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OPERATIONAL SAFETY OF THE HOMOGENEOUS REACTOR TEST

P. R. Kasten

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OPERATIONAL SAFETY OF THE HOMOGENEOUS REACTOR TEST

ABSTRACT

The safety of the Homogeneous Reactor Test (HRT) is dependent upon the reactivity additions associated with physical operations. Physical operations were therefore limited, where necessary, so that the corresponding reactivity addition did not exceed a permissible value. The maximum permissible reactivity addition was determined from the relations between reactivity addition, physical and nuclear design values, and pressure rise and was considered to be that which increased the core pressure by 400 psi. At source power this pressure rise would be obtained if reactivity were added at a rate of 0.008 Δk_e/sec. The above relations are presented, and their usefulness in evaluating operational safety is illustrated.

INTRODUCTION

The Homogeneous Reactor Test (HRT) is a two-region reactor, with a $U^{235}O_2SO_4$-D_2O solution in the core region. The blanket region will contain D_2O during the initial period of operation but may subsequently contain a $U^{238}O_2SO_4$-D_2O solution or a ThO_2-D_2O slurry. The core tank is 32 in. in diameter and is centered in a 60-in.-inside-diameter pressure vessel, as shown in Fig. 1. Reactivity control will be by adjustment of the fuel concentration in the core region and by means of the negative temperature coefficient of reactivity, which has a value of about -2×10^{-3} Δk_e/°C. Normal operating conditions are 280°C, 2000 psi, and 5 Mw, although provisions are made for 10-Mw operation (thermal energy). The core and blanket systems have similar types of flowsheets and equipment, and these are shown in Fig. 2. The core and blanket regions are connected through the pressurizers to help prevent rupture of the core tank.

The safety of the HRT will be a function of the maximum permissible reactivity addition and the possible reactivity additions. Despite the inherent safety associated with a large negative temperature coefficient of reactivity, it cannot be stated a priori that the reactor will be safe under all operating conditions. The limiting feature of the HRT with respect to reactivity addition is the permissible pressure rise within the reactor core. In these studies, two values for the pressure rise were of particular interest, namely 400 and 4000 psi. The 400-psi rise was considered to be the maximum permissible core pressure rise and has been estimated to be about one-half that which would cause failure of the Zircaloy-2 core tank.[1] The 4000-psi rise was assumed to be the maximum permissible reactor pressure rise and corresponds to an increase in the fiber stress in the pressure vessel from 15,300 to 30,000 psi. The latter stress has been estimated to be less than one-half that associated with the ultimate strength of the steel.[1] Since the pressure rise and fall accompanying a reactivity excursion occurs

[1]S. E. Beall and S. Visner, *Homogeneous Reactor Test Summary Report for the Advisory Committee on Reactor Safeguards*, ORNL-1834 (Jan. 7, 1955), pp 52, 59–61, 78–88, 131, 149–152.

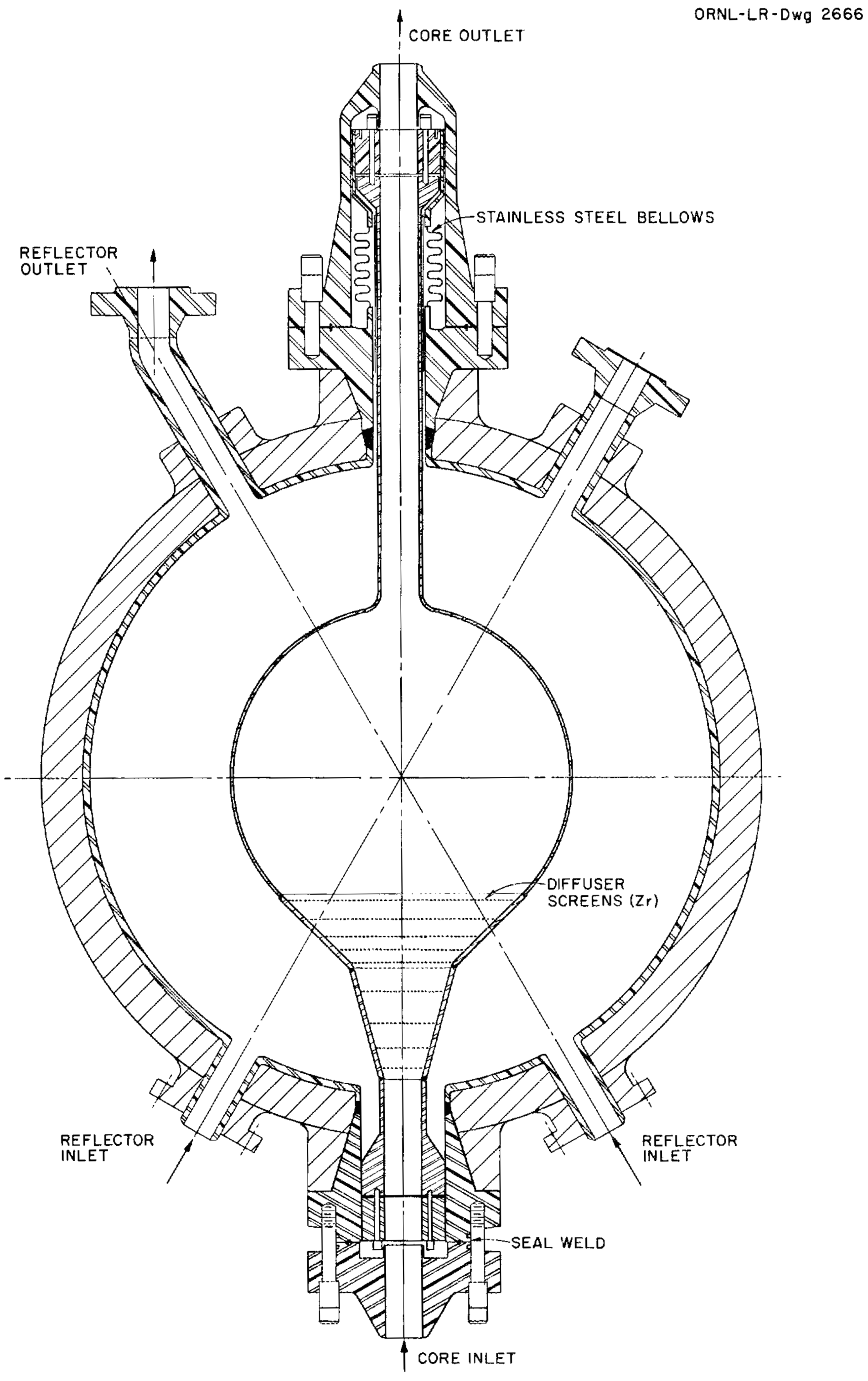

Fig. 1. Assembly of Core and Pressure Vessel.

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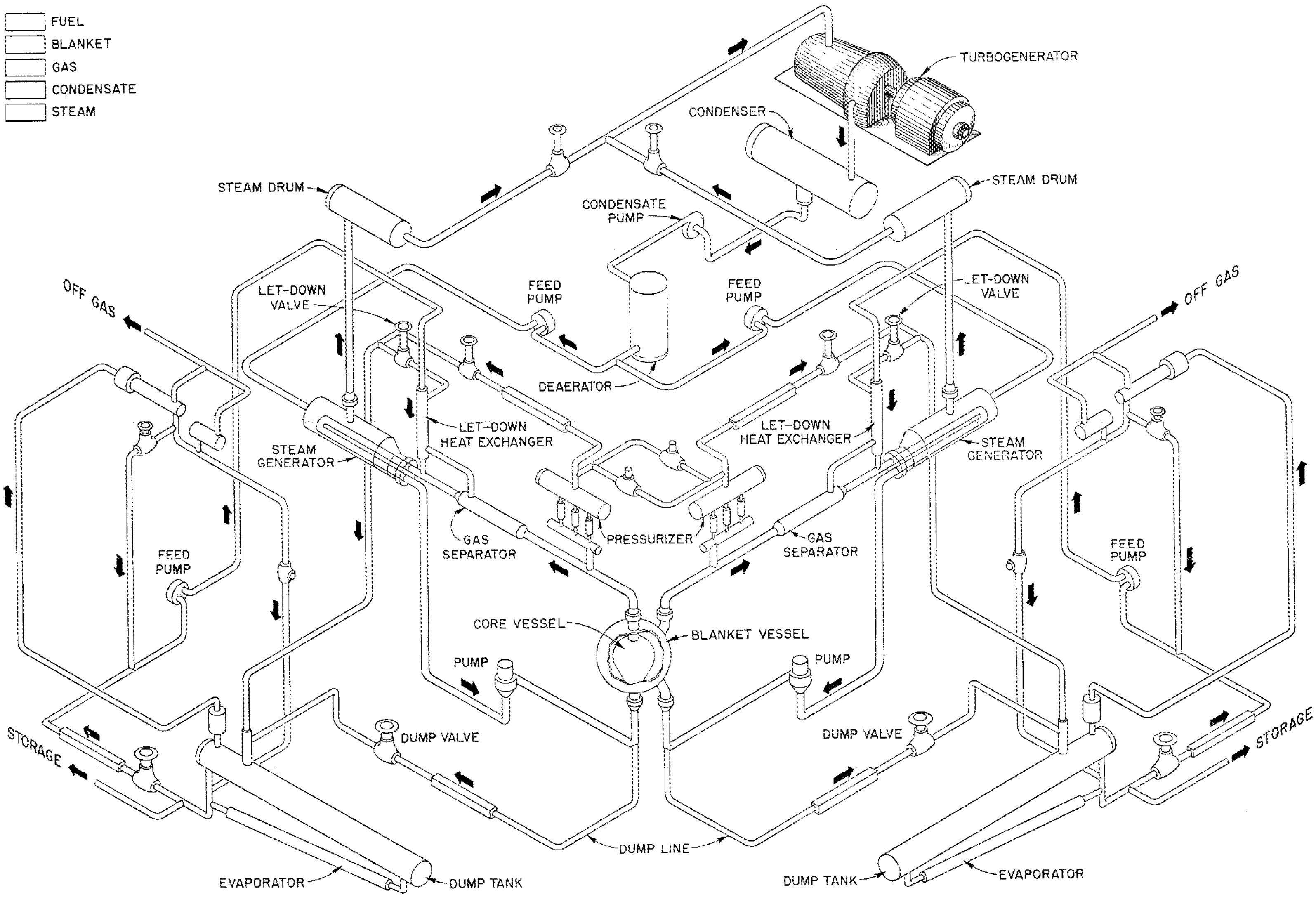

Fig. 2. Reactor Flowsheet – Schematic.

in a short time interval, the above figures may be more conservative than indicated. However, they appear to be reasonable values on which to base safety design criteria.

With a given limit on the maximum permissible pressure rise, it was possible to specify the maximum permissible reactivity addition which could be added to the HRT. Reactor operations were then restricted, where necessary, so that reactivity additions associated with physical events would not exceed the maximum permissible reactivity addition.

The potential reactivity available in the HRT is inherently large, because a high operating temperature is coupled with a high negative temperature coefficient of reactivity. However, all reactivity additions involve a time element. Since it appeared desirable to allow continuity of physical operations, the safety design criteria were developed for continuous, linear rates of reactivity addition. Specifically, the maximum permissible linear rate of reactivity addition was obtained from the equations of motion, in terms of the nuclear and physical parameter values and a specified permissible pressure rise. The physical system was then restricted so that this rate was not exceeded.

EQUATIONS OF MOTION

The neutron density is the fundamental variable in HRT safety and is influenced primarily by the temperature and density of the moderator and by the operational changes which effect a reactivity change. So long as the reactor is not far above prompt-critical, the neutron density is given by the conventional equations of motion.[2] These may also be used when larger reactivity additions are considered, if the prompt-neutron lifetime is assumed to be that associated with the region in which the neutron density is rising most rapidly with time. Under this condition, the over-all rate of increase in neutron density is overestimated, so that a safety factor will exist in reactor designs based upon these equations.

Reactivity additions which involve HRT safety are considerably in excess of that required for prompt-criticality, and for these cases the reactor power reaches a maximum value in times of the order of tenths of seconds. Such time intervals are short compared with the average half life of the delayed-neutron precursors, and so only a small fraction of the precursors formed during the power rise would decay during that time interval. The delayed neutrons from these precursors therefore contribute little to the reactor power while the power is rising; rather, they are formed following the time of peak power and exert a powerful damping influence on the power oscillation, leading to a single, damped power surge.[3] The delayed-neutron density was therefore considered to be

[2]H. Hurwitz, Jr., *On the Derivation and Integration of the Pile Kinetic Equations*, AECD-2438 (April 5, 1948).

[3]W. C. Sangren, *Kinetic Calculations for Homogeneous Reactors*, ORNL-1205 (April 1, 1952).

constant, and so the neutron-density equations could be combined into one equation. In terms of reactor power, this equation was

$$\frac{dP}{dt} = \left[\frac{k_e(1 - \beta) - 1}{l}\right] P + \frac{\beta}{l} P_0 \ , \tag{1}$$

where

k_e = effective multiplication constant,

P = reactor power,

P_0 = P evaluated under initial conditions,

t = time,

β = effective fraction of fission neutrons which are delayed,

l = average lifetime of prompt neutrons.

The appropriate value for β was determined on the basis of the times spent inside and outside the reactor vessel by a fluid particle (slug flow was assumed).

To complete the mathematical system, the relation between k_e and P is required, which requires intermediate relations. For aqueous systems operating above 200°C, k_e is influenced primarily by fluid-density effects, insofar as inherent reactivity changes are concerned. Since reactivity can also be added by physical operations, k_e was considered to be given by

$$k_e = 1 + \Delta + bt + \frac{\partial k_e}{\partial \rho}(\rho - \rho_0) \ , \tag{2}$$

where

b = linear rate of reactivity addition to reactor, Δk_e/sec,

$\frac{\partial k_e}{\partial \rho}$ = density coefficient of reactivity,

Δ = instantaneous reactivity addition,

ρ = average density of fuel fluid,

ρ_0 = ρ evaluated under initial conditions.

The core fluid density is determined from the hydrodynamic equations of continuity and motion, in conjunction with the equation of state for the fluid. In these studies, a one-dimensional flow model was assumed, gas effects were neglected, the core tank was considered to be rigid, and the core inlet fluid velocity was considered to be constant. The continuity equation was then

$$\frac{d\rho}{dt} = -\frac{A}{V_c}\rho_0 u \ , \tag{3}$$

where

A = cross-sectional area of relief pipe,

V_c = volume of core region,

u = deviation in velocity from steady flow velocity of fluid in core exit piping.

The hydrodynamic equation of motion was approximated by the equation

$$\frac{M_r}{144g_c}\frac{dU}{dt} = A(p_c - p_p - a_f|U|\,U) \ , \tag{4}$$

where

M_r = mass of fluid in relief pipe,

g_c = dimensional constant,

p_c = core pressure,

p_p = pressurizer pressure,

a_f = resistance coefficient,

U = average velocity of fluid leaving reactor core through exit piping.

The equation of state for the core fluid was given by

$$p_c - p_c(0) = \frac{dp_c}{d\rho}\left[(T - T_0)\left|\frac{d\rho}{dT}\right| + \rho - \rho_0\right] \ , \tag{5}$$

where T = average core fluid temperature and $p_c(0)$ = initial value of p_c.

Relations are still needed between T and P and between p_p and ρ. Assuming adiabatic conditions within the pressurizer, p_p was given by the equation

$$p_p - p_p(0) = np_0\frac{\rho_0 - \rho}{\rho_0}\frac{V_c}{V_p} \ , \tag{6}$$

where

V_p = volume of pressurizing fluid,

p_0 = pressurizing pressure,

$p_p(0)$ = initial value of $p_p = p_0$,

n = ratio of heat capacity at constant pressure to heat capacity at constant volume for pressurizing fluid.

The relation between T and P is obtained from an energy rate balance on the core fluid. Since the rate of energy transport associated with fluid flow and thermal diffusion is small during times of interest, the energy rate balance was approximated by the equation

$$S_c\frac{dT}{dt} = P - P_0 \ , \tag{7}$$

where S_c = volume heat capacity of the core fluid.

Although the mathematical system is now complete, a more convenient system can be obtained by grouping the parameters according to dimensional analysis. The desired result was obtained by making the following definitions:

$C_2 = \dfrac{ny_2\,p_0}{\rho_0}\,\dfrac{V_c}{V_p}\,\dfrac{l}{\partial k_e/\partial\rho} = \dfrac{144g_c}{v_s^2}\,\dfrac{p_0}{\cdot\rho_0}\,\dfrac{nV_c}{V_p}$, measure of effect of pressurizer volume upon core pressure rise, dimensionless

$$m = \frac{\Delta - \beta}{l}, \text{ sec}^{-1}$$

$$p = p_c - p_c(0), \text{ rise in core pressure, psi}$$

$$v = \frac{1}{l} \frac{\partial k_e}{\partial \rho} A \frac{\rho_0}{V_c} (U - U_0), \text{ normalized increase in velocity of fluid leaving core region, sec}^{-2}$$

$$x = \frac{P}{P_0}, \text{ relative power}$$

$$y = \frac{(T - T_0)S_c}{P_0}, \text{ normalized rise in core fluid temperature, sec}$$

$$z = \frac{1}{l} \frac{\partial k_e}{\partial \rho} (\rho - \rho_0), \text{ normalized change in core fluid density, sec}^{-1}$$

$$\gamma = \frac{\beta}{l}, \text{ sec}^{-1}$$

$$\gamma_f = \frac{288 g_c a_f U_0}{\rho_0 L} = \frac{n_f U_0}{L}, \text{ normalized friction coefficient in core exit line, sec}^{-1}$$

$$\gamma_2 = \frac{144 g_c}{v_s^2 l} \frac{\partial k_e}{\partial \rho}, \text{ conversion factor between net core density change and core pressure rise, in.}^2\text{/sec-lb force}$$

$$\gamma_3 = \frac{U_0 A \rho_0 \partial k_e}{V_c l \partial \rho}, \text{ sec}^{-2}$$

$$\xi = \frac{b}{l}, \text{ sec}^{-2}$$

$$\omega_b^2 = \frac{A^2 \rho_0 v_s^2}{V_c M_r} \approx \frac{A v_s^2}{V_c L}, \text{ square of frequency of hydraulic system, sec}^{-2}$$

$$\omega_n^2 = \frac{1}{l} \left| \frac{\partial k_e}{\partial T} \right| \frac{P_0}{S_c}, \text{ square of frequency of nuclear system, sec}^{-2}$$

The equations of motion then become

$$\dot{x} = (m + \xi t + z) x + \gamma , \tag{8a}$$

$$\dot{z} = -v , \tag{8b}$$

$$\dot{v} = \omega_b^2 \left[z(1 + C_2) + \omega_n^2 y \right] - \frac{\gamma_f}{2\gamma_3} \left[(\gamma_3 + v) \left| \gamma_3 + v \right| - \gamma_3^2 \right] , \tag{8c}$$

(8d) $$p = \frac{1}{\gamma_2}(z + \omega_n^2 y) \ ,$$

(8e) $$\dot{y} = x - 1 \ .$$

The variable of interest is the maximum value of p for a given set of parameter values. Since a general analytic solution to the above system has not been obtained, numerical integration of the above equations was performed on the Oracle. Various initial reactor powers and rates of reactivity additions, as well as instantaneous reactivity additions, were considered.

Although not exact, analytical expressions for p_{max} and x_{max} were derived for the case of an instantaneous reactivity addition. In addition, it was possible to convert a linear rate addition of reactivity to an equivalent instantaneous reactivity addition. To check the validity of the derived relations, the values of p_{max} and x_{max} obtained analytically were compared with those obtained by Oracle calculations. The Oracle results were considered correct, and they established the relationship between the rate of reactivity addition and the equivalent instantaneous reactivity addition on the basis of equal pressure rise. Thus, for a given rate of reactivity addition and initial reactor power level, a particular maximum pressure was obtained. The amount of prompt reactivity added instantaneously which gave the same maximum pressure was termed the equivalent prompt reactivity addition corresponding to a given rate addition and initial power level.

Excellent agreement was obtained between the calculated equivalent prompt reactivity addition and that obtained from Oracle results. The analytical expression for p_{max} could therefore be written in terms of an equivalent instantaneous reactivity addition which was applicable to rate additions of reactivity. The derived expression for p_{max} is given by

(9) $$p_{max} = \frac{m_e^2 \bar{F}}{2\omega_b^2 \gamma_2}\left[0.385 m_e + \gamma_f\left(1 + \frac{m_e^2 \bar{F}}{4\gamma_3}\right)\right] + \frac{C_2 m_e}{\gamma_2} \ ,$$

where

$$\bar{F} = 1 + \frac{1}{2}\left[C_2 + \frac{(\gamma_f + m_e)m_e}{\omega_b^2}\right] ,$$

m_e = equivalent prompt reactivity addition divided by l.

Where applicable, the results obtained from Eq. 9 have compared favorably with the Oracle results.

The relationship between a linear rate addition and the equivalent instantaneous reactivity addition was obtained from the following equation:

$$1 + \frac{\xi}{\omega_{np}^2} = \frac{m_e^2/2\omega_{np}^2}{\ln (m_e^2/2\omega_{np}^2)} \quad , \tag{10}$$

where

$\omega_{np}^2 = \omega_n^2 x_{pc}$,

x_{pc} = reactor power at prompt-critical relative to initial power level.

The value for x_{pc} was obtained from the equation

$$x_{pc} = e^{-M_s^2/2\xi} + \sqrt{\pi} \frac{M_s}{\sqrt{2\xi}} \operatorname{erf} \left(\frac{M_s}{\sqrt{2\xi}} \right) \quad , \tag{11}$$

where

$$M_s = \frac{1 - k_e(0) + \beta}{l} \quad ,$$

$k_e(0)$ = initial value of k_e.

Equations 10 and 11 are plotted in Figs. 3 and 4 and give the particular combinations of initial power level and rate of reactivity addition corresponding to a given equivalent prompt reactivity addition.

PERMISSIBLE REACTIVITY ADDITIONS WITH D_2O BLANKET

To find the maximum permissible reactivity addition, Eqs. 8*a* through 8*e* were numerically integrated on the Oracle, and the parameter values associated with the D_2O blanket were used. The Oracle results are given in Fig. 5 and consist of the peak pressure rise associated with an equivalent instantaneous reactivity addition. As obtained from Fig. 3, a 400-psi pressure rise corresponds to an m_e of 24.5 sec^{-1}, while a 4000-psi rise corresponds to an m_e of 52.5 sec^{-1}. These values for m_e represent instantaneous reactivity additions (reactivity addition = $\Delta k_e = k_e - 1 \cong \Delta k_{eqp} + \beta$) of 1.9% and 3.5%, respectively, since l, the mean lifetime of prompt neutrons, was 5.7×10^{-4} sec for this case and β was 0.005.

Comparison of the two curves in Fig. 5 shows that for a specified pressure rise, the permissible value of m_e increased with decreasing fluid temperature. From a nuclear viewpoint, this indicates that the safest startup procedure would be to bring the reactor up to design power with the fluid temperature low initially. However, such startup would induce severe thermal stresses in the reactor materials if the power increased very rapidly with time; therefore criticality should not be attained until the fuel fluid is near the operating temperature.

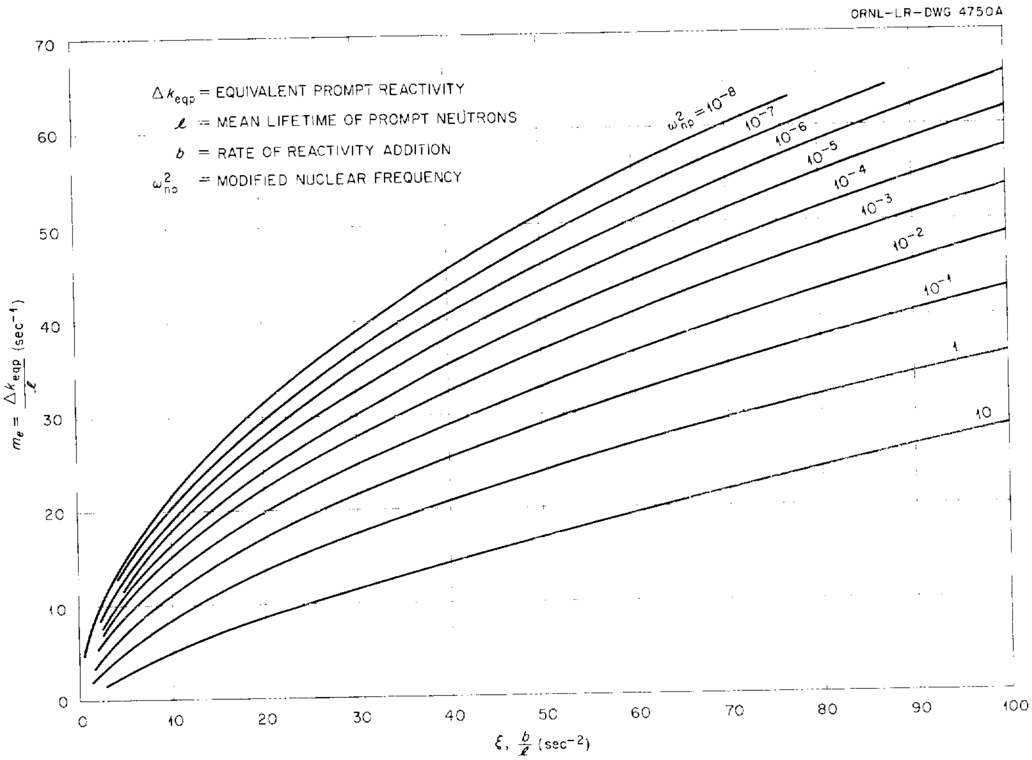

Fig. 3. Relation Between Equivalent Prompt Reactivity and Rate of Reactivity Addition.

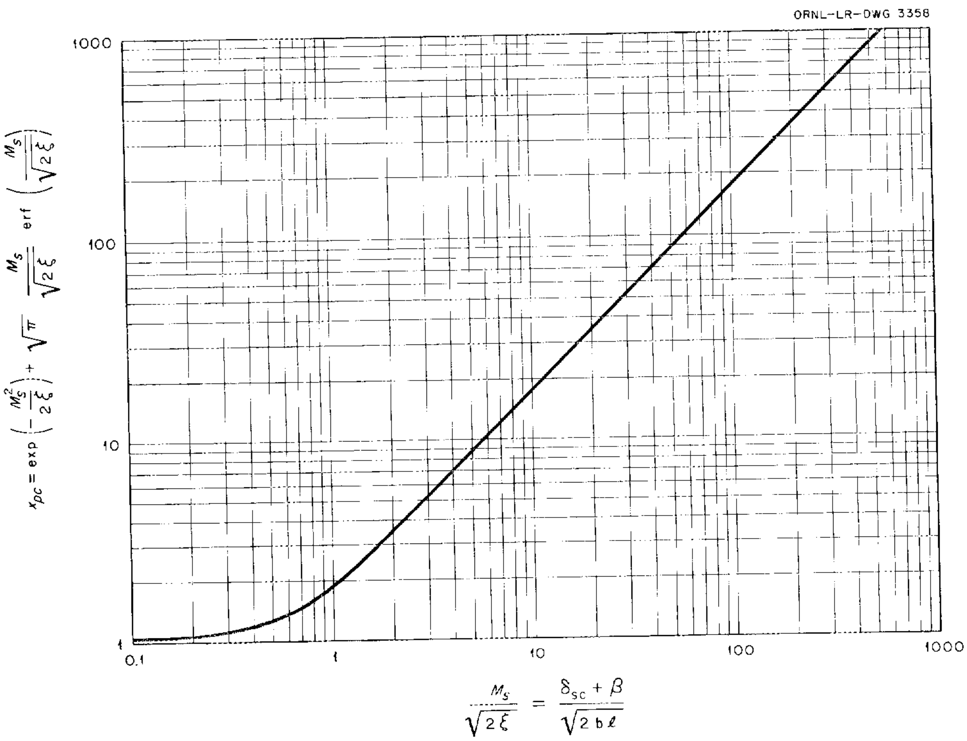

Fig. 4. Neutron Power at Prompt Critical Relative to Initial Power.

The lower the initial power level of the reactor, the lower the permissible rate of reactivity addition for a given pressure rise. Thus the lowest power level – that associated with the neutron source – should be considered. Since the reactor power increases relatively slowly with time until the reactor is prompt-critical, the value of the reactor power at prompt-critical is the important "initial" power level. The lowest value for P_{pc} (P_{pc} = reactor power level at the time the reactor is prompt-critical) was obtained by assuming a source strength of 10^7 neutrons/sec, a rate of reactivity addition of 0.02 Δk_e/sec, and an initial k_e value of 0.5. For these conditions,

$$\omega_{np}^2 = \omega_n^2 \frac{P_{pc}}{P_0} \approx 10^{-7} \text{ sec}^{-2} ,$$

and the reactor power at delayed critical was about 0.04 watt. For an m_e of 24.5 sec^{-1}, the corresponding values for ξ and b were found from Fig. 3 to be 14 sec^{-2} and 0.008 sec^{-1}, respectively. Therefore the maximum permissible rate of reactivity addition would be 0.8% Δk_e/sec if the core pressure rise were not to exceed 400 psi and the reactor were initially at source power.

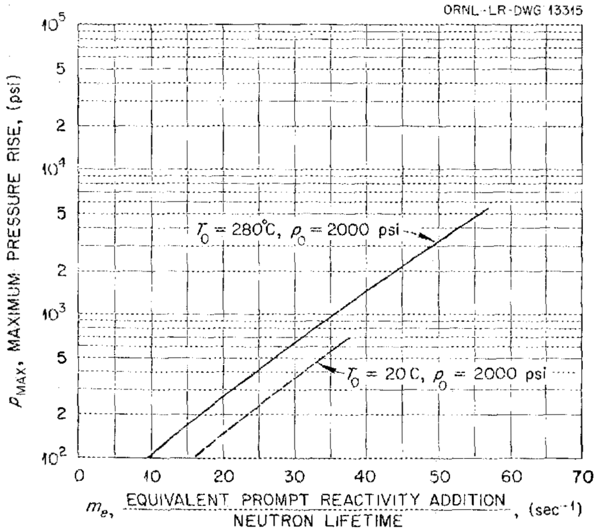

Fig. 5. Maximum Pressure Rise as a Function of m_e for the HRT with a D_2O Blanket.

In the same manner as outlined above, the value of b corresponding to a p_{max} of 4000 psi was found to be 0.031 Δk_e/sec when the initial reactor power was 0.04 watt. Thus it appears that rates of reactivity addition up to 3.1% Δk_e/sec will not rupture the pressure vessel even though the reactor is initially at source power.

SAFETY OF THE HRT WITH D_2O BLANKET

Investigations of HRT safety concern conditions which may endanger the physical system of the reactor as well as reactor personnel. However, the physical system is so designed that personnel are not endangered so long as the system is prevented from being damaged. Some of the most dangerous situations which may cause physical damage to the reactor system are considered in this section.

There are many events which will add reactivity to the reactor. While it is physically impossible to investigate all cases, it is believed that those presented below are the most hazardous ones and that those which are not presented will not endanger the reactor system. As initially presented, the cases represent conceivable reactivity rate additions. Since design against core-tank rupture is required, the discussion of the particular cases will be on the basis of limiting the rate of reactivity addition to less than 0.008 Δk_e/sec. Some of the incorporated designs, however, are based upon limiting the rate of reactivity addition to 0.005 Δk_e/sec, corresponding to a maximum core pressure rise of 300 psi when the initial reactor power is that associated with a neutron source of 10^7 neutrons/sec.

The order of presentation of the cases is not intended to imply order of importance but only to identify the event considered. The cases refer to the HRT with a D_2O blanket at design conditions unless otherwise specified, and the cases are described so as to convey the sequence of events which would have to occur for the reactivity addition to take place.

Case 1

By means of the high-pressure steam boiler, fresh fuel solution could be heated up to about 280°C. The core fuel concentration could then be adjusted to correspond to criticality at approximately 250°C. If the 400A pump were now turned off and the shell side of the heat exchanger were vented to the steam condenser, the fuel solution in the heat exchanger would be cooled. Cooling of the fuel solution to 100°C appears to be possible in about a minute, in which time natural convection cooling would not lower the core temperature to 250°C. If the pump were now started at rated speed, cold fluid would be injected into the core region. The resultant lowering of the core fluid temperature would add reactivity at about 1.7% Δk_e/sec.

To lower the rate of reactivity addition to a tolerable value, the startup speed of the 400A pump has been reduced to one-third its rated value until the fluid in the high-pressure system has passed through the heat exchanger. This has been accomplished by reversing the phase current and running the motor "backwards" for about 45 sec on startup. The phase current will then be reversed and the pump run in normal fashion. Decreasing the initial flow rate to one-third its normal value decreases the rate of reactivity addition from 0.017 to about 0.006 Δk_e/sec.

Case 2

With the reactor initially subcritical and the 400A pump running at normal speed, venting steam from the shell side of the core heat exchanger would lower the shell-side temperature and result in lowering the temperature of the fuel fluid. Since the core temperature coefficient of reactivity is about -0.002 Δk_e/°C at 280°C and since the permissible rate of reactivity addition is limited, the rate of temperature fall in the heat exchanger should also be limited.

The rate of temperature drop in the core fluid is closely approximated by the rate decrease in temperature of the shell-side heat exchanger fluid. Thus the permissible rate of temperature drop on the shell side of the heat exchanger should be limited to about 2.5°C per second, corresponding to a rate decrease in steam pressure of 35 psi/sec if the heat exchanger is operating under design conditions. At lower core temperatures the temperature coefficient is lower, but a given rate of pressure drop will result in a higher rate of temperature decrease. Considering all situations between atmospheric pressure and that corresponding to saturated conditions at 280°C, the permissible rate of pressure decrease should be limited to 20 psi/sec. If the shell pressure decreases at a higher rate, the 400A circulating pump should be stopped. Under normal flow conditions, about 2.7 sec is needed for fluid to travel from the heat exchanger outlet to the core inlet. Once the pump current is stopped, the flow rate drops rapidly (from 400 to 270 gpm in 0.5 sec, to 150 gpm in 1 sec, to 80 gpm in 1.5 sec, to 50 gpm in 2 sec, and to 40 gpm in 3 sec), so that a time delay in stopping the pump of about 1 sec appears sufficient.

The present HRT design has incorporated in it the operating restrictions noted above. If the steam pressure on the shell side of the heat exchanger decreases at a rate greater than 20 psi/sec, the 400A circulating pump is stopped.

Case 3

At low temperatures not all the fuel in the system will be required for reactor criticality. If the fuel solution outside the core system were concentrated and then pumped into the reactor, reactivity may be added at an undesirable rate. The results of calculations indicate that, if the reactor were critical at 20°C and the fuel in the dump tanks were concentrated to about 320 g of U^{235} per liter, reactivity could be added to the reactor at a rate of 1.7% Δk_e/sec by pumping the concentrated fuel solution into the core with the Pulsafeeder pump.[4]

To eliminate the possibility of the above-described event, the fuel intake line from the dump tanks has been adjusted so that 25 liters of solution will always be present in the dump tanks, and the total U^{235} inventory has been limited to 5.0 kg. Under these conditions the fuel concentration will be limited to about 160 g of U^{235} per liter, so that the maximum rate of reactivity addition will be less than 0.008 Δk_e/sec, even though the Pulsafeeder pump is running on high speed (6.3 kg of solution per minute).

If the reactor were initially critical at temperatures greater than 20°C, the critical mass would be greater, and less fuel would be in the dump tanks. At 280°C the possible rate of reactivity addition would be less than 0.002 Δk_e/sec.

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[4] S. Visner, *Fuel Dump Tanks for HRT*, ORNL CF-54-4-30 (April 2, 1954).

Case 4

With the 400A pump off, the Pulsafeeder could pump concentrated fuel solution into the high-pressure system external to the core region. Startup of the 400A pump at this time could add reactivity at about 130% Δk_e/sec if fuel solution at 20°C containing 100 g of U^{235} per liter were in the external piping. This situation has been corrected by permitting fuel injection only when the 400A pump is operating. Thus the injected fuel will be diluted upon entering the core system. This case now reverts to case 3, so that the rate of reactivity addition will be limited to 0.008 Δk_e/sec.

Case 5

During the initial filling of the reactor core, the reactor may become critical before the core vessel is filled if the fluid has a high fuel concentration.[5] Fortunately, under these conditions the sign of the temperature coefficient of reactivity appears to remain negative. Although of relatively small magnitude, the temperature coefficient, in combination with the low rate of reactivity addition associated with this event, is sufficient to maintain a safe condition. A more dangerous situation, which is discussed in a later section, appears to exist for the case of a ThO_2 slurry blanket. Even for that case, however, the situation appears to be safe. The only danger would be in allowing the Pulsafeeder to continue pumping after criticality has been detected. Under these conditions reactivity would be added and the pressure would rise as energy is released. No difficulty should be encountered if the Pulsafeeder pump is stopped within about 1 min following the peak power surge. If the Pulsafeeder were not stopped, the pressure would rise slowly with time.

Case 6

If the reactor were initially critical under design conditions, loss of pressure in the HRT blanket could result in core-tank rupture, with a net addition of fuel into the reactor region. Such an event would result in a high rate of reactivity addition over a short time interval. However, if the blanket pressure were relieved, the check valves (or rupture disks) between the core and blanket pressurizers would respond in such a manner so as to equalize the pressure between the core and blanket. If only the rupture disks were operative, it would require no more than a 400-psi differential to rupture them. Therefore, even though the blanket pressure were relieved, the maximum pressure differential between the core and blanket should not cause rupture of the core tank.

If it is assumed that corrosion had weakened the core tank, a small pressure differential between the core and blanket regions could cause core-tank rupture, with subsequent fluid addition into the reactor. More reactivity would be added if the core

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[5]S. Visner, *Possible Hazard in HRT Startup*, ORNL CF-54-4-81 (April 8, 1954).

pressure were originally higher than the blanket pressure. For this situation, there would be a net addition of core fuel fluid into the reactor following core-tank rupture.

The presence of the hot D_2O liquid (~40 liters) in the pressurizer would cause the core pressure to remain near 2000 psi for a relatively long time if leakage of fluid from the core system took place, and so any initial pressure differential would remain for an appreciable time interval. With only a 100-psi pressure differential between core and blanket, the volume of fluid in the line between the core and pressurizer (~18 liters) could be added to the reactor very rapidly. At the same time, the 400A pump would continue pumping fuel fluid into the core at about 30 liters/sec. Associated with the "instantaneous" fluid addition of 18 liters and the rate addition of 30 liters/sec would be a net reactivity addition of less than 2.7% Δk_e. Since core-tank rupture was assumed to take place, the maximum permissible reactivity addition would be that which would raise the vessel pressure by 4000 psi, and it would correspond to a permissible Δk_e of 3.5%. Thus it appears that the above occurrence would not cause pressure-vessel rupture. However, to eliminate the above pressure differentials, the core and blanket pressurizer volumes could be connected by an open line.

Case 7

If energy removal from the fuel fluid were less than that generated within it, the temperature of the core fluid would increase with time, and might cause two-phase separation of the solution. Also, the fluid might start to boil, which could cause an excessive increase in operating pressure and necessitate a dump. With regard to the latter situation, the important item would be to know within what time interval following shutdown a dump should be initiated.

Two-phase separation would probably occur if the fuel fluid temperature exceeded approximately 320°C and would first occur in the fuel leaving the reactor core. The heavy phase, as it formed, would tend to fall back into the reactor and to redissolve as it contacted cooler fluid. Such action would result in fuel stratification and would probably produce a smaller reactivity increase than if the fuel were uniformly distributed within the core. Since the heavy phase preferentially extracts the fission products, the tendency would be to increase the operating temperature of the reactor, which would cause the reactor to become subcritical. A pessimistic viewpoint would be to assume that all the fuel pumped into the core remained uniformly distributed within the core region. The rate of reactivity addition corresponding to this situation would be 2.6% Δk_e/sec. Such a rate addition would not cause rupture of the pressure vessel, since the permissible rate was found to be 3% Δk_e/sec at source power. In the above situation the reactor power would be much higher than source power, so that the permissible rate of reactivity addition would be appreciably greater. If the initial power level were 5 Mw, a rate addition of 2.6% Δk_e/sec should not cause rupture of the core tank. No special precautions with regard to two-phase separation were therefore taken, since in no case did it appear that the pressure vessel was endangered; also, it appeared improbable that two-phase separation would cause reactor supercriticality, and even if supercriticality should occur, the core tank would not rupture if the reactor power were near 5 Mw initially.

If two-phase separation occurred and the 400A pump were not running, natural convective flow could cause accumulation of the heavy fuel phase at the bottom of the core tank. Although the reactor would be subcritical under these conditions, startup of the pump at this time could add reactivity at a very high rate. However, the above situation implies criticality before the pump current stopped, and so the reactor will again attain a critical condition due to natural convective flow if two-phase separation has not occurred. Thus the stipulation was made that, for the above situation, the pump would not be started unless criticality were attained as a result of natural circulation of fluid.

If stoppage of core fluid flow occurred instantly, the temperature of the fuel solution would rise with time and could reach the boiling point. However, natural-convection circulation would be initiated as soon as the temperature of the fluid within the core increased. Assuming that the flow was zero initially and that it increased as a result of natural-convection forces, the maximum average core temperature would be less than 305°C following operation at 5 Mw and less than 315°C at 10 Mw. For this case the heat exchanger was assumed to be operative. If the steam line from the heat exchanger were closed, the cooling capacity would be limited, and so the fuel fluid temperature would continue to rise with increasing time. However, the rate of rise would be slow and boiling of the core fluid would not take place until about 10 min after the steam line was closed (10 Mw initially). Therefore it would not be necessary to have rapid-response instruments to control the above situation. However, as the fluid expanded, solution would be ejected into the pressurizer volume and would compress the vapor in that volume. If the vapor compressed adiabatically, an increase of 20°C in the core fluid temperature would cause the pressurizer pressure to rise from 2000 to 2800 psi. With the reactor initially at 5 Mw, this could occur in about 40 sec if there were no letdown of fluid from the high-pressure system.[6] The reactor is protected against above-normal operating pressures by means of a pressure signal which initiates a dump whenever the pressure exceeds 2800 psi. Under normal conditions the letdown valve would release fluid from the high-pressure system, which would prevent the pressure from reaching 2800 psi under the above circumstance. Thus, with regard to pressure rise, it appears that a dump need not be initiated for at least 10 min following stoppage of energy removal, and possibly not at all.

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[6]M. W. Rosenthal, *HRP Quar. Prog. Rep. Jan. 31, 1956*, ORNL-2057, p 31–32.

SAFETY OF THE HRT WITH VARIOUS BLANKET MATERIALS

In the two previous sections, reference has been made to the HRT with a D_2O reflector. If other blanket materials are used, it is not clear a priori that reactor safety will be independent of the blanket material, since the nuclear properties would vary with the blanket material. Calculations were therefore performed to study the safety of the HRT as a function of the blanket material.

The physical design of the reactor was assumed to be the same in all cases. Also, the temperature coefficient of reactivity for the core region was found to be relatively insensitive to the different blanket materials. The essential effect of changing blanket materials was to change the average lifetime of prompt neutrons. Calculations were therefore performed on the Oracle in which the lifetime was varied from 5.7×10^{-4} to 1.1×10^{-4} sec, which covered the range of blanket conditions to be encountered in the HRT. The Oracle results are given in Fig. 6 and consist of the maximum pressure rise p_{max} vs m_e for different values of the prompt-neutron lifetime. Since m_e is by definition the equivalent prompt reactivity addition (Δk_{eqp}) divided by l, Fig. 6 can be used to find the relation between p_{max} and Δk_{eqp} for a given value of l. The

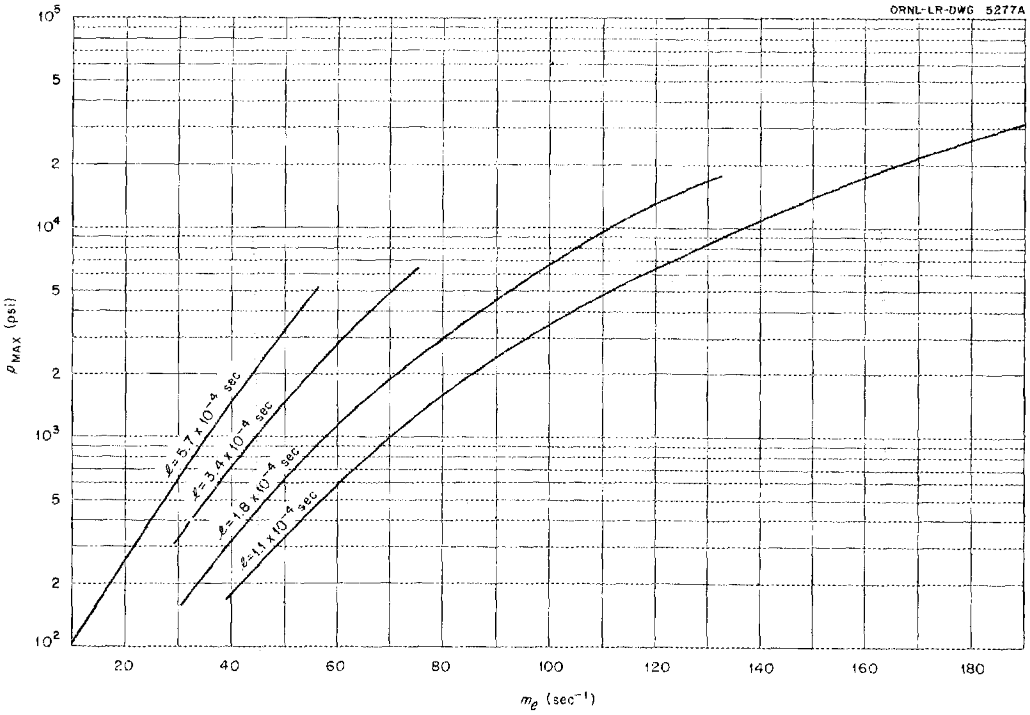

Fig. 6. HRT Core Pressure Rise vs Reactivity Addition for Various Prompt-Neutron Lifetimes.

TABLE 1. VARIATION OF l WITH HRT BLANKET MATERIAL

Lifetime, l(sec × 10^4)	Blanket Material
5.7	D_2O
3.4	UO_2SO_4-D_2O solution (355 g of U per kg of D_2O)
1.8	ThO_2-D_2O (633 g of Th per kg of D_2O)
1.1	ThO_2-D_2O (1349 g of Th per kg of D_2O)

associated parameter values were those of the HRT.[7] The specific variation of l with blanket material is given in Table 1 for reactor operation at 280°C and 2000 psi.

The value of m_e is dependent in a known manner upon initial reactor conditions and the rate of reactivity addition. The results of Fig. 6 can therefore be used to relate a specified pressure rise to a rate of reactivity addition for a given initial power level. Figure 7 summarizes the relations obtained between the rate of reactivity addition and l for a specified core pressure rise and initial power level. In Fig. 7, $k_e(0)$ is the initial value for the effective multiplication constant, and P_0 is the initial neutron power level. For a specified initial power, the rate of reactivity addition required for a particular pressure rise was relatively independent of l and, therefore, of blanket material. Figure 7 also shows that if the initial power level of the reactor were increased the rate of reactivity

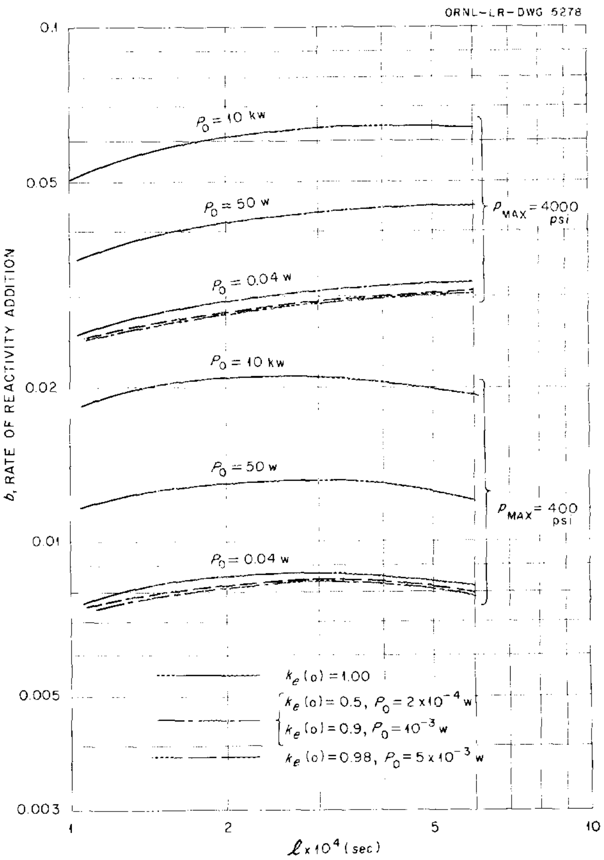

Fig. 7. Rate of Reactivity Addition as a Function of Lifetime of Prompt Neutrons and Initial Reactor Conditions.

[7] M. C. Edlund and P. M. Wood, *Physics of the Homogeneous Reactor Test — Statics*, ORNL-1780 (Aug. 27, 1954).

addition required to produce a specified pressure rise would increase. Also indicated is the relation between $k_e(0)$ and the rate of reactivity addition required to produce a particular pressure rise; it appears that if the same neutron source were present, the permissible rate of reactivity addition would be nearly independent of the initial value of k_e.

With only source neutrons present, Fig. 7 shows that a rate of reactivity addition of about 0.008 Δk_e/sec would cause a core pressure rise of 400 psi, independent of the blanket material. Since the philosophy of HRT safety has been based upon controlling the rate of reactivity addition, it appears that none of the different blanket materials would have a distinct safety advantage over the others if, for the same physical events, the rate of reactivity addition were the same. Consideration will therefore be given to the rate of reactivity addition associated with specific physical events as a function of blanket material.

There are basically two ways of adding reactivity to the HRT, namely, by decreasing the reactor temperature or by increasing the effective mass of fuel within the reactor. Of the seven cases considered previously, the first two were primarily concerned with the value of the temperature coefficient of reactivity, cases 3 through 5 involved the concentration coefficient of reactivity, case 6 concerned a net fuel addition to the reactor, and case 7 involved after-heat and two-phase separation problems.

These cases will now be reconsidered to see whether blanket materials other than D_2O could lead to safety requirements more stringent than those specified in the previous section.

For cases 1 and 2, the rate of reactivity addition would be dependent upon the value of the temperature coefficient. This value as a function of blanket material was obtained by Paré[8] and is given in Table 2. The value given refers to the change in

[8] V. K. Paré, *Temperature Coefficients and Maximum Rates of Increase of Reactivity for HRT*, ORNL CF-54-6-200 (June 15, 1954).

TABLE 2. CORE TEMPERATURE COEFFICIENT OF REACTIVITY IN HRT AT 280°C

Blanket Material	$\partial k_e/\partial T$ (°C^{-1})
D_2O	-1.85×10^{-3}
UO_2SO_4-D_2O (355 g of natural U per kg of D_2O)	-1.85×10^{-3}
ThO_2-D_2O (633 g of Th per kg of D_2O)	-1.99×10^{-3}
ThO_2-D_2O (1349 g of Th per kg of D_2O)	-2.4×10^{-3}*

*Obtained from concentration coefficient of reactivity and critical concentration curve in reference 7.

k_e if the average core temperature were increased. It was assumed that the spatial temperature distribution followed the spatial neutron-flux distribution.

The incidents referred to in cases 1 and 2 would add more reactivity to the reactor as the value of $|\partial k_e/\partial T|$ were increased. With the D_2O blanket, $\partial k_e/\partial T$ was -1.85×10^{-3} °C^{-1} in case 1, while a value of -2.0×10^{-3} °C^{-1} was assumed in case 2. As given in Table 2, the largest value for $-\partial k_e/\partial T$ occurs with the heavy slurry blanket. If $|\partial k_e/\partial T|$ were 2.4×10^{-3} °C^{-1}, rather than 1.85×10^{-3} °C^{-1}, more reactivity would be added by a cooling incident. The maximum effect of such a change in $\partial k_e/\partial T$ would be to increase the rate of reactivity addition by 30%. In the previous section, the safety design for the D_2O blanket was based on a rate of reactivity addition of 0.006 Δk_e/sec, although the permissible rate was approximately 0.008 Δk_e/sec. Therefore an increase of 30% in the rate of reactivity addition (from 0.006 to 0.0078 Δk_e/sec) would not endanger the core vessel, since the permissible rate of reactivity addition was found (see Fig. 7) to be nearly independent of blanket material. The latter result was based on calculations in which $\partial k_e/\partial T$ was assumed to be -1.85×10^{-3} Δk_e/°C. Actually, an increase in $-\partial k_e/\partial T$ would decrease the maximum pressure rise for a given reactivity addition, and so the permissible rate of reactivity addition would increase as $-\partial k_e/\partial T$ increased. The net result is that the degree of safety of the HRT appears to be independent of blanket material for cases 1 and 2.

In cases 3 through 5, the essential parameter was the concentration coefficient of reactivity. The value for this parameter as a function of blanket material was obtained by Beall and Visner[1] from the calculations of Edlund and Wood[7] and is presented in Table 3.

TABLE 3. CONCENTRATION COEFFICIENT OF REACTIVITY IN HRT

Blanket Material	$(\partial k_e/\partial \ln c)_{280°C}$*	$(\partial k_e/\partial \ln c)_{200°C}$*
D_2O	0.29	0.36
UO_2SO_4-D_2O (355 g of natural U per kg of D_2O)	0.20	0.25
ThO_2-D_2O (633 g of Th per kg of D_2O)	0.20	0.25
ThO_2-D_2O (1349 g of Th per kg of D_2O)	0.15	0.20

*The variable c is the fuel concentration in the core fluid (by weight), and the subscript is the reactor temperature at which the coefficient was evaluated.

The largest value for $\partial k_e/\partial \ln c$ was obtained for the case of a D_2O blanket. Thus, for an operational event which involved the concentration coefficient, changing the blanket from D_2O to another material would lead to a safer reactor. However, the coefficient as given in Table 3 refers to a fully filled core region, and so the above conclusion would be valid only for situations corresponding to cases 3 and 4.

In case 5, the reactor may become critical before the reactor core is completely filled. If criticality were attained with the reactor volume nearly filled, the implication would be that the incoming fuel solution was dilute, for which case the rate of reactivity addition would be relatively low. If the fuel solution were extremely concentrated, criticality could possibly be attained with the core about half filled. Because of the poor geometry associated with this situation (insofar as neutrons are concerned), the fuel mass required for criticality would be much less dependent upon the blanket material than if the reactor were filled. Because of the high fuel inventory the most dangerous case would be that associated with a ThO_2-D_2O slurry blanket (1349 g of Th per kg of D_2O). However, with a heavy slurry blanket, the reactor would not be operated at a temperature above 250°C because of the two-phase separation problem and corrosion difficulties which would arise with high fuel concentrations. Assuming that a limit of 250°C is imposed upon the HRT with a heavy slurry blanket, but that operation at 280°C is possible with a light slurry blanket, the case 5 situation would be most dangerous if the blanket material consisted of the light slurry (633 g of Th per kg of D_2O). The specific problem considered was one posed by Beall and Visner,[1] in which the following conditions were assumed:

1. blanket filled with slurry containing 633 g of thorium per kilogram of D_2O,
2. fuel injection pump pumping at high speed, 6.3 kg of solution per minute,
3. concentration of fuel in dump tanks, 27.3 g of U^{235} per kilogram of D_2O,
4. fuel fluid temperature, 60°C.

Under the above conditions the rate of reactivity addition would be about 0.02 Δk_e/min. Such a rate addition would be quite low, and the danger associated with reaching criticality before the core was filled would be a function of the value of the temperature coefficient of reactivity. The value for $\partial k_e/\partial T$ was found to be -6×10^{-4} Δk_e/°C (from 50 to 100°C). By using this value, it was found that the above-described abnormal startup would not lead to a serious condition. However, if the fuel addition were not discontinued after criticality had been attained, the reactor pressure would continue to rise and could eventually cause the dump signal to be initiated.

The sign of $\partial k_e/\partial T$ is of primary concern for this case, but, because of the complicated geometry involved, it is difficult to determine $\partial k_e/\partial T$ accurately. On the basis of the calculations made, $\partial k_e/\partial T$ was always negative, independent of the blanket material, and of magnitude greater than 10^{-4} Δk_e/°C.

In case 6, reactivity was considered to be added instantaneously and as a rate function. Of the blanket materials considered, this situation would be most hazardous when the blanket consisted of the heavy slurry (1349 g of Th per kg of D_2O), since the permissible reactivity addition would be smaller for this blanket material (see Figs. 6 and 7, or Table 5), and in addition a given fuel-volume addition would add more reactivity. The reactivity addition associated with this case would be about 1.6% Δk_e, which is also the maximum permissible reactivity addition (see Table 5). However, the above result was based on operating the heavy slurry blanket reactor at 280°C. Since the maximum operating temperature would not exceed 250°C, the reactivity addition would be less than the permissible addition. The most dangerous situation may then be associated with 280°C operation of the light-slurry-blanket reactor, but the reactivity addition would still be less than the permissible reactivity addition.

The situation depicted in case 7 concerned heat-after-shutdown and two-phase-separation problems. The heat-after-shutdown problem would not be affected by the blanket material and need not be considered further. However, the two-phase-separation problem would be a function of blanket material, for the temperature at which separation occurs decreases as the fuel concentration increases. To protect against two-phase separation, the operating temperature would be lowered when the D_2O blanket is replaced with another material. However, to evaluate the potential hazard, the rates of reactivity addition associated with fuel accumulation in the core region will be evaluated. Assuming that all fuel pumped into the core region stays within the core, the rate of reactivity addition would be a function of the original fuel concentration, the pumping rate, and the concentration coefficient of reactivity. The results obtained are given in Table 4 for cases of initial operation at 280 and 200°C. Comparing the values of $\partial k_e/\partial t$ in Table 4 with the permissible values (see Table 5), it appears that no danger

TABLE 4. POSSIBLE RATES OF REACTIVITY ADDITION DUE TO TWO-PHASE SEPARATION OF FUEL SOLUTION

Blanket Material	$b = \partial k_e/\partial t$ (sec^{-1})	
	280°C	200°C
D_2O	0.026	0.032
UO_2SO_4-D_2O (355 g of natural U per kg of D_2O)	0.018	0.022
ThO_2-D_2O (633 g of Th per kg of D_2O)	0.018	0.022
ThO_2-D_2O (1349 g of Th per kg of D_2O)	0.013	0.018

of pressure-vessel rupture exists, except for the case of a D_2O blanket at an operating temperature of 200°C. However, no two-phase-separation problem exists at that temperature, and so the above rate would not be applicable. Thus, although the hazard associated with two-phase separation would increase as the operating temperature is decreased and as the blanket material becomes a better reflector, these very conditions tend to eliminate the two-phase-separation problem. The most potentially dangerous situation appears to exist with the D_2O blanket, which has been discussed previously.

The above incidents do not include possible hazards associated with dump-tank criticality, slurry settling in the blanket region, compression of gas bubbles, and explosion hazards from D_2-O_2 mixtures. Such cases have been discussed by Beall and Visner.[1] The dump tanks have been designed to be ever-safe, and no danger of rupturing the pressure vessel appears to exist from the other hazards, although more studies should be made of the effect of slurry settling as better methods of calculation become available.

DISCUSSION

The foregoing safety analyses have been based upon the presence of a neutron source of 10^7 neutrons/sec. If the initial neutron power level were increased, the permissible rate of reactivity addition would increase also. For example, a rate of reactivity addition of 3.5% Δk_e/sec would be permissible one day after reactor shutdown following long-term operation at 5 Mw, whereas with only source neutrons present, the permissible rate would be 2.5% Δk_e/sec (the above example neglected the γ,n reactions resulting from the high-energy gammas of the fission products, and so the permissible rate would be slightly higher than 3.5%). Thus the reactor would be able to withstand safely rates of reactivity addition higher than those specified previously, following or during operation at power. Such a conclusion would be valid only if the effect of decomposition gases upon reactor safety were neglected. So far, decomposition gases have been neglected entirely. This would be justified if complete recombination of the decomposition gases were achieved within the reactor, or if the reactor were operating at a power so low that the decomposition gases were not formed (corresponding to the situation where the decomposition gases would be absorbed by the fuel solution). If the reactor were at low power and reactivity were added to the system, then neglect of gas formation as the power increased would be conservative with respect to safety, since the formation of gases would help in decreasing the reactivity of the system. If the initial power were so high that undissolved gases would initially be present within the core region, the compressibility of the fluid would be lower than if no gases were present, and this would have a detrimental effect upon reactor safety. Also, as the gas bubbles are compressed, the system will tend to become more "homogeneous" in the nuclear sense, which would probably add a small amount of reactivity to the system. Thus, any undissolved gases which were initially present would tend to lower the permissible reactivity addition. However, an increase in gas volume would imply an increase in initial reactor power, which would aid reactor safety. The net effect would be as shown in Fig. 8 (the degree of safety would represent the reciprocal of the core pressure rise for a given reactivity addition).

The specific shape of the curve illustrated in Fig. 8 applicable to the HRT has not been determined. However, studies have shown that with no gas recombination the degree of safety of the HRT would be lowest at source power over the range from source power to 10 Mw. With internal recombination, the degree of safety would increase as indicated in Fig. 8. Under normal conditions about 80% of the decomposition gases will be recombined internally within the HRT at 5 Mw power, and about 90% will be recombined while operating at 10 Mw.

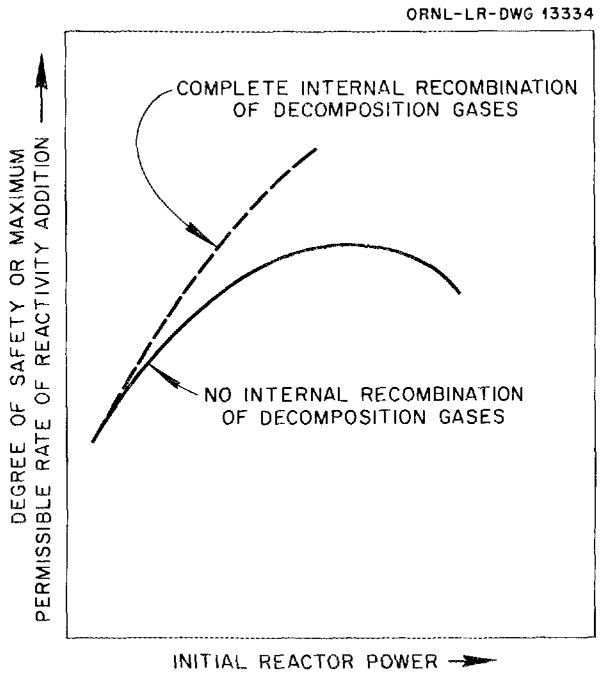

Fig. 8. Degree of Safety as a Function of Initial Power Level for a Given Rate of Reactivity Addition.

In specifying the maximum allowable rate of reactivity addition which would not rupture the core tank, no consideration was taken of the inertia of the fluid on the blanket side of the core tank. Although the core tank may burst if the internal pressure is about 900 psi greater than the blanket pressure under static conditions, the core pressure rise required to burst the core under dynamic conditions would be greater than 900 psi because of the inertial effects of the blanket fluid. Setting the allowable pressure rise at 400 psi during a reactivity addition would therefore be conservative. However, no undue penalty appears to have been paid for this conservatism in the HRT.

The pressure rise in the blanket region has been neglected in these studies, since the power generation within the blanket region would be small compared to that generated within the core fluid. Since the blanket pressurizer is identical with the core pressurizer, the pressure rise in the blanket would not be controlling. An increase in blanket pressure during a power surge would actually increase the permissible pressure rise in the core region.

The studies given previously have pertained to certain operating conditions and a particular physical design. The dynamics of the reactor system would be altered if the operating conditions and/or design parameters were changed.

The number of fission neutrons which are delayed are often thought of as an important factor in reactor safety. However, if reactivity were added as a linear rate function and if there were sufficient delayed neutrons to damp the power oscillation, the delayed neutrons would have little influence upon safety, although they would influence the stability and steady-state operational behavior of the reactor. With reference to HRT safety, the contribution of delayed neutrons would be to damp out any initiated power surge.

SUMMARY

The safety of the HRT has been presented for a variety of operating conditions and blanket materials. Indications are that the outer pressure vessel will not fail even under the most adverse conditions anticipated and that normal operating procedures and safety restrictions are sufficient to protect the core tank against rupture.

The safety of the reactor is dependent upon the core temperature coefficient of reactivity, which has a value of about $-2 \times 10^{-3}\ \Delta k_e/^\circ C$. The different blanket materials influence the value for the prompt-neutron lifetime but have little effect on the core temperature coefficient. The maximum allowable rates of reactivity addition, as well as maximum allowable instantaneous reactivity additions, based upon the limiting pressure rise within the system, are given in Table 5 for reactor conditions of 2000 psi,

TABLE 5. SUMMARY OF HRT SAFETY CALCULATIONS FOR SOURCE POWER CONDITIONS

Variable	Blanket Material			
	D_2O	UO_2SO_4-D_2O[a]	ThO_2-D_2O[b]	ThO_2D_2O[c]
Prompt-neutron lifetime, sec $\times 10^4$	5.7	3.4	1.8	1.1
Rate of reactivity addition required to increase core pressure by 400 psi, $\%\ \Delta k_e$/sec	0.80	0.84	0.80	0.75
Instantaneous reactivity addition required to increase core pressure by 400 psi, $\%\ \Delta k_e$	1.9	1.6	1.3	1.1
Rate of reactivity addition required to increase reactor pressure by 4000 psi, $\%\ \Delta k_e$/sec	3.1	3.0	2.8	2.6
Instantaneous reactivity addition required to increase reactor pressure by 4000 psi, $\%\ \Delta k_e$	3.5	2.8	2.0	1.6

[a] 335 g of natural uranium per kilogram of D_2O.

[b] 633 g of thorium per kilogram of D_2O.

[c] 1349 g of thorium per kilogram of D_2O.

280°C, and a source power level of 10^7 neutrons/sec. The 400-psi pressure rise for the core and the 4000-psi rise for the outer pressure vessel are conservative with respect to allowable yield stresses in these vessels. These values have been assumed to be the maximum permissible pressure rises within the core and pressure vessel, respectively. It can be seen from Table 5 that the permissible rate of reactivity addition is not sensitive to the blanket material, although this is not true for the reactivity addition itself. Increases in the initial power level above source power increase the permissible rate of reactivity addition for a given pressure rise, but not the permissible reactivity addition.

A number of physical events can occur which will introduce reactivity into the reactor. These were investigated to determine whether the pressure rise associated with the reactivity addition exceeded the permissible pressure rise. The particular events studied were: addition of cold fuel solution into the hot critical core by misoperation of the heat exchangers and/or pump; addition of concentrated fuel solution into the reactor by means of the Pulsafeeder pump; the possibility of achieving criticality before the reactor core is filled; loss of pressure in the HRT blanket which would result in core-tank rupture and net addition of fuel into the reactor region; and two-phase-separation and after-heat problems. Where necessary, operational and design changes were incorporated such that the estimated reactivity addition would not cause core-tank rupture. In no case did it appear that rupture of the pressure vessel would take place. No consideration was taken, however, of the effects that radiation may have upon the metallurgical characteristics of the vessels.

TABLE OF NOMENCLATURE

a_f = resistance coefficient, defined by Eq. 4, psi (sec/ft)^2

A = cross-sectional area of core relief pipe, 0.0667 ft^2

b = linear rate of reactivity addition to reactor, Δk_e/sec

c = fuel concentration in the core fluid, grams of fuel per kilogram of D_2O

c_p = heat capacity of fluid, 2.5 kw sec/lb-°C at 300°C, 2000 psi

$$C_2 = \frac{n\gamma_2 p_0}{\rho_0}\,\frac{V_c}{V_p}\,\frac{l}{\partial k_e/\partial \rho} = \frac{144 g_c}{v_s^2}\,\frac{p_0}{\rho_0}\,\frac{nV_c}{V_p}$$

= measure of effect of pressurizer volume upon core pressure rise, dimensionless, about 0.15

$$F = 1 + C_2 + \frac{m_e}{\omega_b^2}(\gamma_f + m_e)$$

= measure of effect of fluid compressibility upon core pressure rise, dimensionless

$$\overline{F} = 1 + \frac{F - 1}{2}\text{, dimensionless}$$

g_c = dimensional constant, 32.2 $\dfrac{\text{ft-lb mass}}{\text{sec}^2\text{-lb force}}$

k_e = effective multiplication constant, dimensionless

$k_e(0)$ = initial value of k_e

$k_e - 1$ = reactivity, dimensionless

Δk_{eqp} = reactivity above prompt-critical which is added to reactor; in case of a rate addition of reactivity, Δk_{eqp} refers to the equivalent prompt reactivity addition, or that amount of prompt reactivity which if added instantaneously would result in the same pressure rise as that obtained if reactivity were added at some specified rate; dimensionless

$\dfrac{\partial k_e}{\partial T}$ = temperature coefficient of reactivity, about -2×10^{-3} Δk_e/°C at 280°C, 2000 psi

$\dfrac{\partial k_e}{\partial \rho}$ = density coefficient of reactivity, about 0.0132 Δk_e-ft^3/lb at 300°C, 2000 psi

$\rho \dfrac{\partial k_e}{\partial \rho}$ = ~0.685 Δk_e per fractional density change, at 300°C, 2000 psi

l = average lifetime of prompt neutrons, sec

L = length of piping between core volume and surface of pressurizing fluid, 10 ft

m = instantaneous prompt reactivity addition divided by mean lifetime of prompt neutrons, $\dfrac{\Delta - \beta}{l}$, sec^{-1}

m_e = equivalent prompt reactivity addition divided by mean lifetime of prompt neutrons (see Δk_{eqp}), $\dfrac{\Delta k_{eqp}}{l}$, sec^{-1}

M_r = mass of fluid which must be moved to eject fluid from core region, 33 lb mass

M_s = $\dfrac{1 - k_e(0) + \beta}{l}$, sec^{-1}

n = ratio of heat capacity at constant pressure to heat capacity at constant volume for pressurizing fluid, dimensionless, about 1.2

n_f = number of velocity heads of fluid lost while fluid moves between core and pressurizer regions, dimensionless; about 6 for safety, about 1 for stability

p = $p_c - p_c(0)$ = pressure rise in core, psi

p_{max} = maximum value of p following reactivity addition, psi

p_c = core pressure, psi

$p_c(0)$ = core pressure evaluated under initial conditions, 2000 psi

p_0 = $p_p(0) \approx p_c(0)$, initial pressure in pressurizer, 2000 psi

p_p = pressurizer pressure, psi

$p_p(0)$ = initial pressure in pressurizer, 2000 psi

P = reactor power, kw

P_0 = P evaluated under initial conditions, kw

P_{pc} = P evaluated when reactor is prompt-critical, kw

S_c = volume heat capacity of core volume $= c_p \rho_0 V_c$ = 1300 kw sec/°C

S_e = number of neutrons from neutron source which are absorbed in fuel fluid, about 10^7 neutrons/sec

t = time, sec

T = average temperature of core fluid, °C

T_0 = T evaluated under initial conditions, 280°C

u = $U - U_0$, deviation of fluid velocity, fps

U = average velocity of fluid in core exit pipe, fps

U_0 = U evaluated under initial conditions, based on 3.5-in.-ID pipe, 440-gpm flow rate, about 15 fps

v = $\dfrac{1}{l} \rho_0 \dfrac{\partial k_e}{\partial \rho} \dfrac{A}{V_c} (U - U_0)$, normalized deviation of fluid velocity in core exit piping, $\sec^{-2}$

v_s = velocity of sound in core fluid

$= \sqrt{\dfrac{dp}{d\rho} 144 g_c}$, 2380 fps at 300°C, 2000 psi

V_c = volume of core region, 10.24 ft^3, 290 liters

V_p = volume of pressurizing fluid, 2.5 ft^3, 72 liters

x = $\dfrac{P}{P_0}$, relative reactor power, dimensionless

x_{max} = maximum value of x following a reactivity addition to reactor, dimensionless

y = $(T - T_0) \dfrac{S_c}{P_0}$ = normalized temperature rise in core fluid, sec

z = $\dfrac{1}{l} \dfrac{\partial k_e}{\partial \rho} (\rho - \rho_0)$ = normalized change in core fluid density, $\sec^{-1}$

β = effective fraction of fission neutrons which are delayed, dimensionless, 0.005

γ = $\dfrac{\beta}{l}$, $\sec^{-1}$

γ_f = $\dfrac{288 g_c a_f U_0}{\rho_0 L} = \dfrac{n_f U_0}{L}$, normalized friction coefficient; about 10 $\sec^{-1}$ for safety studies

γ_2 = conversion factor, $\dfrac{144 g_c}{v_s^2 l} \dfrac{\partial k_e}{\partial \rho}$, (psi-sec)$^{-1}$

γ_3 = conversion factor, $\dfrac{A U_0}{V_c l} \rho_0 \dfrac{\partial k_e}{\partial \rho}$, $\sec^{-2}$

Δ = instantaneous reactivity addition, $k_e - 1$, dimensionless

$\xi = \dfrac{b}{l}$, linear rate of reactivity addition divided by prompt-neutron lifetime, sec^{-1}

ρ = average density of fuel fluid, lb/ft^3

ρ_0 = ρ evaluated under initial conditions of 2000 psi, 280°C; 52.5 lb/ft^3

$\dfrac{1}{\rho}\dfrac{\partial \rho}{\partial T}$ = relative change of fluid density with temperature, -2.7×10^{-3} °C^{-1} at 300°C, 2000 psi

$\omega_b^2 = \dfrac{A^2 \rho_0 v_s^2}{V_c M_r} \approx \dfrac{A v_s^2}{V_c L}$ = square of hydraulic frequency, 3700 sec^{-2}

$\omega_n^2 = -\dfrac{1}{l}\dfrac{\partial k_e}{\partial T}\dfrac{P_0}{S_c} = \dfrac{1}{l}\left|\dfrac{\partial k_e}{\partial T}\right|\dfrac{P_0}{S_c}$ = square of nuclear frequency, sec^{-2}

$\omega_{np}^2 = \omega_n^2 \dfrac{P_{pc}}{P_0}$