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A STUDY OF THE RADIATION BURST IN THE HANFORD HOMOGENEOUS REACTOR

BY

B. R. LEONARD, JR.
TECHNICAL SECTION
ENGINEERING DEPARTMENT

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Criticality Hazards

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By

B. R. Leonard, Jr.

Physics Research Sub-Unit
Applied Research Unit

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A STUDY OF THE RADIATION BURST IN THE HANFORD HOMOGENEOUS REACTOR

ABSTRACT

On November 16, 1951, a partially full spherical reactor using plutonium nitrate fuel was accidentally brought to a prompt critical condition. The energy released in the ensuing reaction was measured to be about 3 megawatt seconds from the temperature rise and the increased beta activity of the fuel. The behavior of the system during the incident has been analyzed. It is shown that the incident resulted from the rapid withdrawal of the safety rod from the system. The dominant feature of the incident was the rapid expansion of the fuel to attain a more favorable geometry until the sphere was full. The net effect of the expansion, however, was to kill the reaction.

The time behavior of the incident has been analyzed in two ways. In the first place, an energy release of 3 megawatt seconds was assumed and from the estimated rates of withdrawal of the safety rod the minimum times for the incident to take place and the shortest periods reached are calculated. The times are found to be greater than about 200 milliseconds and the shortest periods possible are about 10 milliseconds. In the second place, the possible mechanisms of stopping the reaction are evaluated. The incident has then been treated on the basis of a calculation by Fuchs. This analysis shows that the incident occurred in less than 0.5 seconds and that power levels the order of 5×10^7 watts were encountered. The energy release predicted here is in agreement with that measured.

DETAILS

History

A critical mass program has been underway at the Hanford plant. A prime consideration of this program was the review of separation plant

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operations from the standpoint of nuclear safety. An attempt was made to determine the maximum safe mass of plutonium for each part of the processing equipment. To this end criticality experiments were performed for several container geometries and process reagent concentrations. The fuel consisted of solutions of plutonium nitrate and the container geometries studied were tamped cylinders and tamped and bare spheres of different sizes.

Apparatus

A schematic diagram of the reactor assembly is shown in Figure 1. The quantity of fuel in the reactor was varied by means of a rapidly actuated, remotely operated valve in the fuel line from the storage containers. A hollow cadmium sandwiched safety rod is shown in the center of the reactor. This safety rod could be withdrawn from the reactor at either low or high speed with rack and pinion drive and was mechanically released by the opening of a magnetic clutch. This safety rod constituted the strongest poison in the system and was the primary scram device, falling into the reactor upon a signal from the power level meters. The control rod is shown off the center of the reactor. This rod was relatively weak and was the sensitive control employed in the criticality experiments. It also was used as a scram device. Criticality experiments were carried out by remote control from a building about 200 feet from the reactor building.

The Radiation Incident

In the course of the criticality program it became apparent that it would be desirable to determine experimentally the critical mass of a hemispherical shape. As the program had called for a series of experiments in bare spherical reactors, it was decided to make this measurement by half-filling an available sphere and adjusting the concentration to obtain criticality. This was obtained in a spherical segment slightly larger than a hemisphere in a nominal 20 inch diameter sphere. Three additional

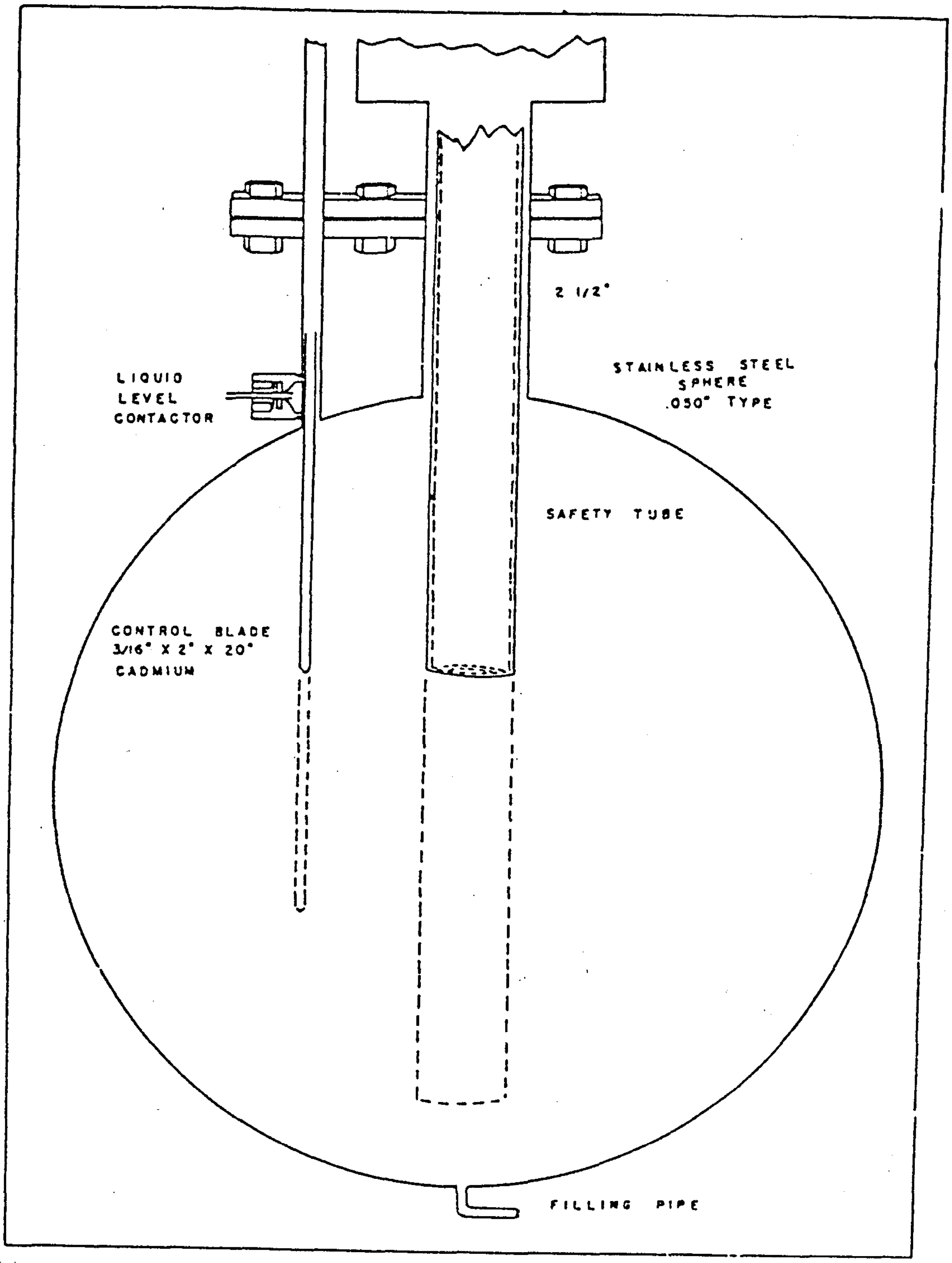

FIGURE 1. A SCHEMATIC DIAGRAM OF THE REACTOR ASSEMBLY.

critical points were found as the fuel was diluted and greater fractions of the sphere volume filled. The last critical point reached was in a volume 88 per cent of the full sphere. As the critical concentration of the sphere was predictable, it was decided to make the final dilution for the full sphere as closely as possible. This required that the total fluid volume be known quite accurately. The method of making this measurement was to add the remaining fuel to the reactor and to determine the total volume by means of the reactor sight glass which gave an accurate measure of the fluid volume. The control and safety rods were inserted and were known to be sufficiently strong to easily override the reactivity of the excess fuel addition. The volume measurement was done carefully and without incident or significant increase in neutron level. Then, instead of draining the reactor for concentration change, an attempt was made to determine where criticality might occur on the rods. As the total strength of the safety rod was known, it was thought that some additional information as to the required dilution could be determined by this measurement. The control rod was pulled first with very minor reactivity effect. Following this, the safety rod was withdrawn intermittently at high speed (2.3 inches/second). A waiting period for the delayed neutron effect of about 15 seconds was made just prior to the incident. This was too short a time to determine whether or not the assembly was critical. The operators next heard the safety controls actuate, instrument indicators moved off scale, scalers jammed, and the most startling manifestation was that of the breakdown of "poppies" playing back through the public address system. The portable "Juno" in the control room was off scale. Presumably a further rod withdrawal had been made.

The Energy Release in the Incident

The energy released in the incident has been determined from the known temperature rise of the fuel and from the increase in radio-activity of the fuel. In addition, a rough check of the energy release has been made from the radiation levels encountered at the control room. Each of these determinations will be discussed in turn.

The Temperature Rise of the Fuel

A thermohm temperature sensitive element taped to the exterior of the stainless steel reactor shell was used for determining the fuel temperature during the course of the criticality measurements. The output of this element actuated a Leeds and Northrop Micromax recorder. Figure 2 shows the temperature variation as recorded during the incident. The curve shows a sudden rise at the time of the incident. Immediately after this the draining of the fuel from the sphere was started and the break in the curve, 15 minutes following the incident, indicates that the sphere is empty. It is evident from the curve that the temperature had not yet reached its peak at this point. In normal operation a time lag of about 30 minutes was necessary before the temperature became constant. This was presumed to be due to lack of intimate contact of the element with the reactor shell. A temperature rise of 8.88°C is obtained by extrapolating the curve to a time of 30 minutes after the rise when the temperature is constant.

The heat equivalents of the fuel involved and the reactor are known. The energy release in the incident is found to be $E = \frac{2.38}{f}$ megawatt-seconds, where f is the fraction of the energy per fission absorbed in the reactor. To determine f, it was assumed that the energy breakup in fission was like that of U^{235} and the values used are those reported in CRR489.[1] The fraction of gamma-rays absorbed in the reactor was calculated to be 0.53 assuming an average gamma-ray energy of 2 Mev. The probability of fast neutron absorption was taken to be the same. The energy absorbed in the 30 minutes following the incident from decay product beta- and gamma-rays was calculated from the curves of Thornton and Houghton[2]

1. G. C. Hanna, CRR489, May 18, 1951.
2. J. K. Thornton and W. J. Houghton, NAA-SR-45, September 1, 1950.

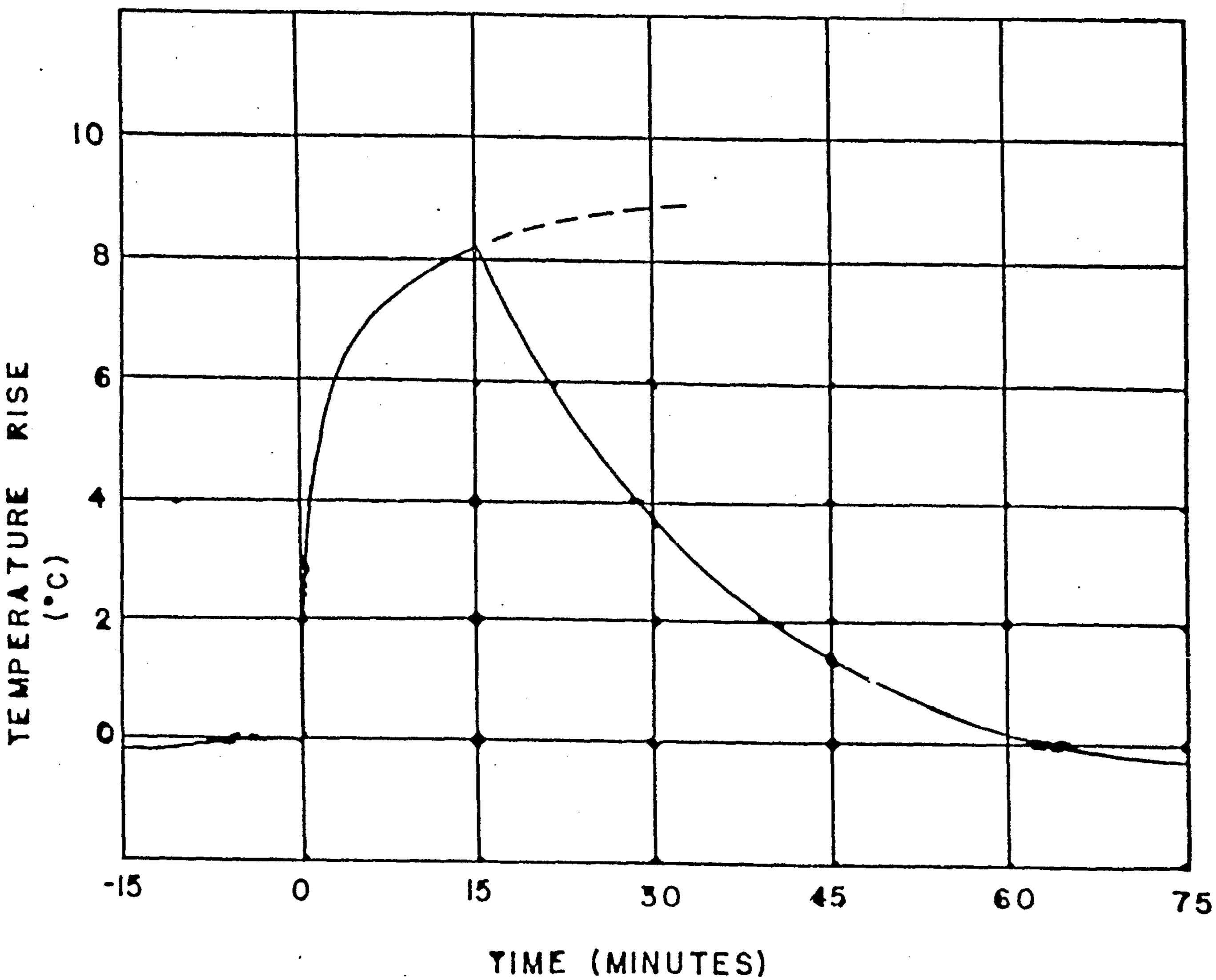

FIGURE 2. THE TEMPERATURE RISE OF THE FUEL AS RECORDED DURING THE INCIDENT.

and the gamma-rays associated with neutron capture in the fuel was also calculated. The value of f was found to be 0.892 of 202 mev/fission. This gives an energy release in the incident of 2.67 megawatt-seconds corresponding to 8.06×10^{16} fissions.

The Increase in Activity of the Fuel

The total beta activity resulting from a given number of fissions of U^{235} has been calculated by Thornton and Houghton[2] on the basis of all known fission products and their decay schemes as a function of time following instantaneous exposure. This is reproduced in Figure 3. The fission yield of Pu^{239} is probably sufficiently like that of U^{235} that this calculation can be used. The number of fissions of the incident can then be determined by measuring the beta activity of the exposed fuel. The determination is complicated by the fact the fuel retains a considerable amount of residual beta activity due to incomplete decontamination in the separations process. Also the entire fuel contents of the experiments were involved in the incident. This made it necessary to substitute a sample of fuel which underwent the separation process at a different time for determining the residual beta activity.

The experimental measurement of total beta activity was made by plating a minute amount of fuel on a thin nylon film. This was counted with an end window beta counter. An aluminum absorption curve was determined to allow an extrapolation through 5.9 mg/cm^2 of air and window to zero absorption. The lower extrapolation limit was used. Appropriate corrections for counter efficiency and geometry were made.

The total beta activity of the fuel involved in the incident was found to be 1.95×10^{12} disintegrations per minute. The residual total beta activity of a sample of fuel of the same concentration not involved in the incident was 0.79×10^{12} d/m. This residual beta activity must be corrected to the decay time after exposure of the fuel involved in the incident and becomes 1.15×10^{12} d/m. The total beta activity due to the incident

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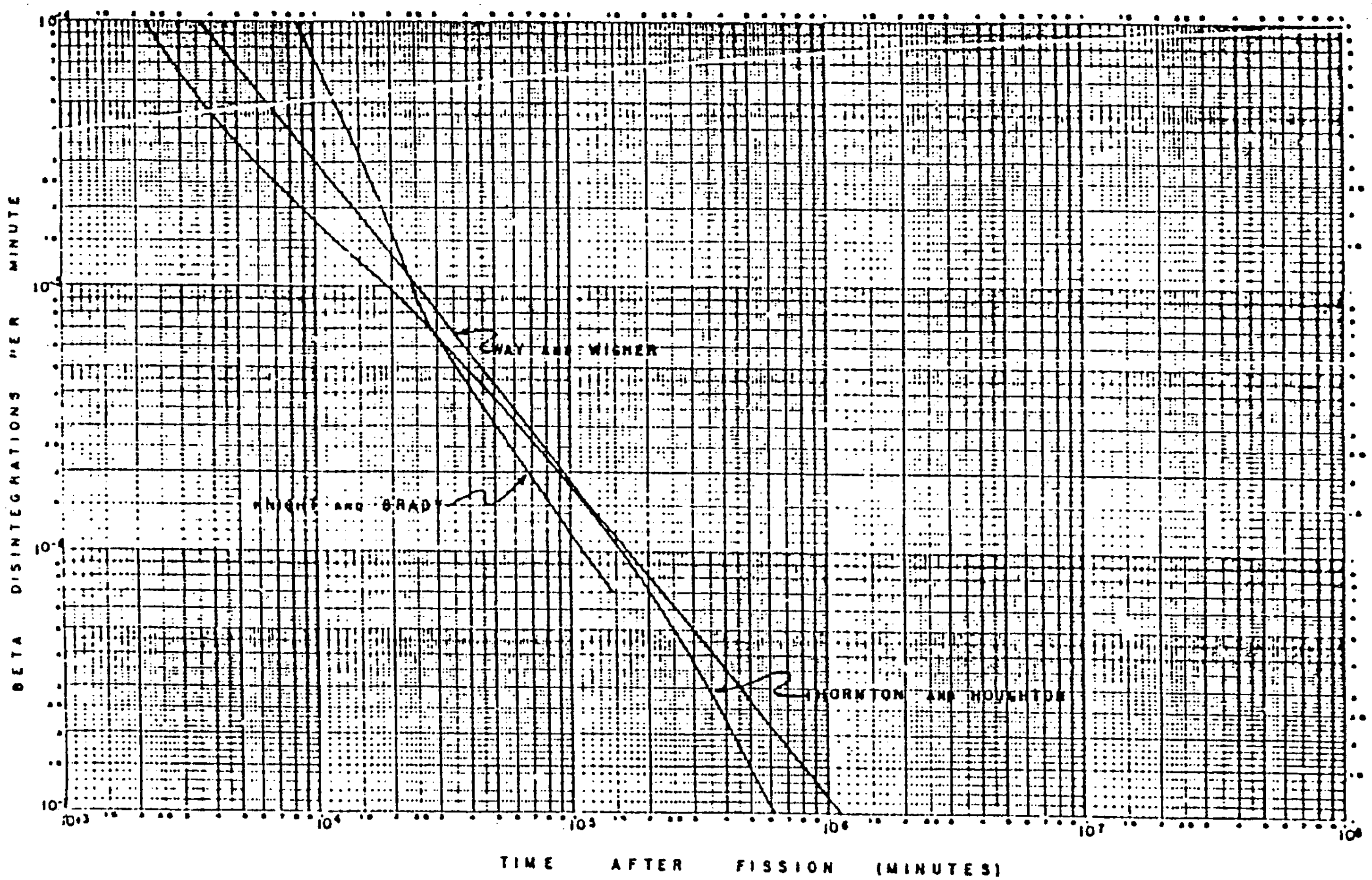

FIGURE 3. THE NUMBER OF BETA DISINTEGRATIONS PER MINUTE PER FISSION VERSUS TIME AFTER FISSION. REPRODUCED FROM THE CURVE OF THORNTON AND HOUGHTON.[2]

then is 0.80×10^{12} d/m. The time elapsed between the incident and the time the samples were counted was 2.0×10^{4} minutes. Referring to Figure 3, it is found that 0.95×10^{-5} disintegrations per minute of beta activity result per fission 2×10^{4} minutes after exposure. The total number of fissions taking place during the incident then was 8.42×10^{16}. This corresponds to 2.79 megawatt seconds.

Radiation Levels

Film badges and pencils were located in the control room which was about 5.85×10^{3} cm distance from the reactor assembly. The Health unit has surveyed these recorders to determine the dosages received in the control room. They find a wide variation in recorded dosage but a dosage not exceeding 600 mrem is indicated. Gamma radiation dosage did not exceed 200 mrem and the average dose was about 145 mrem. Film badges located within the control room but not in the possession of personnel have been interpreted as having detected a maximum of 400 mrem. Rough calculations of the expected dose have been made for comparison with the measured dose and as a check of the energy release.

One calculates that in 30 minutes after the incident 5.40 mev per fission of gamma-rays are radiated from the reactor using the energy breakup in fission as previously discussed.[1] Assuming 8.3×10^{16} fissions occurring in the reactor as a point source 5.85×10^{3} cm from the detectors gives a gamma dosage of 547 mr. This must be corrected for air absorption and shielding. The transmission for this amount of air for 2 mev gamma-rays is 0.82. In addition, it was found experimentally that the metal shell of the tamper tank and the building walls gives a transmission of 0.80. Also, a shadow wall located in the laboratory was found to give a transmission of 0.33 for gamma radiation. The expected gamma-ray dose in the control room then would be 119 mr, in fair agreement with the measured dose.

[redacted]

The shielding and absorption corrections for the neutrons is not known. However, one finds that 2.67×10^8 neutrons per cm^2 are expected at the control room except for absorption and scattering. For 2 mev neutrons, this corresponds to a dose of 1.03 rem before uncertain corrections for scattering and is about twice the uncorrected gamma dose.

ANALYSIS OF THE INCIDENT

Gas Production

An important effect to be considered is the production of gases in the reactor fuel. These gases are formed by the disassociation of the fuel caused by the ionization resulting from stopping the charged particles in the fuel. Most of the ionization results from the fission fragments of course. The gas production is important in two respects. First, the energy absorbed in the gas formation is not measured in the temperature rise of the fuel; secondly, the formation of gases in the fuel may cause an expansion of the fuel. This expansion would result in density and volume changes in the fuel which could be very important.

That gas was formed during the incident is evident from the resulting contamination of the reactor room and known loss of fuel. The temperature of the fuel was well below boiling, yet a small amount of fuel was sprayed through the gaskets of the reactor assembly. These gaskets sealed a volume of air of about 18 liters above the fuel level prior to the incident. Pressures considerably in excess of atmospheric must then have existed in the assembly during the incident.

An estimate of the amount of gas formed during the incident can be obtained from an in-pile irradiation of 0.23 Mol $UO_2(NO_3)_2$ reported by Allen.[3] From this experiment it was reported that 2.7 molecules of gas, mostly H_2, are formed per 100 mev of energy absorbed assuming 200 mev per fission. This indicates a gas formation of about 6.3 cm^3/kw-sec,

3. A. O. Allen and M. Burton, CC-Rn-2613, December 31, 1944.

[redacted]

presumably at equilibrium. In addition, recent Los Alamos experience with the water boiler indicates that about 7 cm^3/kw-sec of gas are carried off by the flushing air. A gas formation of this amount during the incident would indicate a total gas formation of about twenty liters and a momentary pressure greater than 2 atmospheres.

The effect of the gas formation on the reaction depends on the time required for the atoms formed from the disassociation of the liquid to combine to form molecular gas in the liquid. If molecular gas is formed in the liquid in a time short compared to the residence time of a gas bubble in the liquid, the fuel will undergo an expansion. The residence time of the gas bubbles formed in the liquid is known to be the order of one second. Hence, a near uniform expansion of the fuel would take place in the time required for the incident. That molecular gas is probably formed in a time much shorter than times of interest in the incident will be shown.

The problem here is treated on the basis of a calculation of Chandrasekhar(4) on the theory of coagulation of colloids. In this treatment single (atomic) particles are assumed in a system governed by the laws of Brownian motion. These particles are assumed to satisfy a diffusion equation

$$\nabla^2 w = D \frac{\partial w}{\partial t}$$

where the diffusion constant D is given by

$$D = \frac{k T}{6 \pi \eta a}$$

where

a = particle radius

k = Boltzmann's constant

T = absolute temperature

η = coefficient of viscosity

w = density of particles

(4) S. Chandrasekhar, Rev. Mod. Phys. 15, 2, (1943).

[redacted]

It is assumed that the single particles have a sphere of influence R such that a collision of single particles as defined by R yields a double particle (molecular). If the concentration of single particles at time t = O is ν_1, then the concentration of double particles at time t is found to be

$$\nu_2 = \frac{\nu_1^2 \tau}{(1 + \nu_1 \tau)^3}$$

where $\tau = 4\pi \; DRt$

The time in which the concentration of double particles reaches a maximum is to be associated with the time required for the formation of molecular particles and is given by

$$\tau = \frac{1}{2 \nu_1}$$

The initial concentration of single particles ν_1 is estimated by assuming an 85 mev fission fragment having a range of 2.5 cms. in air. The single particles are assumed to result from ionization of the liquid in a cylinder along the path of the fission fragment of effective radius r. An ionization energy of 34 ev per molecule is assumed. In addition, a coefficient of viscosity η = 0.01 dyne-sec/cm^2 is used. The time in which the concentration of double particles reaches a maximum is then

$$t = \frac{1}{8\pi D R \nu_1} \approx \frac{5 \; a \; r^2}{R}$$

Now $\frac{a}{R}$ must be the order of 1/2. Then for the large value of r of 100 A$^{\circ}$,

$$t \approx 2.5 \times 10^{-12} \text{ seconds.}$$

This calculation shows that the time in which the atoms resulting from the disassociation of the liquid diffuse to form molecules is very small. This is largely due to the high density of ionization in the fission fragment track.

 [redacted]

The disassociation of the ionized molecules follows an electronic transition which will probably require times the order of 10^{-8} seconds. Collision times, sticking times and other time features of the recombination are certain to involve times no longer than about 10^{-6} seconds. It then seems certain that molecular gas and, hence, bubbles are formed in the liquid in times short compared to the residence time of the bubbles in the liquid. Since this residence time is longer than the time involved in the incident, the gas formation results in an expansion of the fuel. It is assumed that the expansion effects of single gas molecules are equivalent to those of macroscopic gas bubbles in the liquid.

Period Determination

The object of this analysis is to predict with reasonable accuracy the time behavior of the reactor. A study of the dynamics of the system allows the various mechanisms involved in stopping the reaction to be evaluated and the probable behavior of the incident is determined.

The treatment of the system is based on a slow and a fast neutron group. A single group of delayed neutrons of period τ_d = 10 seconds and density C_d is assumed. The neutrons in the solution are described by

$$D_f \nabla^2 n_f + \frac{K}{P} \frac{n}{\tau_o} (1 - \beta) - \frac{n_f}{\tau_f} = \frac{\partial n_f}{\partial t}$$

$$D \nabla^2 n + P \frac{n_f}{\tau_f} + \frac{C_d}{\tau_d} - \frac{n}{\tau_o} = \frac{\partial n}{\partial t}$$

The subscript f stands for the fast neutrons, β is the fraction of delayed neutrons and is taken as .00364. $K = \nu f \epsilon P$ is the multiplication of the system, where ν is the number of neutrons released per fission and is taken as 2.96, f = macroscopic fission cross section/macroscopic absorption cross section and it is assumed that $\epsilon = P = 1$. The solutions are well known;

 [redacted]

$$n = S T_o \, e^{t/\tau} \qquad n_f = A n$$

where S is a solution of $(\nabla^2 + B) S = O$, A is a constant, B is the buckling and τ is the period. These yield the equation for the period

$$1) \quad \tau = \frac{\tau_d}{2} \left\{ \left[- 1 - \frac{\beta}{\Delta K_{eff}} \left(1 + \frac{\tau_o l_{th}}{\beta \tau_d} \right) - \beta \right] \pm \sqrt{ \left[1 - \frac{\beta}{\Delta K_{eff}} \left(1 + \frac{\tau_o l_{th}}{\beta \tau_d} \right) - \beta \right] + \frac{4 \tau_o l_{th}}{\Delta K_{eff} \, \tau_d} } \right\}$$

where $l_{th} = \dfrac{1}{1 + BL^2}$, $L^2 = \dfrac{1}{3 \sum_a \sum_t}$ and for the sphere

$$B = \frac{\pi^2}{R_c^2} = \frac{\pi^2}{(R + .71 \lambda_t)^2}$$

The condition for criticality is then

$$2) \quad K_{eff} = K \frac{1}{1 + BL^2} \cdot \frac{1}{1 + BL_f^2} = 1$$

where L_f^2 is to be related to the Fermi age for the system.

Equations 1) and 2) together characterize the behavior of the system. As is generally known, accurate predictions are not possible with these equations using accepted values of the constants involved. The following approach then was used. A series of eleven criticality determinations had been made in two bare spheres of nominal 16 and 18 inch diameters. These experimental points were used to determine constants which would fit the data. In this analysis the cross sections for the fuel, other than plutonium, were assumed known. The effect of Pu^{240} was taken into account by assuming an absorption cross section equal that of Pu^{239} and negligible fission cross section. Also L_f^2 was assumed to be given by $33.0 \left(\frac{H_t^o}{H_t} \right)^{1.21}$, where H_t^o

 [redacted]

is the hydrogen concentration of water and H_t the hydrogen concentration of the fuel. Other assumptions would have undoubtedly given equally good results but these assumptions were indicated by the data. The constants to be determined from the data are the fission and absorption cross sections of Pu^{239} which will fit the two group equations. The data do not yield unique values due, in large part, to the experimental errors involved in the fuel analysis. However, a range of possible values is found that fit the data. The numbers chosen were

$$\sigma_a^{49} = 1250 \text{ barns and } \sigma_f^{49} = 975 \text{ barns} .$$

The use of these values gave predictions of the critical mass in the 16 inch and 18 inch spheres that agreed to within about 1 per cent of the experimental values which is about the reliability of the chemical analysis.

A measure of the reliability of this analysis is given by experimental period measurements which were made in the 18 inch sphere. These are shown in Figure 4 with the theoretical prediction. The experimental curve has been shifted about .7 gram to agree with the theoretical curve at the longest period.

The analysis of the incident is further complicated by the fact that the radiation incident occurred in the nominal 20 inch diameter sphere when the sphere was 93 per cent full. The buckling for this geometry is, of course, not known. However, four criticality experiments had been made in the 20 inch sphere at volumes from 57 to 88 per cent full. The four experimental critical mass determinations extrapolate to 1150 grams for the full sphere which coincides with that calculated from the analysis. From these points the buckling for the 93 per cent full sphere can be determined. The experimental points are analyzed to yield values of $B = \frac{\pi^2}{R_c^2}$.

The experimental points are uncorrected for transport cross section but the correction is small except for possibly the 57.1 per cent full case.

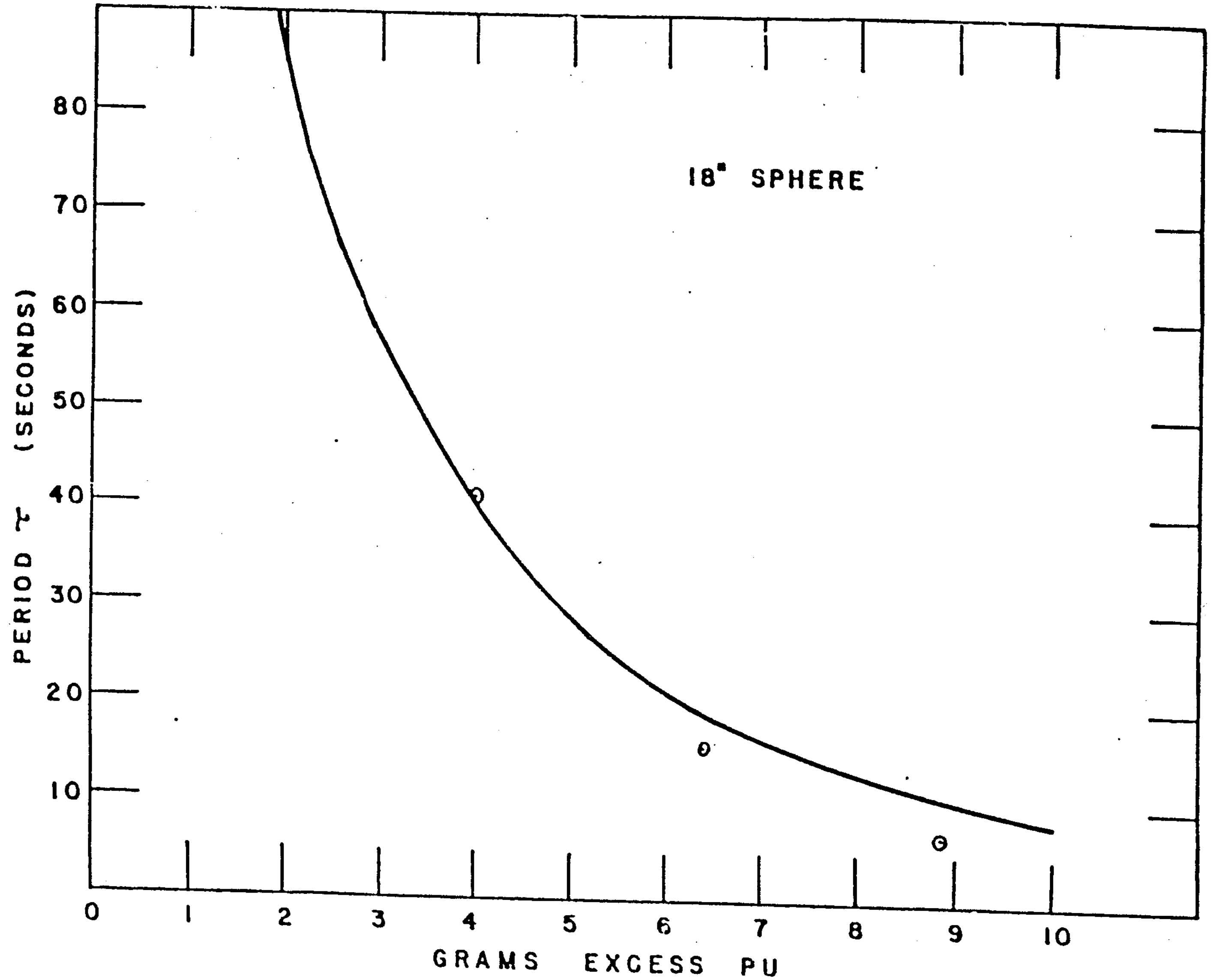

FIGURE 4. THE PERIOD OF AN 18" REACTOR VERSUS EXCESS GRAMS OF PLUTONIUM. THE SOLID CURVE IS CALCULATED FROM EQUATIONS 1 AND 2 AND COMPARED WITH THREE EXPERIMENTAL POINTS.

The value of B for the hemisphere is given by $B = \left(\frac{4.49}{R_c}\right)^2$ according to Weinberg.[5] The variation of buckling with volume is shown in Figure 5, the end points being calculated. From this curve the buckling for the 93 per cent full sphere is found. The shape of this curve is of interest as it is believed to be previously unpublished.

Sufficient information is now available to determine the time behavior of the 93 per cent full sphere where the incident occurred. The variation of period with excess plutonium in grams in the sphere is shown in Figure 6. The horizontal line on the curve represents prompt critical. It is seen that prompt critical is 15 grams from critical in this case. From the known amount of fuel in the reactor, the maximum possible excess grams in the system is known to have been 111 grams. The period for this excess is 2.4×10^{-3} seconds and represents the lower limit of the period. The period after prompt critical is found to be given by $\tau = \frac{1}{4.37\ M}$ where M is the grams of plutonium in excess of prompt critical.

Probable Behavior of the Incident

In order to estimate the manner in which the incident took place, the probable actions of the personnel and apparatus machinery involved must be analyzed. The first item to be noted is that the operator had been removing the safety rod from the reactor at high speed prior to the incident. At least partly because of the insensitive scales on which the instruments the operator was watching at the time were set, the operator was not cognizant of the impending runaway. Therefore, it seems likely that the safety was given another pull at high speed of a duration similar to the preceeding pulls. Analysis of the chart prior to the incident shows that preceeding pulls were the order of 0.65 sec (or much greater) duration.

At this time the effective end of the safety rod was known to be near the center of the reactor. Previous experiments in the 18 inch sphere

5. A. M. Weinberg, M3839, Undated.

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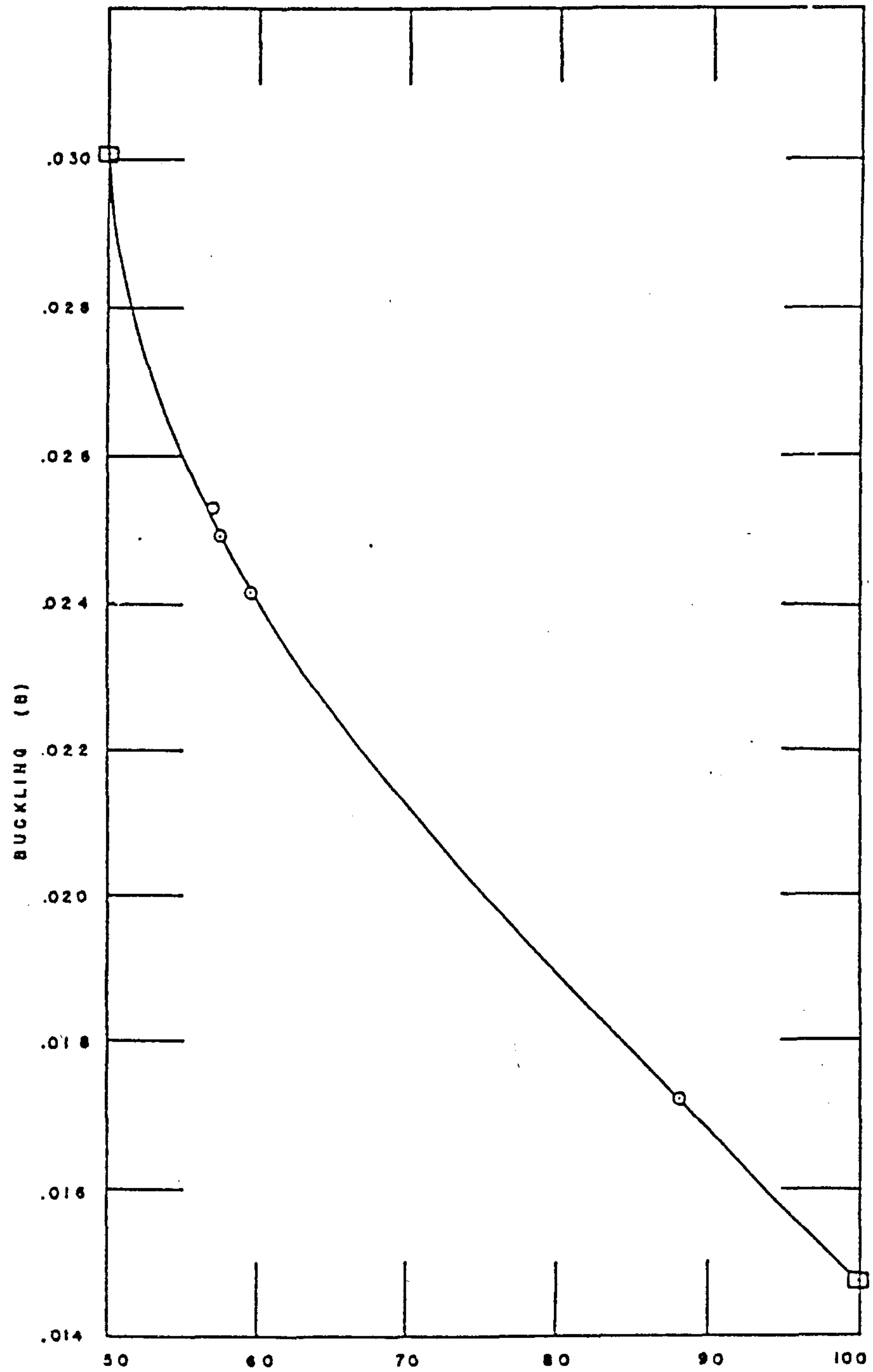

FIGURE 5. THE BUCKLING FOR THE 20" SPHERE AS A FUNCTION OF THE PORTION OF THE FULL SPHERE. THE END POINTS ARE CALCULATED. THE OTHER POINTS ARE OBTAINED FROM EXPERIMENT.

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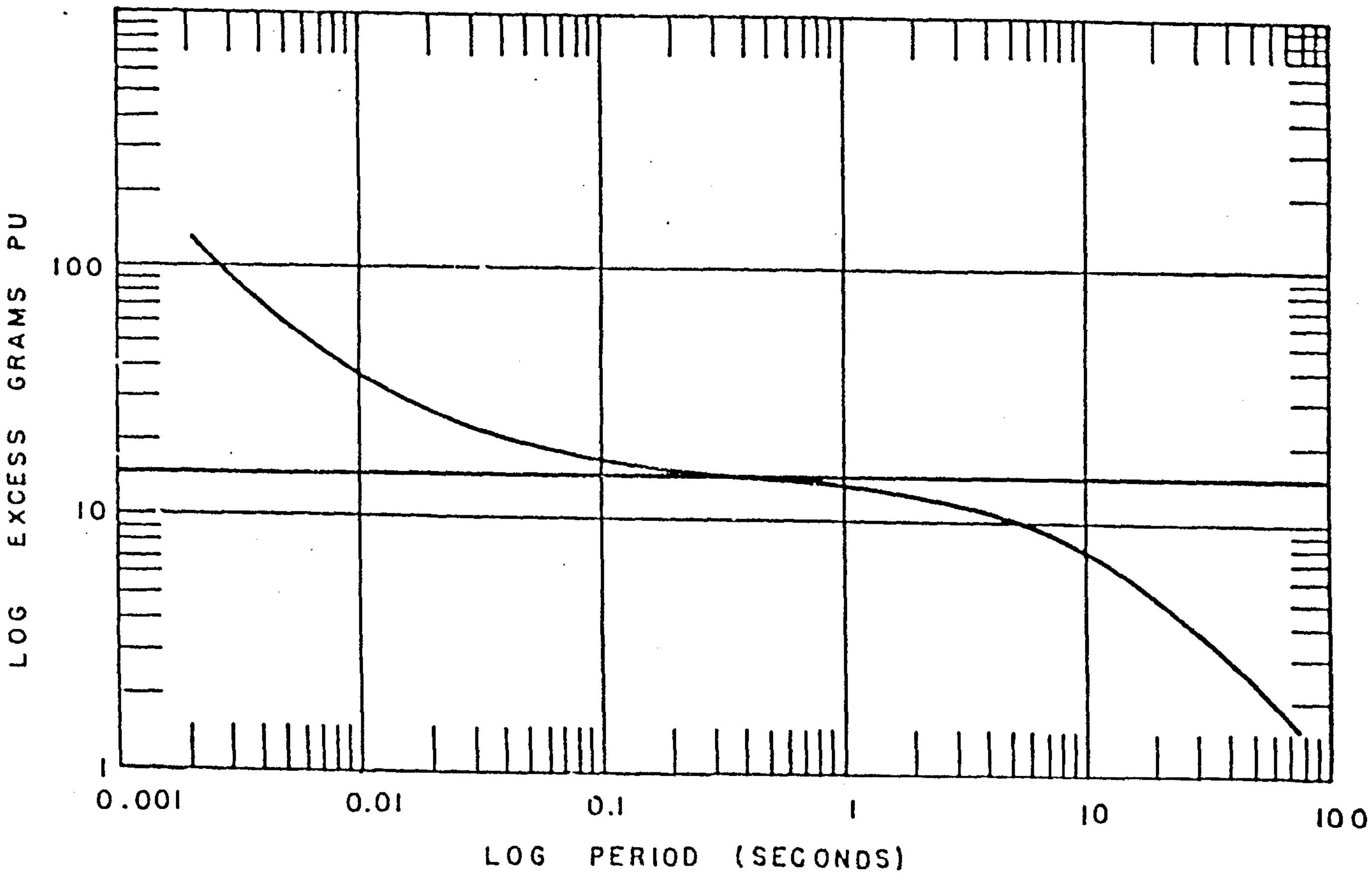

FIGURE 6. THE CALCULATED PERIOD OF THE 93% FULL 20" SPHERE AS A FUNCTION OF THE EXCESS PLUTONIUM. AN EXCESS OF 15 GRAMS OF PLUTONIUM CORRESPONDS TO PROMPT CRITICAL.

indicated a safety rod strength of 270 grams of plutonium in this sphere. Possibly the rod was worth 300 grams in the 20 inch sphere. Also, since the strength of the rod is proportional to the square of the flux, the strength of the rod near the center of the sphere would be about 30 gms/in. The known speed of the rod on high speed was 2.3 in/sec giving an effective rate of withdrawal of about 70 gm/sec. At such rates of withdrawal prompt critical can be reached without increasing the power level by a factor of 10 which is the basis for activating the scram circuits.

The power will increase by 10 very shortly after prompt, however, and the signals will be given for the scram. After the signal is given, a delay of 0.1 to 0.2 sec is involved in transmitting the signal to the scram device. A d.c. activated magnetic clutch must open before the safety rod will stop its outward pull and begin to fall. This probably requires an additional 0.4 to 0.5 sec. Probably a fall of 0.1 sec is necessary for the rod to fall freely far enough to become effective. Thus a time of about 0.5 to 0.8 sec is available after the system has passed prompt critical before the safety rod becomes effective.

As a first approximation, we will assume that the expansion of the fuel has no effect on the reactivity of the system until the sphere is full. After the sphere is full, the expansion of the fuel rapidly cuts off the reaction. This approximation allows us to put a lower limit on the time involved in the incident and the periods reached by the system.

The system then will be characterized as being at an initial power level of 10^{-2} watt. The rapid withdrawal of the safety rod allows the system to reach prompt critical with a power increase of less than 10. After prompt, the period is given by $\tau = \frac{1}{4.37\, a_1 t}$ where a_1 is the effective rate of withdrawal of the rod in grams/sec. Figure 7 shows the period τ reached in time t after prompt for several different values of a_1.

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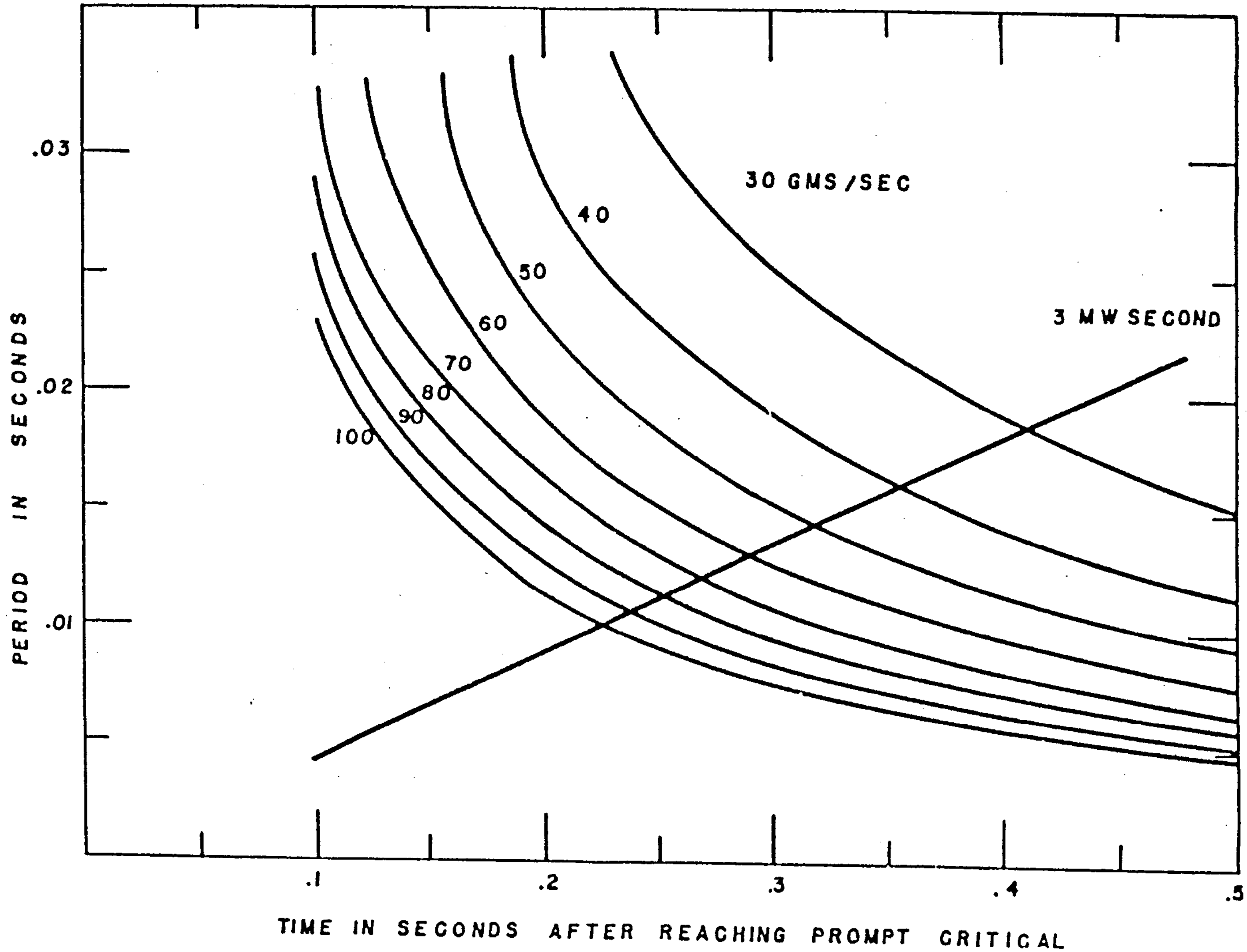

FIGURE 7. THE PERIOD OBTAINED BY THE SYSTEM AS A FUNCTION OF TIME AFTER PROMPT CRITICAL FOR DIFFERENT EFFECTIVE SAFETY ROD STRENGTHS. THE STRAIGHT LINE DENOTES THE TIME REQUIRED FOR AN ENERGY RELEASE OF 3 MEGAWATT SECONDS.

The power increases after prompt according to

$$P = P_o \; e^{4.37 \; a_1 t^2}$$

and the energy released in time t is

$$E = \int_o^t P_o \; e^{4.37 \; a_1 t^2} \, dt \cong P_o \; \frac{e^{4.37 \; a_1 t^2}}{8.74 \; a_1 t} \quad .$$

Assuming an energy release of 3 megawatt-seconds, the times after prompt necessary for this energy to be released are calculated. This limiting time is also shown in Figure 7. For example, Figure 7 shows that for an effective rate of withdrawal of 70 grams/sec, the required energy is released in about .27 seconds after prompt with a minimum period of 12 milliseconds. The figure also shows that larger effective rod strengths do not appreciably affect these figures. The shortest periods reached are about 10 milliseconds and the shortest times are about .23 seconds. These indicate maximum power levels of the order of 10^9 watts. In these short times we have estimated that the safety controls would not have stopped the reaction. The mechanisms of stopping the reaction will now be discussed.

Mechanisms of Cut-Off

That the reaction was probably stopped by some mechanism other than the safety controls is evident. Other mechanisms which have an effect on the reactivity are proportional to the energy expended. These are due to expansion of the fuel by instantaneous gas formation in the fuel. In addition, a negative temperature coefficient of reactivity is indicated. Previous experiments have indicated that the temperature coefficient may be as large as -0.5 grams of plutonium per degree centigrade for this reactor after thermal expansion effects are subtracted. For the temperature rise encountered in the incident this corresponds to a loss of about 4.5 grams. The uncertainty in this figure is rather large.

The effect of expansion of the fuel is three fold. First, there is a positive reactivity increase due to improving geometry until the sphere is full; secondly, there is a negative reactivity change due to loss of moderation until the sphere is full and loss of moderation and fissionable material after the sphere is full. The calculation of these two effects involves uniformly expanding the fuel involved in the incident. The combination of tnese two effects is shown in Figure 8 for an initial excess of 111 grams of plutonium in the 93 per cent full sphere. The loss of reactivity to full is shown to be 6 grams. After the reactor is full and fuel is expelled from the reactor, the system is seen to become subcritical very rapidly.

The final effect of fuel expansion is catching up with the safety rod as it is withdrawn. Prior to the incident, about 3 inches of the safety rod was in the sphere above the fuel level. The effective strength of this portion of the safety can be estimated. An effective rate of withdrawal a_1 = 70 grams/sec. corresponds to a rod strength of about 30 grams/inch at the end of the rod which is near the center of the sphere. The strength of the 3 inches above the fuel level is then calculated to be 6 grams, assuming that the strength is proportional to the square of the flux.

Analysis of the Incident by Fuchs Treatment[6]

This method requires that the multiplication of the system be expressed as

$$\alpha = \alpha_1 - \alpha_2 = at - b\phi$$

where a and b are constants and ϕ is the fraction of fissionable atoms which have undergone fission. Fuchs then studies the differential equation

$$\frac{d^2\phi}{dt^2} = \alpha \frac{d\phi}{dt}$$

6. K. Fuchs, LA596, August 2, 1946.

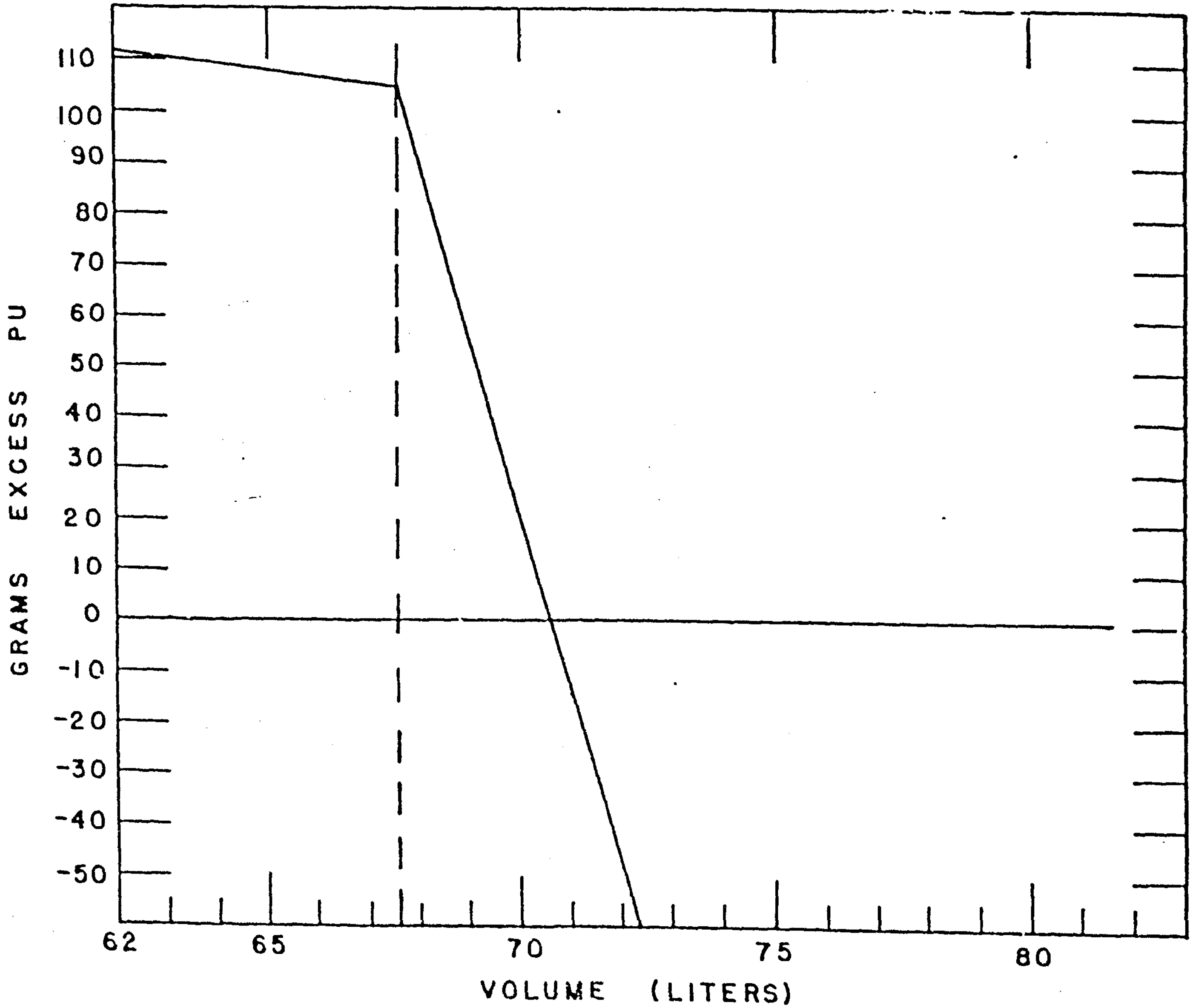

FIGURE 8. THE EFFECTIVE EXCESS PLUTONIUM IN THE SYSTEM ON EXPANSION OF THE 93 % FULL 20" SPHERE. THIS INCLUDES CHANGES IN DENSITY AND BUCKLING ONLY.

for different initial conditions defined by

$$\left.\frac{d\phi}{dt}\right|_{t=o} = \frac{a}{b} f$$

Fuchs' analysis then shows that for $f << 1$ the neutron level rises and falls again in a time

$$t_o = \frac{2}{\sqrt{a}} \sqrt{2 \log\left(\frac{4}{f}\right)} \; .$$

The highest neutron levels are encountered for a period of time given approximately by

$$t_o' = \frac{2}{\sqrt{a}} \sqrt{\frac{2}{\log\left(\frac{4}{f}\right)}}$$

and the efficiency of the system is given by

$$\phi_o = \frac{2 \, a \, t_o}{b}$$

where ϕ_o is the fraction of fissionable atoms which underwent fission during the time t_o. To make use of this treatment, a and b must be evaluated. α_1 has previously been determined to be $\alpha_1 = \frac{1}{\tau} = 4.37 \, a_1 t$ where τ is the period reached in time t after prompt and a_1 is the effective rate of withdrawal of the rod in grams per inch. A value of a_1 of about 70 has been indicated likely.

The evaluation of b is less certain but a reasonable estimate can be made. The temperature coefficient is taken to be worth 4.5 grams and is linear with ϕ. The change in geometry and loss of moderation is worth 6 grams from 93 per cent full to the full sphere. This effect is linear with the volume of gas formed. The effect of catching up with the safety rod has been estimated as 6 grams until the sphere is full. The strength of the rod above the fuel is proportional to $\sin^2 h$, where h is the length of rod in the sphere above the fuel. The volume of gas formed is very nearly proportional to h^2. Then the effect of catching up with the rod is nearly linear

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with the volume of gas formed. The expansion effects then are nearly linear with the volume. However, the volume of gas formed is not quite linear with the number of fissions since the gas is born under pressure. Because of the large volume above the fuel, if the formation of 7 cm^3/kw-sec at NTP is assumed this is still 5 cm^3/kw-sec when the sphere is full. We will assume then that b is given by a loss of 16.5 grams for the volume change to the full sphere and a uniform gas production of 6 cm^3/kw-sec. This corresponds to $b = + 8.76 \times 10^9$.

The value of f is determined by assuming an initial power level of 10^{-1} watt at prompt. For an energy absorbed per fission of 180 mev, f is found to be $\frac{2.09}{a_1} \times 10^{-6}$ where a_1 is the effective rate of rod withdrawal. This value of f satisfies the condition of $f \ll 1$.

This treatment then assumes that the rate of cut-off is directly proportional to the volume. It has been shown in Figure 8 that after the sphere is full, the reaction will cut off much faster than the cut off given by the assumptions for b. The times and efficiencies then that are calculated will be too large and will represent maximum values.

The calculated values of time after prompt for the incident to take place and the calculated values for ϕ_o and the number of fissions involved in the incident are presented in Table I.

Table 1

Effective Rod Strength (gms/sec) a_1	Time Following Prompt Critical for the Incident t (sec)	ϕ_o	No. of Fissions
30	0.688	2.07×10^{-8}	6.86×10^{16}
40	0.600	2.40	7.97
50	0.540	2.71	8.99
60	0.496	2.98	9.89
70	0.461	3.23	10.73
80	0.433	3.47	11.52
90	0.409	3.69	12.25
100	0.390	3.89	12.92

[redacted]

This analysis is seen to give good agreement with the measured number of fissions from temperature rise and beta activity of the fuel. If a gas production of 7 cm^3/kw sec is assumed, the correction to the measured temperature rise of the fuel can be estimated if a heat of formation of 68.5 kg cal per mole of gas is assumed. Then the measured number of fissions from the temperature rise of the fuel becomes 8.85×10^{16} corresponding to 2.93 megawatt seconds. The values shown in Table I were indicated to be too large. Then an effective rod strength of a_1 greater than 50 grams/sec and a time after prompt of less than 0.5 second are indicated by this analysis.

The theory also predicts that the time of highest power is about .057 seconds. Since most of the energy is evolved at peak power this time corresponds to maximum power levels the order of 5×10^7 watts

CONCLUSIONS

The analysis of the incident yields excellent agreement with the measured energy release. The calculation of the maximum time required for the incident of about 0.5 seconds is of particular interest. This tends to justify the assumption of fuel expansion and indeed points to the result that the fuel expansion was the primary factor in stopping the reaction. The estimate of 0.5 seconds as the shortest possible time for the mechanical safety to become effective indicates that the chief contribution of the safety was to prevent further power oscillations.

Emphasis must be placed on the fact that the incident was the direct result of the rapid withdrawal of a strong poison from the reactor. Increasing the reactivity at this rate allowed the system to become prompt critical before the power level had increased sufficiently to actuate the scram device. Short periods were then obtained in a time short compared to that necessary for the mechanical safeties to stop the reaction. Safe

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reactor design then requires that no mechanism be employed which will allow the rapid withdrawal of a strong poison from the system to eliminate possible errors in judgement on the part of the operators.

A startling result of the analysis is the extremely favorable change in geometry resulting from fuel expansion in the partially filled sphere. Had the sphere been full in this incident so that the fuel expansion immediately expelled fuel from the sphere no incident of this magnitude could have occurred. Extreme caution is indicated in experiments involving such partially filled geometries.

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