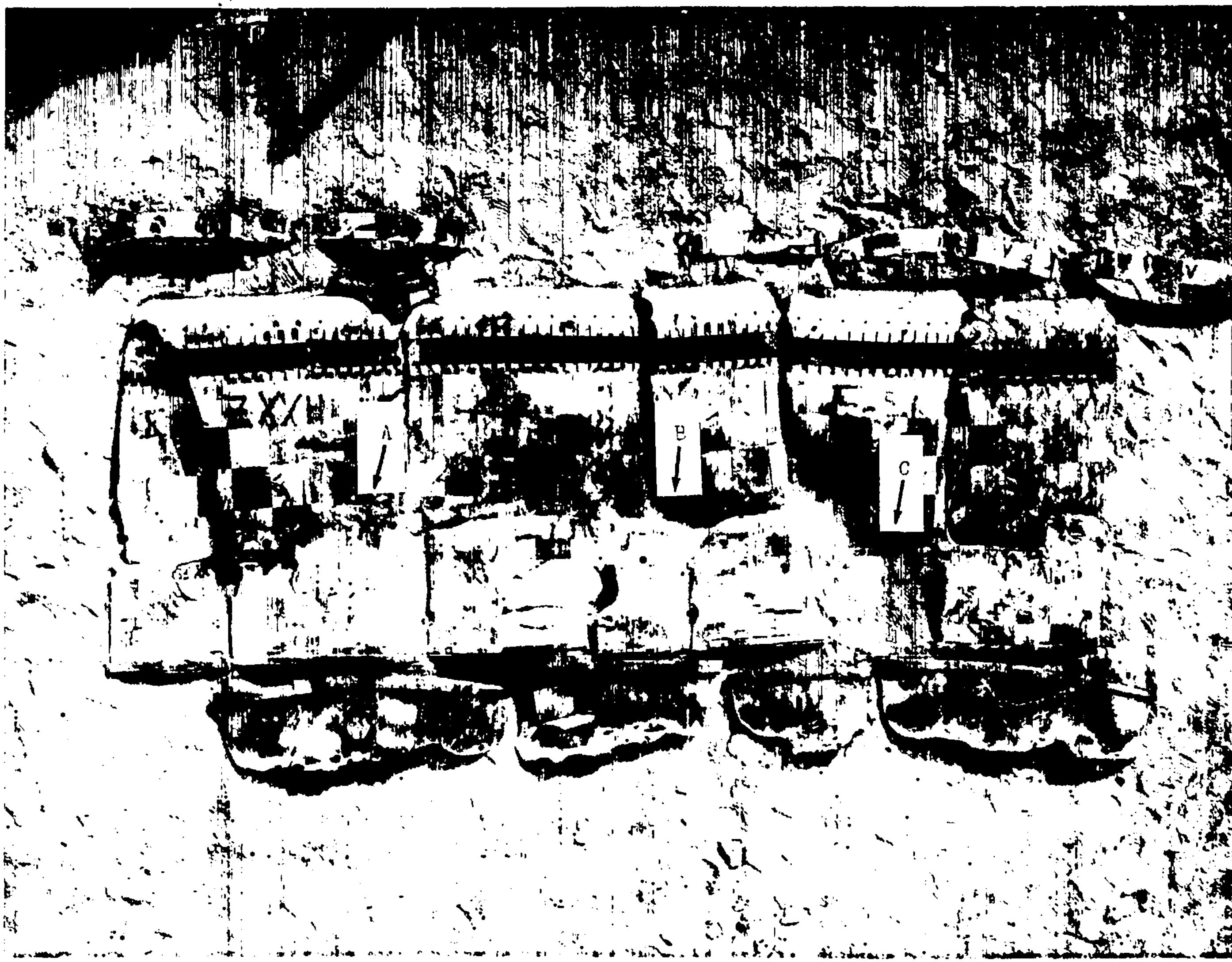

Fig. 13. Recovered sections of the TNT pressure vessel.

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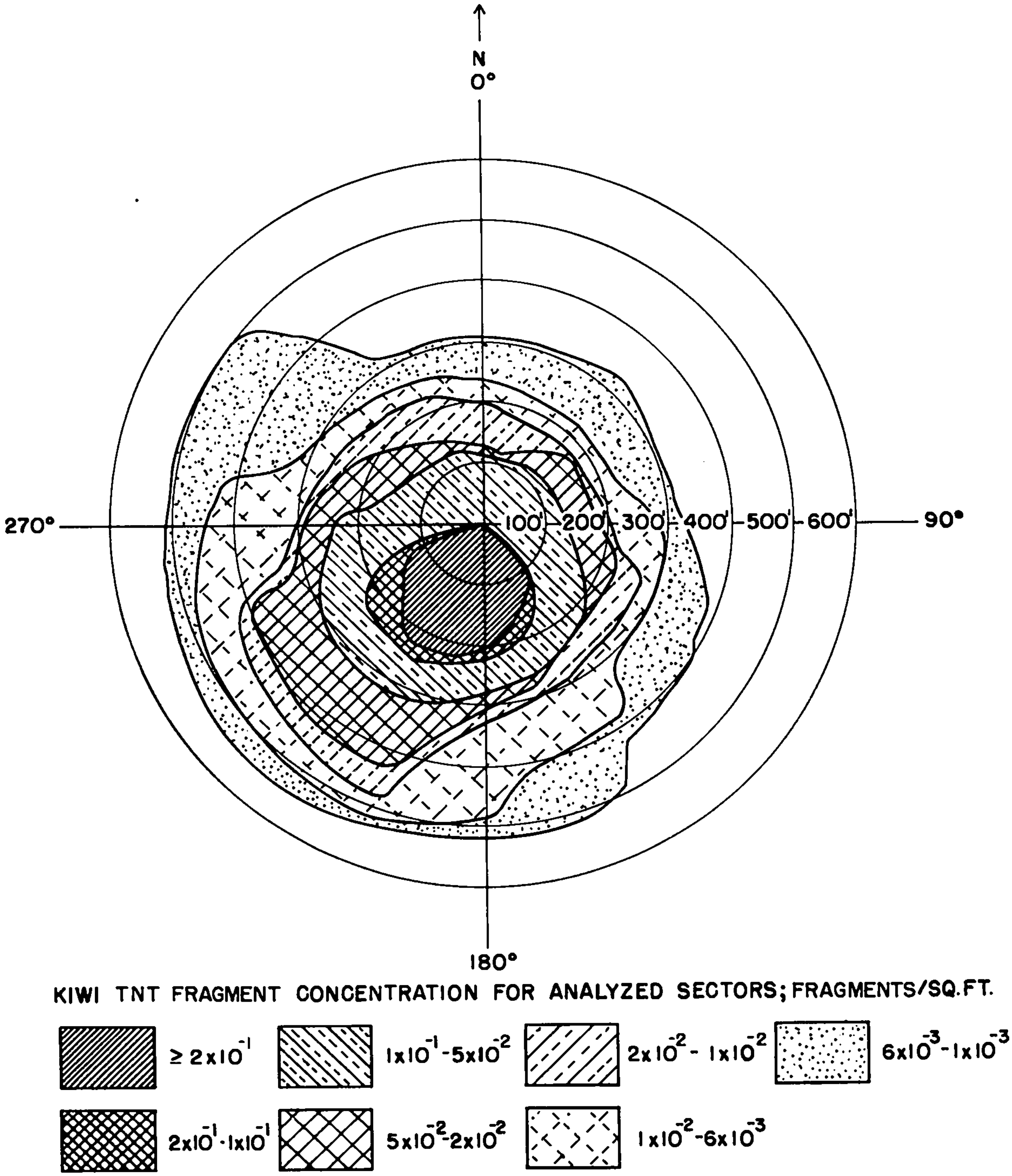

Fig. 14. Kiwi TNT fragment concentration for analyzed sectors, fragments per square feet.

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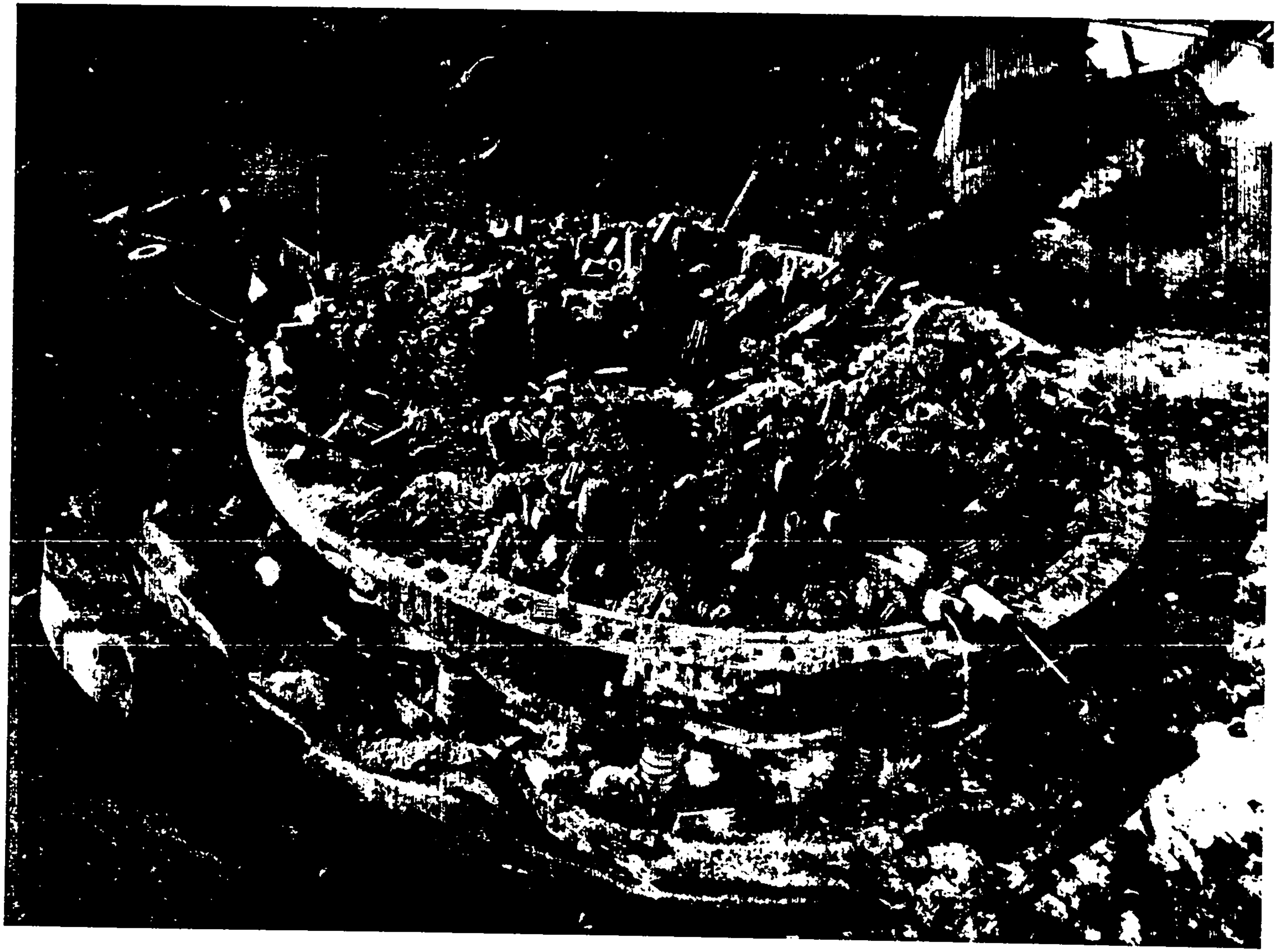

Fig. 15. Reactor base support plate on the test pad.

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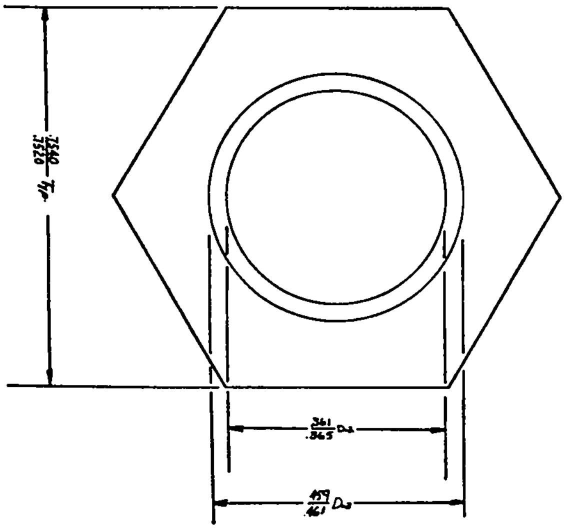

Fig. 16. Cross section of a center element.

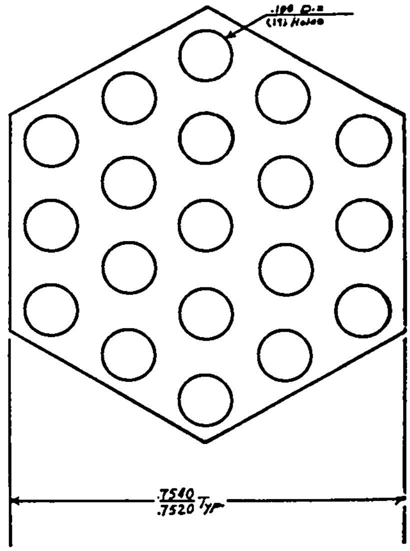

Fig. 17. Cross section of a fuel element.

TABLE I. AREAS OF 45-DEGREE ANNULAR SECTORS

Sector (ft)	Area (ft^2)
1000 - 750	171,938
750 - 500	122,813
500 - 450	18,668
450 - 400	16,703
400 - 350	14,738
350 - 300	12,773
300 - 250	10,808
250 - 200	8,843
200 - 150	6,878
150 - 100	4,913
100 - 50	2,948
50 - 0	982

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TABLE 11. CATEGORY AND NUMBER OF FRAGMENTS IN EACH SIZE CLASS FOR ANALYZED SECTORS

SECTOR	CATEGORY	1/4IN-1/2IN	1/2IN-1IN	1IN-2IN	2IN-4IN	4IN-8IN	8IN-16IN	16IN-32IN
1000FT-750FT	FUEL	15	8	2	8	0	0	0
1800G-2250G	CENTER	5	4	18	32	8	0	0
	F+C	20	12	20	40	8	0	0
1000FT-750FT	FUEL	0	0	1	0	0	0	0
2250G-2700G	CENTER	0	4	8	35	13	0	0
	F+C	0	4	9	35	13	0	0
1000FT-750FT	FUEL	0	0	0	0	0	0	0
3150G-3600G	CENTER	0	14	10	7	2	1	0
	F+C	0	14	10	7	2	1	0
750FT-500FT	FUEL	43	41	144	74	0	0	0
900G-2250G	CENTER	7	87	74	94	8	0	0
	F+C	50	128	218	168	8	0	0
750FT-500FT	FUEL	1	6	18	29	0	0	0
2250G-2700G	CENTER	3	1	26	85	7	0	0
	F+C	4	7	44	114	7	0	0
750FT-500FT	FUEL	0	0	0	3	0	0	0
2700G-3150G	CENTER	0	7	9	33	7	0	0
	F+C	0	7	9	36	7	0	0
750FT-500FT	FUEL	0	0	0	0	0	0	0
3150G-3600G	CENTER	0	4	9	25	10	0	0
	F+C	0	4	9	25	10	0	0
500FT-450FT	FUEL	0	0	0	0	0	0	0
450G- 900G	CENTER	2	2	0	5	1	0	0
	F+C	2	2	0	5	1	0	0
500FT-450FT	FUEL	0	0	0	0	0	0	0
900G-1350G	CENTER	1	0	3	0	1	0	0
	F+C	1	0	3	0	1	0	0
500FT-300FT	FUEL	161	49	46	50	0	0	0
1350G-1800G	CENTER	58	17	74	60	2	0	0
	F+C	219	66	120	110	2	0	0
500FT-450FT	FUEL	0	63	73	48	0	0	0
1800G-2250G	CENTER	0	19	32	26	6	0	0
	F+C	0	82	105	74	6	0	0
500FT-450FT	FUEL	14	4	15	40	0	0	0
2250G-2700G	CENTER	0	16	11	19	7	1	0
	F+C	14	20	26	59	7	1	0
500FT-450FT	FUEL	0	2	0	0	0	0	0
2700G-3150G	CENTER	0	5	0	26	6	0	0
	F+C	0	7	0	26	6	0	0
500FT-450FT	FUEL	0	0	0	0	0	0	0
3150G-3600G	CENTER	7	0	4	2	3	0	0
	F+C	7	0	4	2	3	0	0
450FT-400FT	FUEL	0	0	0	0	0	0	0
450G- 900G	CENTER	6	1	0	3	1	0	0
	F+C	6	1	0	3	1	0	0
450FT-400FT	FUEL	0	0	0	0	0	0	0
900G-1350G	CENTER	1	1	3	1	0	0	0
	F+C	1	1	3	1	0	0	0
450FT-400FT	FUEL	0	135	70	53	0	0	0
1800G-2250G	CENTER	0	30	29	24	4	0	0
	F+C	0	165	99	77	4	0	0
450FT-400FT	FUEL	0	11	41	55	0	0	0
2250G-2700G	CENTER	0	11	29	50	10	0	0
	F+C	0	22	70	105	10	0	0
450FT-400FT	FUEL	0	3	0	2	0	0	0
2700G-3150G	CENTER	16	0	11	35	9	0	0
	F+C	16	3	11	37	9	0	0
450FT-400FT	FUEL	0	0	0	0	0	0	0
3150G-3600G	CENTER	3	0	4	9	0	0	0
	F+C	3	0	4	9	0	0	0
400FT-350FT	FUEL	0	0	0	0	0	0	1
450G- 900G	CENTER	2	0	0	1	0	0	0
	F+C	2	0	0	1	0	0	1
400FT-350FT	FUEL	0	0	0	0	0	0	1
900G-1350G	CENTER	16	2	4	2	1	0	0
	F+C	16	2	4	2	1	0	1
400FT-350FT	FUEL	0	116	201	160	9	0	0
1800G-2250G	CENTER	0	95	50	115	18	0	0
	F+C	0	211	251	275	27	0	0
400FT-350FT	FUEL	85	70	30	70	0	0	0
2250G-2700G	CENTER	27	37	14	54	6	0	0
	F+C	112	107	44	124	6	0	0
400FT-350FT	FUEL	0	0	4	6	0	0	0
2700G-3150G	CENTER	4	12	14	19	4	0	0
	F+C	4	12	18	25	4	0	0

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TABLE 11. (CONTINUED)

SECTOR	CATEGORY	1/4IN-1/2IN	1/2IN-1IN	1IN-2IN	2IN-4IN	4IN-8IN	8IN-16IN	16IN-32IN
400FT-350FT 3150G-3600G	FUEL	0	0	0	0	0	0	0
	CENTER	6	0	2	2	2	0	0
	F+C	6	0	2	2	2	0	0
350FT-300FT 00G-450G	FUEL	0	0	0	0	0	0	0
	CENTER	0	0	0	10	18	6	0
	F+C	0	0	0	10	18	6	0
350FT-300FT 450G-900G	FUEL	0	0	0	0	0	0	0
	CENTER	0	1	9	0	0	0	0
	F+C	0	1	9	0	0	0	0
350FT-300FT 900G-1350G	FUEL	0	4	3	2	0	0	0
	CENTER	1	7	3	15	4	0	0
	F+C	1	11	6	17	4	0	0
350FT-300FT 1800G-2250G	FUEL	0	120	173	176	2	0	0
	CENTER	0	0	0	0	0	0	0
	F+C	0	120	173	176	2	0	0
350FT-300FT 2250G-2700G	FUEL	0	0	72	101	0	0	0
	CENTER	0	42	50	98	14	0	0
	F+C	0	42	122	199	14	0	0
350FT-300FT 2700G-3150G	FUEL	5	4	0	5	0	0	0
	CENTER	3	9	25	9	8	0	0
	F+C	8	13	25	14	8	0	0
350FT-300FT 3150G-3600G	FUEL	0	0	0	0	0	0	0
	CENTER	0	0	6	5	0	0	0
	F+C	0	0	6	5	0	0	0
300FT-250FT 00G-450G	FUEL	0	0	0	1	0	0	0
	CENTER	14	0	10	32	0	0	0
	F+C	14	0	10	33	0	0	0
300FT-250FT 450G-900G	FUEL	0	0	0	4	0	0	0
	CENTER	6	0	6	6	1	0	0
	F+C	6	0	6	10	1	0	0
300FT-250FT 900G-1350G	FUEL	3	8	3	11	0	0	0
	CENTER	23	7	42	24	3	0	0
	F+C	26	15	45	35	3	0	0
300FT-250FT 1350G-1800G	FUEL	7	46	26	5	0	0	0
	CENTER	3	21	21	4	1	0	0
	F+C	10	67	47	9	1	0	0
300FT-250FT 1800G-2250G	FUEL	7	360	154	51	3	0	0
	CENTER	0	213	106	51	1	0	0
	F+C	7	573	260	102	4	0	0
300FT-250FT 2250G-2700G	FUEL	0	78	133	165	2	0	0
	CENTER	0	24	92	110	4	0	0
	F+C	0	102	225	275	6	0	0
300FT-250FT 2700G-3150G	FUEL	0	4	6	6	0	0	0
	CENTER	0	12	31	32	5	0	0
	F+C	0	16	37	38	5	0	0
300FT-250FT 3150G-3600G	FUEL	2	1	0	0	0	0	0
	CENTER	9	4	0	8	0	0	0
	F+C	11	5	0	8	0	0	0
250FT-200FT 00G-450G	FUEL	0	0	0	0	0	0	0
	CENTER	0	30	13	7	5	0	0
	F+C	0	37	13	7	5	0	0
250FT-200FT 450G-900G	FUEL	0	2	4	1	0	0	0
	CENTER	0	10	10	16	7	0	0
	F+C	0	12	14	17	7	0	0
250FT-200FT 900G-1350G	FUEL	11	49	23	3	0	0	0
	CENTER	5	70	46	8	0	0	0
	F+C	16	119	69	11	0	0	0
250FT-200FT 1350G-1800G	FUEL	82	217	138	6	0	0	0
	CENTER	20	140	93	24	3	0	0
	F+C	102	357	231	30	3	0	0
250FT-200FT 1800G-2250G	FUEL	349	630	341	67	0	0	0
	CENTER	227	357	221	49	6	0	0
	F+C	576	987	562	116	6	0	0
250FT-200FT 2250G-2700G	FUEL	97	281	115	8	0	0	0
	CENTER	28	217	90	15	1	0	0
	F+C	125	498	205	23	1	0	0
250FT-200FT 2700G-3150G	FUEL	0	25	14	0	0	0	0
	CENTER	0	114	22	13	0	0	0
	F+C	0	139	36	13	0	0	0
250FT-200FT 3150G-3600G	FUEL	0	3	0	5	0	0	0
	CENTER	0	13	46	30	9	0	0
	F+C	0	16	46	35	9	0	0
200FT-150FT 00G-450G	FUEL	0	24	43	35	6	0	0
	CENTER	0	36	77	76	10	2	0
	F+C	0	65	120	111	16	2	0

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TABLE 11. (CONTINUED)

SECTOR	CATEGORY	1/4IN-1/2IN	1/2IN-1IN	1IN-2IN	2IN-4IN	4IN-8IN	8IN-16IN	16IN-32IN
200FT-150FT	FUEL	0	13	6	5	0	0	0
450G- 900G	CENTER	0	12	20	15	4	3	0
	F+C	0	25	26	20	4	3	0
200FT-150FT	FUEL	0	80	31	15	0	0	0
900G-1350G	CENTER	0	70	71	16	5	1	0
	F+C	0	150	102	31	5	1	0
200FT-150FT	FUEL	293	368	137	13	0	0	0
1350G-1800G	CENTER	50	214	82	14	3	0	0
	F+C	343	582	219	27	3	0	0
200FT-150FT	FUEL	269	572	277	42	8	0	0
1800G-2250G	CENTER	51	313	493	72	11	0	0
	F+C	320	885	770	114	19	0	0
200FT-150FT	FUEL	205	247	81	3	0	0	0
2250G-2700G	CENTER	62	149	62	0	0	0	0
	F+C	267	396	143	3	0	0	0
200FT-150FT	FUEL	0	20	36	51	0	0	0
2700G-3150G	CENTER	0	28	47	40	3	0	0
	F+C	0	48	83	91	3	0	0
200FT-150FT	FUEL	0	35	60	3	0	0	0
3150G-3600G	CENTER	0	50	53	63	5	2	0
	F+C	0	85	113	66	5	2	0
150FT-100FT	FUEL	0	30	16	13	0	0	0
00G- 450G	CENTER	0	13	13	5	1	0	0
	F+C	0	43	29	18	1	0	0
150FT-100FT	FUEL	0	36	44	55	20	0	0
450G- 900G	CENTER	0	32	83	37	40	0	0
	F+C	0	68	127	92	60	0	0
150FT-100FT	FUEL	14	106	36	7	0	0	0
900G-1350G	CENTER	7	101	33	3	0	0	0
	F+C	21	207	69	10	0	0	0
150FT-100FT	FUEL	331	591	207	16	0	0	0
1350G-1800G	CENTER	74	292	117	21	3	0	0
	F+C	405	883	324	37	3	0	0
150FT-100FT	FUEL	512	788	271	39	0	0	0
1800G-2250G	CENTER	95	328	133	17	0	0	0
	F+C	607	1116	404	56	0	0	0
150FT-100FT	FUEL	140	198	70	6	0	0	0
2250G-2700G	CENTER	30	108	45	3	0	0	0
	F+C	170	306	115	9	0	0	0
150FT-100FT	FUEL	0	55	37	15	11	0	0
2700G-3150G	CENTER	0	71	66	9	5	0	0
	F+C	0	126	103	24	16	0	0
150FT-100FT	FUEL	0	95	39	1	0	0	0
3150G-3600G	CENTER	0	98	28	7	3	1	0
	F+C	0	193	67	8	3	1	0
100FT- 50FT	FUEL	29	41	6	0	0	0	0
00G- 450G	CENTER	6	34	5	0	0	0	0
	F+C	35	75	11	0	0	0	0
100FT- 50FT	FUEL	0	162	243	0	0	0	0
450G- 900G	CENTER	0	166	45	38	9	0	0
	F+C	0	328	288	38	9	0	0
100FT- 50FT	FUEL	9	20	6	1	0	0	0
900G-1350G	CENTER	7	14	4	1	0	0	0
	F+C	16	34	10	2	0	0	0
100FT- 50FT	FUEL	3	13	14	0	0	0	0
1350G-1800G	CENTER	2	7	10	0	0	0	0
	F+C	5	20	24	0	0	0	0
100FT- 50FT	FUEL	258	422	207	28	0	0	0
1800G-2250G	CENTER	70	235	115	21	0	0	0
	F+C	328	657	322	49	0	0	0
100FT- 50FT	FUEL	18	20	4	0	0	0	0
2250G-2700G	CENTER	5	13	1	0	0	0	0
	F+C	23	33	5	0	0	0	0
100FT- 50FT	FUEL	10	9	0	0	0	0	0
2700G-3150G	CENTER	1	8	3	0	0	0	0
	F+C	11	17	3	0	0	0	0
50FT- 0FT	FUEL	315	611	235	37	0	0	0
900G-2700G	CENTER	76	302	154	18	0	0	0
	F+C	391	913	389	55	0	0	0
50FT- 0FT	FUEL	173	236	314	147	40	0	0
2700G- 900G	CENTER	24	124	75	21	1	0	0
	F+C	197	360	389	168	41	0	0
TEST PAD	FUEL	78	487	575	259	15	0	0
	CENTER	8	98	137	59	1	0	0
	F+C	86	585	712	318	16	0	0

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TABLE III. ESTIMATION OF TOTAL NUMBER OF FRAGMENTS FROM THE UNANALYZED SECTORS

Sector (ft)	Sector (°)	Fragment Size Classes (in.) 1/4 - 1/2	1/2 - 1	1 - 2	2 - 4	4 - 8	8 - 16	16 - 32	Method of Estimation
1000-750	0- 45	0	14	10	7	2	1	0	Assigned same value as sector 1000-750', 315-360°
1000-750	45- 90	0	14	10	7	2	1	0	Assigned same value as sector 1000-750', 315-360°
1000-750	90-135	10	13	15	23	5	0	0	Average between sectors 1000-750', 45-90° and 1000-750', 180-225°
1000-750	135-180	10	13	15	23	5	0	0	Average between sectors 1000-750', 45-90° and 1000-750', 180-225°
1000-750	270-315	0	9	10	21	7	0	0	Average between sectors 1000-750', 225-270° and 1000-750', 315-360°
750-500	0- 45	0	5	9	30	8	0	0	Average between sectors 750-500', 270-315° and 750-500', 315-360°
750-500	45- 90	0	5	9	30	8	0	0	Average between sectors 750-500', 270-315° and 750-500', 315-360°
500-450	0- 45	4	1	2	3	2	0	0	Average between sectors 500-450', 315-360° and 500-450', 45-90°
450-400	0- 45	5	1	2	6	0	0	0	Average between sectors 450-400', 315-360° and 450-400', 45-90°
400-350	0- 45	4	0	1	2	1	0	0	Average between sectors 400-350', 315-360° and 400-350', 45-90°
100- 50	315-360	23	46	7	0	0	0	0	Average between sectors 100-50', 270-315° and 100-50', 0-45°

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TABLE IV. AVERAGE WEIGHT PER FRAGMENT IN GRAMS COMPUTED FROM THREE DOWNWIND SECTORS

	1/4 - 1/2"	1/2 - 1"	1 - 2"	2 - 4"	4 - 8"	8 - 16"	16 - 32"
Fuel Elements	0.52	1.83	8.02	27.27	78.48	156.96	313.92
Center Elements	0.96	2.10	6.56	27.24	79.98	159.96	319.92

TABLE V. NUMBER OF FRAGMENTS SIZED BY GROUP CMB-14 AND THE TOTAL GROSS WEIGHT OBTAINED

Fuel Elements

Size Class	1/4 - 1/2"	1/2 - 1"	1 - 2"	2 - 4"	4 - 8"	8 - 16"	16 - 32"
No. of Fragments	2915	5032	2089	234	0	0	0

Center Elements

Size Class	1/4 - 1/2"	1/2 - 1"	1 - 2"	2 - 4"	4 - 8"	8 - 16"	16 - 32"
No. of Fragments	654	2628	1237	187	14	0	0

Total gross weight (kg) = 59.2

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TABLE VI. COMPARISON OF COMPUTER PROGRAM RESULTS AND FRAGMENT SIZING DATA

Fuel Elements

Size (in.)	Actual No. of Fragments	Calculated No. of Fragments	Deviation
1/4 - 1/2	3539	3697	418
1/2 - 1	7624	7013	611
1 - 2	4845	5624	-779
2 - 4	2006	1625	-381
4 - 8	116	167	- 51
8 - 16	0	6	- 6
16 - 32	2	0.075	1.92

Mean = 1.066 inches

Standard deviation = 0.782 inch

Center Elements

Size (in.)	Actual No. of Fragments	Calculated No. of Fragments	Deviation
1/4 - 1/2	1071	1355	- 284
1/2 - 1	4576	3689	- 887
1 - 2	3352	4167	- 815
2 - 4	1886	1739	147
4 - 8	330	266	64
8 - 16	17	15	2
16 - 32	0	0	0

Mean = 1.357 inches

Standard deviation = 1.01 inches

Fuel + Center Elements

Size (in.)	No. of Fragments	Calculated No. of Fragments	Deviation
1/4 - 1/2	4610	5054	- 444
1/2 - 1	12200	10685	1515
1 - 2	8197	9809	- 1612
2 - 4	3892	3368	524
4 - 8	446	428	18
8 - 16	17	20	- 3
16 - 32	2	3	1

Mean = 1.177 inches

Standard deviation = 0.884 inch

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TABLE VII. COMPARISON OF STATISTICAL PARAMETERS DERIVED BY VARIOUS ANALYSES

Distribution	$\overline{X}(1)$ in.	$\overline{X}(2)$ in.	$\overline{X}(3)$ in.	S(1) in.	S(2)	S(3) in.
Fuel	1.066	0.84	1.162	0.782	1.84	0.897
Center	1.357	1.12	1.487	1.010	1.96	1.221
Fuel + Center	1.177	0.95	1.286	0.884	1.94	1.044

$\overline{X}(1)$ = mean size obtained from non linear least squares computer analysis
$\overline{X}(2)$ = median size obtained from log-normal graphical analysis
$\overline{X}(3)$ = mean size obtained from standard definition of mean
S(1) = standard deviation obtained from non linear least squares computer analysis
S(2) = standard deviation obtained from log-normal graphical analysis
S(3) = standard deviation obtained from standard definition of standard deviation

TABLE VIII. ACCOUNTABILITY OF REACTOR CORE FUEL AND CENTER ELEMENT MATERIAL

Fuel and Center Material	Weight (kg)
Material collected and analyzed	232
Estimate of material collected but not analyzed	13
Estimate of material remaining on reactor base support plate	100
Total	345
Weight of reactor core (fuel and center elements) prior to excursion	1232
Material not accounted for	887

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TABLE IX. SECTORS FOR EXTRAPOLATION EXPERIMENT

Sector		Number of Fragments						
		Size Classes (in.)						
(ft)	(°)	1/4-1/2	1/2-1	1-2	2-4	4-8	8-16	16-32
100- 50	180-225	328	657	322	49	0	0	0
150-100	180-225	607	1116	404	56	0	0	0
200-150	180-225	320	885	770	114	19	0	0
250-200	180-225	576	987	562	116	6	0	0
300-250	180-225	7	573	260	102	4	0	0
350-300	180-225	0	120	173	176	2	0	0
400-350	180-225	0	211	251	275	27	0	0
450-400	180-225	0	165	99	77	4	0	0
500-450	180-225	0	82	105	74	6	0	0
750-500	180-225	-	-	-	-	-	-	-
1000-750	180-225	20	12	20	40	8	0	0
100- 50	0-45	35	75	11	0	0	0	0
150-100	0-45	0	43	29	18	1	0	0
200-150	0-45	0	65	120	111	16	2	0
250-200	0-45	0	30	13	7	5	0	0
300-250	0-45	14	0	10	33	0	0	0
350-300	0-45	0	0	0	10	18	6	0
400-350	0-45	4	0	1	2	1	0	0
450-400	0-45	5	1	2	6	0	0	0
500-450	0-45	4	1	2	3	2	0	0
750-500	0-45	0	5	9	30	8	0	0
1000-750	0-45	0	14	10	7	2	1	0

TABLE X. EXTRAPOLATION RESULTS

	Size Classes (in.)						
	1/4-1/2	1/2-1	1-2	2-4	4-8	8-16	16-32
Extrapolated Number of Fragments	5884	15544	9933	4372	493	45	0
Actual Number of Fragments	4610	12275	8208	3892	446	17	2
Percent Difference*	28	27	21	12	11	>100	100

*These percentage values are based on the actual values.

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