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EXPERIMENTAL INVESTIGATION OF THE SELF-LIMITATION OF POWER DURING REACTIVITY TRANSIENTS IN A SUBCOOLED, WATER-MODERATED REACTOR

Borax-I Experiments, 1954

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Experiments by W. H. Zinn, H. V. Lichtenberger, J. J. Dickson, J. M. Harrer, W. C. Lipinski, R. A. Cameron, R. O. Haroldsen, M. Novick, G. H. Stonehocker, G. K. Whitham, J. R. Dietrich, and C. B. Zitek*

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Reported by J. R. Dietrich

ABSTRACT

During the early summer of 1954 a series of experiments was made on the Borax-I reactor to investigate the ability of the reactor, when operated in the subcooled condition, to protect itself against the results of sudden, artificially induced increases in reactivity. Inasmuch as this set of experiments completed the program for the Borax-I reactor, the final runaway experiment was intentionally made under conditions which led to destruction of the reactor. In the final experiment a control rod worth four per cent k_{eff} was ejected from the reactor core, inducing an exponential power increase of period 2.6 milliseconds. The results of this final experiment when combined with those obtained in the preceding milder tests indicate the behavior of the reactor over a wide range of conditions of excess reactivity.

The maximum power attained during the final experiment was determined to be between 13×10^9 and 20×10^9 watts, and the total energy liberation was approximately 135 megawatt-seconds. This energy release resulted in melting of most of the fuel plates and failure of the reactor tank. Fuel plate fragments were scattered for a distance of 200 to 300 feet from the reactor, but no widespread dangerous dispersal was observed.

The nuclear energy release during the final experiment was not far different from that which would be expected by extrapolation of the results of previous milder experiments. The thermal conditions induced by the energy release, however, are out of the range of previous experience, and it is therefore difficult to determine whether the ultimate destructive effects are consistent with the hypothesis of a simple steam explosion.

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I. INTRODUCTION

During the Summer and Fall of 1953 a program of experiments was carried out by the Argonne National Laboratory at the National Reactor Test Station to investigate the characteristics of a water-cooled, water-moderated reactor when operating under boiling conditions. The experiments were made on a simple, remotely operated reactor which was constructed specifically for that purpose. Aluminum-enriched uranium fuel elements of the MTR type in a natural-circulation water circuit were used.

The results of the 1953 experiments, which are contained in ANL-5211, established the feasibility of operation under the boiling conditions and demonstrated, further, that such a boiling reactor can be designed to have a high degree of inherent self-protection against the effects of sudden large reactivity increases, such as those that might be postulated, in analyses of reactor safety, as occurring accidentally. This self-protection is the result of the negative "steam coefficient of reactivity" which can be designed into the reactor; that is to say, the reactor can be so designed that the extra steam content of the core which results from a power increase will reduce reactivity because of the displacement of water from the core and consequent loss in neutron moderation, and thereby limit the peak value of the postulated power surge to a safe value. Quite evidently the application of this principle of self-protection is not limited to reactors designed for normal operation as boilers, but holds also for other water-cooled, water-moderated reactors having negative steam coefficients of reactivity. The majority of the tests of the self-limiting characteristic made during 1953 were done with the water in the reactor initially at the boiling temperature, as it would be in an operating boiling reactor. A few experiments were made, however, with the reactor water temperature lower than boiling (this condition is hereafter referred to as the subcooled condition) as it would be in the more conventional water-cooled reactor. The experiments proved that the power was indeed self-limiting under both conditions, but, as had been anticipated, that the maximum power and maximum fuel-plate temperature reached in a transient of given period was appreciably higher for the subcooled than for the saturated case.

The method used for the self-limiting experiments was briefly as follows. The reactor was provided with a number of control rods, one of which could be ejected rapidly downward out of the reactor core under the influence of strong springs and gravity. The reactor was made critical at a very low power (about 1 watt) with this rod inserted to some pre-chosen position in the reactor, and the remaining rods more or less fully withdrawn from the core. The rod was then suddenly ejected and reactor power was allowed to rise on the period characteristic of the amount of excess reactivity introduced by ejection of the rod. Eventually the reactor would produce sufficient steam to check the rise of power, and, in fact, enough to overcompensate the excess reactivity and to reduce the power to a low level.

At some pre-chosen time thereafter (1 to 20 seconds) the remaining control rods were actuated by an electric timer to drop into the core and terminate the experiment. An experiment of this type will hereafter be called an excursion.

Many excursions of this type were made during 1953, the excess reactivity being gradually increased (and the reactor period decreased) from run to run by steps which could be expected to be safe by extrapolation of the results of the preceding tests. For the case of initially saturated water the tests were extended by this procedure to periods as short as 5 milliseconds, corresponding to excess reactivity of about 2.1% k_{eff}. With such short periods the ejection of water from the reactor was rather violent. Water was thrown out of the reactor tank to a height of about thirty feet, and the pressure in the reactor core arising from the rapid acceleration of the water was sufficiently high to deform permanently the fuel plates and render the reactor unusable because of binding of the control rods in the deformed core. The fuel plate temperatures reached under these conditions were by no means dangerous, however, amounting to a maximum of about 640F.

Straightening of the fuel elements was found to be feasible, and by this process the reactor was restored to operable condition, but having been once stressed beyond the yield point, the fuel plates were quite weak, and thereafter even relatively mild tests of the excursion type would result in deformation of the core. The transient tests were therefore discontinued for 1953, and all further work that year was directed toward investigation of the characteristics of steady-state boiling operation. This work indicated that such operation was feasible, and as a result the decision was made to extend the investigation to a new reactor which would approximate much more closely the characteristics of a practical power reactor operating on the boiling principle. For this purpose a new reactor (Borax-II) was designed and built to replace the old (Borax-I) reactor for tests during 1954.

Inasmuch as the steady-state investigations on Borax-I had been completed and the reactor had outlived its usefulness for that purpose, it was proposed that, before its replacement, the reactor be used in 1954 for further subcooled transient experiments of periods long enough that troublesome core deformation would not be encountered, and that, thereafter, the reactor be subjected to a single destructive excursion of very short period, the period to be chosen as that likely to give the most important experimental information. After discussion with the AEC Reactor Development Division and the Advisory Committee on Reactor Safeguards, it was decided that such a final experiment was worthwhile, and that for maximum usefulness it should be done with subcooled reactor water. The most informative period, or excess reactivity, that might be used was judged to be that which would cause incipient melting of fuel plates. By extrapolation of the very meager 1953 data on subcooled excursions it was estimated that the ejection of a control rod worth about 4% k_{eff} would put the reactor ultimately on a period between

2.0 and 2.5 milliseconds, and that the resulting excursion would liberate about 80 megawatt-seconds of nuclear energy which would melt about 4% of the fuel plates (the center sections of the center-most plates).

The proposed program with the Borax-I reactor was carried out during the early summer of 1954. It consisted of a series of excursion experiments with reactor periods in the range 14 to 130 milliseconds, a series of excursions to test reactor fuses and fuse components for ANL, and finally, the short period destructive experiment, which was made on July 22. The final test proved that the predictions of total energy and fuel plate temperatures had been considerably too low. The actual energy of the excursion proved to be about 135 megawatts, and, instead of the melting of a few fuel plates, the melting of the major fraction of the entire core was accomplished. The evidence indicates, however, that the discrepancy between the predicted and observed values of these quantities can be attributed to uncertainties of extrapolation. The results of this energy liberation in the way of peak pressures and explosive violence lie in a region where there has been no previous experimental data, and in this respect at least it is believed that the results are perhaps more informative than they would have been if the experiment had been performed under conditions which actually gave the more modest, predicted, energy release.

This report describes in detail all the 1954 Borax-I experiments except those which were made for the purpose of testing reactor fuses.

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II. DESCRIPTION OF REACTOR AND EXPERIMENTAL METHOD

A. Location

The reactor was located at the Argonne site at the National Reactor Testing Station, near Arco, Idaho. The reactor proper was located 2730 feet northwest of the Experimental Breeder Reactor entrance. It was controlled remotely from a trailer placed just outside the EBR entrance; during reactor operation an exclusion radius of approximately one-half mile was maintained around the reactor.

B. Mechanical Characteristics

The reactor is described in detail in ANL-5211, which covers the 1953 BORAX experiments. The reactor used for the 1954 experiments was identical except for the control rod drive mechanism. The following description is therefore made quite brief.

The reactor installation is shown in a cutaway view in Figure 1. The reactor tank was contained in a larger shield tank of ten-foot diameter which was sunk part-way into the ground and had earth piled around it for additional shielding. Adjacent to the shield tank was a pit with concrete walls in which there was installed equipment for filling and emptying the reactor and shield tanks, and for preheating the water in the reactor tank. Figure 2 is a photograph of the actual installation, as seen from the pit end.

The reactor tank, which was four feet in diameter and about thirteen feet high, contained the reactor core, which consisted of a number of MTR-type fuel elements held at the bottom by a supporting grid and at the top by a removable cover grid. The details of the core arrangement are shown in Figure 3. The core grid could accommodate thirty-six fuel elements, but a maximum of thirty elements was used in the program described here. In operation the reactor tank was filled with water to a height of three to four and one-half feet above the top of the core; this water constituted the reflector, moderator, and coolant.

A detailed description of the fuel elements is given in ANL-5211. These were MTR elements with the end fittings replaced by fittings suitable for the Borax design. Each element contained 18 fuel plates with a combined U^{235} content (90% enrichment) of about 140 grams. The U^{235} in each plate was in the form of a strip of uranium-aluminum alloy, 23.6 inches long by 2.5 inches wide by 0.021 inch thick. The alloy plate was covered with a cladding of pure aluminum, which increased the total dimensions of the fuel plates to 24.6 inches by 2.845 inches by 0.060 inch.

The reactor contained five control rods: a central rod which was alternatively a flat plate or a cross-shaped member as the requirements of the experiment dictated, and four wide flat plates (shim rods) which operated

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in the channels separating the four quadrants of the reactor core. All rods were made of nickel-clad cadmium in aluminum casings. The control rods were attached by extension rods to drive mechanisms located above the top of the reactor tank. The four shim rods were permanently connected to their respective operating mechanisms, but the central rod was attached to its mechanism by an electromagnet, which when released allowed the rod to be spring ejected downward out of the core for the experiments on reactor runaway. Complete rod ejection was accomplished in less than 0.25 second. The magnet was supplemented by a remotely operated fail-safe mechanical latch to prevent accidental ejection of the rod.

The absorbing (cadmium) section of each control rod was twenty-six inches in length (a little more than the height of the active reactor core), but the total length of each rod was somewhat more than twice the core height, to provide positive guidance regardless of rod position. In the shim rods the cadmium insert was installed at the upper end of each rod, whereas the center rod contained the cadmium insert at its lower end. Thus a downward motion of the shim rods caused the reactor to lose reactivity, while a downward motion of the center rod caused a reactivity increase.

A separate drive mechanism was used for each of the five control rods. One of the mechanisms for a shim rod is shown in Figure 4. Since it was designed for use on both pressurized and unpressurized reactors, it was provided with a cylinder and piston (top of drawing) for compensating any upward thrust on the rod due to internal pressure in the reactor vessel. This "pressure equalizer" cylinder was left open to the atmosphere during the experiments described here.

The mechanism produced movement of the control rod by means of a double-acting pneumatic piston, but movement in the upward direction was restricted by a movable stop, whose position was adjusted by a motor-driven lead screw. For normal slow-speed positioning of the rod, pneumatic pressure was kept always in the upward direction, maintaining contact between the rod and the stop nut, and rod position was adjusted by movement of the nut. A fail-safe limit switch was provided which caused the pneumatic pressure to be reversed, driving the rod rapidly down to its fully inserted position, if ever contact was lost between the rod and the stop nut. The pneumatic rapid-insert action could also be independently actuated whenever rapid insertion of the rod was desired. The mechanism was thus equivalent to a mechanical lead-screw mechanism for slow adjustment of rod position plus a pneumatic piston for rapid scram insertion. The pneumatic insertion over the full length of the core was accomplished in about one second.

The mechanism for the central rod was identical with that for the shim rods, but the upper chamber of the pneumatic cylinder was left open to the atmosphere, and the lower chamber was connected permanently to the compressed air to prevent inadvertent ejection of the rod from the core.

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Water for Borax operation was piped from the EBR deep well. The reactor water was deionized by an ion exchange plant located on the Borax site.

When the reactor was in the shut-down condition, water was pumped into the shield tank (Figure 1) to a level sufficiently high to permit approach to, and work on, the reactor. During operation the shield tank was drained, and personnel shielding was achieved by remote operation from the control trailer a half-mile away.

C. Nuclear Characteristics

The important nuclear characteristics of the reactor are summarized here, Further details are given in ANL-5211.

The reactor was slightly supercritical at room temperature when it contained twenty-six fuel elements. The power distribution in the reactor core was measured by foils, at 200°F, after the loading had been increased to twenty-eight elements (Figure 5). The two elements added, beyond the twenty-six originally loaded for criticality, were numbers 13 and 18. With this loading, the reactor had excess reactivity of 2.3% k_{eff} at room temperature (65°F).

The total worth of the central control rod used for all experiments except the last one was 2.55% k_{eff}. Calibration curves of this rod are given in ANL-5211. The calibration of the central rod used for the last, short-period excursion is discussed later (Section IV-A) in this report.

The total worth of the four shim rods was estimated, from partial calibration curves which covered only the first 30% of insertion, to be greater than 15% k_{eff}.

The effective neutron lifetime in the reactor was believed to be $(6.5 \pm 0.5) \times 10^{-5}$ second (see ANL-5211). Figure 6 shows the relation between excess reactivity and asymptotic reactor period for this lifetime.

The measured average temperature coefficient of reactivity, between 94°F and 200°F, was -0.0071% k_{eff} per °F. The calculated average void coefficient of reactivity (this is equivalent to a steam coefficient of reactivity) was -0.27% k_{eff} per percent void in the core water, up to a total void of 20%.

The detailed composition of the reactor core and constants used for reactivity calculations are given in Appendix A of ANL-5211.

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D. Experimental Method

The objects of the experiments were to determine the extent to which the reactor power was self-limiting under "runaway" conditions, and to measure as many as possible of those fundamental quantities which determine reactor behavior under such transient conditions. In essence each experiment involved applying to the reactor, initially either subcritical or critical at very low power (~1 watt), a sudden, precisely specified reactivity increase, allowing the excess reactivity to remain until the ultimate behavior of the reactor became evident, and finally rendering the reactor permanently subcritical by "artificial" means (insertion of shim rods).

The procedure was as follows: The loading of the reactor was adjusted to give approximately the amount of excess reactivity desired for the experiment. With shim rods fully inserted (reactor subcritical) the central control rod was inserted into the core by an amount equal to the desired excess reactivity for the experiment. With the central rod held fixed at that position, the reactor was made critical by withdrawal of the shim rods; the shim rods were then held at that critical position. The central rod could then be ejected (completely) from the core to produce a transient which started from the critical condition, or could be first pulled completely into the core and then completely ejected, to produce a transient beginning from the subcritical condition. At a pre-set but adjustable time after the ejection of the central rod, an electric timer initiated the rapid pneumatic insertion of the shim rods.

For transients of moderate periods the behavior of the reactor power excursion does not depend on the initial state of criticality of the reactor: whether the reactor is initially critical at very low power, or initially subcritical, the central control rod is completely ejected, and the reactor achieves its asymptotic period long before the power has risen to an important value. For the single very short period transient which was run, the excursion was initiated from the subcritical condition to lengthen the time available for complete ejection of the central rod.

The experiments reported here were all made with the reactor water initially at "room" temperature. This temperature covered a range from 66°F to 82°F.

E. Instrumentation

The instruments for steady reactor operation were not important to the experimental results and will not be discussed here (see ANL-5211).

The three principal types of information recorded during the transients were reactor power, as indicated by the output of neutron-sensitive ion chambers, total energy release during the excursion, and surface temperature of selected fuel plates. Total energy was measured by the activation

of specially calibrated cobalt foils. Reactor power and fuel plate temperature were recorded on a single strip of photographic paper by a Heiland magnetic oscillograph employing high speed galvanometers. The oscillograph was located in a trailer about thirty feet from the reactor.

The power signals originated in three different boron-coated ion chambers which fed the Heiland galvanometers through logarithmic amplifiers. The function of the multiplicity of ion chambers was to record neutron flux at positions of various flux densities and thus insure that at least one record would be obtained within the useful current range of an ion chamber. In all cases the chambers were installed outside the reactor tank: in some cases inside the (empty) shield tank; in other cases inside the wooden structure above the pump pit (see Figure 1). The frequency response of a typical logarithmic amplifier was flat to better than 10^3 cycles per second so long as the ion chamber output was above 10^{-8} ampere. The ion chambers gave linear responses for output currents up to 10^{-5} ampere. The galvanometers used in connection with the ion chambers had natural frequencies of 450 cycles per second, and were used with about 60% damping (percent damping equals 100 times ratio of critical damping resistance to damping resistance used). The method of converting ion chamber output to reactor power is discussed in Section III-B below.

For the measurement of fuel plate temperatures the reactor was provided with a special fuel element which consisted of an aluminum box having the same external dimensions as an MTR fuel element, and having longitudinal grooves along the inner faces of its side plates to hold special, removable, flat fuel plates. Chromel-alumel thermocouples were installed on the surfaces of some of these plates near their centers. The couples were made with 3-mil wires, the chromel and alumel wires being welded separately to the plate surface to give, actually, a chromel-aluminum and an alumel-aluminum couple in series, with the plate surface itself forming one element of each junction. Thermocouple outputs were applied directly to galvanometers in the Heiland oscillograph, without amplification. The galvanometers had undamped natural frequencies of 100 cycles per second, and were used with about 60% damping.

For purposes of absolute energy calibration, sections of some of the thermocoupled fuel plates were insulated thermally from the surrounding water. The insulation consisted of a coating, eight to ten mils thick, of a thermo-setting plastic (clear LC-34 Lithcote) on the fuel plate surfaces. The coating was applied in 3-inch square patches, centered around the thermocouple installation, to both sides of the fuel plate. The insulation was shown experimentally to increase the thermal relaxation time of a hot fuel plate in cool flowing water to more than two seconds (thermal relaxation time is here defined as the time for temperature difference between plate and water to decrease by a factor e). The coating was tested for neutron flux attenuation, which was found to be negligible.

III. TRANSIENTS WITH PERIODS LONGER THAN 13 MILLISECONDS

A. Typical Transient Behavior of Reactor Power

Typically, the highly subcooled reactor, if allowed to "run away" on a period longer than 13 milliseconds (the shortest period tested other than the final, very short one), will experience an exponential power increase which continues until the fuel plate temperatures become high enough to form steam in significant quantity. As the steam forms it pushes water out of the reactor core, reduces reactivity, and halts the power rise. In general, the quantity of steam formed is considerably greater than that required to reduce excess reactivity to zero, with the result that, after reaching its maximum value, the power drops rapidly and, except in the case of quite slow transients (initial period >50 milliseconds), goes through a minimum before rising again to reach, sometimes after a series of damped oscillations, a more or less steady value in the 1 to 10 megawatt range. The "steady" operation, of course, occurs when reactor power has so adjusted itself that the steam content of the core remains approximately equal to that which will just compensate the excess reactivity initially applied to the reactor. The magnitude of the steady power therefore depends upon the amount of excess reactivity applied (or the initial reactor period).

In the previous transient experiments with saturated reactor water the power excursions terminated in steady operation only if the initial reactor period was longer than about 30 milliseconds. The "chugging" operation observed when shorter periods were used with saturated water (ANL-5211) was not observed during the tests with subcooled water. Perhaps it would have appeared if periods shorter than 13 milliseconds had been investigated.

Figure 7 illustrates the characteristics of subcooled transients discussed above. It is a record of reactor power during the initial power excursion plus about 10 seconds of subsequent operation. Usually runs of this length were not made, as the long period of steady operation interfered with accurate measurement of the initial transient characteristics. Figure 8 shows reactor power during three different transient runs of longer initial period, but shorter duration, than that of Figure 7. Figure 9 contains a record of reactor power during a transient of still longer initial period (134 milliseconds). In this case the power, after its initial maximum, is evidently settling down to a steady value without going through a minimum.

B. Power Calibration

The basic measurement of reactor energy release during a transient was made by measuring the temperature rise of a fuel plate which was thermally insulated (by a plastic coating) from the reactor water, but which was otherwise a typical fuel plate. The total energy release was then

obtained, in principle, by taking the product of the fuel plate temperature rise, the heat capacity of the fuel plate, the total number of fuel plates, and a suitable factor for correcting the fission rate at the thermocouple location to the average fission rate over the reactor core volume. In practice it was not possible to use this method in all cases because the shorter period transients produced enough heat to damage the plastic coating, and, in some cases, to endanger the thermally insulated plate itself. Consequently, cobalt foils installed in the reactor core were used to indicate the total energy from run to run, and the foils were calibrated by the plate temperature method in the series of four transient runs whose records are re-plotted in Figures 9, 10, 11, and 12. Once the total energy release of an excursion was established, the power calibration for the ion chamber record could be obtained by integrating the record and choosing the power calibration to give the correct total energy.

In order to minimize the effects of heat loss through the insulating coating on the fuel plate, only the initial portion of the power transient, up to the point of maximum power, was used to establish the cobalt foil calibration. The relation of actual counting rate of the foil to the counting rate it would have had if the transient had stopped at peak power was determined by proper intigration of the ion chamber record. The consistency of the calibration is illustrated by the table below, which compares the counting rate which the foil would attain at the time of peak power to the measured temperature rise of the insulated fuel plate up to the time of peak power.

Initial Period of Transient, Sec	ΔT = Fuel Plate Temperature Rise, °F	R = Ratio of total energy to energy release up to time of maximum power	CPM of Cobalt Foil	(R)(CPM)	$\frac{(R)(CPM)}{\Delta T}$
0.134	124	0.280	4131	1160	9.36
0.051	226	0.278	5394	2040	9.03
0.033	254	0.466	4744	2210	8.71
0.021	300	0.471	6094	2870	9.57

The maximum deviation from the average of the numbers in the last column of the table is about 5%. In addition to this uncertainty there is an uncertainty of about ± 7% connected with heat loss from the plate and temperature distribution within the plate. Possible errors in the measurement of power distribution over the reactor volume increase the total uncertainty in the reactor power calibration to about ± 20%. The uncertainty in power distribution is not considered an important one, however, as the power density in the position of maximum flux (approximately the location of the thermocouple) is a more significant quantity than total reactor power.

It is now necessary to specify certain conventions and definitions which will be followed throughout the remainder of this report whenever reference is made to reactor power or energy.

BY REACTOR POWER OR ENERGY IS MEANT THE PROMPT FISSION POWER OR ENERGY WHICH IS CONVERTED TO HEAT IN THE FUEL PLATES. These are the quantities measured by the thermocouples and are believed to be the ones which are important in the transient behavior of the reactor. The total energy release is about 15% higher than the energy defined here.

BY THE TOTAL ENERGY OF A REACTOR POWER EXCURSION IS MEANT THE ENERGY RELEASE (ACCORDING TO THE ABOVE DEFINITION) UP TO THE TIME THE POWER REACHES ITS FIRST MINIMUM. If the power does not go through a minimum before approaching its steady value (e.g., Figure 9), no total energy is specified for the excursion.

The quantity measured by the cobalt foils (and the insulated thermocouples) is energy density rather than total reactor energy. The relation between energy density and total energy changes when the loading of the reactor is changed. Since energy density is considered the more fundamental quantity, ALL REACTOR POWER AND ENERGY FIGURES QUOTED ARE THE EQUIVALENT POWER OR ENERGY VALUES FOR A REACTOR CONTAINING 30 FUEL ELEMENTS. Since the number of fuel elements used for excursions varied only between 27 and 30, the adjustment is in no case large.

C. Relations Among Power, Energy, Fuel-Plate Temperature, and Reactor Period.

Aside from their use for establishing an energy calibration, Figures 9, 10, 11, and 12 provide illustrations of the relations among reactor power, energy, and fuel plate temperature during the transient, and of the general way in which these relations are changed as the initial period of the transient is changed.

The fuel plate temperatures shown in these figures, and subsequently in this section of the report, were taken on the same fuel plate: The two thermocouples were spaced four inches apart, longitudinally on the plate, and symmetrically about the line of maximum neutron flux. The fuel plate was installed in the fuel element in position 21 (Figure 5) as the fourth plate from the control rod channel. The plate used was loaded 20% more heavily with U^{235} than the normal Borax plates (thermocoupled plates of the standard loading were not available at the time). Because of its location and extra fuel loading, the thermocoupled plate should have had somewhat higher power density than any of the normally loaded fuel plates, except, perhaps, those located immediately adjacent to the control rod channels.

The thermocoupled plate did not, however, have the highest power density of any plate in the reactor, as position 20 in the core was occupied by a non-standard fuel element made up of ten plates of still higher fuel loading. This element was installed to provide for measurements in the core which might require more space than that available between the plates of the standard 18-plate MTR fuel element. The U^{235} loadings of the three types of plates are summarized in the table below:

Type of Plate	Location in Core (see Figure 5)	U^{235} Content per plate, gm.
Thermocoupled	Position 21	9.4
Special element	Position 20	15.7
Regular MTR	Everywhere else	7.8

The fuel plate behavior which is illustrated by Figures 9 through 12 is evidently the following. The temperatures of both the bare and insulated sections of the plate rise very nearly together on a curve which is nearly proportional to the integral of reactor power, until the bare plate surface reaches a temperature at which boiling begins at an important rate. This temperature is considerably higher than the saturation temperature of the water under ambient pressure. Once boiling begins, the bare section of the plate is cooled rapidly despite the fact that the reactor continues to produce power for some time. The temperature of the insulated plate continues to rise along a curve which is proportional, except for a small heat loss, to the integral of reactor power. Meanwhile, reactivity is being reduced as a result of the steam formation by the bare plate and other similar plates, and reactor power finally decreases to a very low value.

Since no single fuel plate can produce sufficient steam to shut the reactor down, it is quite evident that the time relationship between peak reactor power and peak temperature of (bare) fuel plate, as well as the ratio of maximum bare plate temperature to maximum insulated plate temperature, will depend upon the local value of power density at the plate location relative to the power density elsewhere in the reactor. Since the plate used for these measurements was located near the maximum power density, the maximum plate temperature occurs early - actually slightly before the power peak in the faster transients. The seemingly odd behavior in the case of the very slow transient (Figure 9), that reactor power begins to decrease before the bare plate temperature reaches the saturation value, is probably explainable as the result of early boiling in the special element containing highly loaded fuel plates.

Having illustrated by Figures 9 through 12 the characteristic variations of power and fuel plate temperature during individual transient runs, this section will, in its remainder, present the quantitative relationships between these variables, as derived from a greater number of transient experiments.

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Figure 13 shows the variation of total energy of the excursion with the reciprocal of reactor period, and Figure 14 shows maximum reactor power as a function of the same variable. The scatter in the total energy values is considerably greater than that observed during the 1953 experiments using water at saturation temperature. It would not be surprising if this greater variation in behavior were characteristic of the highly subcooled condition. It should be mentioned, however, that, although clean deionized water was used for filling the reactor tank, there was an accumulation of sand, and perhaps other contaminants, in the bottom of the reactor tank which could not be easily removed. The possibility exists thay such contaminants affected the consistency of results.

In Figure 15 the total energy per excursion is plotted against the product of reactor period and maximum power. The curve is nearly a straight line, through the origin, of slope 2. A similar result was found in the 1953 experiments. The only fundamental significance of the curve is as an indication that the shape of the power transient, if plotted in a non-dimensional form (time in units of reactor period; power as a fraction of peak power) does not change greatly over the range of periods investigated.

In Figure 16 the maximum surface temperature of the bare fuel plate is plotted as a function of reciprocal period. The 1953 measurements on two fuel plates located in approximately the same position are included. The explanation for the considerably higher temperature of one of the 1953 plates is not known. This plate gave consistently higher temperatures than those of the other 1953 plate throughout a series of transient runs (see AM-5211).

Figure 17 shows the maximum temperature rise of the fuel plate during the transient as a function of the total energy of the power excursion. While the fuel plate temperature is rising from its initial (subcooled) value to the temperature at which rapid boiling begins, heat loss from the plate is low, and the relation between energy and temperature would be expected nearly to coincide with the dashed curve, which represents simply the relation between temperature rise, energy, and heat capacity of the fuel plate. The curve through the experimental points would be expected to intersect this line at a temperature somewhat above saturation, and it is so drawn, although it can hardly be claimed to be well defined by the available data points. The slope of this line is roughly 1/4 the slope of the zero heat loss line. The comparable curve for the 1953 experiments with saturated water had a slope of about 1/2. This difference in slope between the two cases is interpreted to mean simply that, during the time that it is in the range of boiling temperatures, the plate will lose more heat per unit of net steam generated if it is in subcooled water than if it is in saturated water. The result is hardly surprising.

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IV. THE SHORT-PERIOD TRANSIENT

A. Procedure

In principle the procedures and experimental methods used in conducting the short-period experiment were the same as those used for the previous runs, but certain modifications of detail were necessary to meet the new conditions.

To provide the necessary large reactivity addition a stronger central control rod and a larger fuel loading were required. Before replacing the old control rod the reactor core loading was increased to the point where criticality was attained with the old central rod fully inserted and the four shim rods partially inserted. From previous rod calibration (ANL-5211) it was estimated that, under these conditions, the worth of the fully inserted central rod was 2.45%, and of the partially inserted shim rods was 0.57%, giving a total excess reactivity of 3.02% k_{eff}, with an estimated precision of ± 0.15%. The new central rod, an aluminum-canned cadmium cross of 3-inch span, was then substituted for the old rod without changing the fuel loading. The reactor was critical with the new rod inserted 17.23 inches in the core. The core loading was then increased gradually until the reactor was critical with the rod fully inserted. After each addition the differential worth of the rod was determined by the usual period method, yielding the calibration curve of Figure 18-a. Addition of the integral of Figure 18-a to the previously determined point at 17.23 inches gives the total rod worth as 4.37% k_{eff} (Figure 18-b). The core loading was then reduced slightly, giving criticality at a rod insertion of 21.5 inches, an indicated excess reactivity of 3.96% k_{eff}. The estimated uncertainty is ± 0.20% k_{eff}. This loading, which was used for the fast excursion, consisted of 30 fuel elements, in the pattern shown in Figure 19.

In order to reduce the length of leads to the ion chambers, and thereby shorten the time response of their circuits as much as possible, the logarithmic amplifiers were set up near the entrance to the pump pit, and the ion chambers were mounted directly on the amplifiers.

The special fuel element containing the thermocoupled fuel plate was moved from position 21 to the lower flux position 26 (Figure 5) in the hope that it would record a larger fraction of the transient before failing. The two surface thermocouples on the plates (both bare) were connected to high-speed galvanometers in the Heiland oscillograph. The natural frequency of these galvanometers was 450 cycles per second, the same as those used with the ion chambers. In addition to the thermocoupled fuel plate in the core, a single thermocoupled insulated fuel plate was installed on the top core support plate, at a distance of some six inches from the core, where the thermal neutron flux was lower than that near the center of the core by more than a factor of ten. This thermocouple was connected to one of the slow

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galvanometers (natural frequency 100 cycles per second). The function of this plate was to serve as an auxiliary measurement of energy, of particular value in case it was impossible to recover the cobalt foils after the experiment.

A pressure transducer of the strain-gage type was submerged in the reactor water, at the same depth as the central plane of the reactor core, and about six inches away from the core. The range of the transducer was 0 - 1000 psi and its undamped natural frequency was 750 cps. The transducer was over-range protected to 3000 psi. It was necessary to connect the transducer to one of the slower galvanometers (100 cps) in order to attain the desired deflection sensitivity.

Two foil holders, each containing a series of cobalt foils, were inserted longitudinally into the core at the locations indicated in Figure 19. One of the holders, consisting of a flattened aluminum tube, contained thick (1-gram) cobalt foils, one centimeter square. The other holder, made of a flattened stainless steel tube, contained quarter-inch lengths of 40-mil cobalt wire. A third holder was installed at a calibrated position just outside the reactor tank. This holder carried a longitudinal string of 0.1-gram, 1-centimeter square gold foils.

Several movie cameras, which could be started remotely from the control trailer, were set up at various distances from the reactor. Two of the cameras had speeds of 500 frames per second; the rest of the cameras were operated at 64 frames per second.

A number of preparations were made in anticipation of possible explosive ejection of the contents of the reactor tank. The supporting carriage for the control rod mechanism, which previously had been simply sitting on its supporting rails (Figure 1), was fastened to the shield tank wall by three welded angle iron ($3" \times 1/4"$) struts. The base plate of the rod drive mechanism, which was fastened to the carriage by four bolts, was also attached to the shield tank wall by a number of struts which were only tack welded.

A number of smoke pots, which could be fired remotely from the control trailer, were installed on a pole near the reactor. It was the function of the smoke to indicate the position of any cloud of fission products that might issue from the reactor.

The experiment had been discussed several weeks in advance with members of the IDO Radiation Protection Section, and plans had been made for health physics coverage of the experiment by that group. On the morning of the experiment they placed film monitors and drop-out plates at many points inside the immediate Borax area, as well as along the expected wind trajectory, at distances up to about four miles. They also made available

two smoke generators for indicating wind pattern over extended periods of time. Radiological monitoring was handled by five two-man monitoring teams in radio-equipped cars and power wagons, centrally directed from a point near the EBR building.

It had been decided that the most favorable wind condition for the experiment was a light wind from the northeast. Such a wind would follow a path approximately normal to a line drawn between the EBR and Borax sites, and would carry any air-borne debris out into the large uninhabited desert area to the southwest. Mr. Paul Humphrey, IDO meteorologist, furnished frequent wind forecasts, and on the morning of the experiment was present at the Borax control point to give on the spot meteorological advice and forecasts.

After a day of waiting, favorable wind conditions for the experiment prevailed on the morning of July 22. A preliminary excursion, of period about 20 milliseconds, was run at 5:30 AM on that day to check operation of the instruments. The loading of the reactor was then adjusted to its final value (Figure 19). In the process of making the final loading it was found necessary to straighten several fuel elements to ensure full and rapid ejection of the central control rod. Final adjustments of the reactor were completed about 8:00 AM. A final wind check showed the wind to be from the northeast with velocity of 8 mph near the ground, and 20 mph at 250 feet above ground level. The forecast was for continuation of these general conditions for at least another hour.

The reactor was made critical to establish the critical position of the central rod (21.5 inches, Figure 18). The central rod was then fully inserted into the reactor, making it subcritical, and the shim rods were run in and left in for a few minutes to hasten the decay of power to a very low level. The shim rods were then fully withdrawn, leaving the reactor subcritical by about 0.4% k_{eff} under the influence of the fully inserted central rod. After a final inspection to re-check that no persons were closer than the control trailer to the reactor (1/2 mile), one of the smoke pots was fired, and 10 seconds later, at 8:20 AM the central rod was ejected from its fully inserted position.

In a very short time after the release of the central control rod a column of what appeared to be dark grey smoke was ejected from the reactor to a height of some 80 feet. The difference in appearance between this material and the silvery-white mixture of steam and water which had been ejected during the slower-period 1953 experiments was striking. Shortly thereafter the sound of a medium sharp detonation reached the control trailer, and a slight tremor of the trailer was felt. In a few seconds the smoke cleared away, and it was apparent that the entire superstructure of the reactor, containing the control rod mechanism, had been carried away. Figure 20, which contains prints of a sequence of movie frames, shows the progress of the

explosion. The camera used for the first twelve frames shown stopped because of interruption of its power, and the remainder of the frames were taken by a different camera.

Immediately after the excursion, all attention was given to questions of health physics (see section below). It was soon evident that previous predictions had been confirmed in that no important radiation exposure of any kind was received at the control point. The wind continued in the southwesterly direction, and the smoke (from the pots at the reactor) rose to a considerable height before becoming so diffuse as to be indistinguishable. The cloud never came near the EBR building. About an hour after the experiment a team consisting of Borax and IDO Radiation Protection personnel entered the reactor area by cutting through the fence on the north side and removed the photographic chart containing the instrumental record of the excursion from the Heiland oscillograph. The radiation intensity inside the instrument trailer was then 1 r/hr and only minor exposures were received in carrying out this operation. Subsequent trips were made into the area to remove the film from the cameras.

B. Records from Borax Instrumentation

After development, the chart from the oscillograph proved quite readable, although it was too badly fogged by radiation to be reproduced in this report. Figure 21 is a direct tracing of the chart, however. The various records are labeled on the figure. The ion chamber records show a high-frequency oscillation which begins abruptly, at a time which varies, among the different records, from 1 to 4 milliseconds after peak deflection. This is probably a microphonic disturbance in the amplifiers or in the ion chambers themselves, resulting from the reactor explosion. The disturbance was evidently transmitted through the concrete pit walls and the earth, since an air shock would require some 20 milliseconds to cover the 25 feet between reactor and ion chambers. It is unlikely that any important mechanical deformation took place in the reactor much before the peak ion chamber readings, since any such deformation would almost certainly lead to a very rapid decrease in reactivity with an accompanying decrease in neutron flux. Once this disturbance has begun, the ion chamber records no longer agree with each other, although their traces can be followed with fair certainty. By the end of another 40 or 50 milliseconds new disturbances have begun which convert the records to "hash." By this time the chambers are no doubt responding primarily to gamma radiation from the expelled reactor material. The amplifiers themselves were blown over by the explosion. The sudden decrease in deflection (point B) was caused by the general failure of instrument power.

The two thermocouples on fuel plates in the core (traces 8 and 9) failed before peak power was reached; the one which lasted longest gave a maximum reading of 690°F. Thermocouple failure does not necessarily

indicate the beginning of an explosion, as many failures have occurred in the past with much slower transients. They may be caused by the mechanical deformations of the fuel plate which result from thermal expansion.

The thermocouples on the external fuel plate survived for 8 to 10 milliseconds after peak power was reached. It seems reasonable that they may have been broken in the general disintegration of the reactor.

The trace of the pressure transducer disappears after reaching an indicated pressure of about 200 psi at about the time peak power is reached. The galvanometer trace, however, is lagging the transducer output by about 2 milliseconds.

The ion chamber giving the highest deflection (trace 1) was installed purposely in a sensitive position to give a good trace for period determination. It indicates a period of 2.6 milliseconds. The neutron fluxes at the other chambers were unfortunately too low to give good period measurements - the chamber currents did not rise soon enough to values at which the amplifiers give good high-frequency response. Consequently the traces are not quite linear, and the indicated periods vary from 2.6 to 3.4 milliseconds. The curve of fuel plate temperature (trace 9) indicates a period of 2.4 milliseconds, and the two thermocouples on the external fuel plate (traces 6 and 7) indicate periods of 2.8 and 2.5 milliseconds, respectively. None of the other measurements are believed to approach the accuracy of that from trace 1, however, and its value, of 2.6 milliseconds, is used in the remainder of this report.

Most of the gold foils that had been located just outside the reactor tank were found soon after the experiment. Over the course of the next three weeks two of the 1-gram cobalt foils and four of the cobalt wires were found among the reactor debris. The energies indicated by all of the cobalt foils and by one of the gold foils are given in the following table:

Type Foil	Location	Total Energy of Excursion Mw-sec
1-gram Co	In core, 9 3/4" from top	135
1-gram Co	In core, 2" from top	181
Co Wire	In core, 17" from top	128
Co Wire	In core, 13" from top	125
Co Wire	In core, 9" from top	133
Co Wire	In core, 2" from top	170
Au	Outside reactor tank, even with top of core	150

Of the foil measurements, that of the 1-gram cobalt foil, 9 inches from the top of the core (135 Mw-sec) is believed to be most reliable because its type and location correspond most nearly to those used for the original energy calibration. Further, it agrees well with the three cobalt wires which were installed well within the core. Both the foils installed in the core at the 2-inch level indicate considerably higher energy. This is believed to be simply a discrepancy in the curve used for the axial flux distribution. The distribution curve used was made in 1953. It is believed that the installation of the new rod drives before the 1954 experiments may have resulted in a higher position of the shim rods when in their "fully withdrawn" condition, and hence less shadowing of the top end of the core; or the axial flux distribution may have become flatter during the excursion because of the formation of steam near the center of the core, and because of the beginning of disintegration of the core. The indication of the external gold foil is believed to be too high because of higher neutron leakage through the thick water reflector during the excursion than during the calibration runs. The reason for the higher leakage has not been established, but it is indicated by the fact that the distribution of activation along the axial string of foils varies between the two runs. The distribution is considerably flatter in the case of the fast excursion.

Other indications of energy are open to more question than the foil activations. The energy as determined from the temperature of the external fuel plate is uncertain because the thermocouple failed before it became evident that the temperature distribution within the plate had equalized. If equalization had failed to occur, however, the surface temperature would have indicated too low an energy. Actually, the indicated energy, on the assumption of constant temperature through the fuel plate thickness, is 180 Mw-sec. This value, of course, depends upon the measurement of the ratio of thermal neutron flux at the external plate to the thermal flux at some position in the core. There is some possibility that this measurement is in error, since it was difficult to ensure accurate placement of the foil on the plate, which was submerged under several feet of water. Any change in neutron leakage from the core under the conditions of the excursion would, of course, affect the measurement also.

There is evidence, however, that the thermocouple calibration itself may be in error. A Ba-140 fission product analysis was made on a sample of the external plate by E. P. Steinberg of the ANL Chemistry Division. After allowing for the fissions produced by several runs which were made with the external plate installed, prior to the final excursion, the total energy of the final excursion, as determined by the fission product analysis, is 109 Mw-sec. Mr. Steinberg estimates that the analysis is accurate to within $\pm$ 10 %.

Throughout the remainder of this report, the energy value of 135 Mw-sec, as determined by the 1-gram cobalt foil, will be accepted as

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the value of the total energy of the excursion. It should be correct to within a few per cent in relation to the energies of other excursions made prior to the final one, although in absolute magnitude it is subject to the uncertainties discussed in Section III-B.

Using the established value of the total energy, it is possible to replot the ion chamber records of Figure 21 in terms of absolute reactor power. In Figure 22 such a plot has been made, to a linear rather than a logarithmic scale. In plotting the portion of the curve that follows the maximum - the region in which the ion chamber records fail to agree - the upper record (Trace No. 1) was used. This choice was an arbitrary one. Since the power calibration depends upon integration and normalization of the curve to the proper energy value, an error in the shape of the curve will produce an error in power calibration. A plot based on Trace No. 2 (the flattest curve) would give a peak power of 13×10^9 watts. The power calibration must be considered uncertain between that value and the one shown in Figure 22.

Also plotted in Figure 22 are the two important fuel-plate temperature records and the record from the pressure transducer. All records except the latter have been corrected for the galvanometer time response. The early discontinuity in the pressure curve precludes a complete correction of the curve, but, as mentioned previously, the approximate effect of correction is to shift the curve to the left by about 2 milliseconds. This would indicate that the pressure began to rise rapidly about 3 milliseconds before peak power was reached.

Evidently, after disappearance of the pressure trace the pressure rose rapidly and to a very high value. The diaphragm of the transducer was designed for protection against excess pressure to to 3,000 psi by a stop which the diaphragm contacted when the pressure reached a value of about 2,200 psi. The installation of the diaphragm in the transducer was such that there was little possibility of deflection of the diaphragm by any agency other than a surrounding pressure. The transducer was ejected from the reactor by the explosion, but was recovered and disassembled. It was found that the diaphragm had contacted the stop with sufficient force to upset the end of the stop, and to press a permanent dent into the diaphragm (Figure 23). Analysis of the condition of the diaphragm and stop by W. S. Flinn of ANL Reactor Engineering Division indicates that the peak pressure was at least as high as 6,000 psi, and probably higher than 10,000 psi. The duration of the pressure is of course not indicated.

The results from the slower movie camera have already been presented (Figure 20). The faster cameras gave some additional results which are of considerable importance. Just prior to the appearance of the ejected material above the upper edge of the shield tank, a flash of light from the tank can be seen illuminating the shadows underneath the control

rod mechanism. This flash is extinguished before any ejected material comes into view. The flash lasts about 3 milliseconds (one frame in one of the high speed cameras, and 2 frames in the other high speed camera which evidently was not in synchronism with the first one). This flash is evidently of nuclear origin, similar to those that had been photographed previously in excursions of less violence (ANL-5211). The extinction of the flash indicates that, as would be expected, the nuclear excursion was terminated before any very large displacement of the reactor materials had taken place.

A second phenomenon shown by the high speed cameras is the presence of pieces of material in the ejected debris which seem to be emitting light of sufficient intensity to be plainly visible, even though the excursion was made in bright sunlight. It has been postulated that these may be hot fragments of fuel element which are burning in air.

C. Examination of Fuel Plates and Fragments

The explosive force of the excursion broke the reactor tank and completely disassembled the reactor core. Some of the fuel elements and fuel element fragments remained in the shield tank and the pump pit, while others were blown completely out, the smaller fragments travelling as far as 200 feet. It was quite evident that extensive melting had occurred. Only one fuel element was found which contained all or nearly all of its original fuel plates (Figure 24). From their appearance, it seemed that the plates on the convex side of the element (the side nearest center of core) had experienced melting of the "meat" over almost the entire length, although the clad had given way in spots only. On the concave side of the element it appeared that melting of the "meat" had extended to within about 3 inches of the ends of the plates. This element was evidently the one which had occupied position 6 in the core (Figure 19). The average neutron flux over this element was estimated to be about 1/2 the average over the entire core.

A number of the side plates of fuel elements were found holding clusters of end fragments of fuel plates (Figure 25), the remainders of the plates having been melted or torn away. Other side plates were found with no fuel plates remaining. These gave the appearance of having had the fuel plates rather neatly stripped from their grooves (Figure 26).

Among the individual plate fragments were some which gave the appearance of having had the "meat" melt and flow out, while the clad remained intact. An example is shown in Figure 27. This particular plate was one of the loose plates which had been used in the special thermocoupled fuel element. Punchings from this plate fragment were analysed for the uranium-aluminum ratio by the ANL Chemistry Division. The ratio for such punchings (meat plus clad) was found to range from 10% to 50% of the ratio for a similar, but undamaged, fuel plate. The lower of the ratios were found in the punchings taken near the frayed edge of the fragment.

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Other typical fragments are shown in Figures 28, 29, and 30. Many small sheets of clad, with some fuel alloy still adhering, as shown in Figure 28, were found. Another common type of fragment was a small pellet of spongy aluminum, as shown in Figure 30. The sample shown is one of the largest of those found. Although the material of these pellets was spongy in texture, as though it had been blown up by the evolution of gas, it was quite malleable, and obviously metallic. Analysis of two of these pellets by the ANL Chemistry Division showed the uranium-aluminum ratio to be 30 to 40% higher than that of punchings (meat plus clad) from new fuel plates. When heated in vacuo the pellets evolved gas slowly. This gas was shown to be at least 90% hydrogen, and in quantity corresponded to a hydrogen content of about 0.018% by weight in the pellet. In order to extract this quantity of gas the samples had to be heated approximately to the melting point.

Observers who visited the contaminated area south of the reactor (Figure 38) shortly after the excursion reported the presence of a white powdery deposit, which was taken to be aluminum oxide, in connection with the fuel plate fragments. Examination and analysis of surface samples from the earth in the vicinity did not establish the presence of such an oxide. When, after several days, it became practical to examine the ground carefully and in detail, the white deposit was no longer in evidence. Analysis of silt deposited from water pumped out of the pump pit during cleanup operations did not yield definite answers as to the presence of oxide from fuel plates.

D. Explosive Effects

It has been mentioned that the explosion was heard as a rather loud report in the control trailer. In order to form some estimate of the force of the explosion, construction dynamite was exploded at a distance of half a mile from the control trailer shortly after the reactor excursion. Those who had witnessed the Borax excursion were asked to compare it with the dynamite explosion. Shots of 1, 2, 3, and 4 sticks were made, each stick being about 1/2 pound of 40% dynamite. Opinions varied considerably. Those who had been inside the control trailer for both kinds of explosion had the opinion that the Borax excursion sounded like 2 sticks of dynamite, but not as sharp as the dynamite. Most of the observers who had been in the open thought that about 3, but not more than 4, sticks was a proper comparison, but they felt that the Borax excursion was a sharper explosion.

The damage done to the equipment perhaps gives a more quantitative idea of the explosive effect. The breaking of the reactor tank was the most striking manifestation of explosive force. Figure 31 is a view down into the shield tank shortly after the excursion, showing the dished bottom head of the reactor tank, which was all that remained, and the large hole that

was torn in the shield tank, on the pump pit side, by flying tank fragments. Figure 32, a view into the pump pit, shows the hole in the shield tank more clearly. Figures 33, 34, and 35 show fragments of the reactor tank after they had been removed from the pit.

Longitudinally, the tank had been made in two sections, the bottom section being a right cylinder with dished bottom head, and the top section having a slight taper, and, of course, being open at the top. The two sections were flanged, gasketed, and bolted together. The water level in the tank had stood nearly at the top of the upper section. The explosion broke the bolts fastening the two sections of tank, tossed the upper portion of the tank out of the shield tank, and deposited it at the bottom of the shield mound (Figure 36). The walls of the upper section, which previously had had a uniform taper, were bulged into a nozzle shape.

The fact that the reactor tank failed was not surprising, since it was constructed of 1/2-inch carbon steel for a design pressure of 125 psi. It was not expected to withstand pressures greatly in excess of 1,000 psi. The manner in which it fragmented, without regard for flanges or other reinforcements, was, however, striking. The tank fragments were examined by W. S. Pellini, Metallurgist, of the U. S. Naval Research Laboratory, who has conducted researches on the brittle fracture of steels. It was his opinion that the tank had been subjected to a pressure much greater than its breaking strength. He was able to estimate, by examining the lines of parting, that the breaking process had occupied a time of about 1/2 to 1 millisecond, and that the pressure had therefore been maintained at a high level for at least that length of time. He was of the opinion, however, that the fragments did not in themselves give information about the rate of rise of pressure.

A second manifestation of the force of the explosion was the carrying away of the control rod mechanism. This mechanism, which weighed about 2,200 pounds, sat on a base plate about 8 feet above the top of the reactor tank. Except for the base plate, about 4 feet square, the top of the 10-foot shield tank was essentially unobstructed. The force of the explosion plus the impingement of water and debris on the base plate tore the plate loose from its carriage, and, as revealed by the high speed movies, tossed the mechanism about 30 feet into the air. Figure 37 shows the control rod mechanism in the position it occupied after the fast excursion. The long extension rods which transmitted motion from the mechanism to the control rods are still attached, as is a heavy steel spider which supported guide bearings for the extension rods in the reactor tank.

In order to get some idea of whether the energy of the nuclear excursion was sufficient to account for the explosion damage, discussions were held with Mr. W. E. Morris, Chief of the Explosion Effects Division of the U. S. Naval Ordnance Laboratory, who visited the Borax site some days after the excursion and inspected the results. Mr. Morris made calculations

indicating that explosive charges in the range 6 to 17 pounds of TNT would produce comparable damage to the reactor and shield tanks. The equivalent, energy-wise, of the 135 Mw-sec of nuclear energy released in the excursion is about 70 pounds of TNT.

E. Health Physics Measurements

A number of observations, primarily related to health physics and radiation control, were made by the IDO Radiation Protection Section. With the consent of Dr. G. V. Beard, Chief, IDO Health and Safety Branch, those observations which contribute to the understanding of the excursion phenomenon are summarized here. The discussion and theoretical estimates applied to the data are those of the author. Full details of all the observations of the Radiation Protection Section are expected to be presented in a forthcoming IDO report.

During or immediately following the excursion an instantaneous dosage rate in excess of 400 mr/hr was indicated on survey meters at the distance of approximately 1/2 mile from the reactor. Within approximately 30 seconds the rate had decreased to 25 mr/hr and continued to decrease rapidly. Within less than 5 minutes the readings had decreased to less than 1.0 mr/hr.

These intensities, which were undoubtedly from pure gamma radiation, seem consistent with the energy release of the excursion. At the time of the excursion the air temperature was 53.8°F, and the barometric pressure was 25.285 inches. Taking an effective air attenuation length of 270 meters for delayed fission-product gammas under these conditions, one estimates that, if no other shielding than air were present around the total mass of fission products from an excursion of 135 Mw-sec, the radiation intensity at 1/2 mile would be about 110 mr/hr after 30 seconds. Actually, something like half the fuel remained in the shield tank and pump pit. Of the remainder, it seems reasonable to assume that its radiation might be attenuated by a factor of 2 or 3 by local obstructions.

Beta-gamma film packets located at 1500 feet from the reactor, roughly down-wind but outside the path of fall-out, recorded exposures of 50 mr/hr. These exposures were probably primarily from gammas originating in the material which stayed in the reactor vicinity. The total integrated exposure from complete gamma decay of all fission products of a 135 Mw-sec excursion would be about 140 mr if only air shielding were present.

An incidental observation of gamma radiation from the excursion was afforded by a large EBR ion chamber which is used for monitoring exhaust air. The chamber record went off scale immediately after the excursion and came back on scale 2.5 minutes later, indicating between 8 and 15 mr/hr.

This reading is higher than that given by the survey meters, converted to the same time, by a factor of 2 to 4. Some of the discrepancy is perhaps attributable to the higher location of the chamber (near the top of the EBR building) from which it could "see" the fragments on the ground more directly. The record is, however, puzzling in other respects. Once it returns on-scale it appears to decay approximately as $t^{-3.4}$. It seems probable that the instrument does not recover immediately from the over-range transient excitation.

The air-dispersed material from the reactor was blown in a direction about 35 degrees west of south. Mobile monitoring teams crossing the trajectory of the material at 8:35 AM. (15 minutes after the excursion) at a distance of about 0.8 mi. from the reactor, recorded a maximum reading of 5 mr/hr with open-window survey meter, 3 feet above ground. A similar reading at 8:45 AM, about 2.3 miles from the reactor, gave 2.0 mr/hr. The maximum readings at these same distances, at 9:15 - 9:20 AM, after the air-borne material had definitely passed over, were 6 mr/hr, with open-window meter 1 inch above ground. By 10:30 the following morning these intensities had decayed to 0.05 mr/hr. The intensities were maintained at roughly the maximum level over a path width of about 500 feet, and fell to about 1/10 the maximum along the edges of a path about 1500 feet wide.

For comparison with the foregoing observations, an estimate has been made by the author of the total activity of the fuel left in the immediate vicinity of the reactor, by extrapolation of later surveys in the reactor area (cf. section F, following). This estimate indicates that the fuel, if spread uniformly over an area of 5×10^8 square feet, would give a reading of 6 mr/hr on an open-window meter 1 inch above ground, 1 hour after the excursion.

About two hours after the excursion the wind direction changed to a direction roughly the reverse of its original direction. Starting at about 1:30 PM, and continuing into the afternoon, the beta-gamma air-monitoring station at the Central Facilities area of NRTS showed a background increase which reached a peak of about 5 times the normal value, and then began to decrease. The abnormality had disappeared by the following day. This observation was the only indication of air-borne activity from the excursion at sites in the NRTS area other than the vicinity of the Borax reactor.

Figure 38 shows the results of a survey of the contaminated area just outside the fence of the Borax area, made on August 2. The maximum values at that time in the area outside the fence were about 200-250 mr/hr. The contours inside the fence can be indicated only approximately because of the presence of large fragments, giving local high readings, on the ground. On July 22, a few hours after the excursion, the general levels inside the reactor area fence varied from about 10 r/hr at the entrance of the pump pit (but outside the pit) to about 100 mr/hr near the north corner of the fence.

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The peculiar ejection pattern, with practically all of the ejected material lying to the south of the reactor, is believed to be the result of deflection of the ejected material by the base plate of the control rod mechanism. The position of the carriage of the mechanism indicates that the mechanism probably tilted toward the north as it pulled loose from the carriage.

F. Survey of Remaining Fuel

An estimate of the fuel remaining in the Borax vicinity was derived from a rough survey of the gamma activity in all areas where measurable activity remained after about two weeks.

Spot checks over the contaminated area outside the Borax fence determined that the ratio of total (open window) activity to gamma (closed window) activity was about 3.5. This conversion was applied to the data from which Figure 38 was derived to get the total gamma activity outside the fence. After all the obvious large pieces of fuel element had been picked up from the ground, and from inside the shield tank and pump pit, gamma surveys of these areas were made to determine the area integration of the activity. The large pieces of fuel elements were then laid out in a number of groups, and the area integral of the gamma radiation from each group was determined.

A decay curve of the fuel fragment activity was constructed by combining measurements made by Borax personnel with those made by the IDO Radiation Protection Section (Figure 39), and this curve was used to convert all the survey measurements to the same day, arbitrarily chosen as August 19. The integrated radiation intensities of fuel in the various locations on this date are given in the Table below.

Description of Fragments	Area Integral of γ Intensity on 8/19/54, $(cm^2)(r)/hr$
General distribution of fragments outside fence (Figure 38)	24×10^4
General distribution of fragments inside fence	38×10^4
Fragments remaining in shield tank	4×10^4
Fragments remaining in pump pit	33×10^4
Large pieces of fuel element	10×10^4
Fragments mixed with other miscellaneous debris	4×10^4
Total	113×10^4

The following method was used to determine the activity which would have been exhibited by all the fuel if it had been present.

There was on hand a fuel element which had been in the reactor for all of the experiments during 1953, but had been removed from the core before the 1954 tests. This element was removed from its coffin and surveyed, with the same meter as that used for the other surveys, on August 19. Its integrated activity was $2.14 \times 10^4 (cm^2)(r)/hr$. Also available was an element which had not been used in 1953, but had been used for a few excursions, of known total energy, during 1954. It was surveyed on August 31, and found to have integrated activity of $0.20 \times 10^4 (cm^2)(r)/hr$. Using this measurement for normalization, and the decay relations of Reactor Handbook, Vol. I, p. 739, Table 2.1.3, the effects of all excursions made during 1954 were added up, the result being, that if the fuel element had been used for all the 1954 runs, its activity on August 19 would have been $2.44 \times 10^4 (cm^2)(r)/hr$. After adjustments were made for the ratio of flux at the positions of the normalizing elements to the average flux in the reactor core, the total indicated activity of the core on August 19 was found to be, by coincidence, just $113 \times 10^4 (cm^2)(r)/hr$.

Obviously the foregoing estimates are very rough, since, for example, it is assumed that the average gamma shielding of all material surveyed on the ground is the same as the self-shielding (for gammas) of a fuel element. Furthermore, the ground surveys are necessarily far from precise. It can at least be said, however, that the survey gives no indication that any large fraction of the fission products left the vicinity of the reactor.

G. Reclamation of Reactor Equipment

Although the reactor tank and its contents were completely wrecked, and the general contamination made it impractical to continue experiments at the Borax I site, it was possible to reclaim the major items of equipment which were outside the reactor tank. This equipment was removed to the uncontaminated area outside the west fence of the Borax I site and was there decontaminated by washing with water, detergents, and solvents. After decontamination repairs were made if necessary.

The control rod mechanism (Figure 37) was repaired and installed on the Borax II reactor site, which has been set up about 200 yards east of Borax I. The pumps which have characteristics applicable to Borax II have also been reclaimed. The electronic and recording portions of the instrumentation were essentially undamaged and required no decontamination beyond the removal of surface dust. None of the equipment which was located outside of the pump pit and reactor tank (e.g., air compressors, water deionizer, switch gear) was damaged; all of the equipment applicable to Borax II has been installed with that reactor.

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V. DISCUSSION OF EXPERIMENTAL RESULTS

Inasmuch as it was not possible to progress in the experiments by gradual steps from the relatively mild excursions to the final destructive one, the question arises as to whether the differences in the observable effects may be attributed simply to quantitative differences in the fundamental processes involved, or whether qualitatively different phenomena, of a type absent in the milder excursions, occurred in the final experiment. Various aspects of this question will be considered in the following discussion.

An almost trivial question is whether the period attained in the fast excursion was consistent with the amount of excess reactivity supplied and with the rate of its application. Since a period as short as 2.6 milliseconds has not previously been attained in a reactor of relatively long neutron lifetime, the question is perhaps worth some comment in passing. The observed period of 2.6 milliseconds is longer than that which would result if the total available excess reactivity (3.96%) had been applied before the shutdown process came into effect. An excess reactivity of 3.26% is sufficient to produce an asymptotic period of the observed magnitude. Actually it had been calculated before the experiment that the reactor power would have risen sufficiently to begin the shutdown process by the time the rod had added about 80% of the available excess reactivity. The results confirm this estimate to within the limits of precision as determined by the uncertainties in neutron lifetime and available excess reactivity. The fact that the rod was still in motion during the part of the transient recorded by the instruments would hardly be expected to show up as a non-linearity in the logarithmic ion chamber records, since the rod would not travel far during the short duration of the record.

An effect which is present in both the mild long period excursions and in the short period excursion, but which changes in magnitude between these two conditions to such an extent that it becomes in effect a qualitative difference in behavior, is the distribution of temperature within the fuel plate itself. Whereas theoretically the temperature difference between the center and the surface of the fuel plate, before boiling begins, amounts to only a few per cent in the case of a period of 15 to 20 milliseconds, it amounts to more than a factor of two in the case of the 2.6 millisecond period. Figure 40 is a calculation, by W. M. Sandstrom, of the theoretical temperature distribution in a fuel plate when the power generation in the meat of the fuel plate is rising exponentially on a 2.6 millisecond period and heat is being lost from the surface of the fuel plate only by solid conduction into the outside water. Since it is only the surface temperature which is affected in forming the steam to limit reactor power, it is evident that this effect alone is one which contributes to the production of higher maximum temperatures in the fuel plates.

Despite the effect described above, the measurements on the fast excursion, when compared with those on the slower period excursions, show what appears to be a rather rational behavior of total energy and maximum reactor power. In Figure 41 the total energy of the excursion is shown as a function of reciprocal reactor period. The lower points on this plot are derived from those which were previously shown in Figure 13, but from all energies four megawatt seconds were subtracted, as a correction for the more or less constant amount of energy that must be supplied in all cases simply to raise the fuel plate temperature to the boiling point of water. Obviously some such correction must be made if a rational extrapolation is to result, but the choice of the magnitude of the correction is somewhat arbitrary. The four megawatt seconds chosen is the amount of energy which would raise the mid-point temperature of the average fuel plate to the boiling point. With this correction the data points, including that for the fast excursion, appear to lie roughly on a straight line on the log-log plot, and it seems reasonable to believe that the curve so obtained would give approximate values for energy of excursions in the interpolated region between the two sets of data. Further it should be pointed out that extrapolation of the curve of maximum power (Figure 14) to a period of 2.6 milliseconds would predict a maximum power of 14×10^9 watts. This value lies between the two limits which have been established for the maximum power of the fast excursion.

With regard to the destructive and dispersive effects produced by the final experiment, the evidence is that they are compatible with the magnitude of the nuclear energy release. Since, however, they imply a very rapid rise of pressure to a quite high peak value, it is reasonable to inquire whether such pressure characteristics could be produced by the transfer of heat from metal fuel plates (or fuel plate fragments) to water. Unfortunately, there is little in previous experience which throws light on this question. Certainly, however, the answer will depend strongly on the maximum fuel plate temperature reached in the excursion, and a consideration of fuel plate temperatures will at least contribute to the intuitive thoughts on the problem.

Naturally, the thermocouples on the fuel plates recorded only the early part of the temperature excursion. Yet one of them did last until the surface temperature of the fuel plate reached approximately the critical temperature of water. At that time only about 20% of the total nuclear energy release of the excursion had taken place. If a temperature distribution approximately like that of Figure 40 prevailed at that time (as it should have, since the power increase was still approximately exponential), the metal at the center of the plate must have been already partly melted.

If it is assumed that all of the 135 Mw-sec of nuclear energy released during the excursion was effective in raising the fuel plate temperature (no heat loss), and if it is further assumed that no evaporation of fuel plate metal occurred, the maximum temperature reached by the hottest portion of

the hottest fuel plate would lie between 5000 and 7000°F, depending on whether a flat temperature distribution, or one like that of Figure 40 is assumed within the fuel plate. The boiling point of aluminum at atmospheric pressure is 4185°F.

Actually, the foregoing assumption must be a poor one, since the ion chamber records (Figure 22) indicate that an important fraction of the total energy release occurs while the power is decreasing. This decrease can only be caused by disassembly of the reactor core, or by the ejection of water from the core - that is to say, by the transfer of heat from the fuel plates to the water. As has been stated in a previous section, the indication is that in the milder subcooled excursions only about 1/4 of the energy, over and above that required to raise the fuel plate temperature to the boiling point of water, appears as a further increase in fuel plate temperature. The 1953 experiments showed that, in the case of excursions with saturated water, only about one-half the total energy appeared as fuel plate temperature rise, even for reactor periods as short as 5 milliseconds. It therefore seems reasonable to assume that not more than half the total energy is effective in raising fuel plate temperature in the case under discussion. With this assumption the maximum temperature lies between 2300 and 3300°F, again depending on the assumption with regard to internal temperature distribution.

To summarize, then, it is known that most of the fuel plates reached the melting temperature, and it is surmised that a large fraction reached temperatures in the range 2000 to 3000°F. The entire heating process was accomplished in an interval of time of the order of 10 milliseconds with the fuel plates in intimate contact with cold water. At the time of maximum pressure the fuel plates may already have disintegrated sufficiently to increase their surface area to an important degree. Clearly this situation is one which has not previously been realized experimentally, at least on any large scale, and one which involves fundamental properties of water that have not been investigated experimentally. While it is probable that further theoretical analysis will lead to a better understanding of the problem, it can only be said now that the very brief study which has been made to date has not revealed any aspect of the results of the excursion which can definitely be shown incompatible with the hypothesis that the explosion was purely a "steam" explosion.

The alternative view, of course, is that an important release of chemical energy, resulting from a reaction between aluminum and water, accompanied the nuclear release. Perhaps the most troublesome question to be answered if this view is adopted is why, if a significant fraction of the aluminum reacted, the reaction stopped before a still larger fraction was involved. Clearly there is now lying on the ground a large quantity of finely divided metallic aluminum which, during the excursion, was molten. If it is accepted that the presence of this unreacted material is not inconsistent with the assumption that other material reacted violently, then it is not

possible to reach a conclusion from a material balance, since only rough inventories can be made of either the remaining aluminum or uranium, and the reaction of a small fraction of the total aluminum would suffice to give an energy release comparable to the nuclear release.

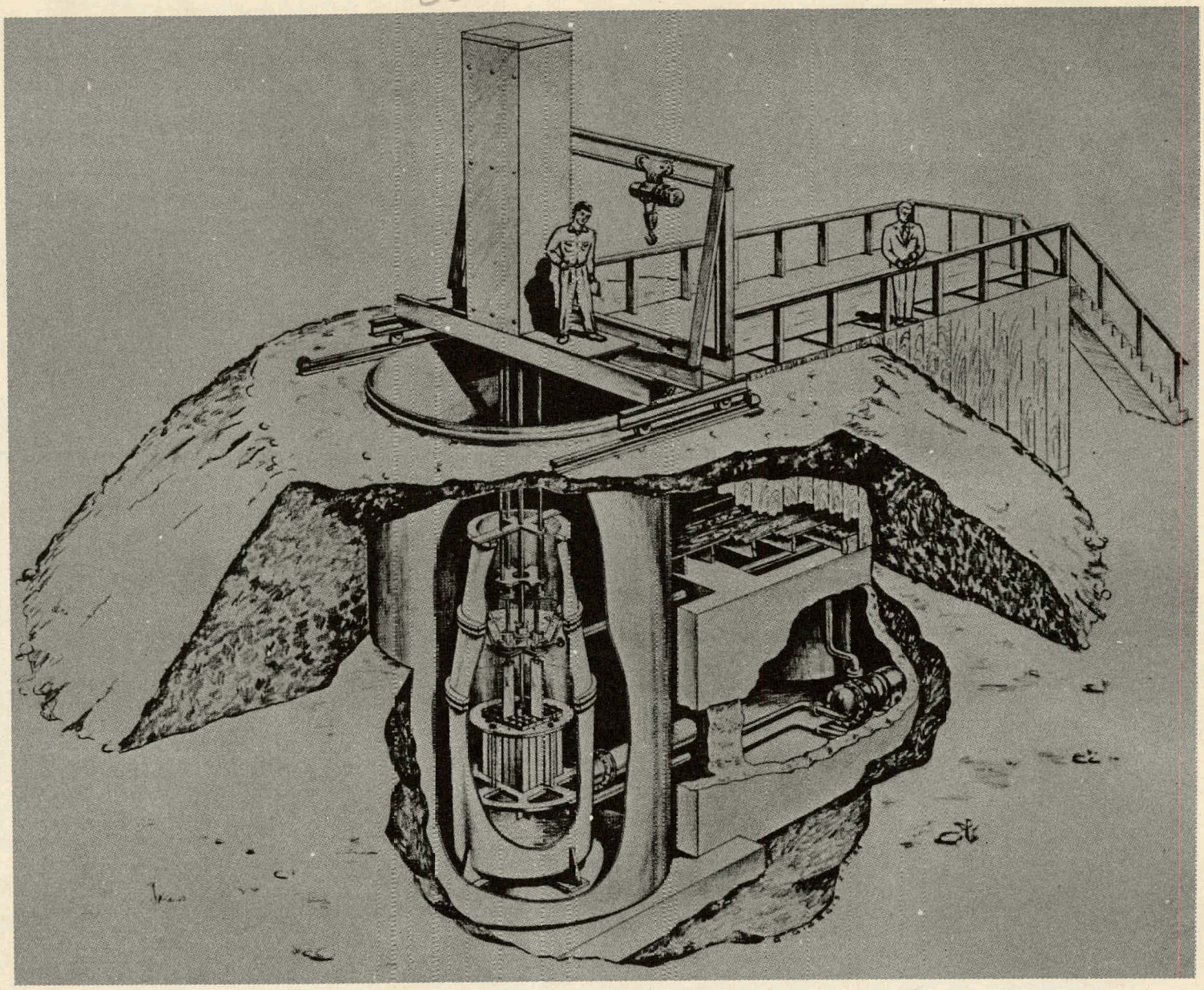

FIG. 1

CUTAWAY DRAWING OF BORAX INSTALLATION

37

Figure 2

Borax I Reactor Site

The view is toward the reactor through the pump pit. The trailer on the left contains the recording instruments. Tanks on the right hold a supply of shield water and deionized reactor water.

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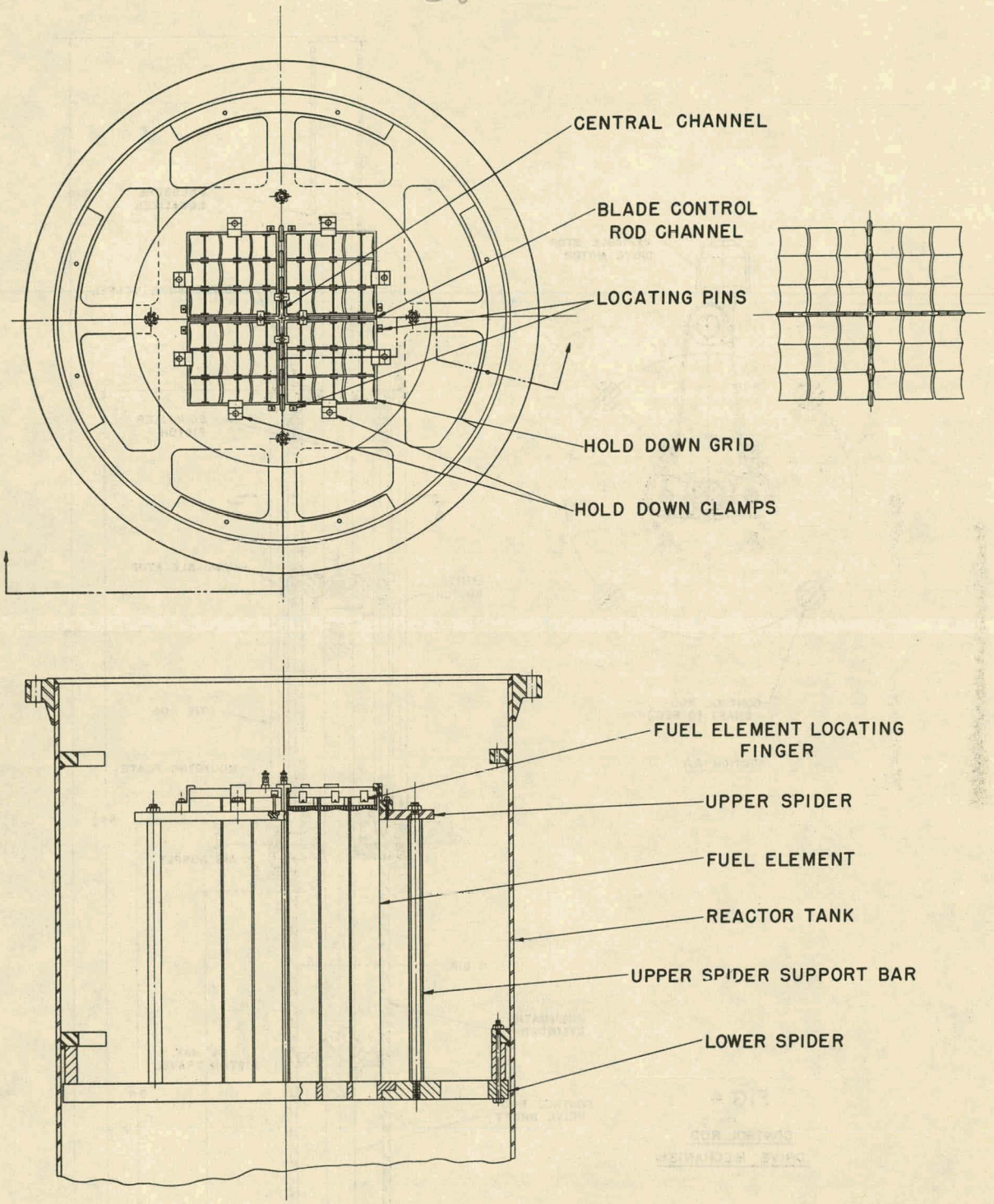


Figure 3

Core Arrangement

Only the lower section of reactor tank is indicated (cf. Figure 1)

39

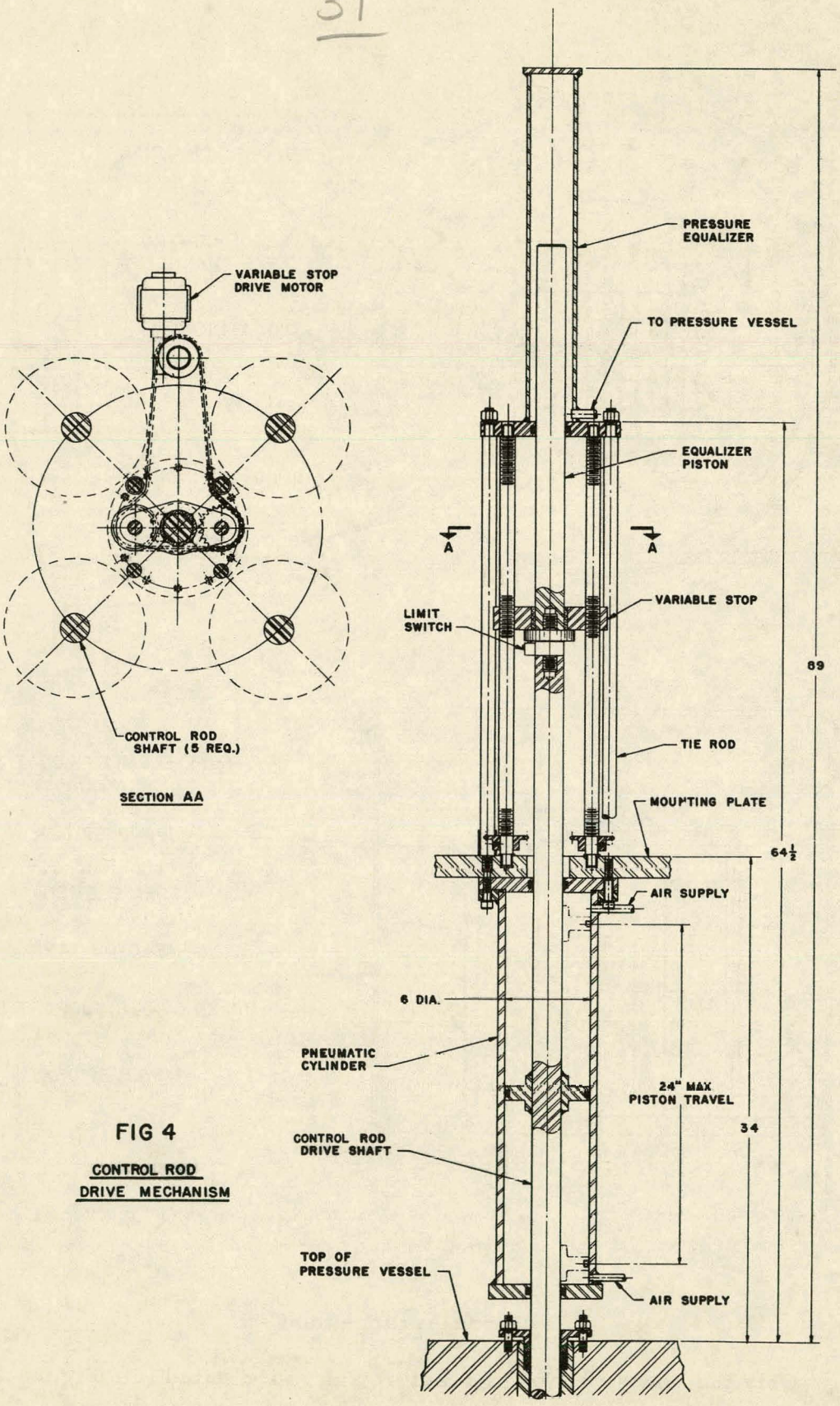
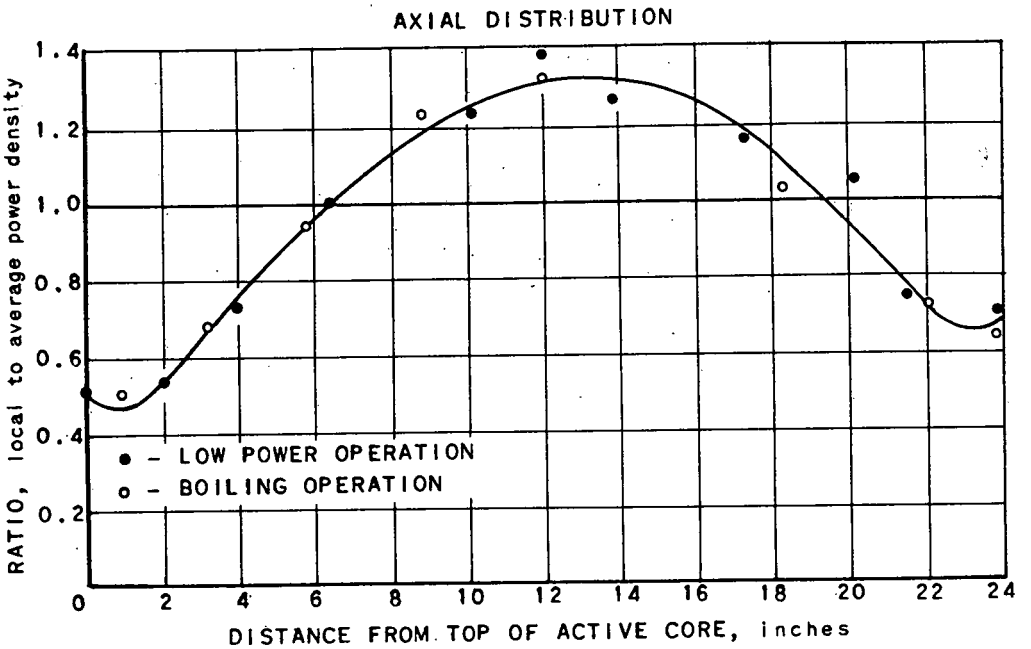


FIG 4

CONTROL ROD
DRIVE MECHANISM

40



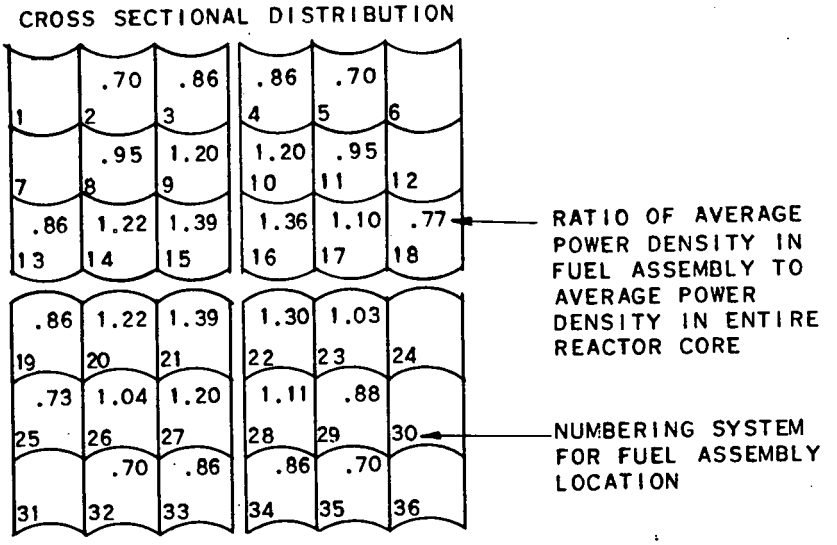


FIG. 5

DISTRIBUTION OF POWER DENSITY
IN REACTOR CORE

41

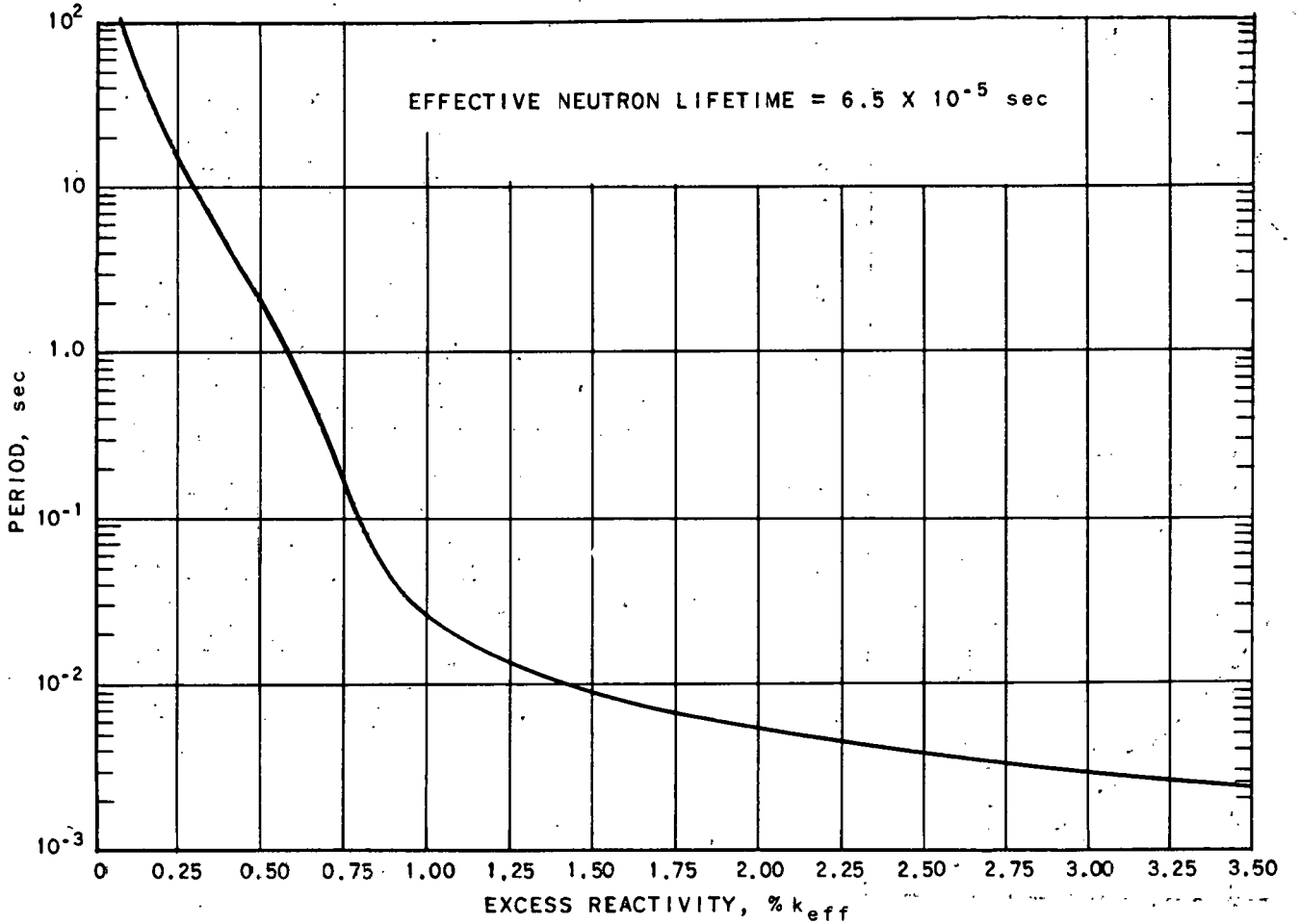


FIG. 6
CALCULATED ASYMPTOTIC PERIOD AS
FUNCTION OF EXCESS REACTIVITY

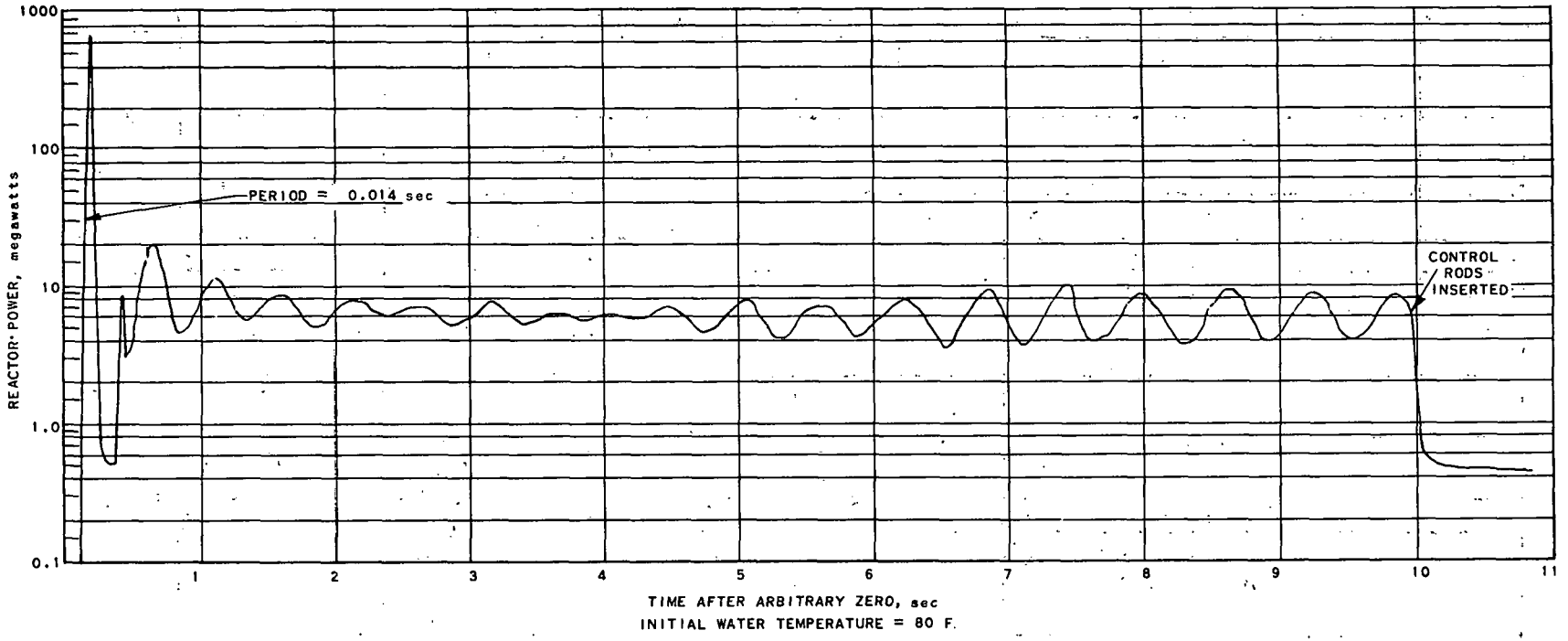


FIG. 7
REACTOR POWER VARIATION DURING 10 SECOND RUN
FOLLOWING INITIAL EXCURSION OF 14 MILLISECOND PERIOD

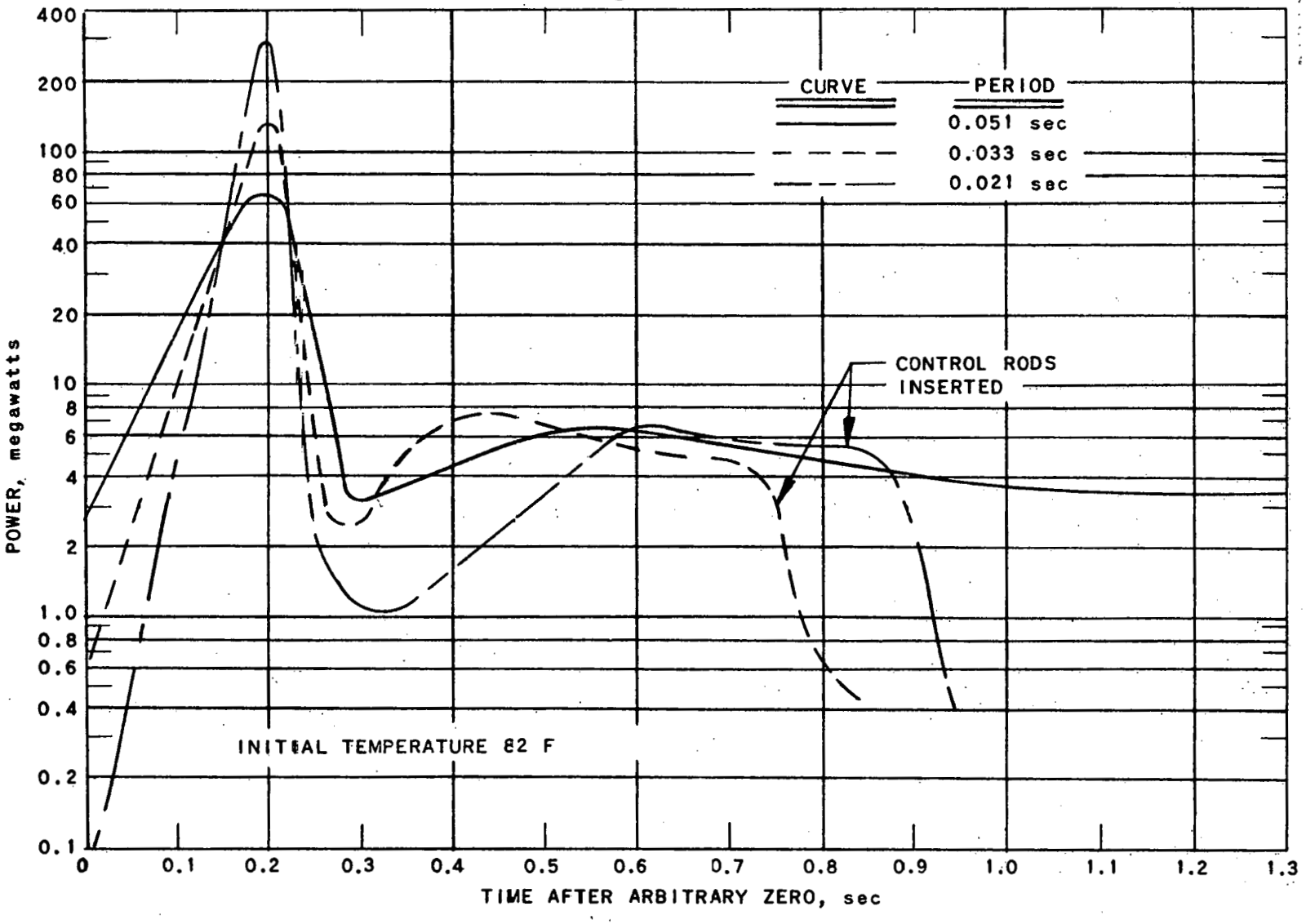
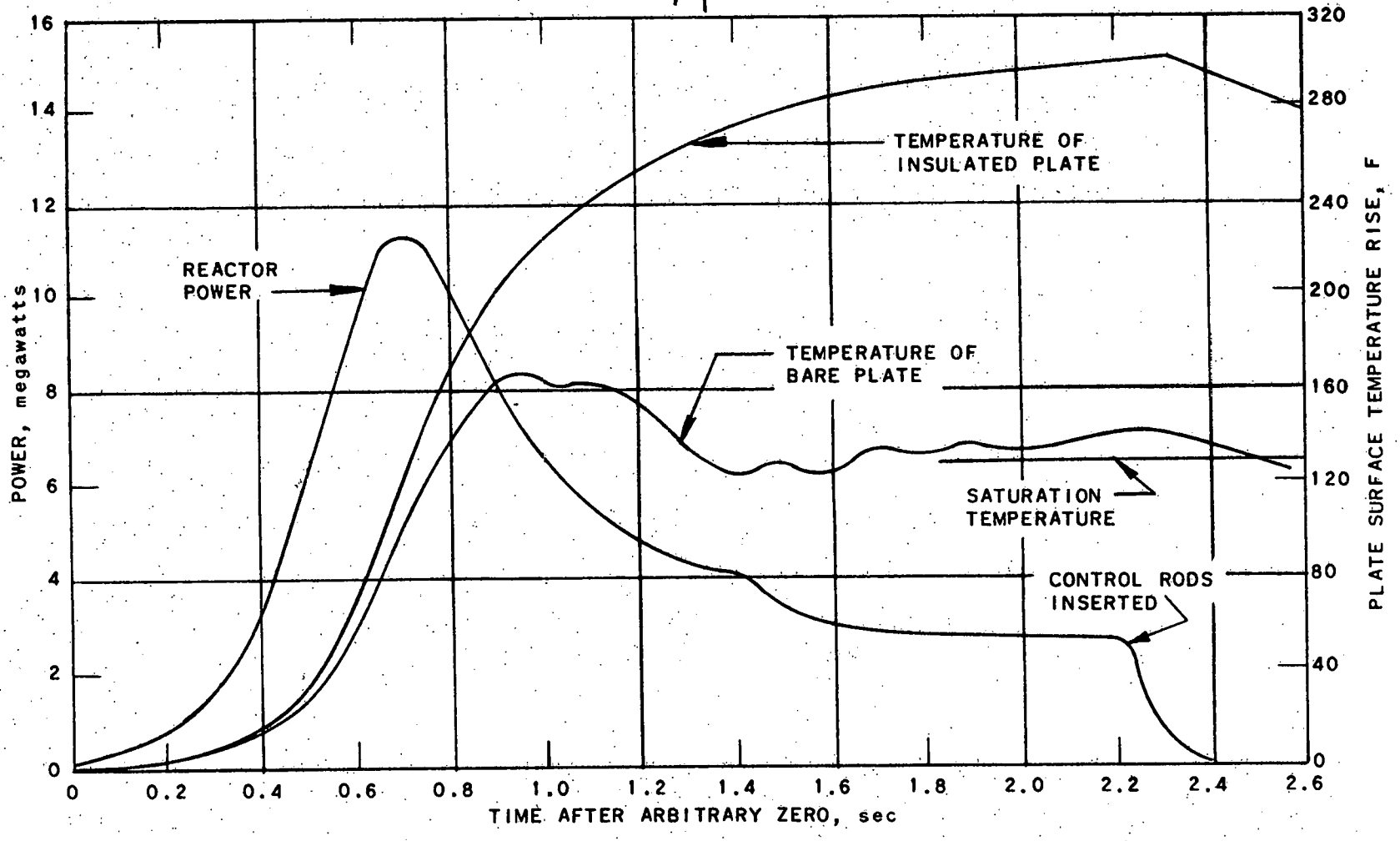


FIG. 8
POWER EXCURSIONS OF THREE DIFFERENT PERIODS

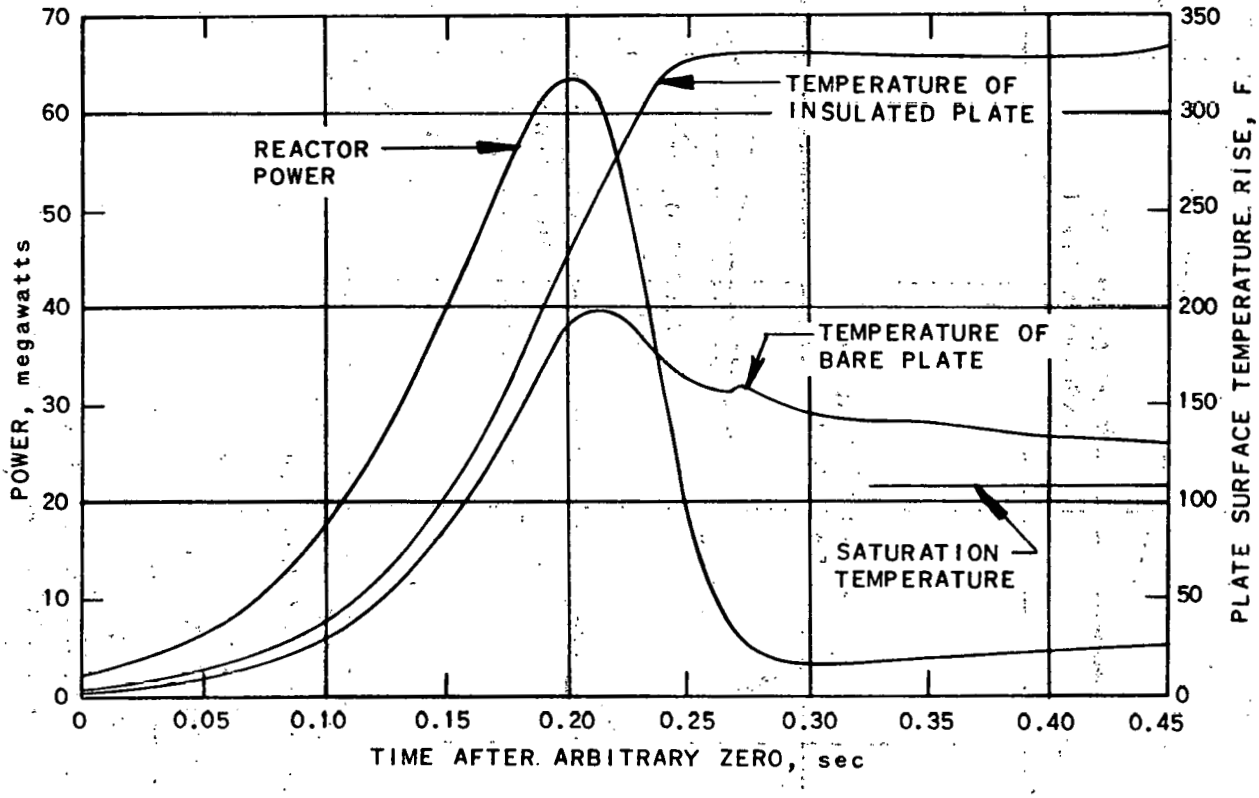


PERIOD = 0.134 sec

INITIAL TEMPERATURE = 80 F

FIG. 9
POWER AND FUEL PLATE TEMPERATURE RISE DURING EXCURSION

45

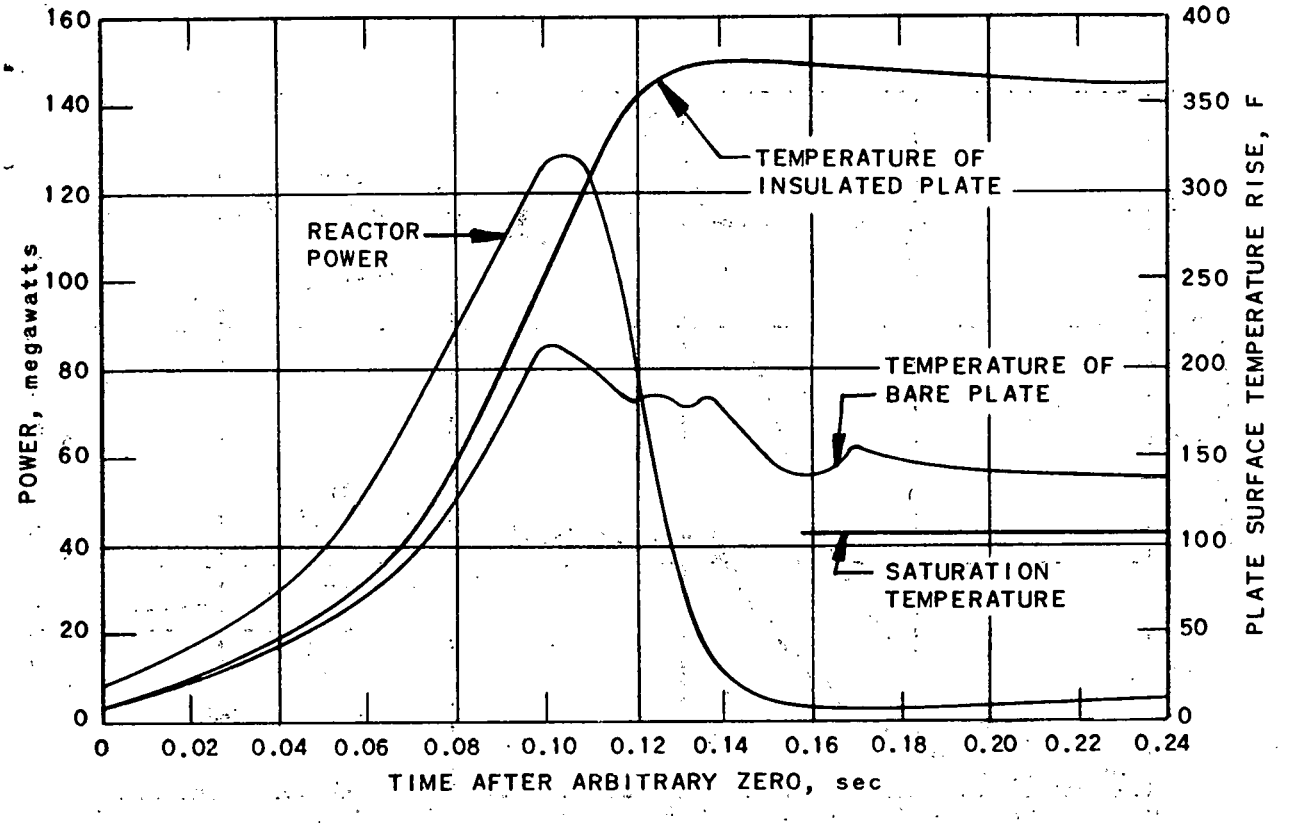


PERIOD = 0.051 sec

INITIAL TEMPERATURE = 82 F

FIG. 10
POWER AND FUEL PLATE TEMPERATURE
RISE DURING EXCURSION

46

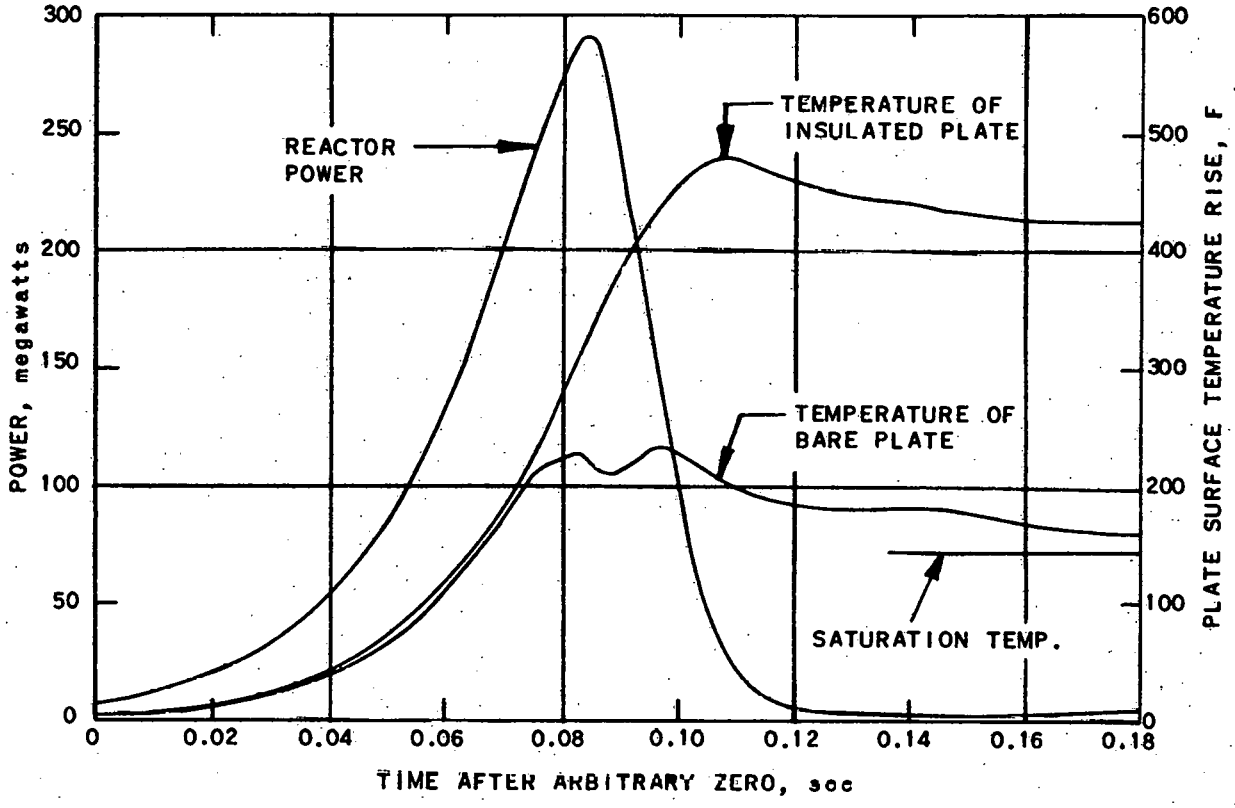


POWER = 0.033 sec

INITIAL TEMPERATURE = 81 F

FIG. 11
POWER AND FUEL PLATE TEMPERATURE RISE DURING EXCURSION

47



PERIOD = 0.021 sec
INITIAL TEMPERATURE = 82 F

FIG. 12
POWER AND FUEL PLATE TEMPERATURE RISE DURING EXCURSION

48

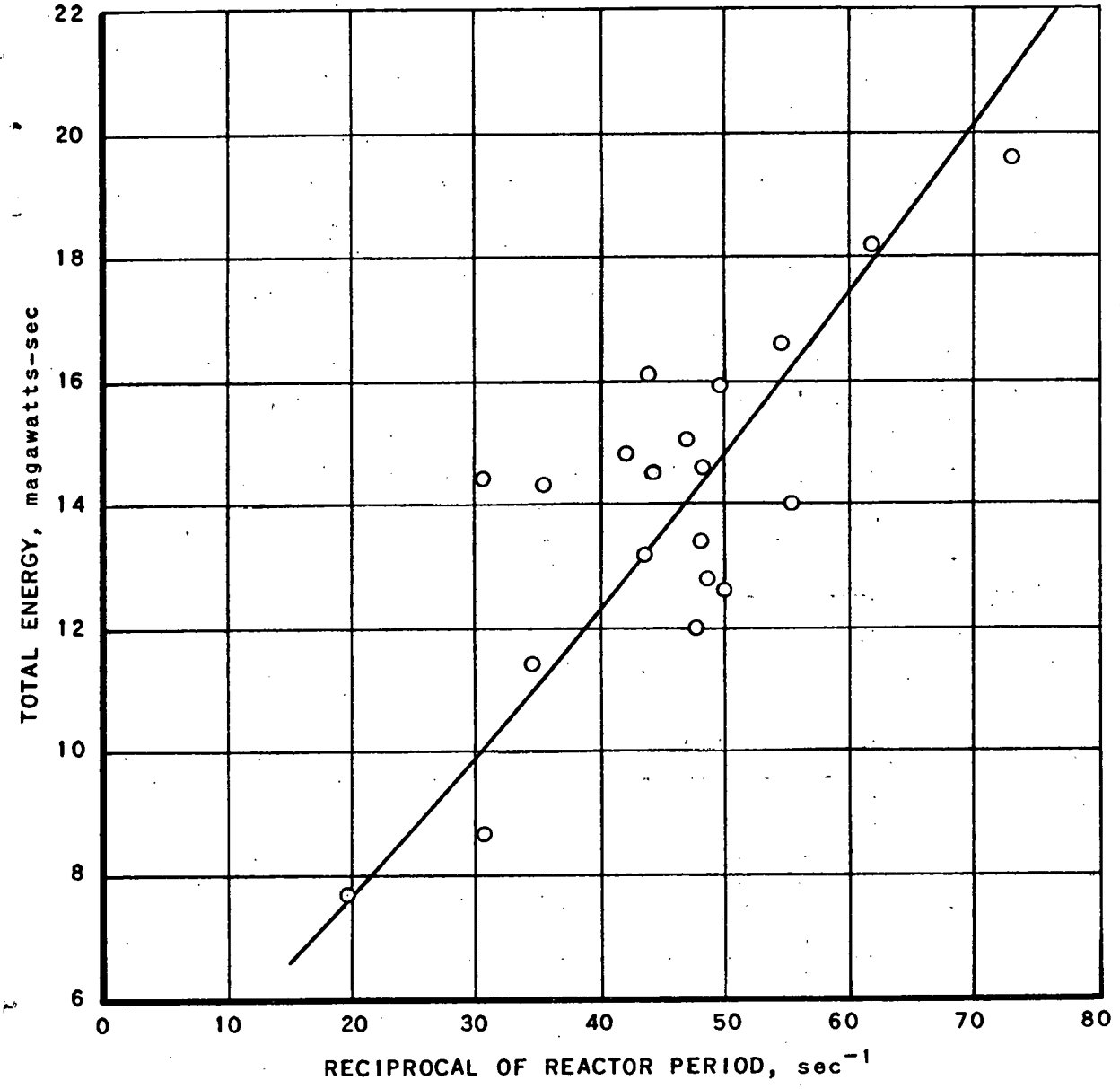


FIG. 13
TOTAL ENERGY OF POWER EXCURSION AS A FUNCTION OF RECIPROCAL PERIOD

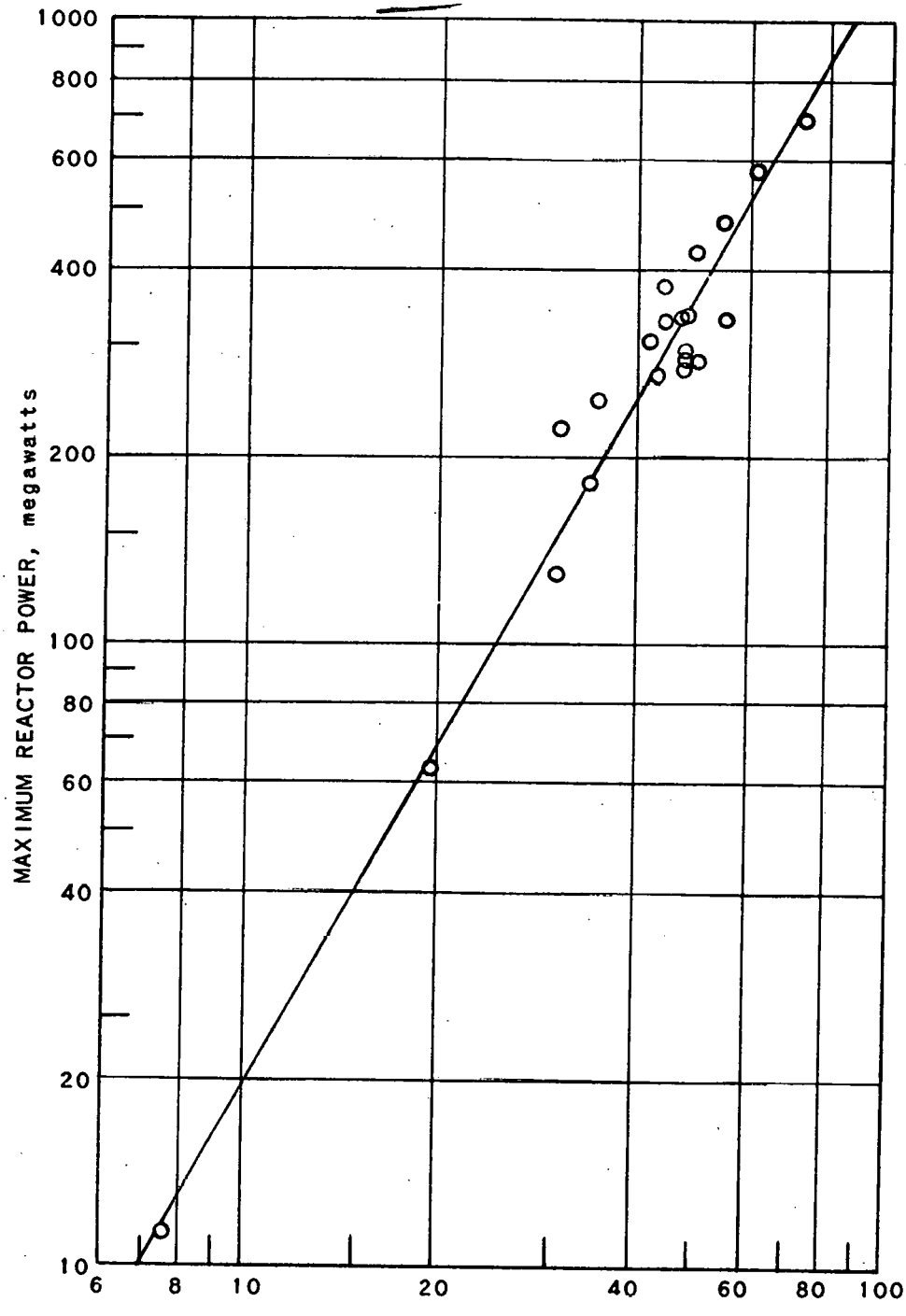


FIG. 14
MAXIMUM REACTOR POWER
IN EXCURSION AS A
FUNCTION OF RECIPROCAL PERIOD

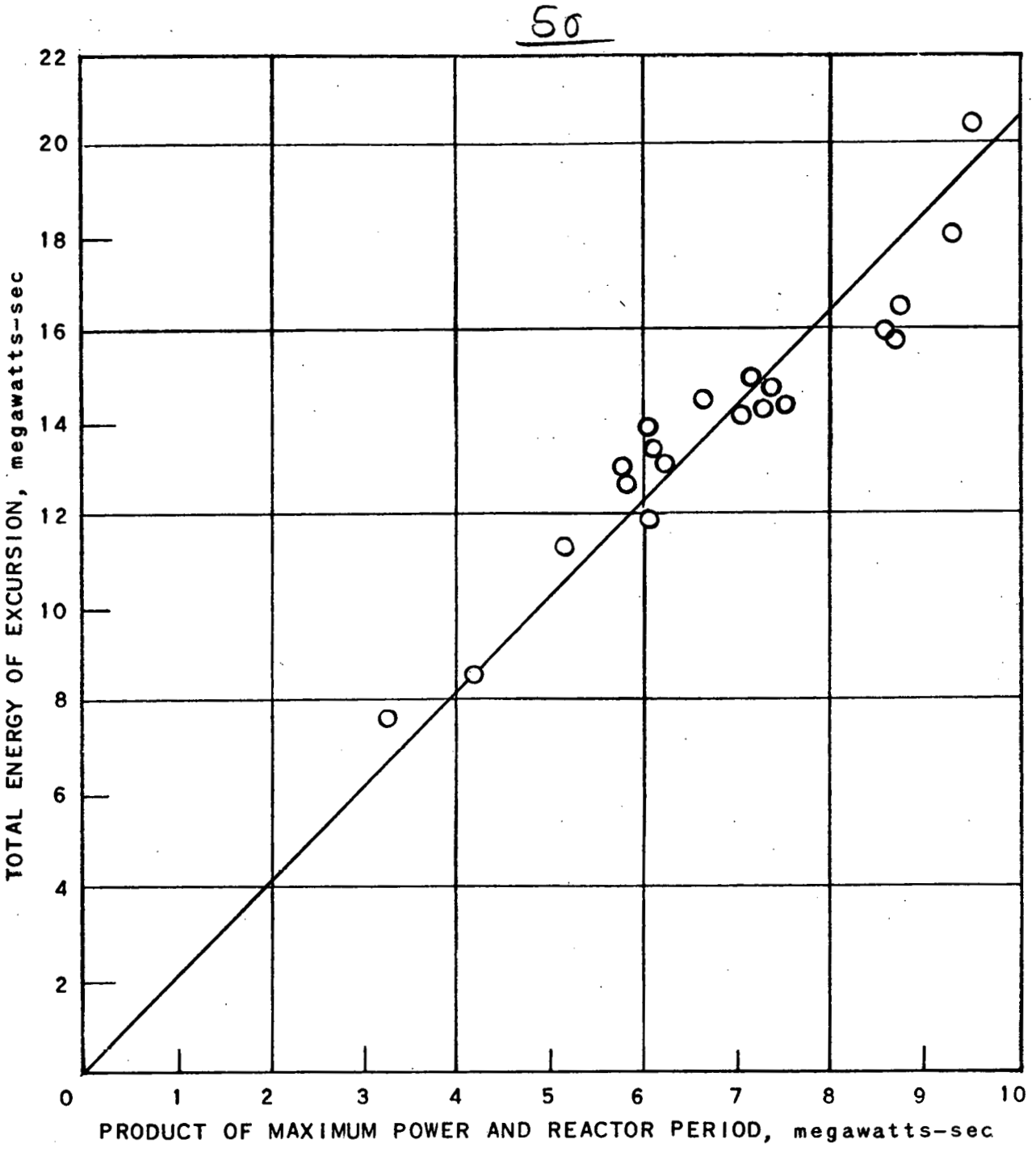


FIG. 15
RELATIONSHIP OF PERIOD, MAXIMUM POWER
AND TOTAL ENERGY IN EXCURSIONS OF VARIOUS PERIODS

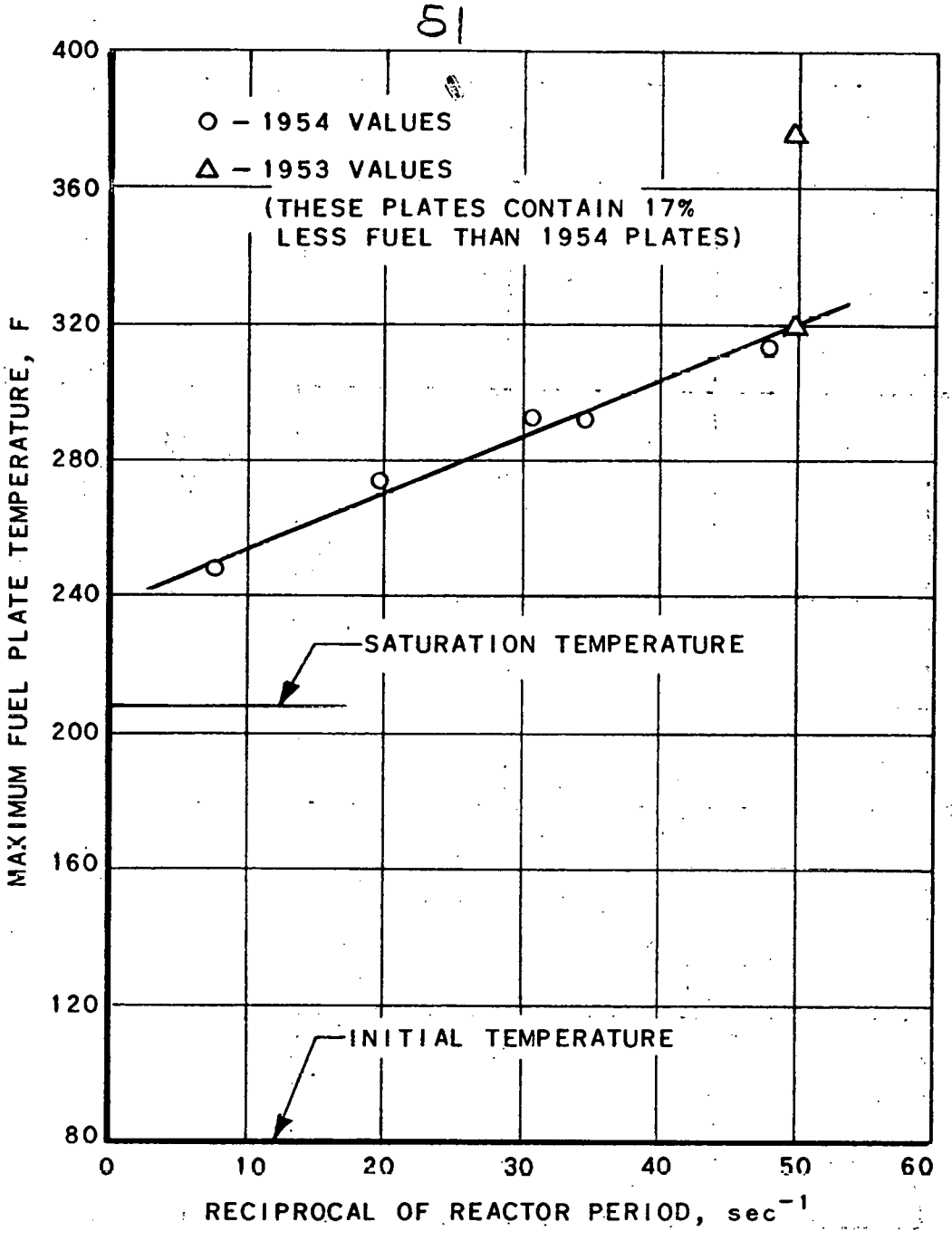


FIG. 16
MAXIMUM FUEL PLATE (SURFACE) TEMPERATURE REACHED IN POWER EXCURSION AS A FUNCTION OF RECIPROCAL PERIOD

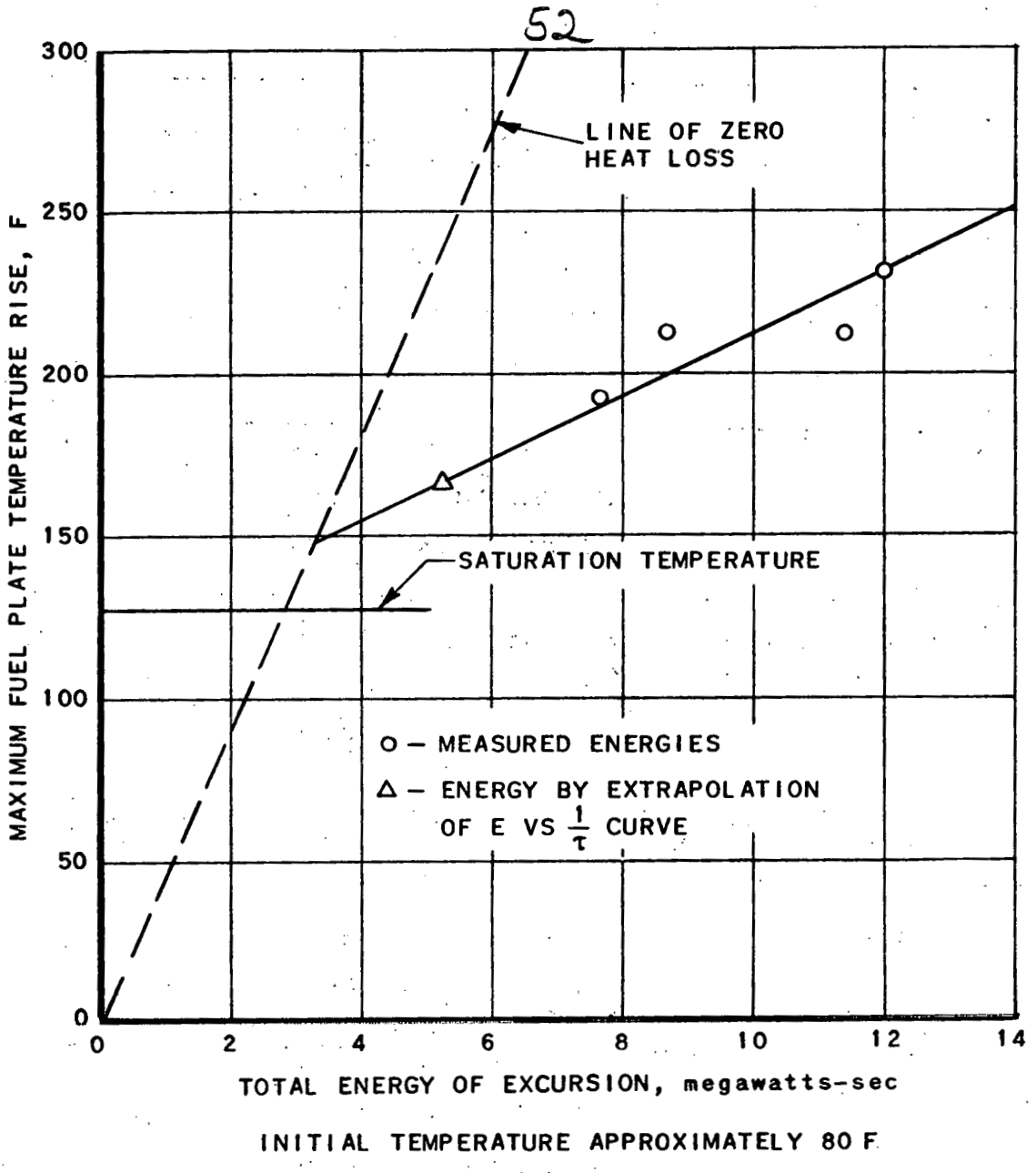
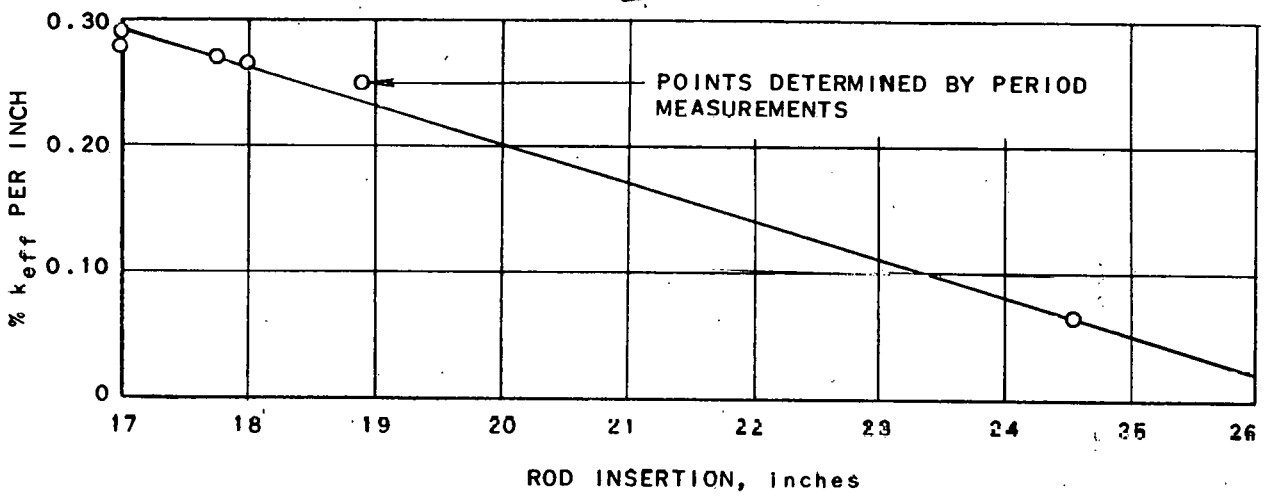
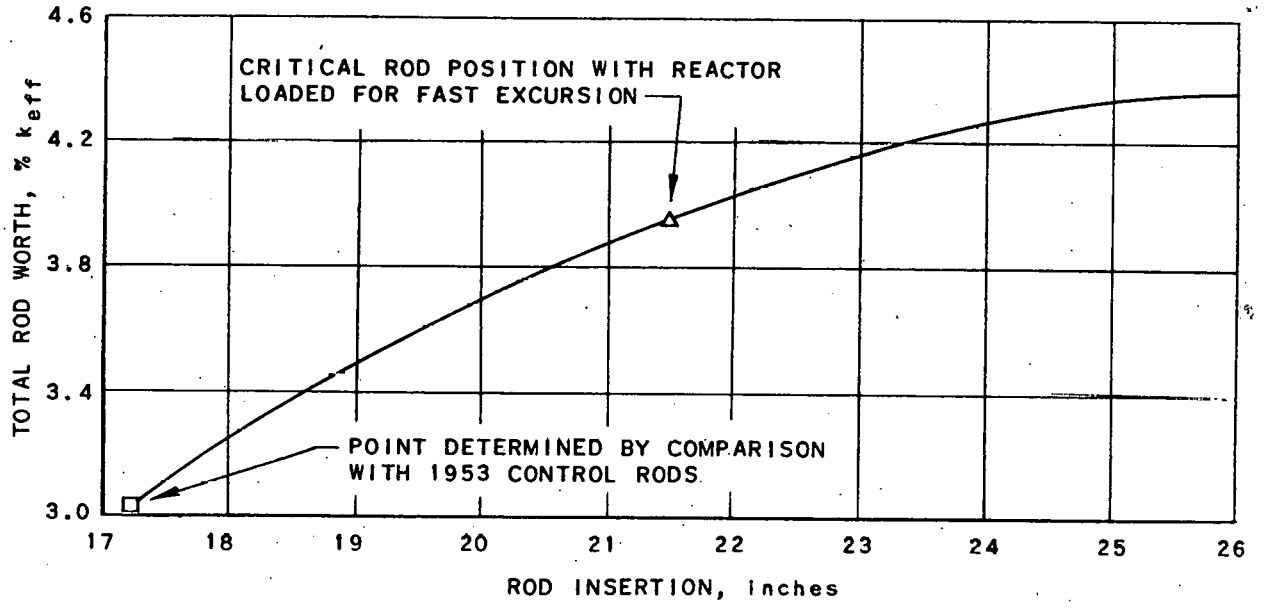


FIG. 17
RELATION BETWEEN TOTAL ENERGY OF EXCURSION AND MAXIMUM FUEL PLATE (SURFACE) TEMPERATURE RISE

53



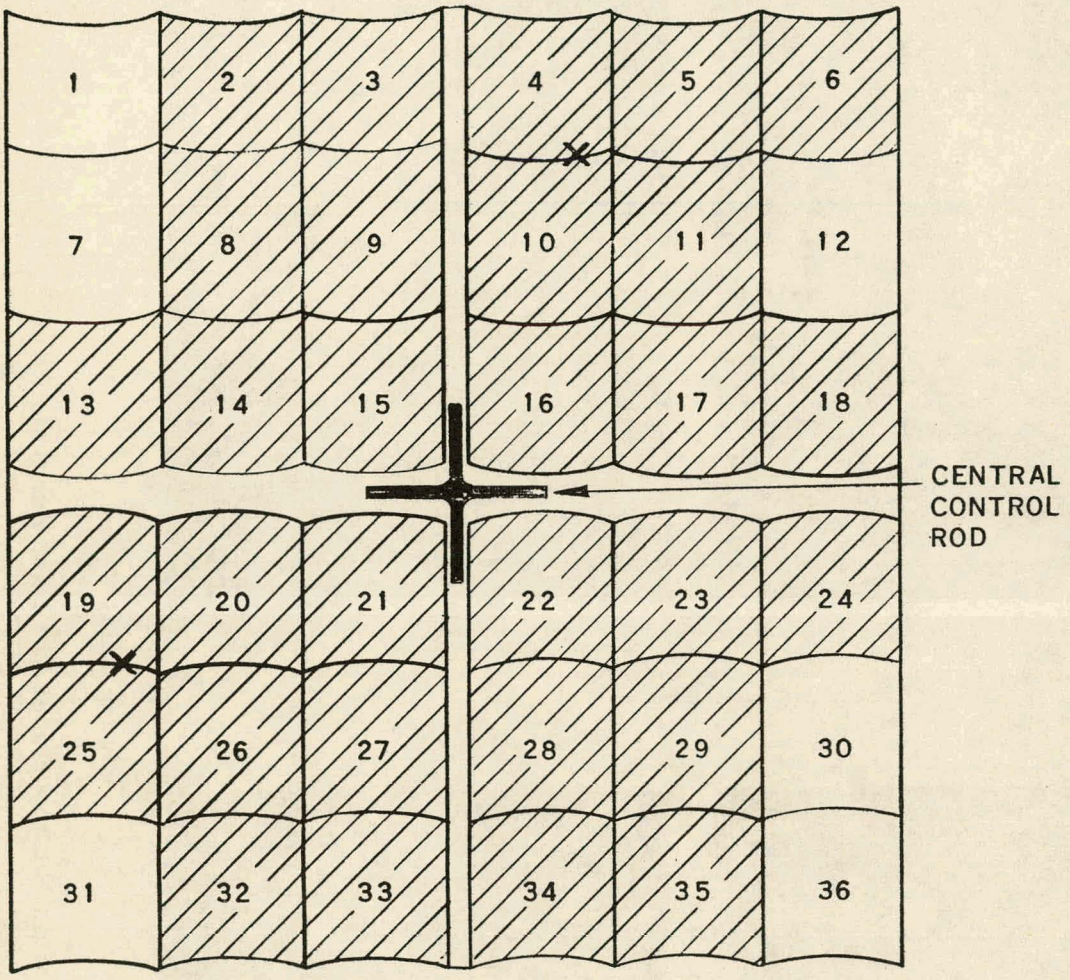
a. DIFFERENTIAL CALIBRATION



b. INTEGRAL CALIBRATION CURVE

FIG. 18
PARTIAL CALIBRATION OF CENTRAL CONTROL ROD USED FOR FAST EXCURSION

54



X – INDICATES POSITION OF FOIL HOLDERS

FIG. 19
CORE LOADING PATTERN
FOR FAST EXCURSION

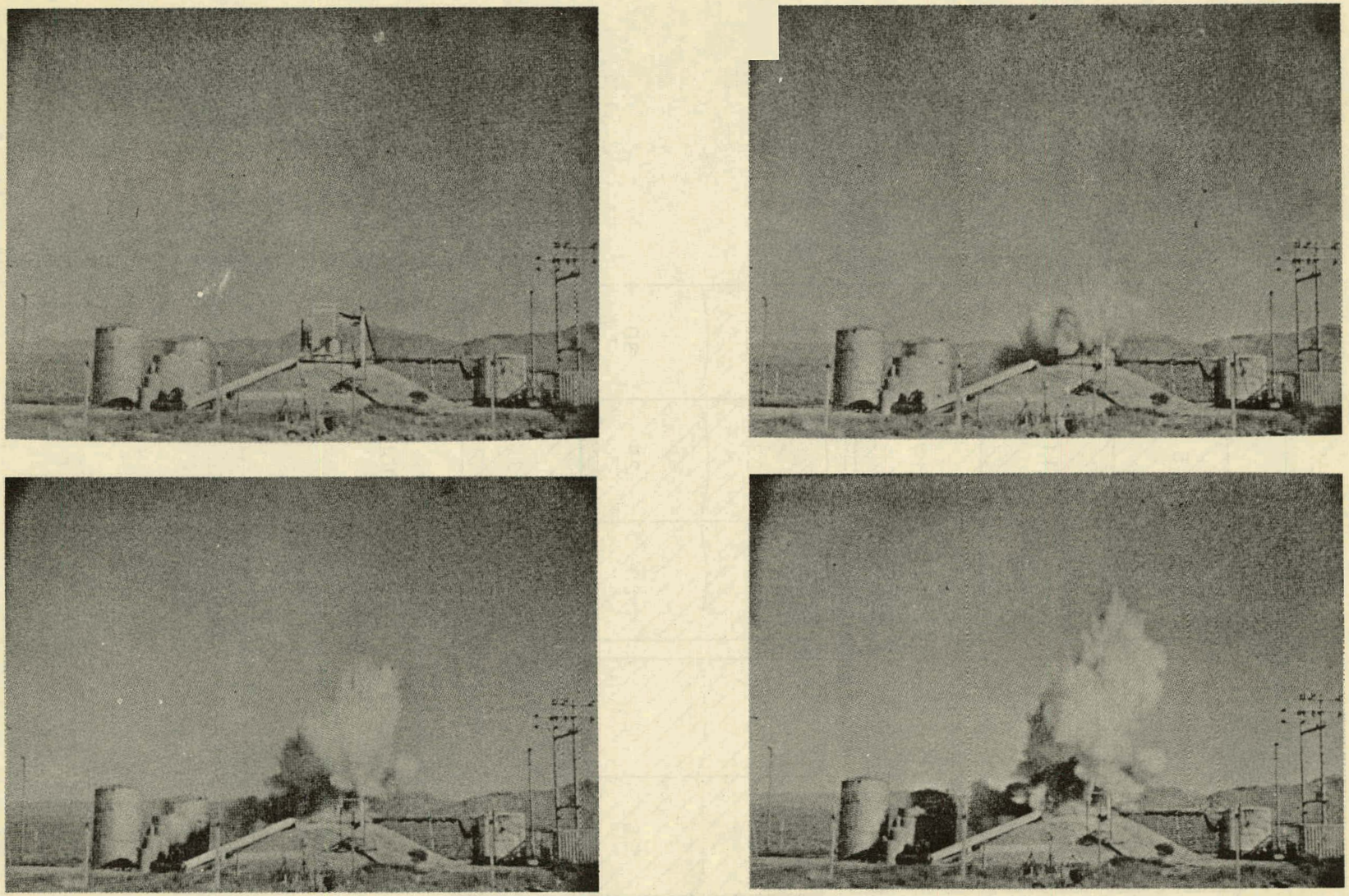


Figure 20(a)

Motion Picture Record of Fast Excursion

The pictures, except the final one, are consecutive frames taken at a speed of 64 frames per second

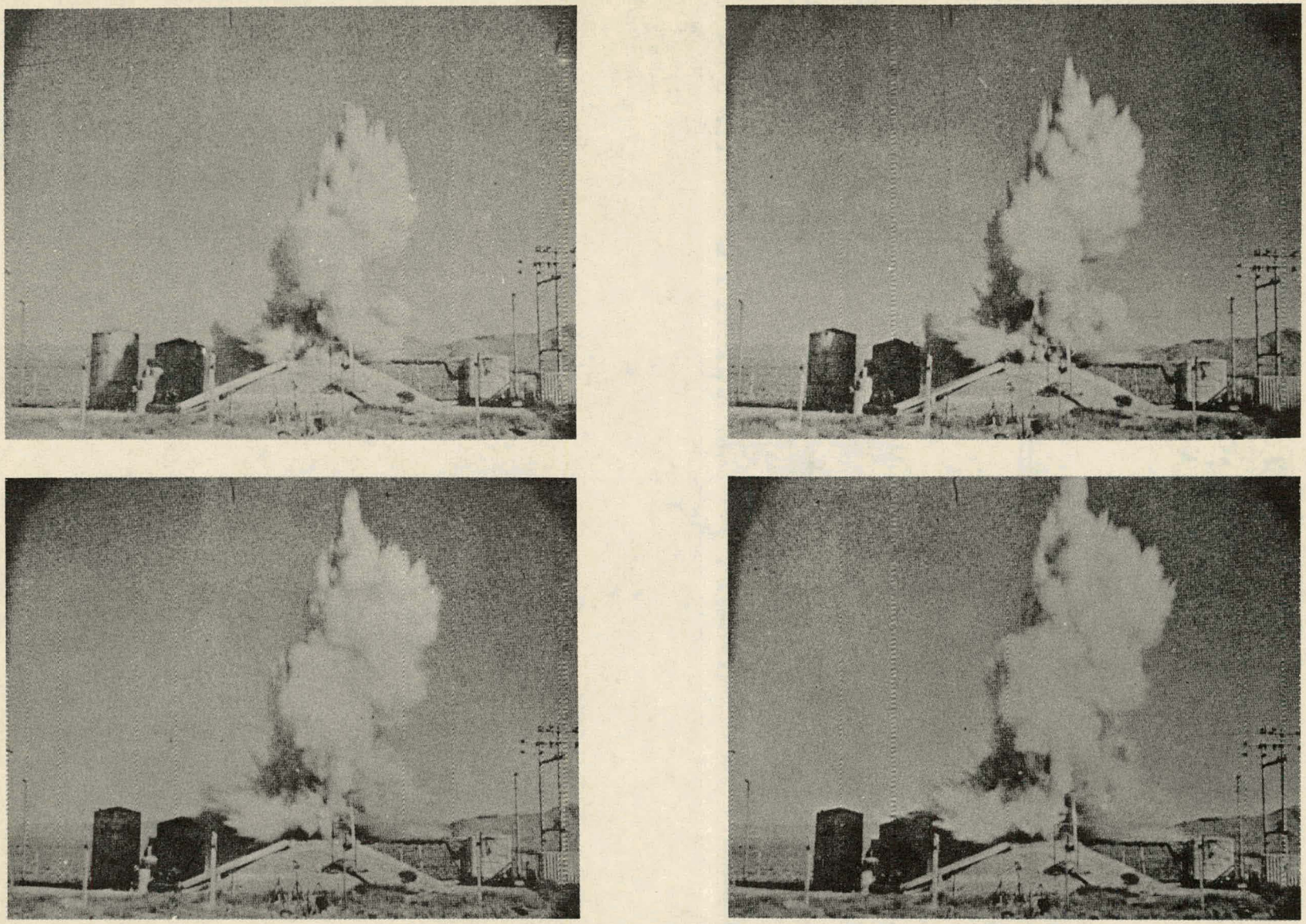
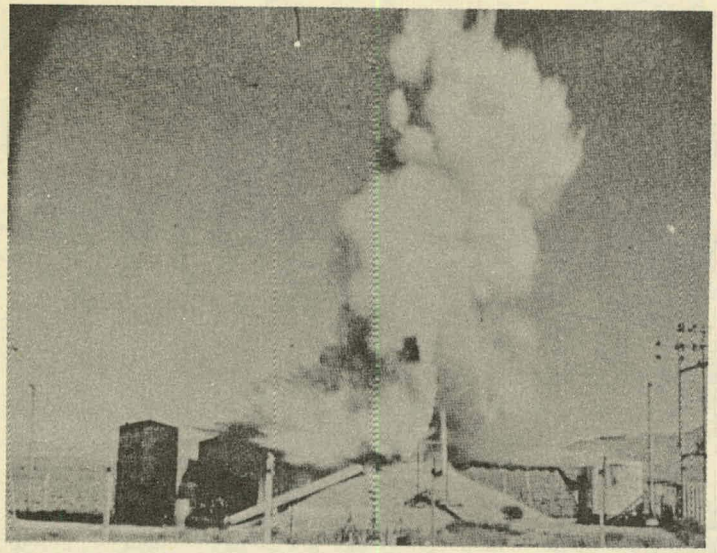
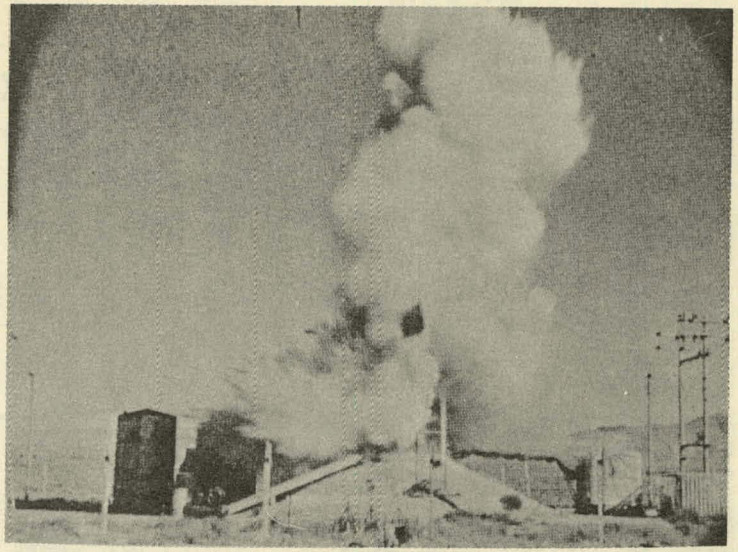
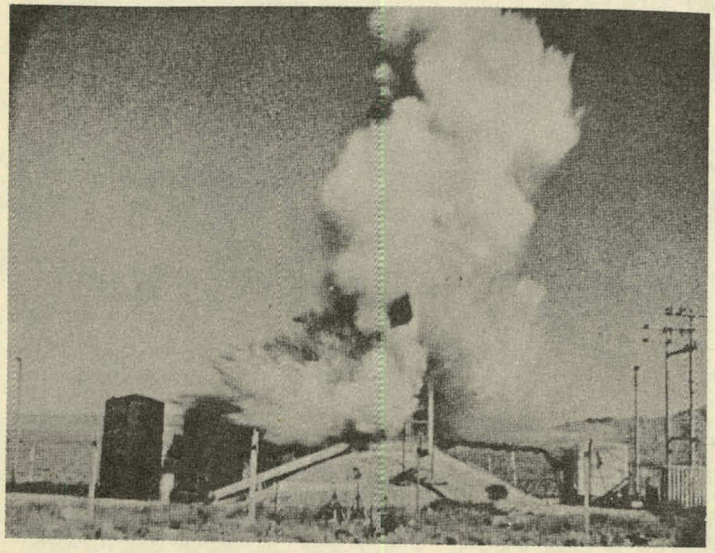


Figure 20(b)

Motion Picture Record of Fast Excursion







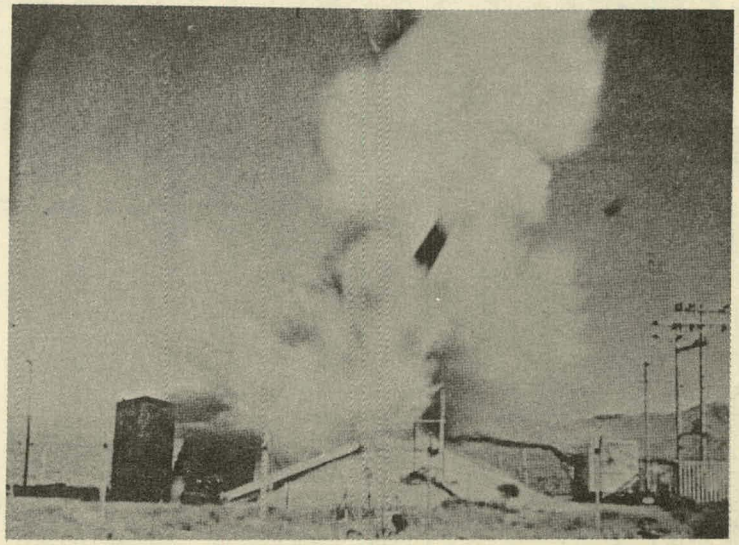


Figure 20(c)

Motion Picture Record of Fast Excursion

58

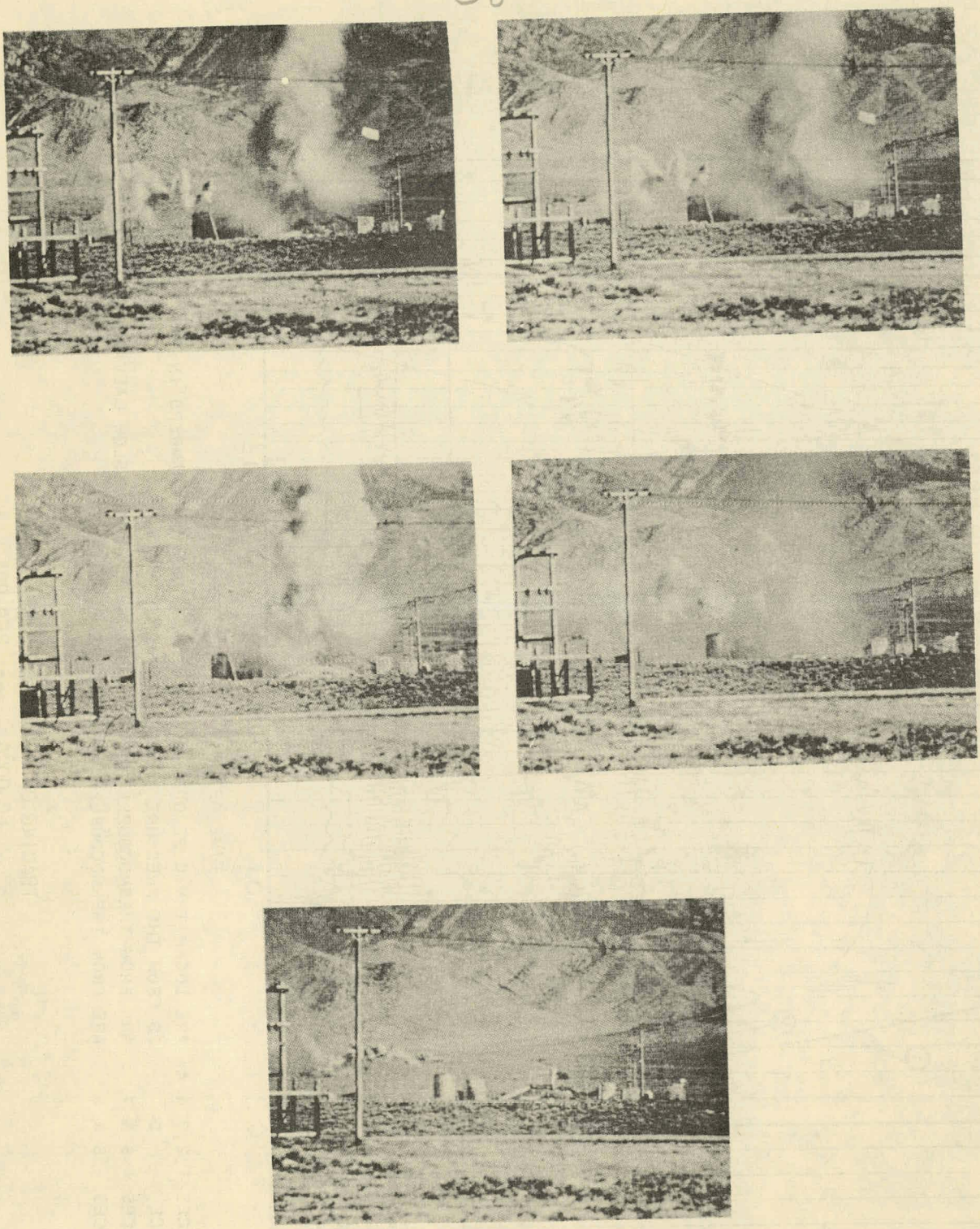
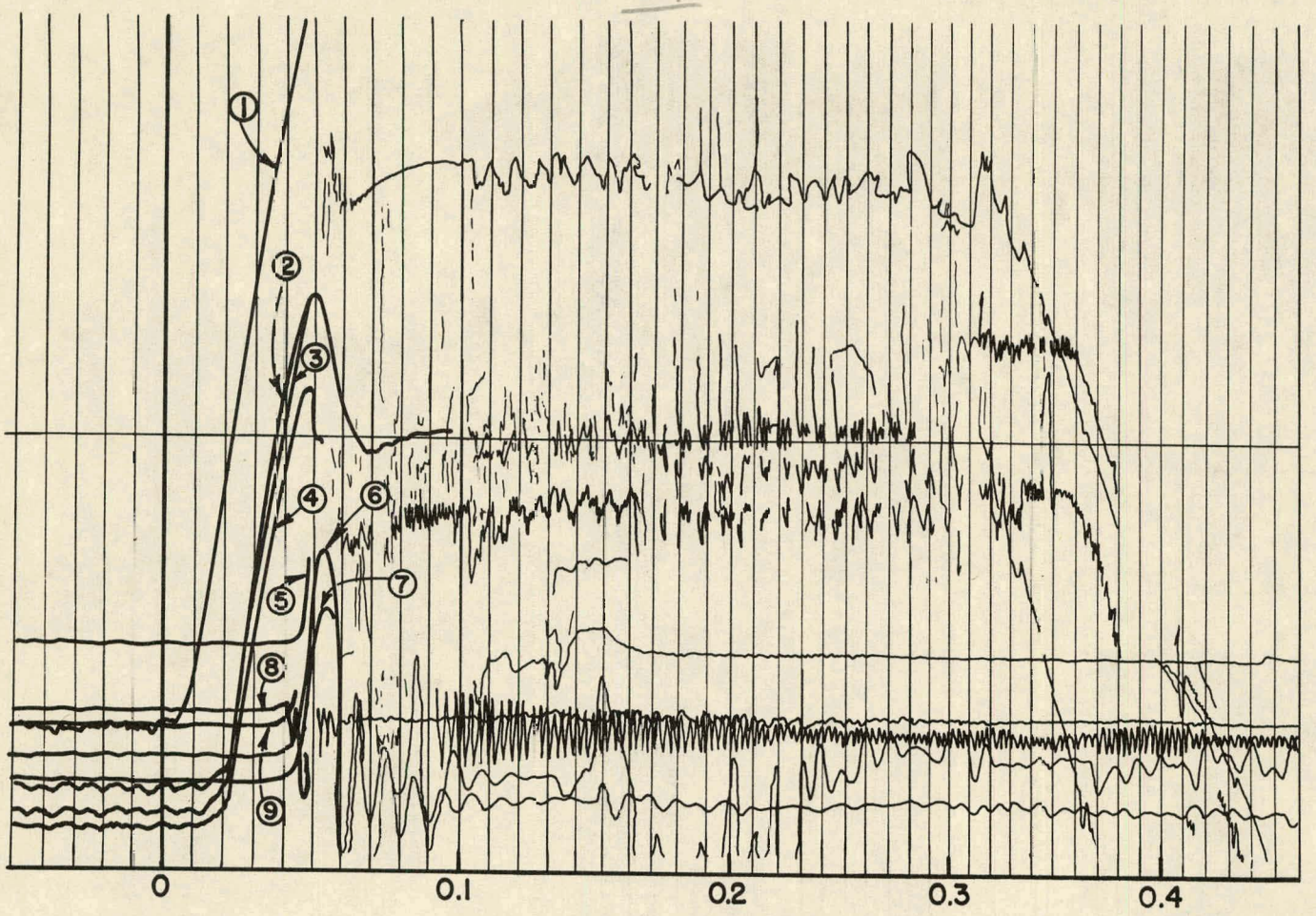


Figure 20 (d)

Motion Picture Record of Fast Excursion



TRACES	1,2,3 & 4	ARE LOGARITHMIC RECORDS OF CURRENTS FROM ION CHAMBERS IN VARIOUS POSITIONS
TRACE	5	IS FROM THE PRESSURE TRANSDUCER
TRACES	6 & 7	ARE FROM THERMOCOUPLES ON EXTERNAL FUEL PLATE (SLOW GALVANOMETERS)
TRACES	8 & 9	ARE FROM THERMOCOUPLES ON INTERNAL FUEL PLATES

FIG. 21
TRACING OF RECORD OF FAST EXCURSION
(0.0026 - sec. PERIOD)

60

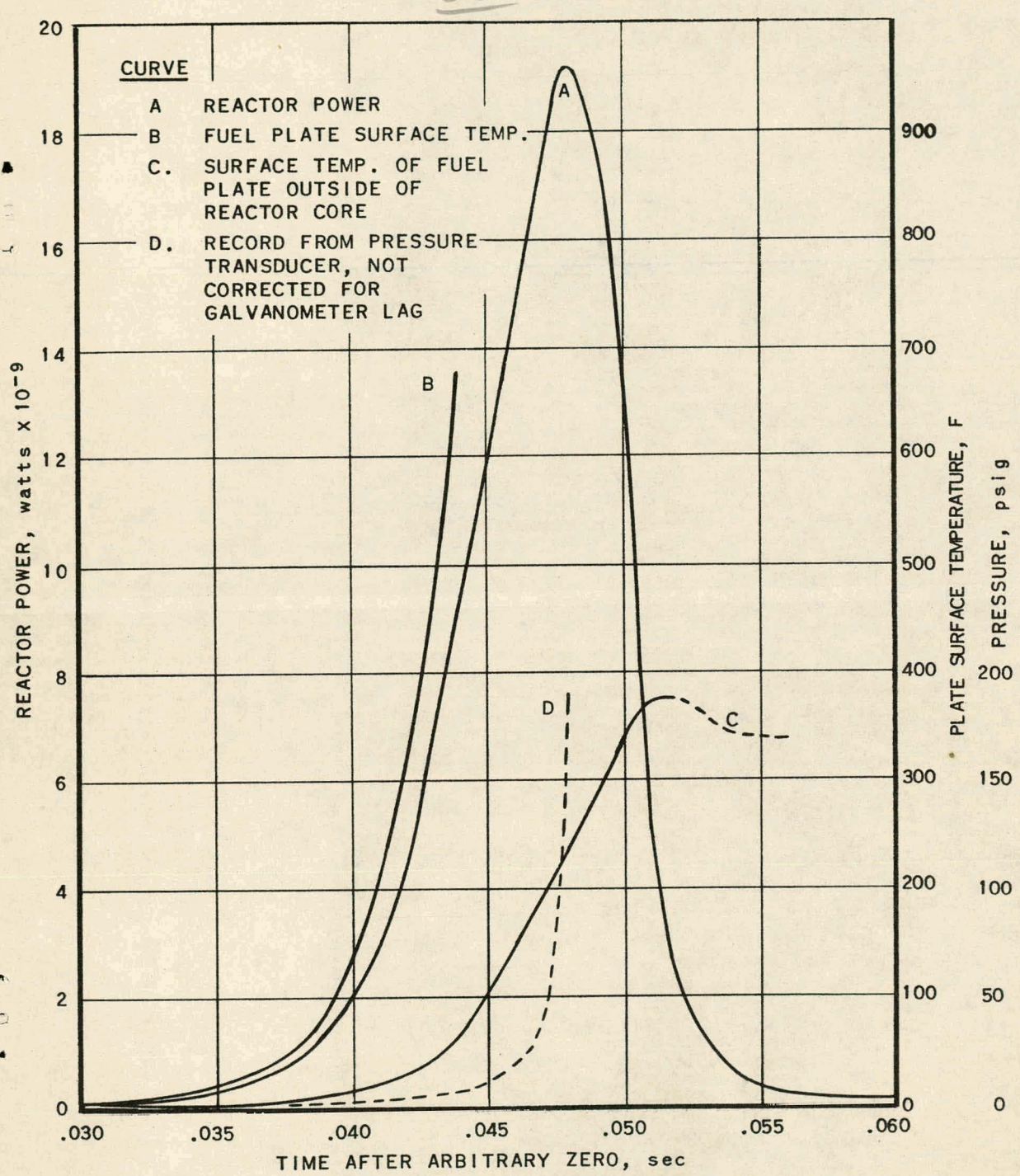
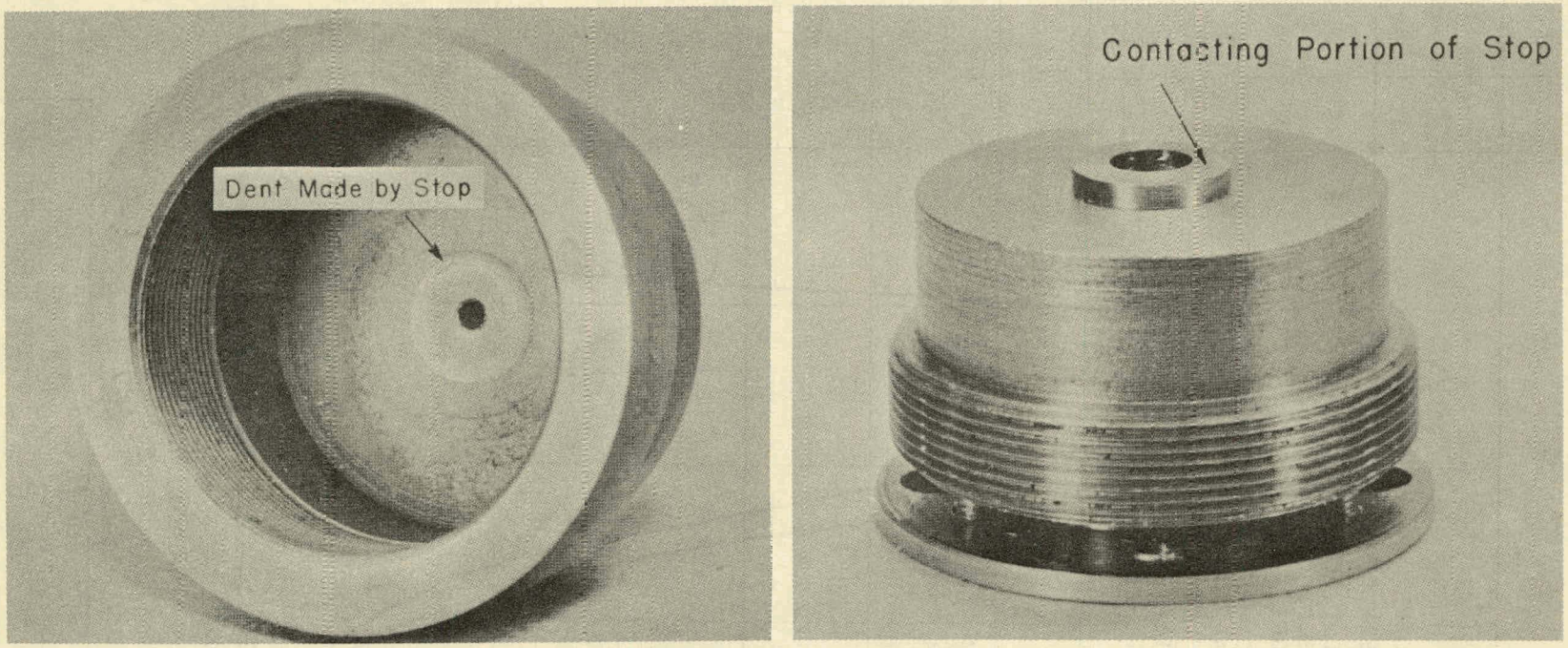


FIG. 22
REPLOT OF POWER, FUEL PLATE TEMPERATURE AND PRESSURE RECORDS FOR EXCURSIONS OF 2.6 MILLISECOND PERIOD

61



(a) Inside View of Diaphragm

(b) Diaphragm Stop

Figure 23

Photographs of Pressure Transducer Diaphragm and Stop after Fast Excursion

62

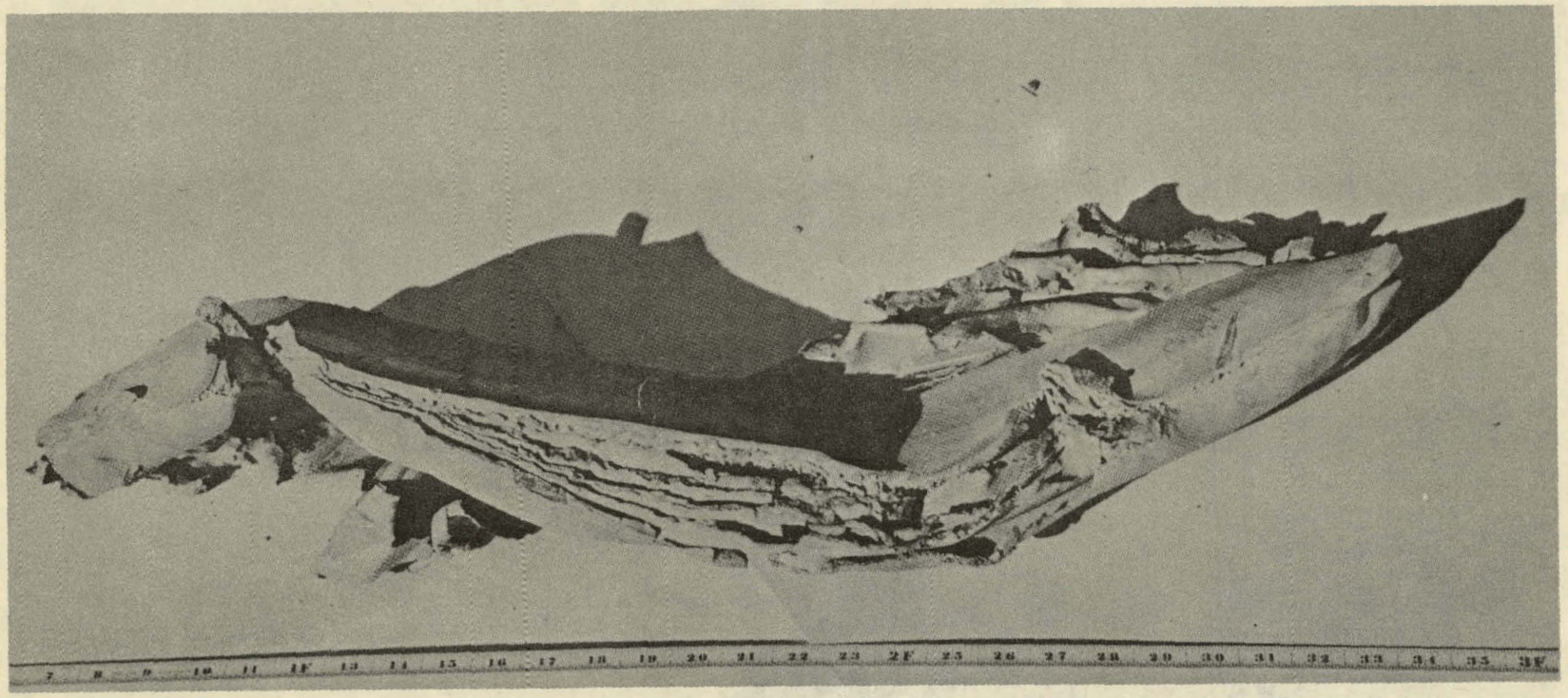


Figure 24

Fuel Element after Fast Excursion

This was the only element found which appeared to contain nearly all of its original plates

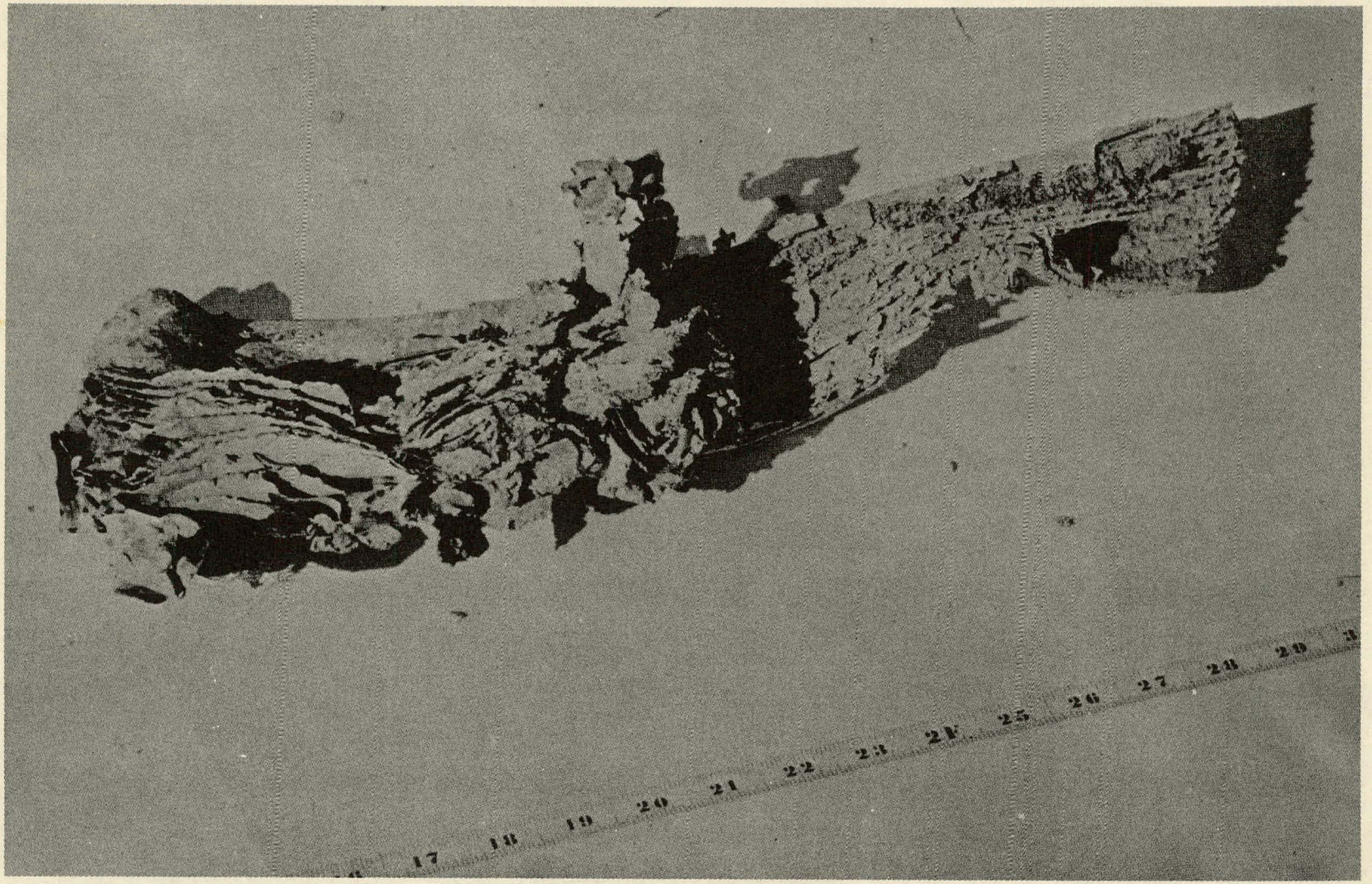


Figure 25

Fuel Element Side Plate with Attached Cluster of Fuel Plate Fragments

64

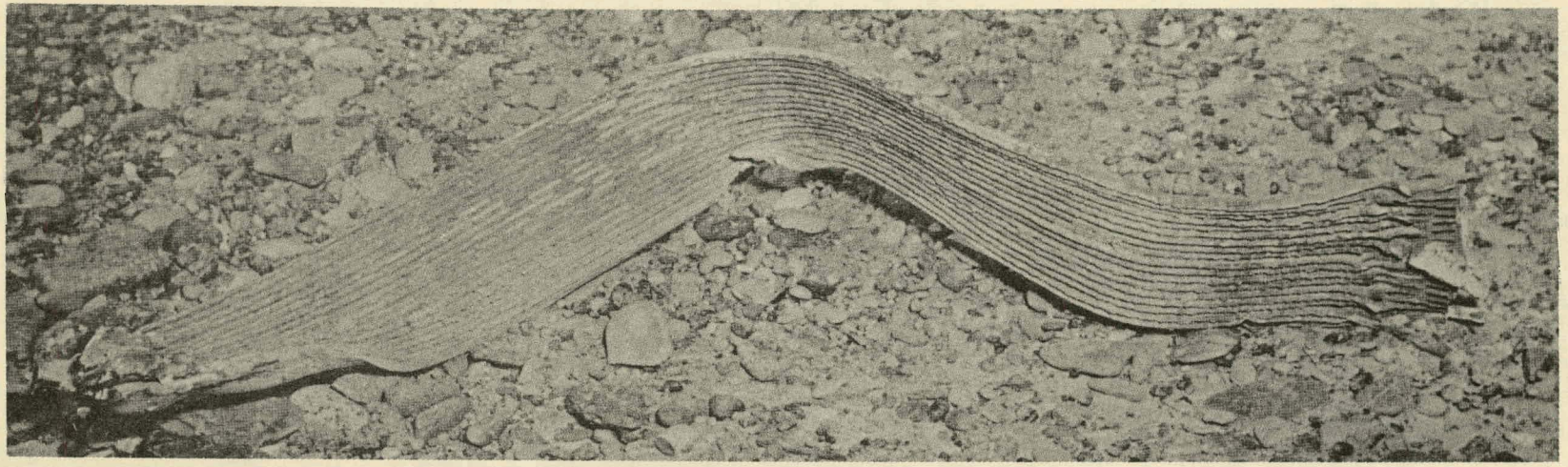


Figure 26

Fuel Element Side Plate

65

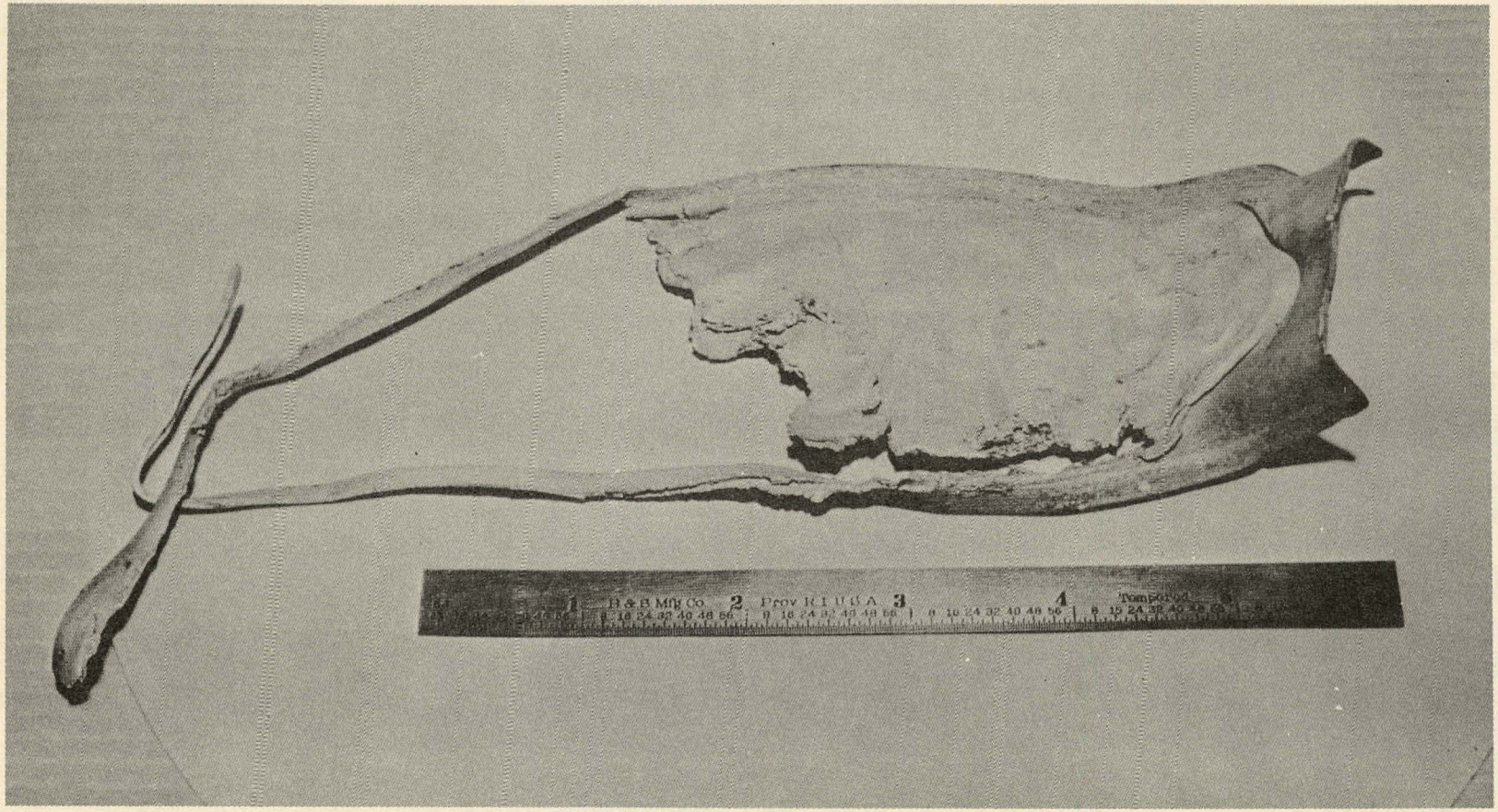


Figure 27

Fragment of Flat Fuel Plate from Special Removable-Plate Fuel Element

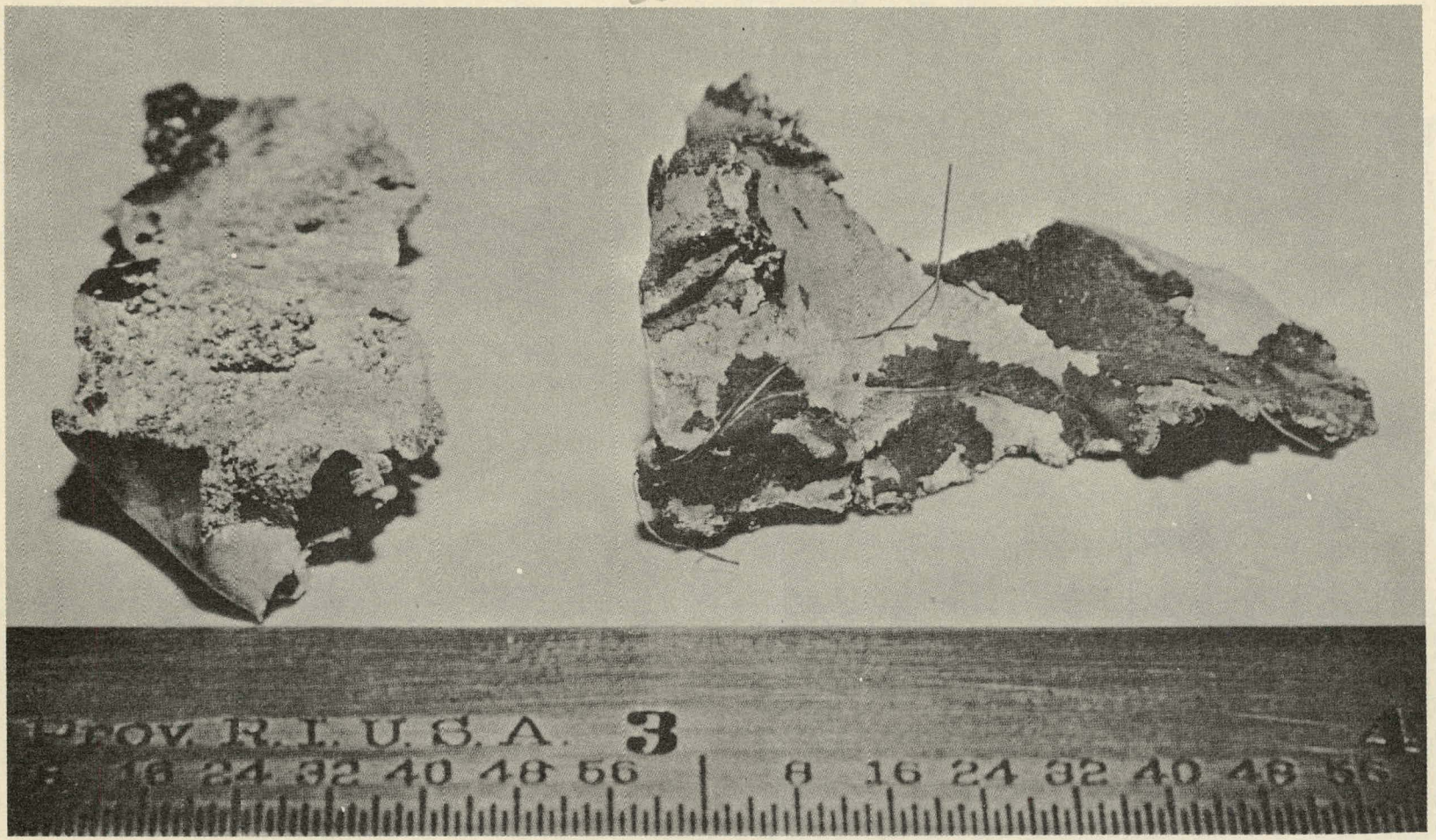


Figure 28

Fragments of Fuel-Plate Clad

The small strands of steel wool attached to the right-hand sample were originally part of the thermal insulation on the outside of the reactor tank

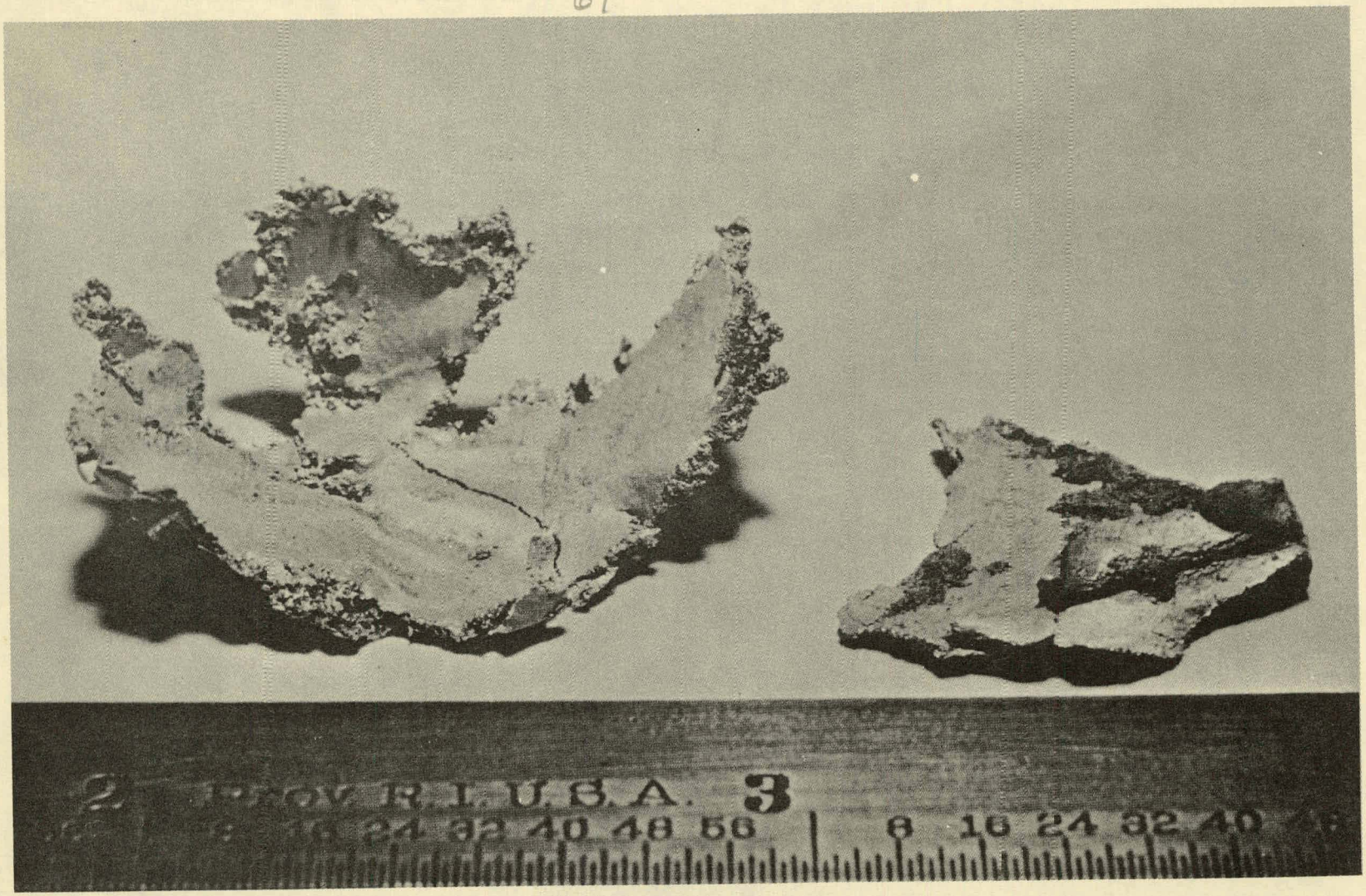


Figure 29

Fragments of Fuel Plates

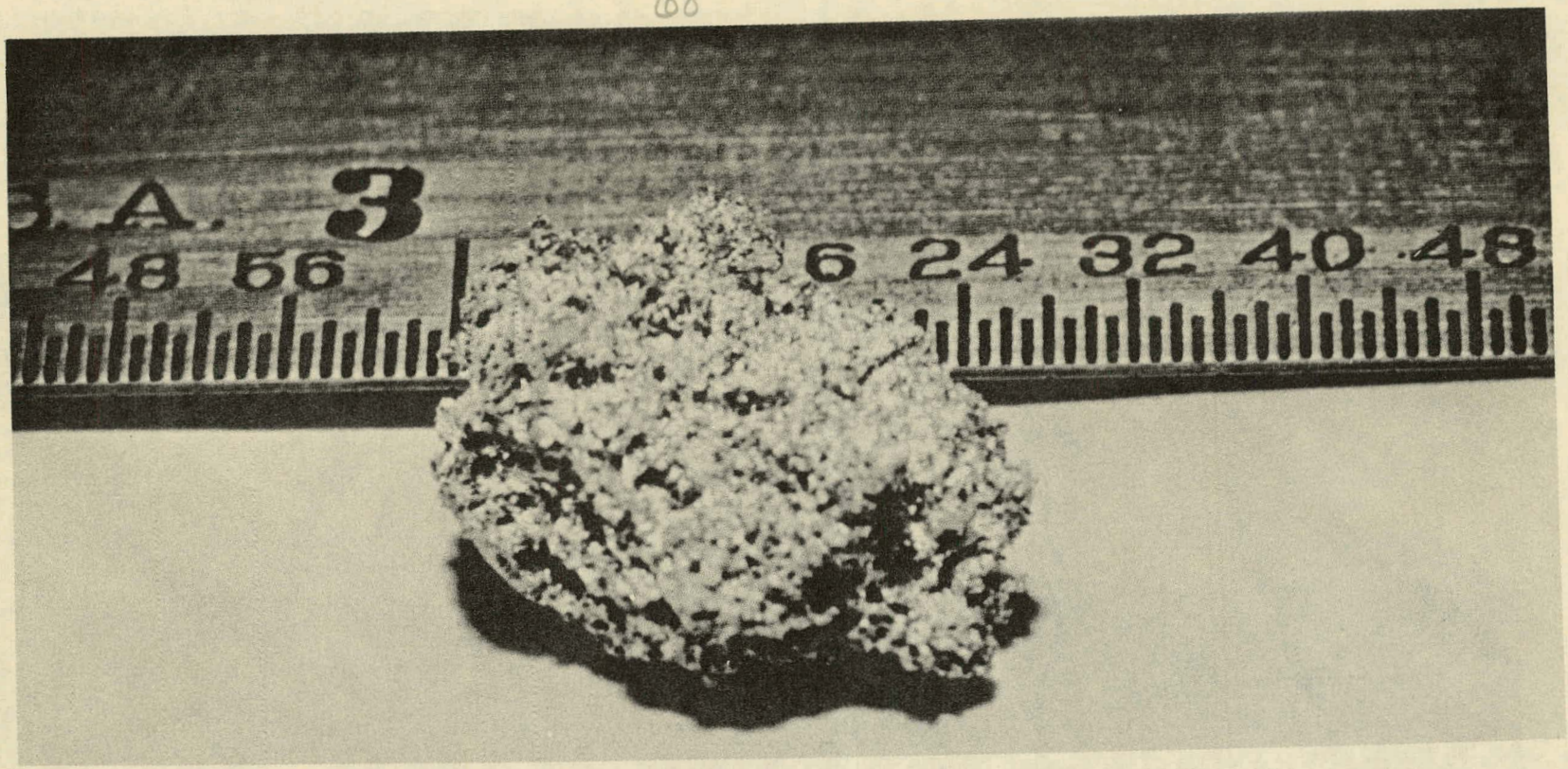


Figure 30

Pellet of Spongy Aluminum-Uranium Mixture

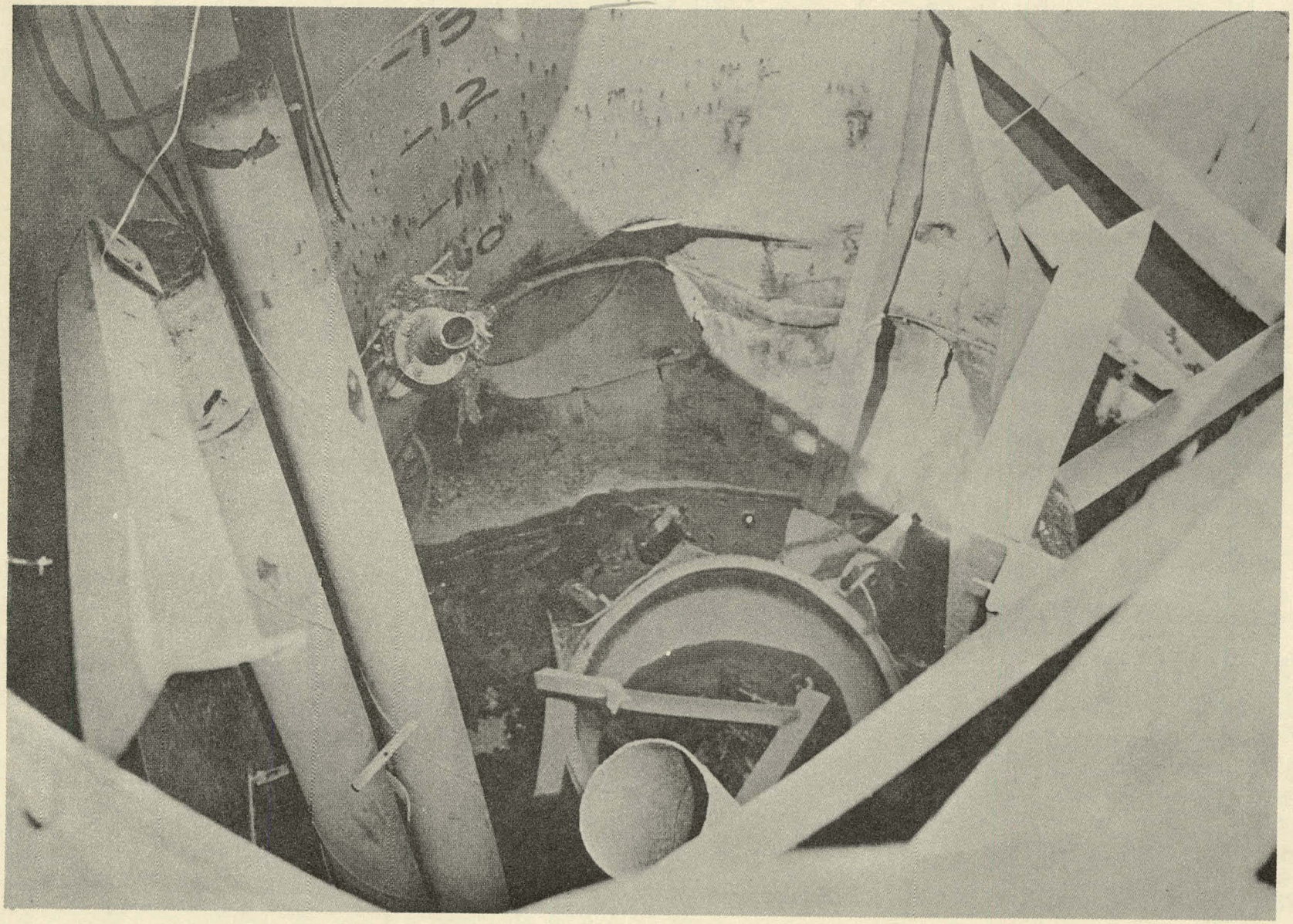


Figure 31 View into Shield Tank after Fast Excursion

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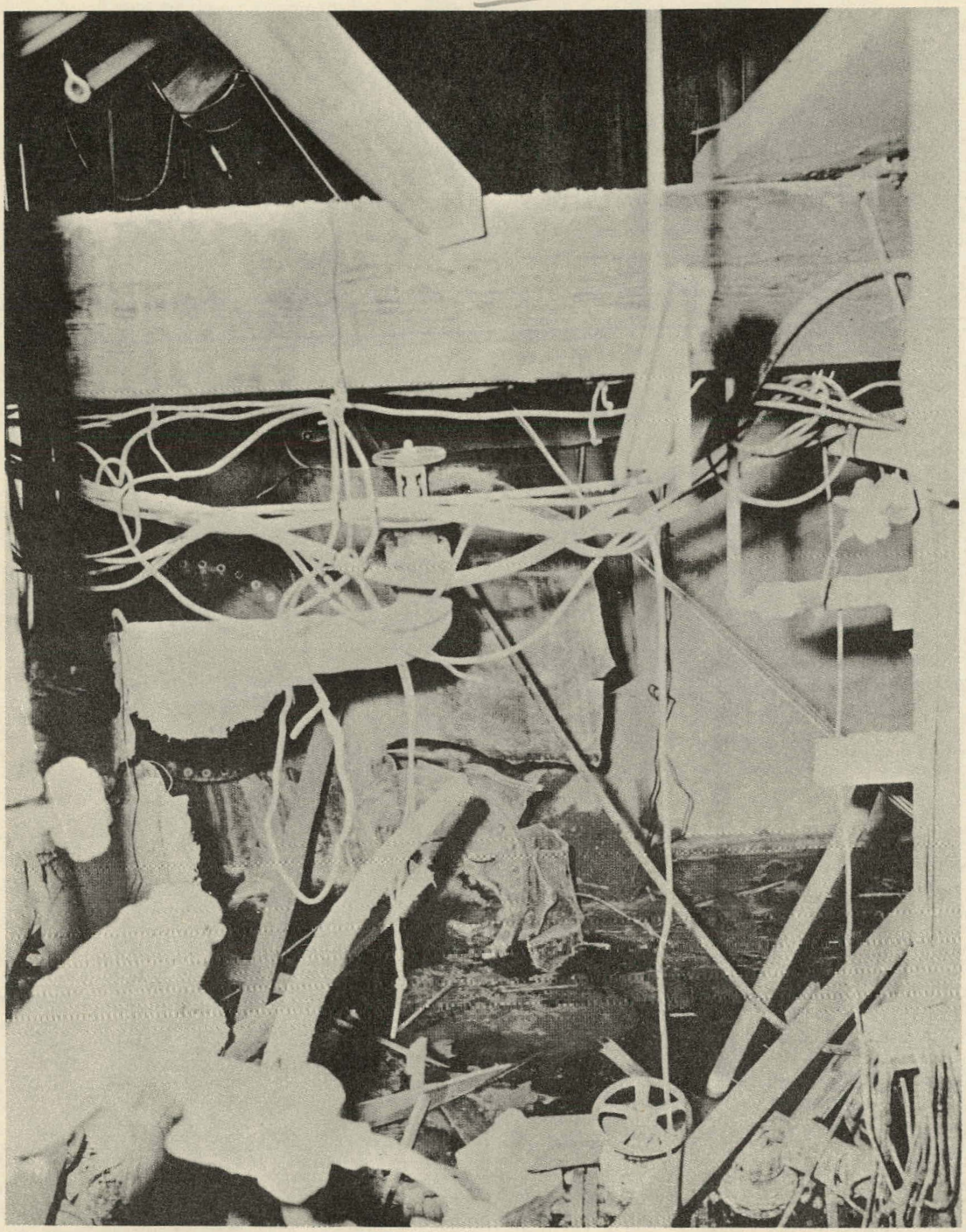

Figure 32

View into Pump Pit After Fast Excursion

Ripped shield tank shows in background. Before the excursion the tank was behind a 16 inch cemented concrete-block wall, which was demolished

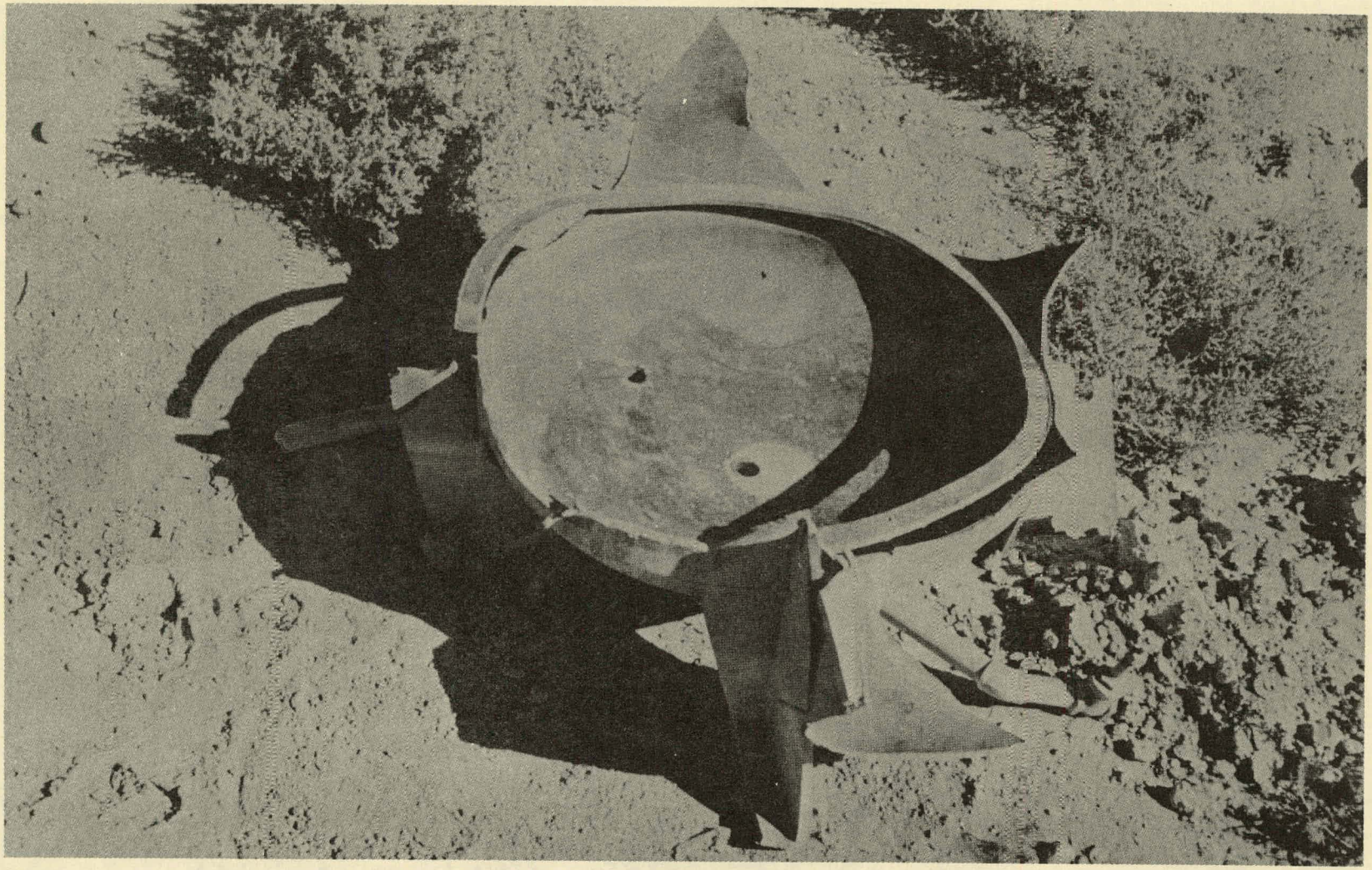

Figure 33

Dished Bottom Head of Reactor Tank, after Removal from Shield Tank

72

Figure 34

Fragment of Reactor Tank

Figure 35

Reactor Tank Fragments

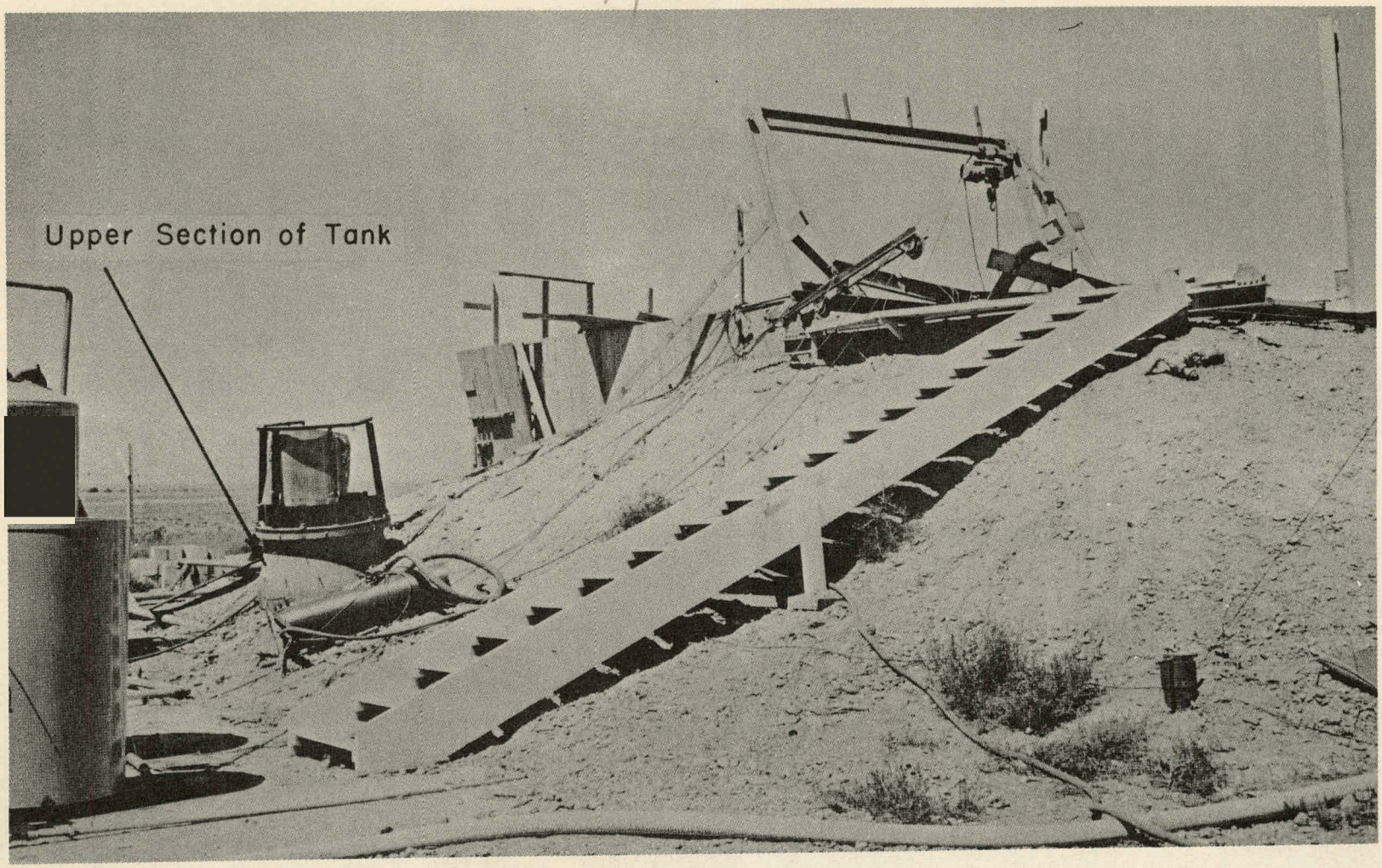

Figure 36

West Side of Shield Mound, Showing Upper Section of Reactor Tank in Position it was Found After Fast Excursion

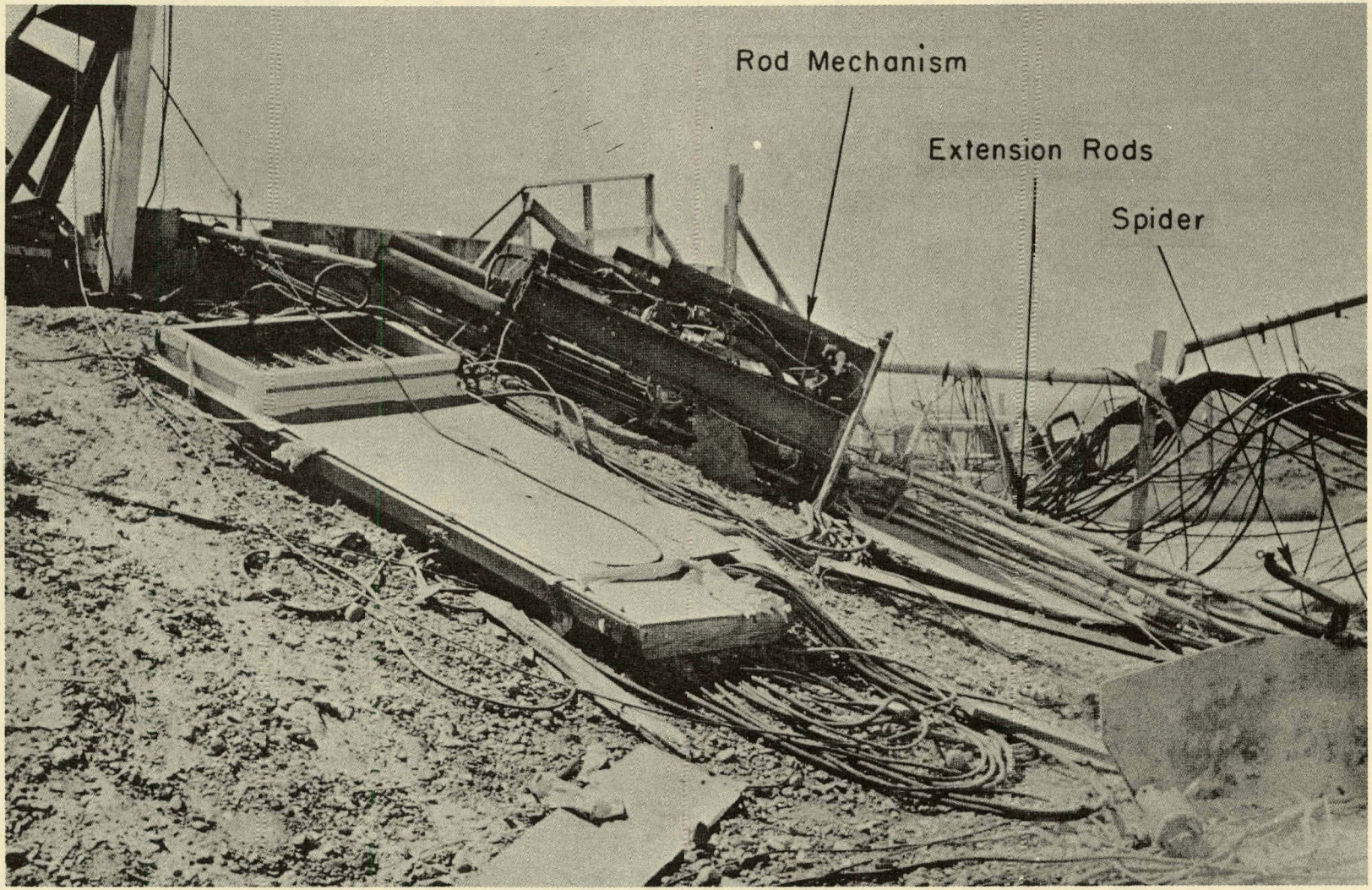

Figure 37

East Side of Shield Mound, Showing Control Rod Mechanism after Fast Excursion

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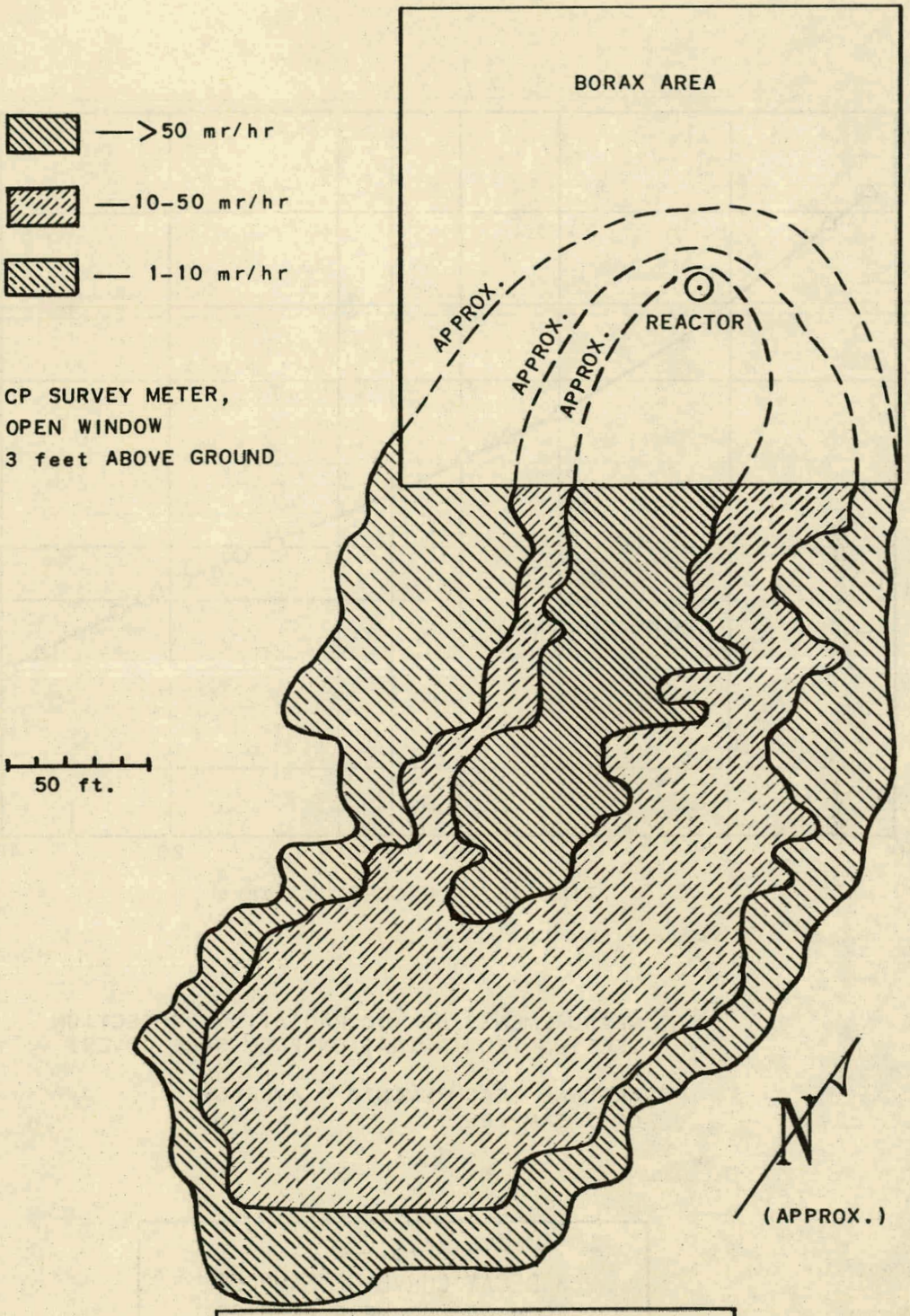
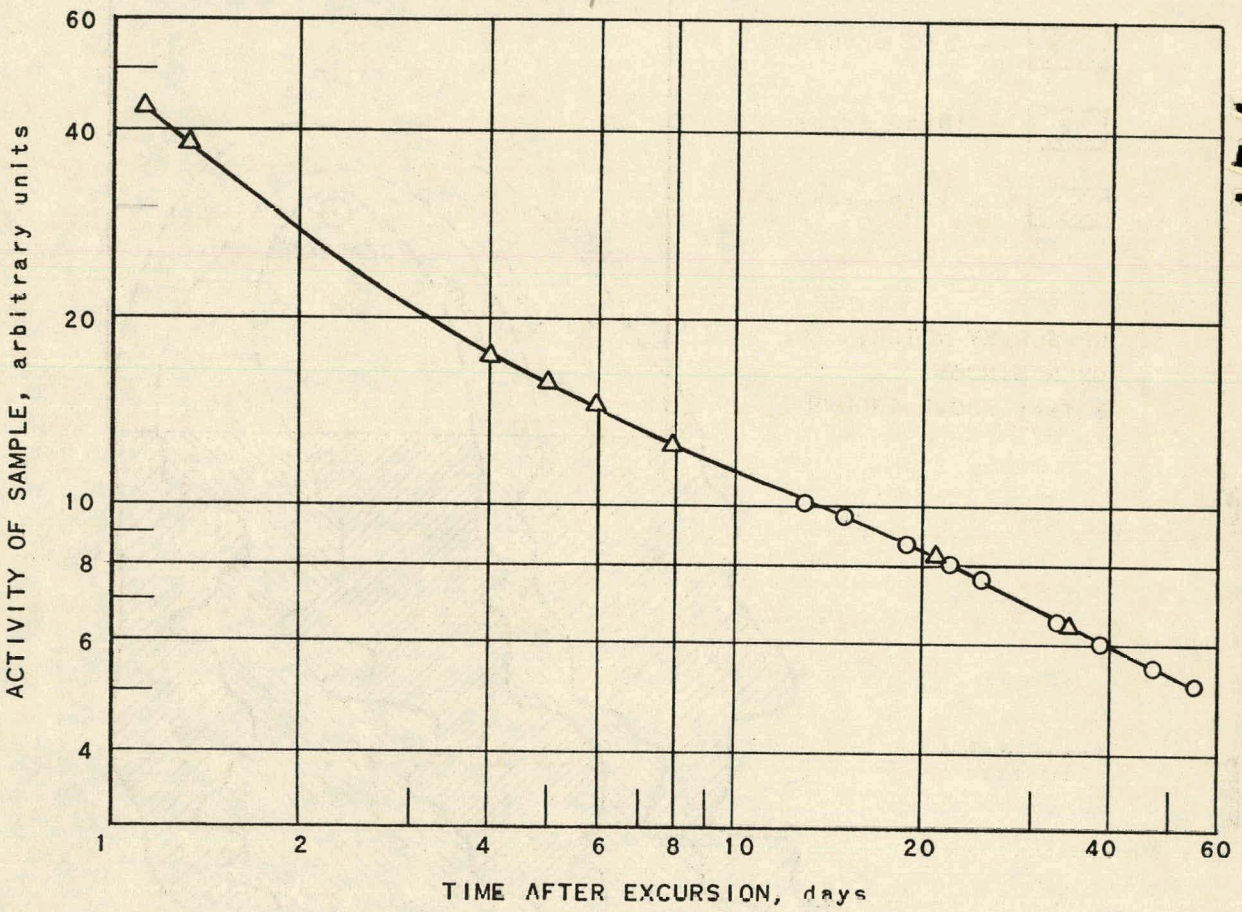


FIG. 38
SURVEY OF CONTAMINATED AREA AROUND
BORAX REACTOR BY IDO RADIATION
PROTECTION SECTION ON 8-2-54



△ MEASUREMENTS BY IDO RADIATION PROTECTION SECTION (CONTAMINATION FROM SHOE COVER)

○ ARGONNE MEASUREMENTS - AVERAGE OF 7 SAMPLES

FIG. 39
β DECAY CURVE OF SAMPLES
FROM GROUND NEAR REACTOR
AFTER 2.6 MILLISECOND EXCURSION

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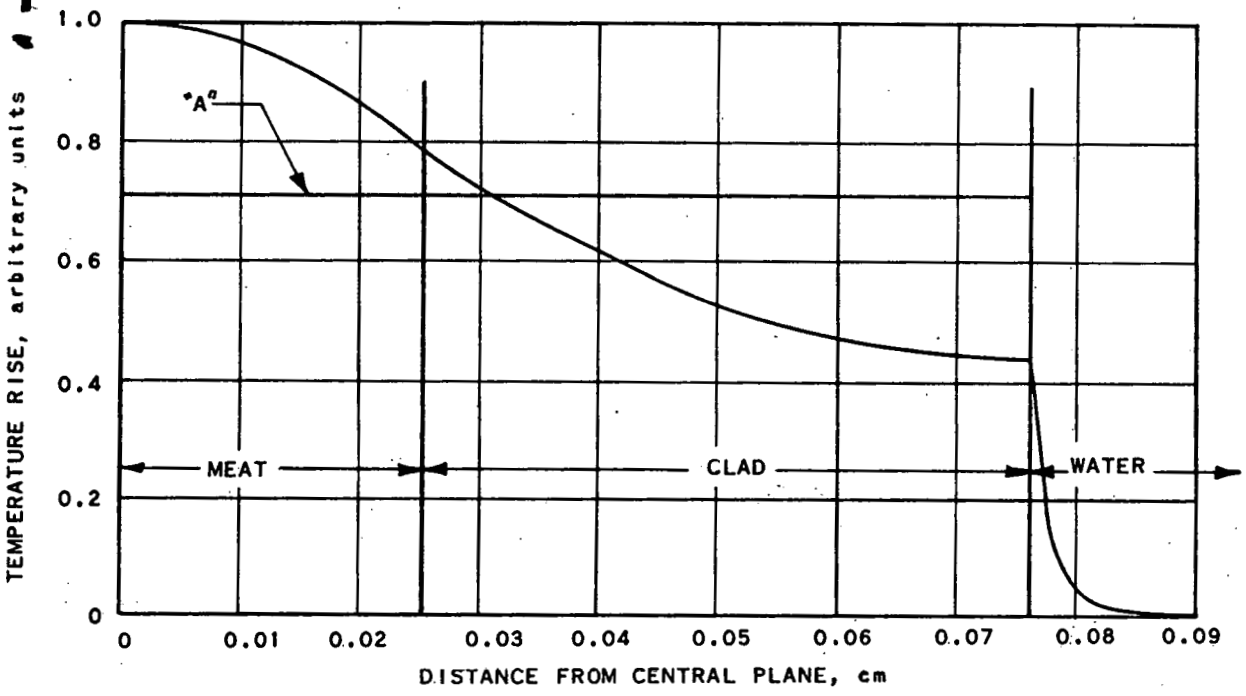

LINE 'A' MARKS UNIFORM TEMPERATURE RISE WHICH WOULD EXIST IF FUEL PLATE CONDUCTIVITY WERE INFINITE AND NO HEAT WERE LOST TO WATER

FIG. 40
CALCULATED DISTRIBUTION OF TEMPERATURE RISE IN FUEL PLATE DURING EXCURSION OF 0.0026 SECOND PERIOD, BEFORE BOILING BEGINS

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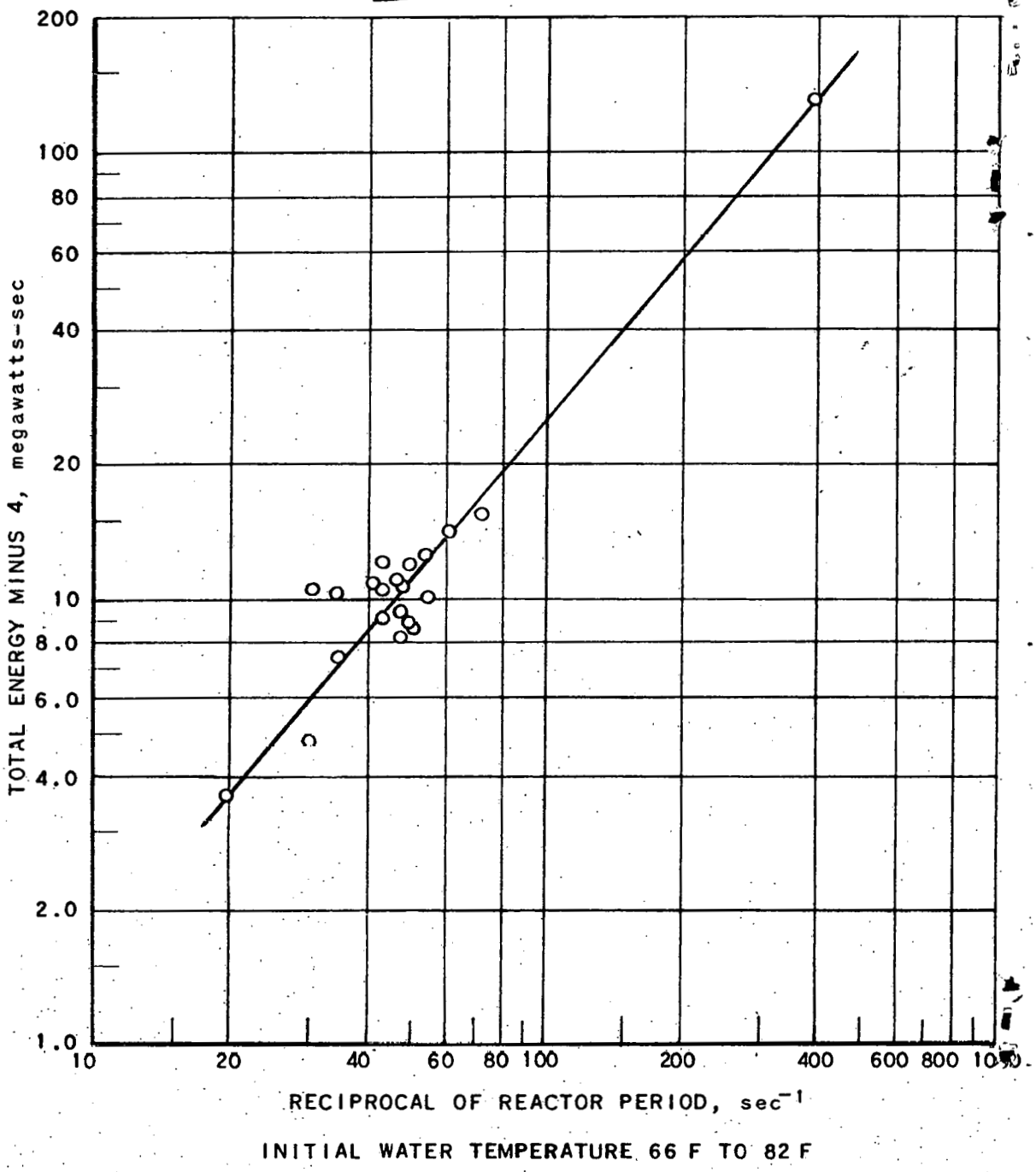

FIG. 41
TOTAL ENERGY OF EXCURSION MINUS ENERGY REQUIRED (4 mw-sec) TO RAISE TEMPERATURE OF CENTER OF AVERAGE PLATE TO THE BOILING POINT

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