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THE EFFECTS OF PRESSURE AND FLOW ON ROOM
TEMPERATURE POWER EXCURSIONS IN SPERT III

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US ATOMIC ENERGY COMMISSION

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ABSTRACT

This report summarizes the effects of pressure and forced coolant flow on the reactor response to step insertions of reactivity in the Spert III facility. Every power excursion, covering a period range from 500 msec to 10 msec, corresponding to step insertions of reactivity from 88ϕ to 125ϕ was self-limiting regardless of initial system pressure or flow rate. Several significant points were observed during the investigation of the effect of initial system pressure. Perhaps the most important of these is the fact that it is possible to suppress boiling up to the time of peak power without significantly increasing the maximum power even for periods as short as 10 msec. This indicates that the reactivity normally compensated by the formation of steam can be compensated by other mechanisms with little change in power-burst behavior. The energy release to time of peak power increases only about a factor of two when the subcooling is increased from 80°C at atmospheric pressure to 320°C at 2500 psi. The fuel-plate surface temperature also increased with increasing system pressure.

The results of using forced coolant flow to suppress boiling were somewhat different than those observed in the pressure effect series. For long-period tests, since the fuel plate surface temperatures were reduced by the increased rate of heat transfer to the water and, since the hot water was then swept from the core, the reactivity compensation contribution due to water and fuel-plate expansion was reduced. In this long-period region where the energy generation rate is sufficiently slow, enough energy was removed from the core region to eliminate the initial power peak that had been observed in the no-flow tests. Instead of peaking, the power continued to rise until it reached a high enough level that the available flow was unable to remove sufficient energy from the core region, at which time the exponential power rise was terminated and the power sought an equilibrium level. For tests with initial asymptotic periods shorter than about 50 msec, the energy generation rate is increasing so rapidly that the heat cannot be removed from the core region at a rate sufficient to affect the initial power peak. Under these conditions, the initial burst is essentially the same as in the no-flow case. However, following the peak, the power again seeks an equilibrium level which is approximately proportional to the flow rate. In some cases the equilibrium level is higher than the initial power peak. The power rise during a 10-msec period transient does not deviate from an exponential until the power level is within one decade of peak power. Since the water moves only about 5 in., out of a total 36-in. core length, during this decade of power rise at the maximum available flow rate, it is reasonable that the flow rate has no significant effect on the initial power burst for short-period tests.

The effect of flow rate on the power behavior is essentially the same with an initial system pressure of 2500 psi as it is with atmospheric pressure. However, increasing the flow rate tends to reduce the higher fuel plate temperature observed as the initial system pressure is increased. In some cases, the flow reduces the plate temperature more than the higher pressure increases it.

THE EFFECTS OF PRESSURE AND FLOW ON ROOM TEMPERATURE POWER EXCURSIONS IN SPERT III

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I. INTRODUCTION

Spert III was designed to facilitate study of the effects of the initial pressure, initial temperature and forced coolant flow rate on reactor response during nuclear excursions. The available system parameters of 2500 psig, 650°F and 20,000 gpm make it suitable for investigating problems pertinent to pressurized water power reactors and, to some extent, boiling water reactors. Since December 1958, critical studies have been carried out over the full range of environmental conditions. Both static and transient tests have been conducted to study the separate and combined effect of initial system pressure and coolant flow on the kinetic behavior at room temperature. The results of the criticality studies and the static tests were reported earlier [1]. Most of the information contained in this report has been reported either orally or in progress reports [2, 3, 4, 5, 6]. The purpose of this report is to collect the existing information and to describe in general the overall effects of initial system pressure and flow rate on the transient response of the Spert III reactor.

The tests discussed here cover a period range from 500 msec to 10 msec, corresponding to step insertions of reactivity from 88¢ to 125¢. Initial system conditions encompassed pressures up to 2500 psi, flow rates up to 20,000 gpm, or 18 ft/sec through the core, and combinations of these system variables. To prevent cavitation of the pumps, all flow tests required a system pressure of at least 230 psi. All of the tests were initiated with the system initially at room temperature.

These tests were run for a dual purpose. First, to observe the effect that system pressure and forced coolant flow have on the reactor response to step insertions of reactivity. These transients were performed with the initial system conditions more closely simulating a power reactor than previous tests in the Spert series. Second, these tests provided an opportunity to check models and theories of reactor behavior over a wider range of parameters. By increasing the initial system pressure, and consequently the saturation temperature, the time from initiation of the transient to boiling was increased. In many cases boiling was suppressed completely. By forcing large volumes of water through the core, the energy partition between the fuel plates and the moderator could be extensively altered. Besides removing more energy from the fuel plates, during the longer period tests, much of the hot water also was removed from the core region. Thus, three of the variables thought to be most important in the self-limiting behavior of heterogeneous, water-cooled, plate-type reactors were altered by adjusting the initial system conditions.

To assess the effectiveness of other shutdown mechanisms in the absence of boiling, a preliminary analysis of the total reactivity compensation contribution from fuel-plate expansion and moderator heating was made. Since the scoping results were in good agreement with the experiments, more refined calculational methods were undertaken. In these later calculations, spatial variations in the void coefficient of reactivity and in the fuel plate surface temperature were taken into account by sectionalizing the core both radially and axially. The nonlinear expansion of water with temperature was also included. The results of the more refined calculations [7] indicate that the actual amount of reactivity compensated varies from a factor of 1.2 (in the very-short-period region) to a factor of 2 (in the long-period region) greater than the values calculated for the combined effect of fuel plate expansion and moderator heating.

A summary of the reduced data from the 126-step transients is presented in the Appendix.

II. GENERAL DESCRIPTION OF THE FACILITY

The Spert III facility consists of a reactor vessel, a pressurizing tank, two primary coolant loops with two pumps and a heat exchanger in each, a secondary water system, a water treating system, and the necessary auxiliary equipment. The reactor vessel and primary coolant loops are designed for a maximum operating pressure and temperature of 2500 psi and 650°F. The maximum coolant flow rate is 20,000 gpm and the heat removal system is capable of removing 60 MW for short periods of time.

The reactor and coolant system are remotely operable, with the controls located in a control center building which is approximately 1/2 mile from the reactor. No personnel are permitted in the reactor area during nuclear operations. A complete description of the facility has been published previously [8] and only those features pertinent to the understanding of the test results will be described here.

A schematic flow diagram of the Spert III coolant system is shown in Figure 1. Each primary loop consists of two circulating pumps, a heat exchanger, and the necessary flow control and check valves. The maximum coolant flow rate in each loop is 10,000 gpm. Coolant enters the bottom of the reactor vessel, flows upward through the core, reverses direction and flows downward through the thermal shield region just inside the vessel wall, and leaves the vessel near the bottom.

Fig. 1 Spert III process flow diagram.

Pressurization of the system is accomplished by means of a steam pressurizer vessel connected to the system through a static line. The pressure is automatically controlled by staged operation of sixteen, 12-kW, immersion-type electric heaters.

The reactor vessel has an inside diameter of 4 ft. and an overall height of about 19 ft. The vessel was designed for a maximum pressure and temperature of 3500 psi at 650°F. It is of laminated construction with a 3-1/2-in.-thick wall. The inside layer is clad with nominal 1/8 in. of stainless steel, type 304L. The control rod drive mechanisms are mounted on the vessel head.

The internal structure has been designed for a plate-type stainless steel core described later in this section. Figure 2 presents a cross-sectional view of the core taken through the core centerline. A cruciform rod is located in the geometrical center of the reactor. This transient rod is utilized to initiate reactor excursions by the rapid ejection of poison from the core. Eight fuel-poison control assemblies are located in the off-axis positions and provide normal operating control.

Fig. 2 Spert III core cross section.

Sixty-eight positions are provided in the reactor lower grid, eight of which are occupied by the fuel-poison control assemblies. Most of the fuel positions in the core are filled by type 1S assemblies. In order to provide space for the transient rod, the four central fuel assemblies are of a smaller (type 2S) size. Surrounding the core is a 1/2-in.-thick stainless steel core skirt and four stainless steel thermal shields.

Figure 3 is a pictorial cross section of the Spert III type 1S fuel assembly. The assembly is a plate-type, stainless steel unit consisting of fuel plates, side plates, upper and lower end-boxes, and a center reinforcing plate. The

Fig. 3 Spert III fuel assembly (type 1S).

reinforcing plate increases the strength of the assembly and minimizes vibration of the fuel plates. To reduce pressure differentials in the core, the end-boxes have been cut away to permit the pressure inside and outside this assembly to equalize. The larger of the two sizes of assemblies (type 1S) is approximately 3 x 3 in. with 38 fuel plates while the smaller (type 2S) is approximately 2.5 x 2.5 in. with 32 fuel plates. These assemblies contain 638 g and 442 g of U-235, respectively. The active core height is a nominal 36 in.

The fuel plates consist of an approximately 93%-enriched, UO_2 -stainless steel center, 0.020 in. thick, which is clad on each side with 0.005 in. of stainless steel, type 304L. The water channel between plates is 0.128 in. thick.

In order to maintain proper flow distribution in the reactor core, filler pieces are provided for insertion in those grid positions not occupied by fuel assemblies or control assemblies. These fillers are stainless steel boxes of the same external dimensions as the type 1S fuel assemblies. The upper and lower ends of the boxes are closed except for a 29/64-in. orifice. The walls of the box are 1/8 in. thick. The upper and lower end-boxes are identical to those of the fuel assemblies. Other differently shaped filler blocks form the outer boundary of the reactor core and fill out the cylindrical area enclosed by the core skirt.

A cutaway view of a control rod is presented in Figure 4. The control assemblies are the fuel-poison type, containing fuel in the lower section and poison in the upper section. Each pair of assemblies is joined by a yoke to form a control rod which is driven by a single drive mechanism. The fuel section consists of 32 fuel plates similar to those in the type-2S fuel assembly and each section contains 414 g of U-235. The poison sections consist of hollow boxes of boron-10-bearing, stainless steel alloy.

Fig. 4 Spert III control rod.

The transient rod is cross-shaped with the lower section constructed of boron-10-bearing stainless steel alloy and the upper section of stainless steel. This rod is used to keep the reactor sub-critical while the control rods are raised above their normal critical position by an amount predetermined to give the desired excess reactivity for a power excursion test. Rapid ejection of the transient rod poison section will then result in essentially a step-wise addition of reactivity.

III. INSTRUMENTATION

Since the results presented here represent the response of certain detectors, a brief description of the detectors is included.

Power level indication was obtained from four uncompensated B-10-lined neutron-detecting chambers, of which two were commercially made (G. E.-Model GR9) and two were designed and made at Spert. These chambers were physically positioned to measure leakage neutron flux such that power coverage could be maintained over nine decades during a test. Normally, however, two chambers were used to detect peak power while the other two were used for period measurement and burst shape description; therefore, 5 decades of power were usually covered during a transient.

Five mil chromel-alumel thermocouples spot welded to the surface of the fuel plates were used for temperature measurement. Thirty-two thermocouples, eight on each of four assemblies, were installed in the core, but only 17 to 20 thermocouple signals were recorded during any single test. The eight thermocouples on a given assembly were all attached to one outside fuel plate and positioned to give an indication of the vertical temperature profile but with preference given to the maximum flux region; ie, the thermocouples were only two or three in. apart near the flux peak but were separated by six in. in the lower flux regions. The failure rate of the thermocouples was appreciable and it was necessary to replace the thermocoupled assemblies several times during the testing described in this report. The temperature data presented here were obtained from thermocouples located at the flux peak of a centrally located fuel assembly and are the maximum temperatures observed.

Several other variables, such as transient pressure and strain, also were recorded but are not discussed in this report. Several of the many strain gauges that are located on the pressurizer, reactor vessel, and piping were monitored during the transient testing but the maximum strains detected were less than 3% of the yield stress of these components. A study of the strain gauge data has been published separately [9]. The data obtained from in-core pressure transducers will be included in a separate study now in preparation.

The outputs of the detectors are amplified at the reactor building before being transmitted the 1/2 mile to the control center where they are recorded on two 26-channel optical-recording oscillographs in which galvanometer deflections are recorded on photographic paper that can be transported at speeds up to 115 in./sec.

A process panel at the control center is used to control and record the system parameters governing the initial conditions of a test.

IV. FIDUCIAL SERIES

A fiducial series of transient tests was run to facilitate correlation with existing data. For this fiducial series, the reactor vessel was vented to the atmosphere and the water was about six ft above the top of the core. The water was initially at room temperature and the starting power was about 10 watts for each of these tests. There was no forced coolant flow.

Figure 5 compares peak power vs reciprocal period (ω) for the fiducial series in Spert III with two different fully-enriched plate-type cores that were tested in Spert I. The top curve represents the data from an aluminum-clad plate-type core (B core) which was slightly larger than the Spert III core (C core) while the lower curve is from a stainless steel clad plate-type core (P core) that was much smaller in size. All three curves exhibit the same general shape; ie, a slope of about 1 for periods longer than 250 msec and a slope of about 2 for periods shorter than 90 msec. However, the period at which the change in slope occurs is a function of prompt neutron lifetime and thus varies for these three cores. The breakpoints for the two stainless-steel-clad cores with similar prompt neutron lifetimes occur at about the same period, whereas, the breakpoint for the longer prompt neutron lifetime aluminum-clad B core occurs at a much longer period. A few pertinent characteristics of the three cores are listed in Table I. A more complete discussion of the static characteristics of the C core is contained in a previously published report [1].

Fig. 5 Comparison of peak power vs reciprocal period for B core, P core, and C core.

TABLE I
COMPARISON OF CORE CHARACTERISTICS

	B Core	P Core	C Core
No. of Assemblies	64	19	52
No. of Plates/assembly	12	18	19
Grams of U-235/plate	7	28.6	16.8
Cladding	Al	S.S.	S.S.
Assembly size	3 x 3 x 24 in.	3 x 3 x 22 in.	3 x 3 x 36 in.
Temperature Coeff. @20°C	-1.7¢/°C	-0.3¢/°C	-1.8¢/°C
Ave. void coeff.	-5.3¢/%	-46¢/%	-45¢/%
ℓ/β_{eff}	11×10^{-3}	2.3×10^{-3}	3×10^{-3}

A plot of energy to time of peak power vs reciprocal period, shown in Figure 6, illustrates the similarity of the power burst shape between the three cores. In the long period region, where the peak power for the B core is approximately the same as for the C core, the energy to peak power also is about the same. In the same region, the peak power of the P core is less than the peak power of the C core by about a factor of two, and this is reflected in the energy

Fig. 6 Comparison of energy to time of peak power vs reciprocal period for B core, P core, and C core.

plot. For each of the cores, the period at which the energy begins increasing with decreasing periods corresponds with the period at which the breakpoint occurs in the peak power versus alpha curve.

A plot of the temperature at time of peak power as a function of reciprocal period is nearly the same for the P core and the C core as can be seen in Figure 7. The same plot for the B core is similar in the small α region but begins to deviate near an α of 10 corresponding to a period of 100 msec. Boiling temperatures are reached during 100-msec periods in the B core but periods as short as 35 msec are necessary before boiling temperatures are reached at time of peak power in the P core and C core. These temperatures are consistent with the higher peak powers observed for a given period with the aluminum core.

Fig. 7 Comparison of temperature at time of peak power vs reciprocal period for B core, P core, and C core.

The maximum temperature reached during the test stays near boiling (100°C) until the periods become shorter than about 100 msec, as can be seen in Figure 8. At this point, the B core temperatures began to rise rapidly and reached 350°C for a 10-msec test. The C core and P core temperatures do not begin to rise appreciably until periods of about 25 msec are reached. The P core temperatures then rise faster than the C core temperatures and a 270°C temperature was recorded for a 10-msec-period test. The maximum temperature during a 10-msec-period test in the C core was 225°C.

Fig. 8 Comparison of maximum temperature vs reciprocal period for B core, P core, and C core.

V. EFFECTS OF PRESSURE

The hypotheses regarding the self-limiting response of plate-type water-moderated reactors to step insertions of reactivity rely strongly on an effective water density change for explanation of the behavior. The effective water density change includes plate expansion, water density change due to temperature change, boiling, and possibly radiolytic or other gas formation. The results from previous Spert I tests indicate that, for short-period power excursions, the formation of steam voids is a very important contributor to the reactivity compensation which limits the power burst. By increasing the system pressure, the onset of moderator boiling can be delayed or possibly even suppressed. With a major contributor to self-shutdown delayed or suppressed, the shape of the power burst should be altered. The results of a series of tests initiated with system pressures up to 2500 psi indicate that, in general, the peak power is a little higher and the burst a little broader. As also would be expected, much higher temperatures are reached. However, in some cases, even for short periods, the power excursion was self-limiting without any indication of boiling temperature having been reached. This indicates that, given a chance, the ordinarily less important shutdown mechanisms, such as plate and water expansion, become the primary shutdown mechanisms without appreciably affecting the power burst behavior.

All tests in the pressure effect series were carried out with the initial moderator temperature near room temperature and the system liquid full. The solid line in Figure 9 is an expanded portion of the peak power vs reciprocal

Fig. 9 Effect of 100 psig on peak power as a function of reciprocal period.

period (α) curve from the fiducial test series. With an initial system pressure of 100 psig and for periods shorter than about 20 msec, the peak power can be seen to deviate from the fiducial series data. For an 11-msec test, the peak power is about 25% higher than for the corresponding atmospheric test. Figure 9 also includes atmospheric tests that were run periodically throughout the series as check points. These check points agree quite well with the fiducial data; in fact, if they deviate at all, they are below the fiducial data.

Figure 10 shows the effect of system pressure on a series of nominally 11-msec tests, corresponding to reactivity insertions of about 1.25\$. The first thing that will be noticed is the scatter in the data. This is partially due to the fact that the periods actually are not all 11 msec but range from 11.3 msec to 10.6 msec. The significant point illustrated by this figure, however, is the substantial increase in peak power with a system pressure of only 65 psia and the relatively constant peak power observed as the pressure is subsequently increased to 2500 psia. At present there are no data to illustrate the shape of the peak power curve as the pressure is increased from atmospheric to 65 psia.

Fig. 10 Effect of pressure on peak power of 11-msec transients.

A series of nominally 18-msec-period transients, corresponding to reactivity insertions of 1.12\$, indicate the same general behavior only of lesser magnitude. An increase in system pressure from atmospheric to 65 psia, resulted in an approximately 15% increase in peak power. Essentially no increase in peak power was observed as the pressure was subsequently increased to 2500 psia.

In the introductory remarks to this section, the importance of investigating transients in which the onset of boiling can be delayed or suppressed completely was indicated. Figure 11 shows the effect of 100 psig system pressure has on the temperature reached at time of peak power. The solid line indicates the approximate temperature at time of peak power with the system at atmospheric pressure. The 100-psig data appear to begin deviating slowly from the atmospheric line at a period of about 30 msec and then make a rather abrupt change at about a 20-msec period. For periods shorter than 20 msec, the temperatures continue to rise at approximately the same rate as for the atmospheric tests. Until the time of the abrupt change, saturation temperatures were not observed before time of peak power. However, the change did result in the temperature rising above the saturation point, indicating boiling may have been an important, if not necessary, mechanism in the self-limitation of the tests with periods shorter than 20 msec. The peak power vs alpha curve (Figure 9) also indicated a change at about the same period which is consistent with the higher temperatures observed.

Fig. 11 Effect of 100 psig on temperature at time of peak power as a function of reciprocal period.

For the short period tests it is more interesting to look at the temperatures as a function of system pressure. Figure 12 shows some of the data for tests with initial asymptotic periods of nominally 18 msec. The temperatures plotted are the hottest measured fuel-plate surface temperatures at the time of peak power. Data are shown from the two different test series which were performed using different sets of fuel assembly thermocouples. The saturation temperature also is shown as a function of pressure. It is seen that the temperature at time of power maximum, $\theta(t_m)$, increases by about 20% with the first 100-psi pressure increase but that, for pressure above 200 psia, $\theta(t_m)$ is less than the saturation temperature and is approximately constant with further pressure increase. A

Fig. 12 Effect of pressure on temperature at time of peak power and energy to time of peak power for 18-msec transients.

200°C temperature rise is apparently sufficient to limit the excursion by non-boiling expansion, and increasing the pressure further does not increase either the peak power or the temperature at the time of peak power.

The nuclear energy release at the time of power maximum, $E(t_m)$, also is shown as a function of system pressure in Figure 12 for the first series of data.

Figure 13 shows the peak temperature reached by the hottest measured fuel-plate surface for the test series with initial periods of approximately 18 msec. For system pressures above 2000 psi it appears that boiling does not take place at any time during the test, even after the power rise has been halted.

Figure 14 shows the $\theta(t_m)$ data for excursions with periods of about 11 msec. For these short-period tests, the fuel-plate surface reached the saturation temperature by the time of peak power until the initial system pressure exceeded about 2000 psia. Boiling does not occur before the time of power peak at a pressure of 2500 psi. As for the longer period tests, the largest change in peak power and in the energy release, $E(t_m)$, occurs in the first 100-psi system-pressure increase. The energy released up to the time of the power maximum is approximately 18 MW-sec for pressures above 200 psi.

The maximum measured fuel-plate surface temperatures for the 11-msec tests are shown in Figure 15. Although the maximum temperature increases more slowly with pressure than does the saturation temperature, θ_{max} is still above boiling at 2000 psi. The rapid increase in the maximum temperature reached for pressures above 2000 psi is reproducible and is almost certainly associated

Fig. 13 Effect of pressure on maximum temperature for 18-msec transients.

Fig. 14 Effect of pressure on temperature at time of peak power and energy to time of peak power for 11-msec transients.

Fig. 15 Effect of pressure on maximum temperature for 11-msec transients.

with the rapidly decreasing heat transfer rates as the water immediately adjacent to the plates surface approaches the critical temperature.

In Figure 16, the power and the fuel-plate surface temperature data are shown as functions of time during two 11-msec tests, one at atmospheric pressure and the other at 2500 psi. The 2500-psi test reached a power maximum of about 930 MW, about 30% higher than the atmospheric peak. The time of the peak is delayed about 10 msec and the burst is noticeably broader for the high pressure test. The atmospheric pressure test displays a more rapid power drop following the peak and the power recovers rapidly toward an equilibrium power, whereas, for the high-pressure test, the power continues to decrease throughout the post-burst region of the test.

The plate surface temperature for the 2500-psi test shows further indication of the poor heat transfer after the temperature reaches the critical point. The plate surface remains substantially above the 354°C saturation temperature for a relatively long time after the power level has decreased by a factor of a hundred; whereas, for the atmospheric pressure test, the temperature drops below saturation soon after the heat source is removed. The next figure helps illustrate that this behavior is a rather abrupt change and is related to the high temperatures. In Figure 17 the same 2500-psi test is compared with a 1900-psi test on a more expanded scale. In this figure the plate-surface-temperature rise has been plotted on a log scale in order to facilitate shape comparisons. The temperature for the 1900-psi test peaks rather sharply soon after the saturation

Fig. 16 Time behavior of power and temperature during 11-msec transients with atmospheric pressure and 2500 psig.

Fig. 17 Time behavior of power and temperature during 11-msec transients with 2500 psig and 1900 psig.

temperature is reached and the plate surface remains above boiling temperature for only about 85 msec. For the 2500-psi test, on the other hand, the plate-surface-temperature trace has a broad top and remains above saturation for about 400 msec, even though the power has dropped to the same or lower level than in the 1900-psi test.

To summarize briefly, the self-limitation of power excursions in plate-type, water-moderated reactors is the result of the interaction of several reactivity feedback mechanisms which involve effective density change in the moderator. For short-period tests at atmospheric pressure, boiling of the moderator is the largest contributor to shutdown. The Spert III tests have shown that, as the system pressure is raised, the delay and eventual suppression of boiling merely causes an increase in the temperature rise of the fuel plates with a resultant increase in the reactivity compensation arising from water and fuel-plate expansion, and with no gross change in the power burst.

VI. EFFECTS OF FLOW

The effect of using system pressure to delay or suppress the onset of steam void formation was discussed in the previous section. However, this also may be accomplished by increasing the volume of water in which the energy is stored. This may be done by using forced coolant flow. This method also has the advantage, for the purpose of investigating self-shutdown mechanisms, of reducing the amount of water expansion in the high flux regions of the core since the expanded water is constantly being replaced by cooler water. By the same token, the plate expansion should be less for a given amount of energy generated since more of the energy is being transferred to the water. For short periods and high initial pressures, it appears that enough reactivity can be compensated by plate expansion and water expansion or other mechanisms to limit a power burst without formation of steam voids. A decrease in the plate expansion and removal of the expanded water from the core might necessitate a much higher nuclear energy input to limit the power burst. In the long-period region, where self-shutdown probably is due almost completely to water and plate expansion, the rate of energy generation is relatively small and a large flow rate could conceivably remove a large portion of the energy from the core region in a very short time. In this case, the power burst would not be limited until the power level was high enough that the flow rate was unable to remove a sufficient amount of the energy being generated. The energy left in the core region would eventually become sufficient to limit the burst.

Since it is necessary to have a positive suction pressure when the coolant pumps are in operation, flow and pressure tests could not be completely separated. The results of a series of tests initiated with a system pressure of 230 psi and flow rates varying from 0 to 18 ft/sec through the core substantiated the above thoughts. There was no change in peak power due to flow for periods shorter than 50 msec that could not be explained by scatter or slight differences in period. Figure 18 illustrates this for several periods and flow rates. However, for several of the long period tests, the peak power was eliminated completely or reduced to an inflection point. The flow rate definitely altered the post-burst behavior of the power for all periods and in some cases, the quasi-equilibrium power at the end of the run was actually above the peak power. The power at the time of scram for these tests cannot be considered a true equilibrium power since the water from the core region has not had time to complete even one cycle of the piping.

The decrease in temperature at time of peak power due to forced coolant flow is illustrated in Figure 19. These data are for the same transients for which the peak powers are shown in Figure 18. Until the temperature at $\theta(t_m)$ is above saturation, it increases at about the same exponential rate with decreasing period for all flow rates. The temperatures do not exceed saturation at time of peak power until the periods are shorter than 18 msec and seem to be converging to a maximum just slightly above saturation for periods shorter than 10 msec. Figure 20 shows essentially the same general behavior for the maximum temperatures reached during the tests.

The overall effect of forced coolant flow can best be illustrated by a family of power and temperature-time-behavior curves for approximately equal periods but at different flow rates, such as those in Figure 21. With no flow the power burst for a 500-msec test is very broad but does have a definite maximum;

Fig. 18 Effect of flow on peak power as a function of reciprocal period.

however, the addition of just 1 ft/sec of flow is sufficient to eliminate the peak and the power was still rising at the time of scram. With an 18-ft/sec flow rate, the power does not even deviate from an exponential rise until it is about a decade higher than in the no-flow or 1-ft/sec test. The power was still rising and reached almost 100 MW by the time of scram with 18-ft/sec flow rate as compared to a peak power in the no-flow test of less than 3 MW. The high flow rate kept the fuel-plate temperature below 140°C but enough energy was put into the water to raise the bulk water temperature about 20°C. Near the end of the runs, the plate temperature of the 18-ft/sec test had exceeded that of the no-flow test and was about equal to that of the 1 ft/sec. This seemingly ambiguous temperature behavior was due to the much higher power levels reached when there was forced coolant flow.

The same general behavior is shown for 300-msec test in Figure 22. A flow rate of 5 ft/sec is more than sufficient to eliminate the 4-MW power peak of the no-flow test. By the time of scram, the power for the 5-ft/sec test had reached 25 MW and the temperature had exceeded that of the no-flow case.

Figure 23 shows the effect of flow on a nominal 160-msec test. With no flow there is a definite power peak of about 6 MW. The power peak is eliminated with a 2-ft/sec flow rate. By increasing the flow rate to 5 and then 18 ft/sec, the power continues to rise exponentially longer and reaches a progressively higher level at time of scram. In this example, the temperatures have not yet crossed but appear to be converging near the end of the run.

Fig. 19 Effect of flow on temperature at time of peak power as a function of reciprocal period.

Fig. 20 Effect of flow on peak temperature as a function of reciprocal period.

Fig. 21 Time behavior of power and temperature for 500-msec transients and various flow rates.

Fig. 22 Time behavior of power and temperature for 300-msec transients and various flow rates.

Fig. 23 Time behavior of power and temperature for 160-msec transient and various flow rates.

A slightly different behavior for the 40-msec tests is evident in Figure 24. The maximum flow of 18 ft/sec was not sufficient to eliminate the power peak. However, there is only a slight reduction of power immediately after the peak followed by a gradual increase in power until scram. The power at the time of scram was actually higher than the peak power. The 5-ft/sec power trace lies between the no-flow and 18-ft/sec test as would be expected. The temperature for the maximum-flow-rate test crossed over the 5-ft/sec trace shortly after $\theta(t_m)$ and was almost equal to the no-flow temperature by the end of the run. The peak powers have been normalized for this and subsequent comparisons to eliminate the effect of slight differences in period.

Essentially the same behavior for 20-msec transients is illustrated in Figure 25 except that the power appears to have reached a quasi-equilibrium level lower than peak power at time of the test termination even for maximum flow. The quasi-equilibrium power is a decade higher with 18 ft/sec as compared with the no-flow case. The temperature crossover is very evident in this example.

It was mentioned earlier that the power at time of scram was at best a quasi-equilibrium level. The true equilibrium level would be influenced by the inlet water temperature which in turn would be controlled by the heat exchangers. When the heat exchangers are removing an amount of energy from the system equivalent to the energy being generated in the core or, in other words, that the core inlet temperature is a constant, a true equilibrium has been reached. If the heat exchangers are removing less energy than is being generated, the core inlet water temperature will increase causing the power level, and consequently the energy generation rate, to decrease until equilibrium is reached. Conversely, if more energy is being removed than is being generated, the power will increase until an equilibrium is reached. If the response time of the process system

Fig. 24 Time behavior of power and temperature for 40-msec transients and various flow rates.

Fig. 25 Time behavior of power and temperature for 22-msec transients and various flow rates.

temperature control mechanism is insufficient to counteract transient changes in temperature, the heat removal system could be sufficiently far out of phase with the temperature sensing device that the temperature gradients in the water could initiate power oscillations. In actual operation the control mechanism probably is sufficient to compensate short period temperature transients. Instability might also arise from operating with a large void volume in the core, due to the non-linearity of the feedback mechanism and the rapid growth and collapse of nucleate bubbles.

The approximate period for which a given flow rate will eliminate the initial power peak can be determined from Figure 26. The minimum power immediately following the initial power peak is plotted as a function of reciprocal period, with flow as a parameter, on the same plot with the peak power versus reciprocal period curve. The intersection of the straight line correlation of minimum power for a given flow rate with the peak-power curve occurs at the period where the peak power becomes an inflection point for that particular flow rate. This period can be determined for any flow rate from 5 to 18 ft/sec by extrapolating between the plotted flow rates.

Fig. 26 Minimum power as a function of reciprocal period for various flow rates.

To briefly summarize the effects of forced coolant flow, the power recorded at the initial burst describes a definite peak as shown in the no-flow case (Figure 24). However, as this initial flow rate is increased the post burst section of the power curve is raised until a point is reached where the flow rate is sufficiently large that the initial peak is no longer discernible. The flow itself will not appreciably influence the initial burst until this point is reached.

The post burst behavior is definitely affected by flow with the quasi-equilibrium power being approximately proportional to flow rate and sometimes higher than the peak power. The minimum power following the initial power burst also increases with increased flow. The increased heat transfer rate reduces the temperatures reached at time of peak power but in some cases the temperatures at time of scram were higher than those with lesser flow rates due to a higher quasi-equilibrium power level. Thus, as long as the flow rate is sufficient to remove enough energy from the core region to inhibit the action of the shutdown mechanism, the power will continue to rise. When the energy generation rate is large compared to the removal rate, the effect of flow on the initial power burst will be negligible.

VII. COMBINATION EFFECTS

When studying the effect of a particular parameter on a given system, it is desirable to vary only the parameter of interest while the rest of the system is maintained at as near constant conditions as possible. However, interaction of parameters is not always obvious from an independent study so it also is desirable to qualitatively observe the results while varying more than one parameter at a time. Several tests were run with forced coolant flow and an initial system pressure of 2500 psi which more closely resembles the actual operating condition of a power reactor although the initial temperature was still only about 25°C. No interaction of effects was apparent as the results appeared to be a simple combination of the individual effects.

Four 160-msec transients are represented in Figure 27, showing the time behavior of power and temperature as a function of system pressure and flow rate. Increasing the pressure from 230 psi to 2500 psi has no effect on the power-burst shape even with 2 ft/sec coolant flow so it was necessary to show only two power curves. The upper power curve represents 2 ft/sec flow-rate tests with initial pressures of 2500 psi and 230 psi while the lower curve represents no-flow tests at the same pressures. However, a difference will be noted in the temperature. While varying parameters separately, it was observed that an increase in pressure resulted in an increase in temperature, while an increase in flow rate decreased the temperature. As then would be expected, the highest temperatures resulted from the no-flow, 2500-psi tests. An increase in flow rate decreased the temperature but not enough to compensate for the high pressure. The lowest temperatures were observed, of course, during the 2-ft/sec flow test at 230 psi.

Fig. 27 Time behavior of power and temperature for 160-msec transients with various flow rates and system pressures.

Figure 28 is the same type of plot for 20-msec tests and again it is necessary to show only two power traces. The slight difference in peak power was probably due to the difference in period. In this case the flow rate was 18 ft/sec which appears almost sufficient to completely compensate for the increase in temperature due to 2500-psi system pressure. It is interesting to note the wide variation in temperature observed with essentially no variation in maximum power.

Fig. 28 Time behavior of power and temperature for 20-msec transients with various flow rates and system pressures.

In the section on pressure effects it is pointed out that, probably due to poor heat transfer as the temperature of the water adjacent to the fuel plates nears the critical point, the fuel plate surface temperature remains substantially above the 354°C saturation temperature for a relatively long time after the power level has decreased by a factor of a hundred. The effect of using flow to remove this high temperature water from the fuel plate surface is illustrated by two 10-msec tests in Figure 29. With flow, the temperature peaks sharply at a maximum considerably less than the 550°C peak of the no-flow test. The significant point, however, is the temperature behavior following the peak. For the flow test, the temperature has dropped below 200°C within 100 msec after maximum temperature while it is still around 500°C for the no-flow test. The water near the plate surface that was above the critical temperature was quickly swept away restoring a higher heat-transfer rate. This behavior also is reflected in the power shape. As the temperature begins to drop rapidly, the power reverses its downward trend and increases until the temperature reaches a minimum. Then, as the temperature begins to rise, the power reaches a peak and decreases until the temperature reaches its second peak. This behavior is repeated as small damped oscillations in both power and temperature until a quasi-equilibrium level is reached.

Fig. 29 Time behavior of power and temperature during 10-msec transients at 2500 psi with no flow and 18 ft/sec.

Figure 30 compares the same maximum condition test illustrated in Figure 29 with a fiducial series 10-msec-period test. The combined effect of pressure

Fig. 30 Comparison of time behavior of power and temperature for maximum system condition 10-msec test with an ambient system condition 10-msec test.

and flow is seen to result in a slightly higher peak power, a slightly broader burst shape, and a much higher quasi-equilibrium power. The pressure causes a much higher maximum temperature but it is reduced rapidly after peaking because of the coolant flow. The temperature at termination of the run is still much higher than that of the atmospheric test due to the much higher power level at this time.

VIII. SUMMARY

The first 100-psi increase in system pressure constitutes almost the complete effect of pressure on the transient response of the system. In this region, the power burst is slightly broadened and the maximum power is a little higher. Any subsequent increase in pressure has very little effect on the power behavior. The energy to peak power approximately doubles as the pressure is increased from atmospheric to 100 psig but remains relatively constant from 100 to 2500 psig. Both the temperature at time of power maximum and the maximum temperature continue to increase with pressure but the largest change is made with the first 100 psig increase. This statement must be qualified slightly as the maximum temperature for the 10-msec, 2500-psi test was very high. However, since the critical temperature of water had been exceeded, this must be considered a special case. It is interesting to note that, even for the shortest periods, boiling was suppressed at time of peak power with no gross change in the power burst.

The effect of flow is dependent on period but a definite behavior trend is apparent. If a sufficient flow rate is available, the power peak observed in the fiducial and pressure-effect series can be eliminated. This was demonstrated for periods as short as 100 msec. For periods shorter than about 40 msec, the maximum available flow rate of 18 ft/sec was not sufficient to affect the peak power but did alter the post-burst behavior. Since the effect of flow is dependent on the removal of energy from the core region, the fact that flow has little effect on short period transients is reasonable since, at 18 ft/sec, the water equilibrium power level was approximately proportional to the flow rate. The temperatures were substantially lower during the tests with flow than for the atmospheric and pressure tests except for some higher temperatures near the termination of the test due to the high quasi-equilibrium power levels.

The combined effect of pressure and flow can be reasonably predicted from the individual effects. The initial power burst is slightly higher and slightly broader, characteristic of the increased pressure, and the post burst behavior has the characteristics of the flow tests. The forced coolant flow tends to reduce the high temperatures inherent in pressure tests which results in a temperature behavior lying between that of atmospheric tests and pressurized tests.

Some fuel plate deformation and blistering was detected following the series of combined flow and pressure tests. The blisters were not ruptured and only slight fission product activity was detected in the air and water. A more complete discussion of the fuel assembly damage was published earlier [10, 11].

Further analysis of the data is continuing in an attempt to more accurately describe the shutdown mechanisms involved. It is presently planned to analyze the data using a special digital computer program to determine the frequency response of the reactivity feedback processes from the time behavior of the power. This will permit a direct evaluation of the relevant time constants associated with the various shutdown mechanisms. Garner's work [7], attempting to calculate the compensated or feedback reactivity at the time of peak power from physical considerations, also will be further refined to obtain a more accurate determination of the discrepancy between the calculated results and those derived from the experimental data. From these analyses, it should be possible to obtain better knowledge of the magnitude and time behavior of the unknown

mechanism, or mechanisms, which were not included in the calculation but which apparently contribute to the shutdown of the reactor. Such added information will aid in identifying the physical processes involved and in assessing the relative importance of all of the contributing feedback mechanisms under different initial conditions.

As a final summary it can be concluded that operation of the Spert III facility at 25°C with flow rates up to 20,000 gpm (18 ft/sec through the core) and system pressure up to 2500 psi does not significantly affect the ability of the system to safely withstand step insertions of reactivity up to at least 1.25\$. It appears that, over the range of parameters covered by this report, if the contribution from one shutdown mechanism is restricted, another mechanism will replace it without an appreciable increase in energy to time of power maximum.

IX. REFERENCES

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X. APPENDIX - TRANSIENT DATA SUMMARY

Record #	System Pressure psig	θ_1 °C	Flow gpm	τ msec	α sec ⁻¹	$\phi(t_m)$ MW	$E(t_m)$ MW-sec	$\theta(t_m)$ °C	θ_m °C
01292	0	24	0	940	1.06	2.0	5.4	71	101
01307	0	25	0	490	2.04	3.2	4.6	75	103
01309	0	26	0	162	6.2	7.9	3.3	71	110
01311	0	27	0	4800	0.21	0.45	6.9	63	66
01422	0	24	0	130	7.7	8.9	3.0	57	107
01425	0	25	0	9300	0.107	0.27	5.7	49	64
01446	0	26	0	83	12.1	15	3.0	68	105
01470	0	27	0	68.3	14.6	19	2.5	72	113
01593	0	24	0	39	25.6	57	4.1	93	119
01595	0	25	0	17	59	280	7.3	135	157
01604	0	25	0	14	71	400	8.3	138	170
01676	0	25	0	10.1	99	820	11.4	179	225
01859	0	23	0	22.7	44.1	190	7.0	130	141
01863	0	23	0	10.9	92	790	11.9	164	214
01868	110	24	0	505	1.96	3.0	4.5	79	114
01872	110	28	0	155	6.45	8.2	3.5	70	137
01878	110	33	0	93	10.8	15	3.5	77	150
01934	110	28	0	57	17.5	26	3.3	89	168
01938	110	29	0	39.1	25.6	57	4.2	99	177
01941	110	30	0	23.6	42.4	150	6.7	139	196
01945	110	29	0	18.3	54.6	280	9.2	192	223
01940	110	30	0	14.2	70.4	490	11	211	245
01952	110	31	0	10.8	92.2	860	15	239	281
01955	0	34	0	11.4	87.7	560	8.9	164	204
01958	0	25	0	17.5	57.1	260	6.6	141	157
01961	500	25	0	17	58.9	300	9.2	203	273
01964	500	28	0	11	90.9	880	15	253	331
01967	0	28	0	10.7	93.5	620	16.5	160	206
02064	1000	25	0	17	58.9	320	8.9	207	295
02067	1000	26	0	10.6	94.3	960	16.2	281	360
02117	1900	21	0	18	55.6	250	8.0	183	323
02121	1900	23	0	11.5	87	800	15.6	312	402

Record #	System Pressure psig	θ_i °C	Flow gpm	τ msec	α sec ⁻¹	$\phi(t_m)$ MW	$E(t_m)$ MW-sec	$\theta(t_m)$ °C	θ_m °C
02124	0	24	0	17.4	57.5	260	7.3	137	169
02127	0	25	0	10.9	91.7	630	10.3	172	211
02132	100	26	0	480	2.1	2.9	4.2	76	116
02137	100	27	0	150	6.7	7.2	2.8	71	135
02141	100	26	0	55	18.2	27	3.4	82	161
02145	100	27	0	36.4	27.5	58	2.2	101	173
02148	100	28	0	25.4	39.4	110	5.4	136	188
02152	110	27	0	18.6	53.7	240	7.9	181	216
02157	0	28	0	18.0	55.6	240	7.4	137	153
02221	0	24	0	18.0	55.6	250	7.4	143	161
02223	110	22	0	18.1	55.2	270	9.5	192	221
02225	505	21	0	17.9	55.9	270	8.8	192	274
02227	1000	23	0	18.5	54.1	260	9.2	209	299
02230	1900	23	0	17.4	57.4	300	9.6	202	332
02233	0	23	0	10.9	91.8	650	11.7	171	214
02235	110	23	0	10.8	92.6	870	15.9	250	297
02237	1000	25	0	11.0	90.9	910	17.0	304	377
02240	1900	25	0	11.0	90.9	890	15.7	311	437
02244	2500	27	0	11.0	90.9	930	17.5	329	543
02246	0	28	0	10.7	93.5	600	8.5	161	208
02850	230	25	0	39	25.7	68	4.9	85	151
02853	230	26	220	45	22.2	42	3.6	80	171
02900	230	31	1069	39.4	25.4	55	4.2	105	161
02901	230	31	0	42	24	44	3.8	99	173
20903	230	29	2040	37.1	27	57.0	4.0	99	140
02906	230	31	5000	40.9	24.6	46.0	3.2	83	111*
02908	230	32	10,000	40.4	24.8	46	3.9	86	102*
02909	230	34	0	52.6	19.0	30	3.3	86	162
02911	230	36	20,000	37.0	27.0	58	4.5	91	105*
02914	230	32	0	39.3	25.4	53	4.1	106	181
02968	230	31	0	21.9	45.7	200	7.7	167	247
02972	230	325	5000	21.3	46.9	210	7.8	156	219
02974	230	33	10,000	21.9	45.7	160	5.9	123	174
02977	230	31	20,000	22.0	45.5	185	6.9	119	160
02980	230	32	0	22.9	43.7	195	8.1	156	224
02982	230	28	5000	10	100	1050	19	274	364

Record #	System Pressure psig	θ_i °C	Flow gpm	τ msec	α sec ⁻¹	$\phi(t_m)$ MW	$E(t_m)$ MW-sec	$\theta(t_m)$ °C	θ_m °C
02985	230	33	10,000	9.7	103	1000	18	249	367
02987	230	35	0	9.7	103	1040	17	259	353
02990	230	33	20,000	9.9	101	1000	17	168	343
02994	230	33	0	9.7	103	1040	16	340	357
03037	230	33	10,000	187	5.3	44 ⁺	80 ⁺	129	138 ⁺
03038	230	33	0	163	6.1	6.6	2.8	75	138
03040	225	31	5000	161	6.2	17 ⁺	21 ⁺	113	112 ⁺
03042	250	33	20,000	166	6.0	63 ⁺	62 ⁺	113	109 ⁺
03044	230	32	2000	164	6.1	8.8 ⁺	13 ⁺	117	119 ⁺
03045	230	32	0	157	6.4	7.1	2.8	78	137
03047	230	29	500	154	6.5	6.4	3.1	76	139 ⁺
03049	230	28	500	314	3.2	3.9	4.6	92	142 ⁺
03050	230	28	0	300	3.3	3.8	3.2	77	125
03091	230	28	1000	313	3.2	4.8*	6.8	102	151 ⁺
03093	230	29	5000	310	3.2	25 ⁺	73 ⁺	141	142 ⁺
03096	230	31	200	516	1.9	2.9	3.2	76	120 ⁺
03098	230	29	500	510	1.96	2.8*	4.1	99	140 ⁺
03099	230	28	0	525	1.9	2.59	3.8	79	113
03101	230		1000	490	2.04	4.85 ⁺	16.6 ⁺	133	133 ⁺
03103	230	31	20,000	25	40.8	152	6.9	102	134 ⁺
03105	230	29	2000	160	6.3	6.9*	3.5	80	125 ⁺
03107	2500	33	20,000	22.1	45.3	182	7.3	110 ⁺	147 ⁺
03109	2500	33	0	19.8	50.5	224	7.9	174 ⁺	325 ⁺
03111	2500	31	2000	134	7.4	7.1*	3.1	75 ⁺	133 ⁺
03112	2500	29	0	125	8.0	7.1	2.3	72 ⁺	142 ⁺
03115	2500	34	20,000	9.6	104.2	1080	17.4	224 ⁺	391 ⁺
03163	0	28	0	19.2	52.1	240	7.4	136	148
03165	20	29	0	18.5	54	230	8.2	154	166
03167	0	24	0	21.5	46.5	170	6.6	127	129
03169	0	21	0	93.5	10.7	12	2.5	69	130
03171	0	21	0	120	8.3	8.6	2.5		
03546	0	22	0	18.6	53.8	275	7.6	140	154
03548	0	22	0	11.2	89.3	750	1.2	163	203
03550	50	23	0	18.7	53.5	290	9.8	168	190
03551	50	23	0	11.3	88.5	890	15.1	199	236
03553	75	24	0	18.4	54.4	300	9.4	170	198

Record #	System Pressure psig	θ_i °C	Flow gpm	τ msec	α sec ⁻¹	$\phi(t_m)$ MW	$E(t_m)$ MW-sec	$\theta(t_m)$ °C	θ_m °C
03555	75	24	0	10.8	92.6	910	16.4	212	251
03557	250	27	0	18.3	54.6	280	9.6	173	221
03558	250	27	0	10.9	91.8	930	16.2	227	269
03560	500	29	0	10.7	93.5	910	17.4	259	299
03562	175	21	0	10.6	94.3	860	15	212	247
03564	2500	21	0	18.2	55.0	300	9.9	179	327
03566	2500	21	0	10.7	93.5	990	21.1	299	511
03568	0	21	0	40.0	25.0	600	4.3	86	115
03570	0	21	0	160	6.3	6.6	2.9	65	111
03572	2500	23	0	156	6.4	8.2	2.7	61	137
03573	2500	23	0	36.3	27.6	68	4.9	97	176
03575	2000	23	0	10	100	930	17.8	288	376
03577	250	23	0	11	90.9	830	15.7	215	257
03578	175	23	0	11.2	89.3	790	14.1	201	240
03597	230	31	20,000	500	2.0	28 ⁺	3.0 ⁺	71 ⁺	71 ⁺
03608	230	32	20,000	10.9	91.8	730	15.0	182 [#]	252 [#]
03610	230	35	5000	10.6	94.3	810	15.3	217 [#]	265 [#]
03612	230	32	0	11.4	87.8	800	13.8	224 [#]	268 [#]
03614	230	33	5000	21.5	46.5	175	7.2	144	207
03616	230	32	20,000	511	1.96	150 ⁺	642 ⁺	159	159 ⁺
03618	230	34	20,000	40.4	24.8	108	5.0	78	190
03620	0	30	0	9.9	101	820	12.4	162 [#]	211 [#]

* Higher at scram

+ Still increasing at scram

Abnormally high reading on another TC

**PHILLIPS
PETROLEUM
COMPANY**

ATOMIC ENERGY DIVISION