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Experimental Study of Transient Behavior in a Subcooled, Water-Moderated Reactor

F. SCHROEDER, S. G. FORBES, W. E. NYER, F. L. BENTZEN, AND G. O. BRIGHT

Atomic Energy Division, Phillips Petroleum Company, Idaho Falls, Idaho[1]

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As a part of a program of reactor safety investigations, the response of a heterogeneous, water-moderated and -reflected reactor (SPERT I) to instantaneous reactivity additions has been studied experimentally with initial temperature of 20°C and initial power level of 5 watts. Excess reactivity additions from approximately 0.3% to 1.4%, which result in asymptotic reactor periods from 10 sec to 7 msec, produced self-limiting power bursts with peaks up to 1300 Mw. Plots of the typical behavior of reactor power, fuel plate temperatures, and transient pressures for these tests are presented and discussed. Maximum reactor power, fuel plate temperature, pressure, energy release, and other quantities are correlated as functions of reactor period. The instantaneous excess reactivity of the system during the transient test has been computed from the experimental power behavior and typical results are shown. The reactivity compensation necessary to limit a power burst of this type has been determined and is discussed as a function of initial reactor period. Several mechanisms for the self-shutdown of the reactor are postulated and discussed in light of the experimental results.

INTRODUCTION

In order to provide information to the nuclear reactor industry for the evaluation of reactor hazards, the U. S. Atomic Energy Commission is currently supporting a program of reactor safety investigations (*1*). A major part of the current program is the heterogeneous reactor test facility (SPERT—Special Power Excursion Reactor Tests) operated by Phillips Petroleum Company for the U. S. Atomic Energy Commission at the National Reactor Testing Station in Idaho (*2*). The purpose of this program, which is a continuation and extension of the BORAX I experiments (*3*) carried out by the Argonne National Laboratory, is to provide comprehensive information on the kinetic behavior of enriched-fuel, water-reflected and -moderated reactor systems.

Some 400 kinetic tests have been conducted with the SPERT I reactor in the

[1] Work done under contract to the U. S. Atomic Energy Commission.

period between September, 1955 and December, 1956. A general description of a part of these data has been reported previously (*4*).

This paper will discuss in more detail the 56 tests initiated by stepwise additions of reactivity from an initial water temperature of approximately 20°C. Detailed descriptions of the site, reactor, and the static experiments which have been performed are contained in references (*4*) and (*5*). The reactor control and transient instrumentation are described in detail in another report (*6*).

DESCRIPTION OF REACTOR

The reactor core, consisting of enriched uranium-aluminum fuel assemblies, is contained in an open tank four feet in diameter and ten feet high. Usually, this tank is filled to a point about two feet above the top of the core with water which serves as moderator and reflector. The reactor tank is in turn contained in a larger tank situated below grade level. There are five blade-type control rods. The outer four serve as shim-safety rods. The central transient rod, which in its normal rest position has the cadmium portion below the reactor core, is raised to bring poison into the core. Transients are initiated by releasing the suspended rod and driving it downward out of the reactor.

Figure 1 shows the reactor grid arrangement and Fig. 2 is a cutaway view of a SPERT fuel assembly showing the inner construction and the exterior dimensions. These figures also show the coordinate system used in the identification of locations within the reactor core. The important nuclear characteristics of the core are given in Table I.

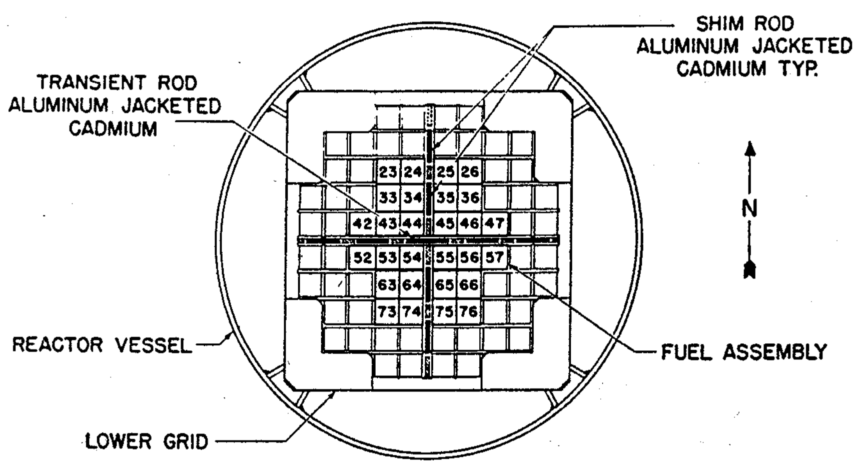

FIG. 1. SPERT I reactor core diagram showing lattice position numbering system.

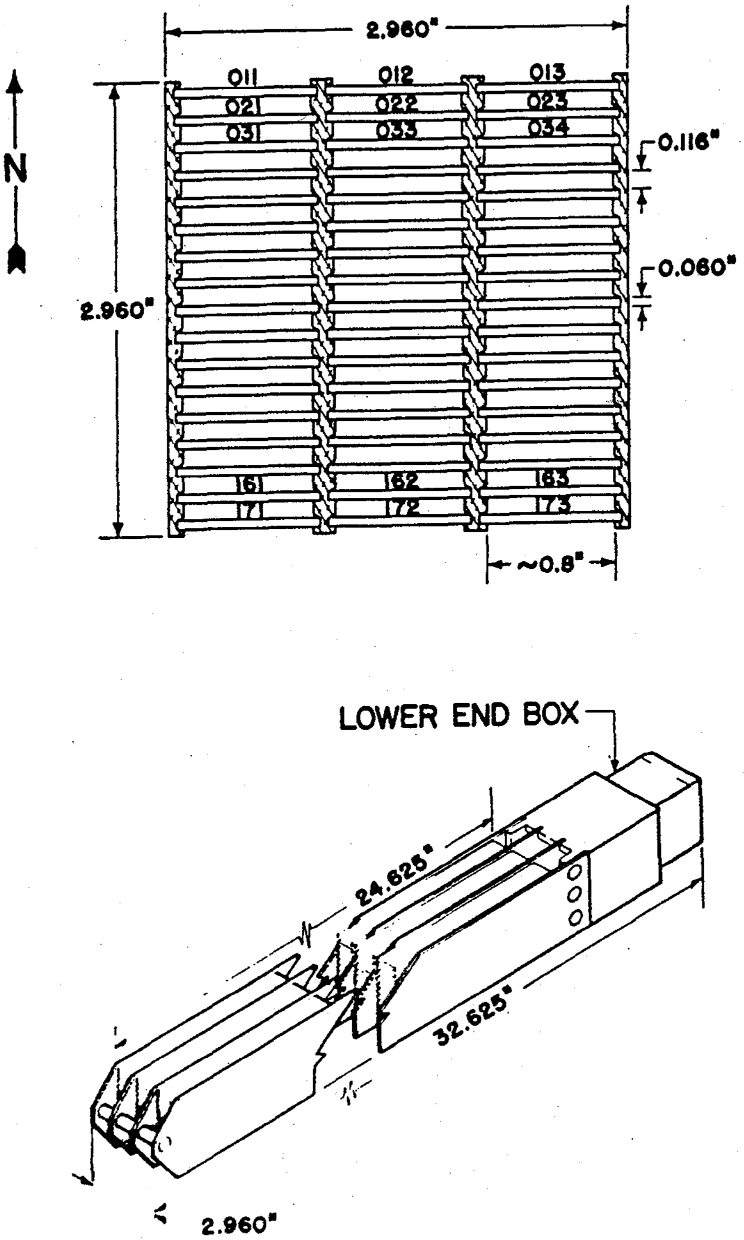

FIG. 2. SPERT I fuel assembly (Type *A*), showing fuel plate numbering system. Location of thermocouples is specified by three coordinates: (1) lattice position (see Fig. 1), (2) fuel plate number, (3) distance from horizontal center line of reactor core in inches (positive up). For example, 55–172–3 indicates a position 3 inches below centerline on the south center plate of the assembly in position 55.

Critical mass (23 fuel as
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Prompt neutron lifetime
Reactivity loss from 20°(
Temperature coefficient :
Temperature coefficient :
Average void coefficient
Maximum void coefficien
Reflector void coefficient
Volume of water in core

Neutron flux, fuel p measurements made d made at a point outsi have been calibrated i niques (*6*). Other quan fast neutrons, and Če readings. Temperatures couples attached to the end boxes at the botto tion. All signals are rec multichannel oscillogra galvanometer system is gible distortion.

EXPERIMENTA

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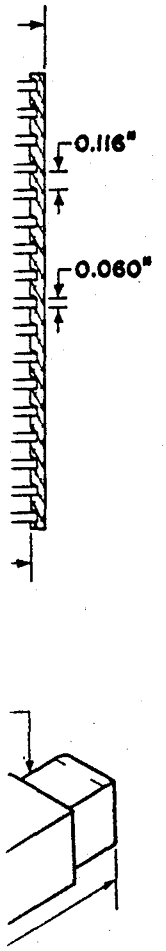

numbering system. Loca-
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TABLE I

CHARACTERISTICS OF SPERT I CORE (TYPE A)

Critical mass (23 fuel assemblies, 18°C)	3.86 kg U^{235}
Excess reactivity (28 fuel assemblies, 18°C)	4%
Prompt neutron lifetime	50 μsec
Reactivity loss from 20°C to 97°C (boiling)	1.05%
Temperature coefficient at 20°C	-0.9×10^{-2}%/°C
Temperature coefficient at 97°C (boiling)	-2.0×10^{-2}%/°C
Average void coefficient for core	-3.5×10^{-4}%/cm^3 void
Maximum void coefficient (center of core)	-7.2×10^{-4}%/cm^3 void
Reflector void coefficient (adjacent to core)	-0.69×10^{-4}%/cm^3 void
Volume of water in core	5.4×10^4 cm^3

INSTRUMENTATION

Neutron flux, fuel plate temperatures, and water pressures are the primary measurements made during the transient. The neutron flux measurements are made at a point outside the reactor tank by boron-lined ion chambers which have been calibrated in terms of the total reactor power by calorimetric techniques (*6*). Other quantities related to reactor power such as gamma radiation, fast neutrons, and Čerenkov radiation are used to supplement ion chamber readings. Temperatures are measured at selected points in the core by thermocouples attached to the fuel plate surfaces. Pressure transducers mounted in the end boxes at the bottom of fuel assemblies provide transient pressure information. All signals are recorded one-half mile away at the Control Center on two multichannel oscillographs. The transient response of the combined electronic galvanometer system is such that a 1-msec period can be followed with negligible distortion.

EXPERIMENTAL TECHNIQUE FOR STEP-TRANSIENT TESTS

Prior to each test the critical position of the shim rod bank is determined with the cadmium section of the transient rod out of the reactor core. The reactor is then made subcritical by pulling the transient rod cadmium section upward into the core. The reactor power is allowed to decay to a level of several watts, at which time the shim rod bank is withdrawn to a predetermined position for the transient. Ejection of the transient rod from the core then leaves the reactor supercritical by an amount determined by the displacement of the shim rods above the critical position. The time for the rod ejection does not have an important effect on the transient behavior of the reactor since the reactivity addition is completed while the reactor power is low compared to the level at which self-shutdown effects become important.

A short time after the ejection of the transient rod, the power rise becomes exponential with a period determined by the reactivity addition (Fig. 3) (*7*). It is this asymptotic reactor period τ and its reciprocal α that are referred to in

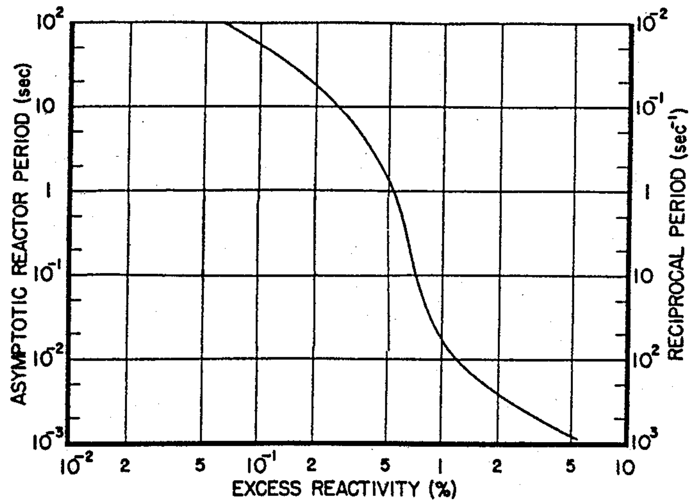


FIG. 3. Excess reactivity *versus* asymptotic reactor period (in-hour relation) for effective neutron lifetime of 50 μsec using Keepin and Wimmett delayed neutron data (7).

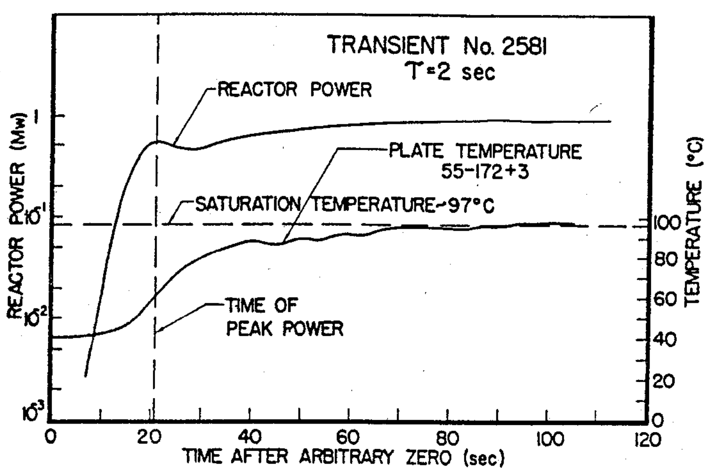


FIG. 4. Representative behavior following 0.48% reactivity addition (α = 0.5 sec^{-1}).

the following discussion. The power continues to rise exponentially until the energy accumulated in the shutdown mechanisms is sufficient to cause an appreciable reduction in the reactivity of the system. As the reactivity continues to decrease, the power passes through a maximum and thereafter approaches a quasi-equilibrium value either monotonically or in an oscillatory fashion. The test is usually terminated by a programmed scram shortly after the initial burst.

REPRESENTATIVE TRANSIENT BEHAVIOR

Examples of the reactor behavior for reactivity insertions resulting in initial reactor periods of 2 sec, 550, 110, 35, 16, and 7 msec are shown in Figs. 4 through 9. These plots display the reactor power, fuel plate surface temperatures, and transient pressures as functions of time during the tests.

Two-second Test

For a relatively long period test, such as is shown in Fig. 4 (τ = 2 sec) the

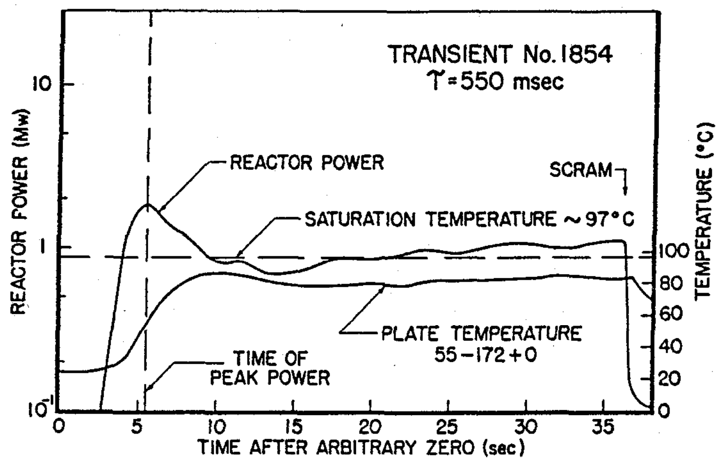


FIG. 5. Representative behavior following 0.60% reactivity addition (α = 1.8 sec^{-1}).

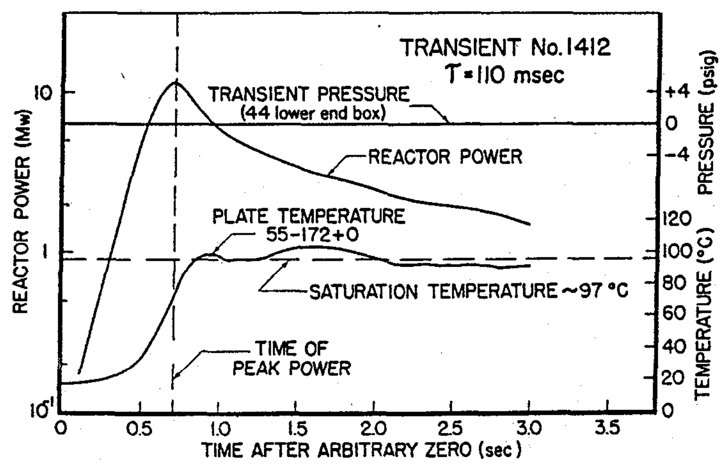


FIG. 6. Representative behavior following 0.71% reactivity addition (α = 9.1 sec^{-1}).

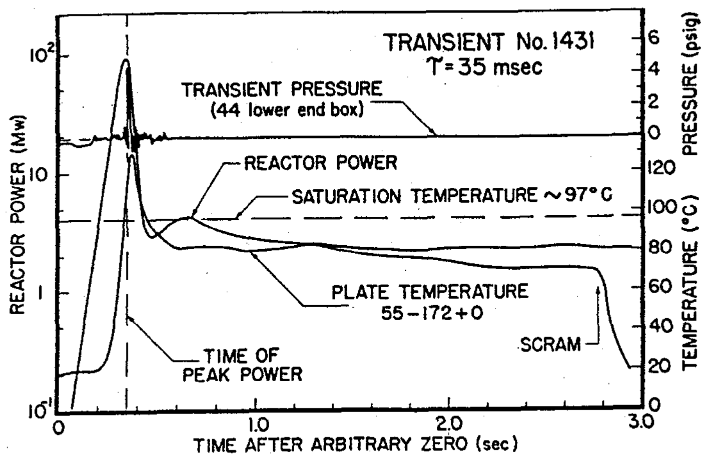


FIG. 7. Representative behavior following 0.85% reactivity addition (α = 29 sec^{-1}).

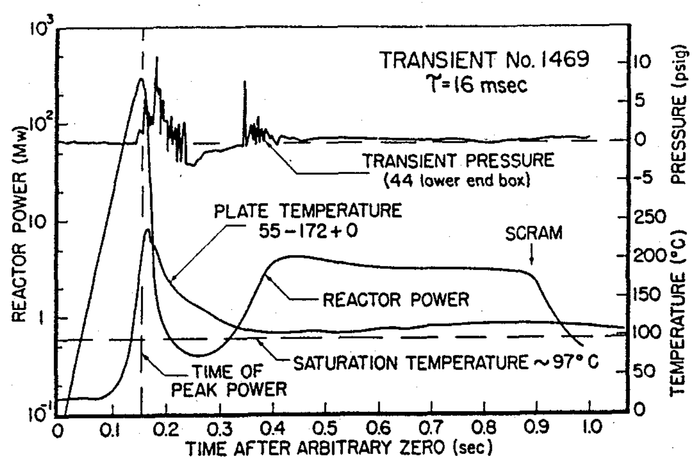
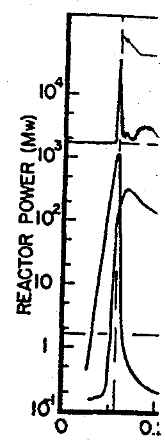


FIG. 8. Representative behavior following 1.0% reactivity addition (α = 62 sec^{-1}).

power is checked at a low level by self-shutdown effects. After a slight undershoot, the power rises toward an equilibrium level somewhat less than one megawatt. The fuel plate surface temperature does not reach saturation temperature until late in the test, well after the initial power surge. No pressure indications are observed in these long-period tests.

550-msec Test

Figure 5 displays the behavior for a 550-msec period test. The power behavior begins to show a noticeable overshoot, but the fuel plate surface tem-



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110-msec Test

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35-msec Test

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16-msec Test

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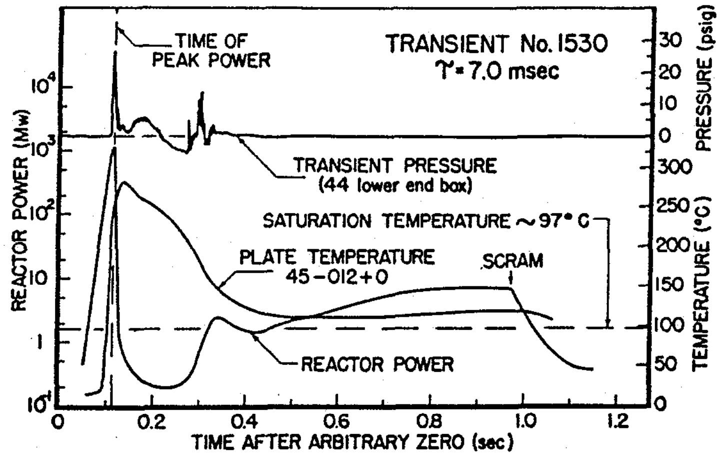


FIG. 9. Representative behavior following 1.4% reactivity addition (α = 143 sec^{-1}).

perature in the center of the core still does not reach saturation temperature during the initial burst.

110-msec Test

For a 110-msec period (Fig. 6) the power reaches a peak of approximately 12 Mw and subsequently decreases monotonically toward the apparent equilibrium level of approximately one megawatt. The plate surface reaches saturation temperature, but only after the power peak is passed, and continues substantially at boiling for the remainder of the test.

35-msec Test

In the period range between 50 msec and 35 msec, marked changes in behavior occur. At 35-msec periods the power peak has become much more pronounced and a power undershoot appears after the burst. This is referred to as "oscillatory-type" behavior. Measurable pressures appear and the plate surface temperature in the center of the core reaches saturation temperature in advance of the power peak, although the maximum still occurs after the power peak (Fig. 7).

16-msec Test

Figure 8 shows the behavior for a 16-msec period transient. The power rises to a maximum of about 300 Mw, drops quite rapidly to a level less than 0.5 Mw, and rises again to finally approach a value of the order of 3 or 4 Mw. In this case the fuel plate temperature reaches saturation temperature well before the power peak, rises to a maximum of about 250°C, decreases rapidly in the region of the power minimum, and remains near boiling for the rest of the run. The transient pressure begins to show two distinct regions of disturbance separated by a depression below the static value. The first disturbance begins at about the time of the power maximum. The second appears near the time of the maximum rate of power increase following the undershoot.

7-msec Test

The shortest period tests of the 20°C series were of approximately 7-msec period (Fig. 9). The maximum power level is about 1300 Mw and the power curve now displays signs of an overshoot in the recovery to equilibrium power after the burst. At the time of peak power, the plate surface temperature in the center of the core has reached a temperature approximately 150°C in excess of saturation temperature. Transient pressures in the fuel assembly endbox in the center of the core reach about 25 psig.

The dependence of the power burst-shape on the transient period can be seen in Fig. 10. Reactor power curves have been normalized at their peaks and have been plotted in terms of reactor period rather than real time in order to facilitate comparison of their shapes. As the period is decreased, the power behavior is seen to change from damped to "oscillatory" and the ratios of peak power to the power minimum following the burst and of the peak power to the equilibrium power both increase.

The pressure data obtained in the transient tests were taken from a variable-reluctance-type pressure transducer mounted in the lower endbox of a fuel assembly at the center of the reactor core. Figure 11 displays in idealized form the characteristic shape of pressure transients near the time of peak reactor power. These curves were synthesized from several pressure traces in each of four period regions. A small pressure surge is seen to always precede the power peak with the larger disturbance following the power maximum.

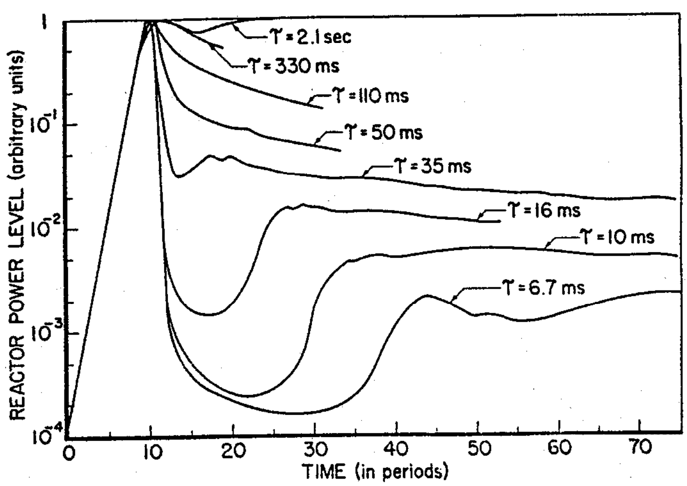


FIG. 10. Power burst shape as a function of initial reactor period τ. Power curves have been normalized at peak values and are plotted in units of τ.

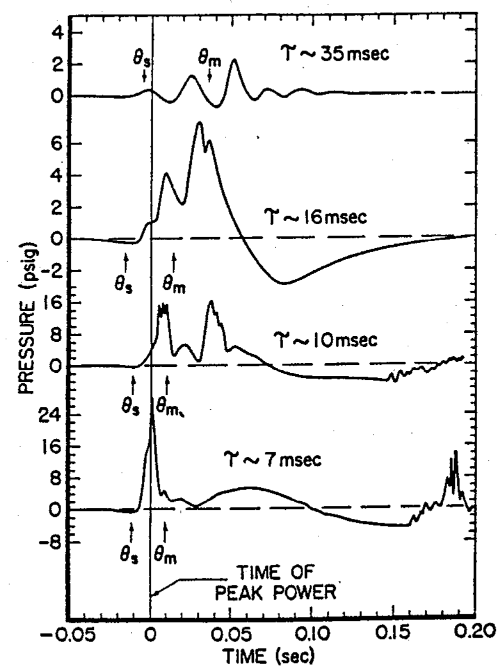


FIG. 11. Idealized transient pressure shapes for four reactor periods. θ_s and θ_m indicate approximate times at which fuel plate surface temperatures reached saturation temperature and maximum, respectively.

The temperature data obtained for these transient tests were taken from thermocouples which are peened into the fuel plate surfaces at selected points in the core. They do not represent the true surface temperature, but correspond to the temperature at some point in the outer 0.010 inch of the cladding. The rapid spatial variation of temperature in the core and within the fuel plate makes it difficult to select a thermocouple trace to represent typical temperature behavior. However, some general statements can be made.

For τ longer than 200 msec the temperature traces do not reach a well-defined maximum, but approach saturation temperature long after the power burst. In the 100-msec period region, saturation temperature is reached approximately 20 msec after the power peak and the temperature remains near boiling thereafter. At $\tau = 50$ msec, saturation temperature is reached about 5 msec after the power peak, and a definite maximum appears which follows the power peak by the order of 50 msec. For periods of 35 msec, the time of saturation temperature leads the power maximum by about 30 msec and the time of temperature maximum follows the power maximum by about 30 msec.

For shorter periods, the temperature, following its maximum, shows an initial rapid drop followed by a slower rate of decrease, and finally drops rapidly to-

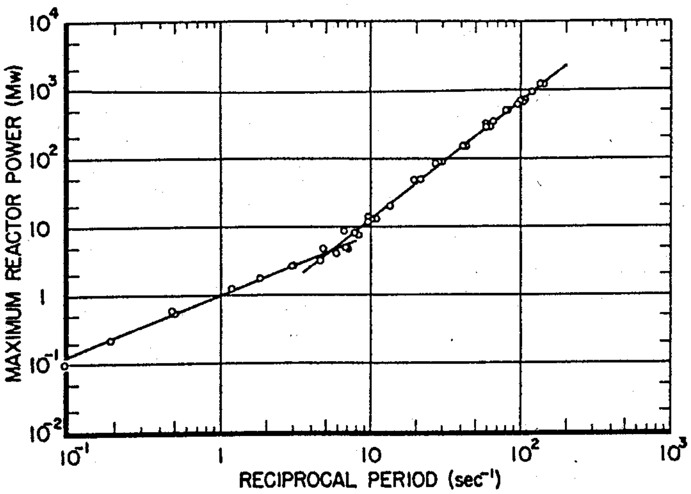


FIG. 12. Maximum reactor power as a function of reciprocal reactor period.

ward saturation temperature. For τ about 16 msec, the time of occurrence of indicated saturation temperature leads the power peak by about 20 msec and the temperature maximum lags by about 10 msec. At τ = 7 msec, these times are both about 10 msec.

DATA CORRELATIONS

A number of characteristics of the series can be presented advantageously as functions of reciprocal period. For example, in Fig. 12 the variation in maximum reactor power is shown as a function of α. These data are fit by two straight line sections (on the logarithmic plot) having approximate slopes of 0.8 and 1.7 for the lower and upper portions, respectively. The point of intersection occurs at approximately five reciprocal seconds. In some cases test results were nearly in coincidence and were plotted as a single point.

In order to give an indication of the energy scale of the transient, the energy released up to the time of the first power peak $E(t_m)$ has been selected as the representative quantity. The total energy release of the power burst might have been used for the short-period tests, but this quantity loses significance for the long-period tests in which there is no unique point defining the end of the burst. The relationship between α and $E(t_m)$ is shown in Fig. 13. It should be noted that a minimum occurs in this curve at an α roughly corresponding to the point of intersection mentioned for the peak power *versus* α curve. The slope of this curve in the short period region is approximately 0.7 on the logarithmic plot.

Another measure of the shape changes in the initial burst as a function of the reactor period can be obtained from Fig. 14. Here the maximum power in the burst ϕ_m multiplied by the transient period τ is plotted *versus* the energy release

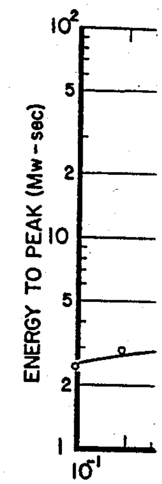
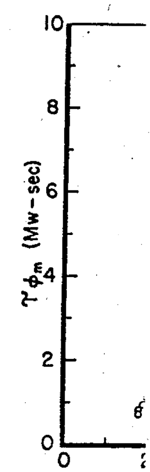


FIG. 13. Energy r



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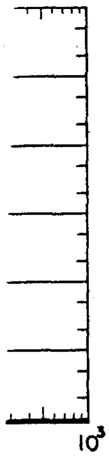

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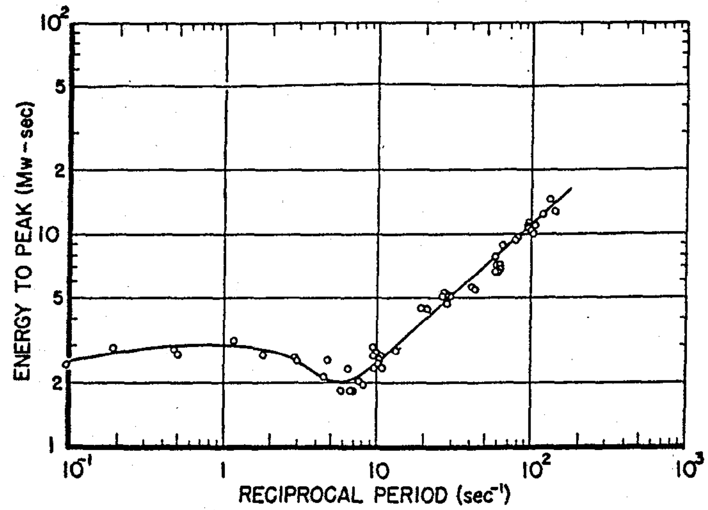


FIG. 13. Energy released to the time of maximum reactor power as a function of reciprocal reactor period.

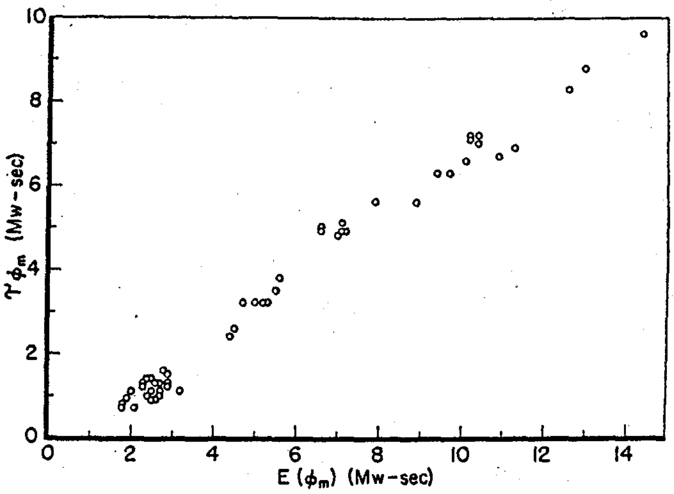


FIG. 14. Product of maximum reactor power ϕ_m and reactor period τ *versus* energy released to time of maximum reactor power $E(\phi_m)$.

to the peak of the excursion. This plot indicates that the shape changes for the initial part of the power burst are not great. These data may be fit approximately by a line with a slope between 0.5 and 1. A slope of one is predicted by the "exponential approximation" for the power burst-shape which assumes that the power rises exponentially to the peak. A simple model[2] for reactor kinetics,

[2] A model treated originally by K. Fuchs at Los Alamos.

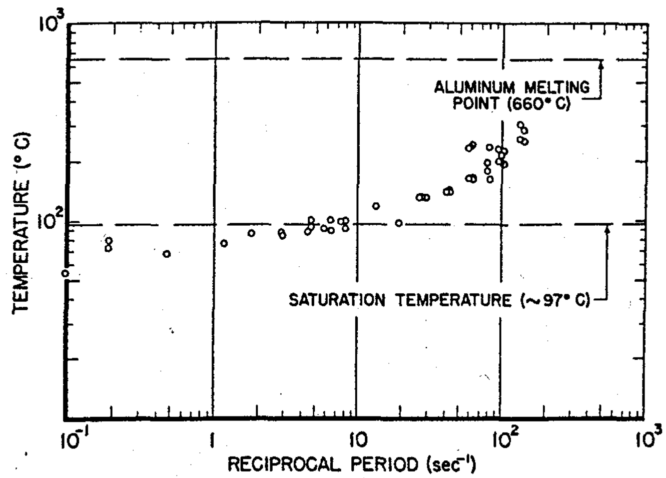


FIG. 15. Maximum fuel plate surface temperature as a function of reciprocal reactor period. Thermocouples were located at horizontal centerline of reactor core in a central fuel assembly.

which includes no delayed neutrons and which provides for an energy coefficient of reactivity but no energy escape or time delays in the transfer of energy to the moderator, predicts slope of 0.5 for this curve.

Figure 15 is a plot of the maximum temperature reached by the fuel plate surface as a function of the reciprocal period. The point measured was within a few inches of the center of the reactor core, which is sufficiently close to the point of maximum power density to approximate the surface temperature of the hottest plate in the reactor. For α less than approximately 10 sec^{-1} ($\tau \sim 100$ msec), this temperature plot loses significance because there is no clearly defined maximum. In fact, all temperatures would ultimately approach boiling due to the finite heat capacity of the system. Where a peak in the temperature curve exists, it occurs after the time of maximum reactor power but approaches the time of peak power as α increases. These data indicate that the melting point of aluminum would be reached at the center of the plate, which is hotter than the surface, for an α of approximately 200 sec^{-1} (τ = 5 msec).

Figure 16 displays the fuel-plate surface temperature reached at the time of the peak reactor power, again as a function of the reciprocal period. The smallest α for which the fuel-plate surface reaches saturation temperature prior to the power burst is near 20 sec^{-1} ($\tau \sim 50$ msec).

Figure 17 is a plot of the maximum transient pressures as a function of the reciprocal reactor period. Because of the rapid fluctuations in the pressure, some smoothing was employed in selecting the maximum values. While it can be observed that the pressure is rising rapidly for large α, the scatter in the data is too great to permit accurate extrapolation.

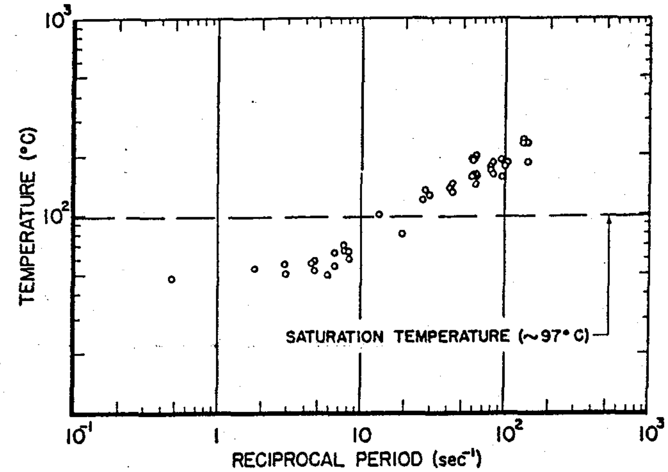


FIG. 16. Fuel plate surface temperature at the time of maximum reactor power as a function of reciprocal reactor period. Thermocouples were located at horizontal center line of reactor core in a central fuel assembly.

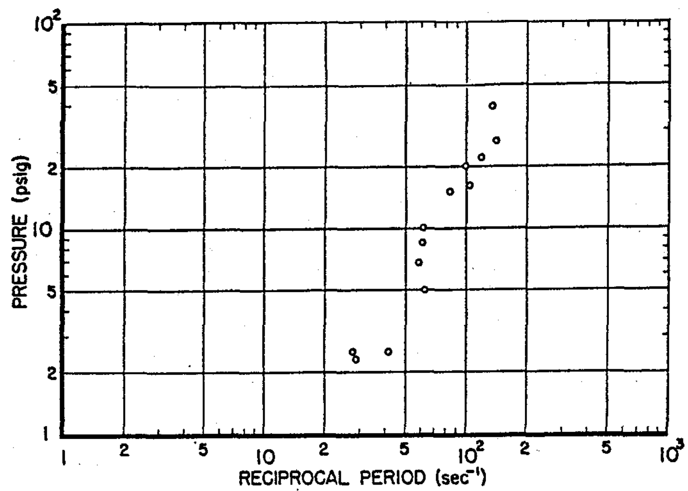


FIG. 17. Maximum transient pressure as a function of reciprocal reactor period. Pressure transducer was located in lower endbox of a central fuel assembly.

REACTIVITY BEHAVIOR DURING TRANSIENT TESTS

Some insight into the behavior of the shutdown mechanisms during a reactor transient can be obtained by an examination of the instantaneous reactivity of the system during a power burst. Following a method developed at Argonne National Laboratory (*8*), the reactor kinetic equations have been programmed for the IBM 650 computer in order to allow computation of the instantaneous

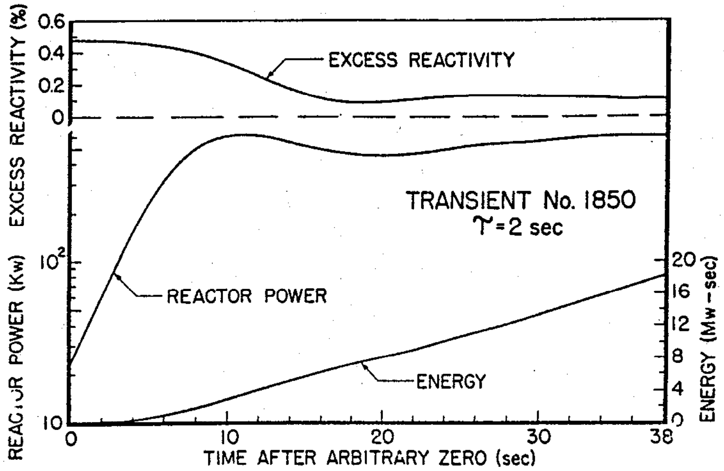


FIG. 18. Instantaneous excess reactivity during a 2-sec period transient test. Also shown are reactor power and energy release.

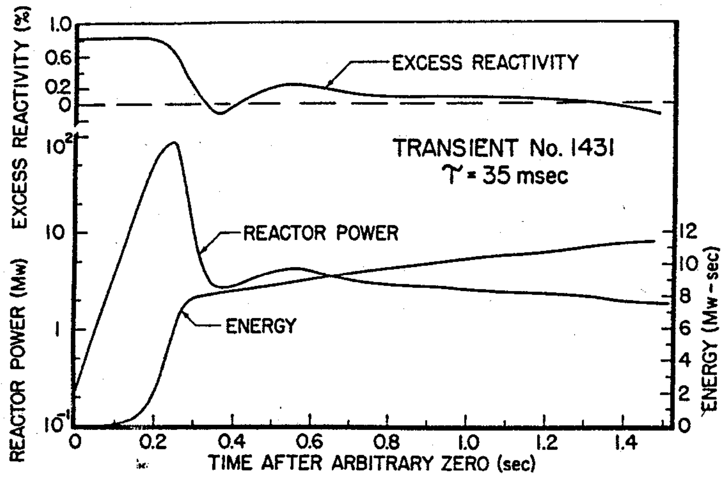
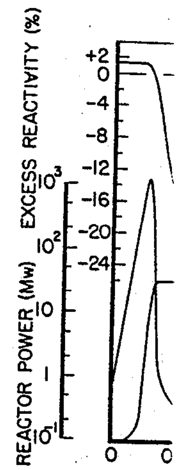


FIG. 19. Instantaneous excess reactivity during a 35-msec period transient test. Also shown are reactor power and energy release.

excess reactivity $\Delta k(t)$ of the system from the experimentally observed power behavior. This analysis is given in detail in reference (*9*). The results of computations for three typical transients are shown in Figs. 18 through 20. It will be noted that, for a 2-sec initial period, the reactivity of the system is still greater than one at the end of the test. This is to be expected, since the delayed neutrons are not yet in equilibrium. The reactivity of the system will always be greater than one at the time t_m of the first power maximum, since the relative



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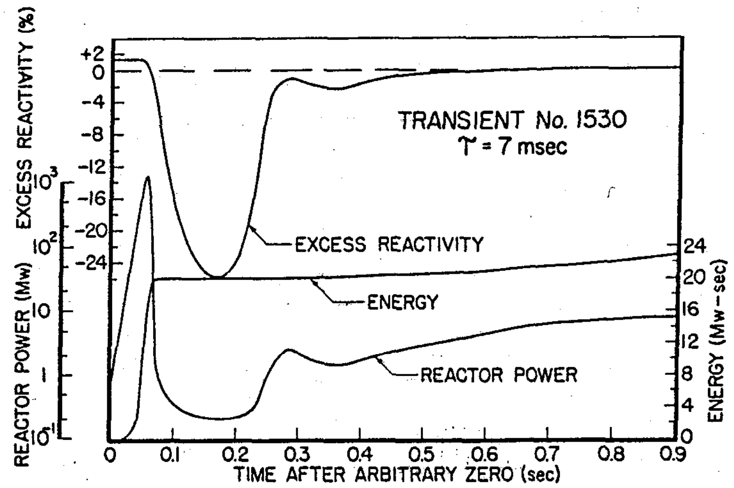

FIG. 20. Instantaneous excess reactivity during a 7-msec period transient test. Also shown are reactor power and energy release.

contribution of the delayed neutrons is reduced during a power rise. The excess reactivity does reach a negative value after the power maximum for the 35-msec test (Fig. 19). This is the period region where power undershoots are first observed and where maximum plate temperatures begin to exceed saturation temperatures. Following the power maximum in the 7-msec test (Fig. 20), a very large negative excess reactivity is present in the system, which is related, of course, to the large undershoot in the power behavior. The power recovery following this undershoot occurs with the system in a subcritical condition and indeed $\Delta k(t)$ never goes positive again during the test. This can occur because the multiplying properties of the system are increasing rapidly while the source from delayed neutrons is decreasing slowly.

From these calculations the instantaneous excess reactivity in the system at the time of the peak of the power burst $\Delta k(t_m)$ may be obtained. The difference between this quantity and the initial reactivity inserted, $\Delta k(0)$, then yields the reactivity compensated by the system at the time of maximum power, $k_c(t_m)$. Figure 21 is a plot of $k_c(t_m)$ as a function of reciprocal reactor period. The initial reactivity inserted, $\Delta k(0)$ (obtained from the in-hour relation, Fig. 3), and the prompt portion of this reactivity addition $[\Delta k_p(0) = \Delta k(0)(1 - \beta) - \beta]$ are also plotted as functions of α in this figure. These two curves are asymptotes for $k_c(t_m)$ in the long- and short-period regions, respectively, since at extremely long periods it is necessary to compensate almost the entire reactivity addition in order to check the power rise, while for short periods compensation of the prompt part of the reactivity addition is sufficient. Since the forms of the $\Delta k(t)$ curves

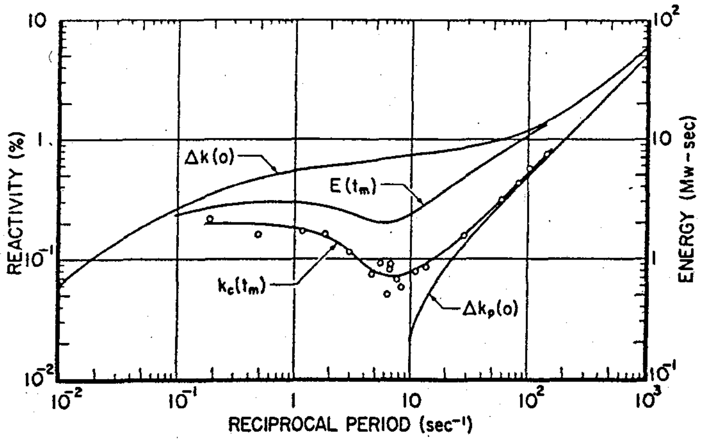

FIG. 21. Excess reactivity inserted $[\Delta k(0)]$, prompt excess reactivity inserted $[\Delta k_p(0) \equiv \Delta k(0)(1-\beta) - \beta]$, reactivity compensated at time t_m of maximum reactor power $[k_c(t_m) \equiv |\Delta k(t_m) - \Delta k(0)|]$, and energy released at t_m, $E(t_m)$, *versus* reciprocal reactor period.

depend on the shapes of the power bursts, the behavior of the $k_c(t_m)$ curve between the two asymptotes is determined by the reactor properties and the test conditions. The experimental $k_c(t_m)$ displays a minimum near the α corresponding to the break in the maximum power *versus* α curve. The observed scatter in the points on both curves in the region of 5 sec^{-1} is indicative of the extreme sensitivity of the reactor period to minor changes in reactivity near prompt critical. The experimental curve of the energy released at the time of the peak of the power excursion $E(t_m)$ has been reproduced on this plot for comparison. As would be expected in a system with an energy coefficient of reactivity, the $E(t_m)$ curve and the $k_c(t_m)$ curve have quite similar shapes. In fact, the similarity in shape implies that the portion of the energy released which is available for use in reducing the reactivity at t_m is not a rapidly varying function of α.

DISCUSSION OF RESULTS

Self-shutdown is dependent on the instantaneous energy storage in various mechanisms, and thus the partition of the energy among these mechanisms becomes an important consideration. For instance, energy released by fission in the fuel plates does not contribute to effects in the moderator such as thermal expansion and boiling until such time as the energy has been transferred to the water. The accumulation of energy in a given mechanism tends to lag the power behavior in the sense that it is an integral effect rather than an instantaneous one. The instantaneous values of the stored energies are, of course, determined by the input rates and escape rates. Energy in a given mechanism may be derived from more than one source and in particular may consist of a combination of delayed and prompt effects.

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Shutdown mechanisms which may be important for the SPERT I type of reactor are the following:

Fuel Plate Heating

Heating of the fuel plates results in two main effects—Doppler broadening and changes in the core geometry due to plate expansion. Both effects are prompt but small for SPERT I. The mechanism for energy escape is simply heat transfer to the moderator or to structural parts of the core.

Moderator Heating

Heating of the moderator results in density changes and neutron temperature effects. Part of this heating is prompt, since it is a result of neutron and gamma-ray heating; part is delayed, since it depends on the heat transferred by conduction from the fuel plates. Changes in density may take place by thermal expansion of the liquid, formation of steam, and liberation of dissolved gases. Steam formation is more effective than expansion in terms of density change per unit energy. The large thermal gradients existing in the moderator next to a rapidly heated plate make it possible for the layer next to the plate to be well above saturation temperature, even though the remainder of the moderator is still essentially unheated. Conduction heat transfer is the principal means of moderator heating in these tests; therefore, the existence of fuel plate surface temperatures in excess of saturation temperature becomes a necessary (but perhaps not sufficient) condition for boiling to take place. The finite growth rate of bubbles in superheated water and the necessity for nucleation centers constitute possible delay mechanisms in addition to the delay in energy transfer. Important mechanisms for energy escape are convection, which carries hot water and steam from the core, and, in the case of steam, recondensation in colder portions of the moderator.

Radiolytic Gas Production

The formation of radiolytic gas in the moderator results principally from recoil protons and electrons, since fission fragments are confined within the fuel plates. The energy deposition is prompt, but the moderator density changes necessary to produce shutdown effects may exhibit delays resulting from the time required to form a gas bubble by aggregation of individual molecules. Radiolytic gas may disappear from the core by convection, recombination, chemical reactions, and dissolution.

The relative effectiveness of these mechanisms varies with time during the course of a transient and also depends on the initial conditions for the test. It is apparent that, for α less than about 20 sec^{-1}, boiling cannot be a shutdown mechanism, since none of the fuel plate surface temperatures reaches saturation until after the power peak. During tests in which α is large, steam formation definitely occurs, but the presence of actual steam voids prior to the power peak has not been demonstrated.

The region of small α is more readily analyzed since boiling is not a factor.

The effect of fuel plate heating is small and will be disregarded. The remaining effects, radiolytic gas production and nonboiling moderator heating, can be estimated by assuming that the former is proportional to the energy release and that the moderator is heated principally by conduction. The energy transferred to the moderator can be estimated if the temperature of the fuel plate surface is assumed to rise exponentially to the time of the peak power t_m. In this case, the energy transfer is determined by α, the fuel plate surface temperature at t_m, and the thermal diffusivity of the water. The temperature rise in the water at t_m thus may be calculated and the resulting reactivity compensation determined. Comparison of this value with the experimentally determined $k_c(t_m)$ shows that only about 20% of the required reactivity compensation is achieved by moderator expansion.

An estimate of the production of radiolytic gas may be made by assuming that one hydrogen molecule is formed for each 100 ev of ionizing radiation absorbed in water (*10*), and that the energy available for this process is 3% of the energy released by fission. It is further assumed that gas production immediately results in a density change and that the back reactions take place slowly compared with the time scale for a power burst. From the energy released at the time of peak power $E(t_m)$ and the experimentally determined moderator density coefficient, the reactivity compensation at t_m may be calculated. It is found that this effect in combination with that calculated from conduction heat transfer gives good agreement with the $k_c(t_m)$ obtained from the experimental power trace. The greatest disagreement occurs for α of 143 $\sec^{-1}$ where the calculated $k_c(t_m)$ is only about half of that obtained experimentally. In this region boiling is at least possible if not required. For smaller α the error is about $\pm 30\%$. Considering the assumptions involved, agreement of this kind is probably fortuitous, but it does appear that radiolytic gas production is an important effect in self-shutdown. More detailed calculations, which take into account the actual fuel plate surface temperature behavior during the transient, as well as the spatial variations within the core, are currently in progress. More accurate determinations of the gas production under transient conditions are needed.

An extension of the analysis into the region of boiling heat transfer is a considerably more complicated problem which is currently under investigation and will include the results of tests initiated from 85°C and boiling. Although shutdown by boiling may become important as α increases, it must do so gradually rather than suddenly becoming the dominating effect as soon as saturation temperatures are reached, since other mechanisms account for an appreciable part of the required reactivity compensation even in the region of large α. The absence of a discontinuity in the ϕ_m *versus* α curve above α of 20 lends support to this conclusion.

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sidered. The gradual disappearance of a true power peak as α decreases to a small value is a consequence of the transient equilibrium between the generation and escape of shutdown effects. For large α, the delayed energy transfer from the fuel plates to the moderator produces a large overcompensation of reactivity after the burst, resulting in a large undershoot in the power $\phi(t)$. The subsequent energy escape produces a secondary power rise after the initial power burst. It is entirely possible for such time delays to result in sustained or even diverging power oscillations even though none of the reactivity coefficients is positive. The existence of such oscillations in the SPERT I reactor has been demonstrated (*11*).

Acknowledgments

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