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PRESSURE RISE IN TBR FOLLOWING
RAPID ADDITION OF REACTIVITY

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October 14, 1955

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M. W. Rosenthal

October 14, 1955

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RAPID ADDITION OF REACTIVITY

SUMMARY

In order to provide information for evaluation of hazards associated with operation of the Thorium Breeder Reactor, the peak pressure rise which would occur in the reactor core during a power excursion has been related to rate of reactivity addition and equivalent instantaneous reactivity addition. The reactivity increase engendered by a rapid reduction in heat-exchanger steam pressure has been obtained as a function of rate of change in boiling temperature. From these results the magnitude of the core pressure surge that would follow a specified decrease in steam pressure can be estimated.

INTRODUCTION

The large negative temperature coefficients of reactivity associated with homogeneous reactors serve to reduce the power rapidly in the event of a rise in core temperature, thus providing operating stability and, in most cases, safety from power excursions. Conversely, however, a negative temperature coefficient provides a mechanism for the addition of reactivity (i.e., increase in the multiplication factor) by lowering of the core temperature, a condition achieved in circulating systems through the introduction of cold fuel solution into the core. Following the addition of sufficient reactivity to an initially critical or subcritical reactor, the system becomes supercritical and the power rises rapidly. The core temperature increases until the level is reached at which the reactor is prompt critical. At this

point the power begins to decrease but is sustained above the equilibrium value for a time by the delayed neutrons generated at the higher power levels. The temperature therefore continues to rise and exceeds the initial temperature.

The rise in core temperature which follows introduction of reactivity causes expansion of the fuel solution and expels fluid from the core vessel into the pressurizer. If this expansion is rapid, an appreciable force is developed in accelerating the liquid contained in the line connecting core tank to pressurizer; this force is in addition to any caused by compression of the pressurizer fluid at a rate faster than the system is designed to relieve. The increased core pressure results in higher fluid density, thus maintaining the reactivity higher than that normally corresponding to a given temperature and making the power excursion more severe. The maximum pressure developed during a surge may be high enough to endanger the core tank and pressure vessel.

The instantaneous addition of reactivity to a homogeneous reactor results in a peak pressure rise that, for excursions of sufficient magnitude to be of interest, is essentially independent of initial power, although for higher power levels the peak is reached faster. The introduction of cold solution into a core results in a rate of reactivity increase rather than an instantaneous change, and the period of cold solution addition in most situations lasts longer than the time required for the peak pressure to be attained. Therefore, for the same rate of reactivity addition, before the maximum pressure is reached more reactivity is introduced into a reactor initially at low power than one at high power. It follows then, that for rate additions the magnitudes of the power and pressure increases are dependent on the initial power, and more

extreme surges occur with lower initial power levels.

An event which will result in rapid introduction of cold solution into a reactor core is the sudden increase in rate of heat removal in the heat exchanger which would follow a decrease in steam pressure. For such an occurrence under defined conditions the change in temperature of the exit solution from the heat exchanger can be calculated as a function of time. The ensuing rate of change in core temperature can be estimated by assuming some reasonable model to represent mixing within the core vessel (e.g., uniform residence time or complete mixing).

In order to evaluate the hazard associated with addition of reactivity to the TBR, the maximum rise in core pressure which would occur for a given event has been related to the initial power level and the rate of reactivity addition. The time dependent temperature of the solution leaving the heat exchanger for various linear rates of decrease in steam-wide temperature has been obtained and combined with the temperature coefficient of reactivity to yield the rates of reactivity addition to the core. From this information the magnitude of a pressure surge which would follow a specified steam pressure decrease can be estimated.

BEHAVIOR OF TBR

The response of the Thorium Breeder Reactor to rapid decrease in steam pressure in the heat exchanger has been estimated using the present concept of the high pressure system.¹ The initial reactor conditions employed in the calculations are conservatively chosen to result in prediction of the most extreme effects that would result from the type of incident considered.

Relation of Pressure to Reactivity Addition

The effect of reactivity addition to a system initially at low power is treated in reference 2 and equations derived for approximating the maximum pressure rise which will occur in the core of a homogeneous reactor during a power excursion. These relationships have been applied to the TBR¹ and the maximum pressure rise estimated as a function of instantaneous reactivity addition, ρ_e , and rate of reactivity addition, $\dot{\rho}$. The results of these computations are plotted in Fig. 1 for two low initial power levels: 10^{-7} kw corresponding to a source of 10^7 neutrons per second, and 1 kw.

The equations employed in obtaining Fig. 1 are presented in APPENDIX A and the values of the quantities involved given there and in NOMENCLATURE AND PARAMETER VALUES.

Heat Exchanger Behavior

The shell side of the TBR heat exchanger contains water boiling at the equilibrium temperature corresponding to the elevated pressure of the steam in the system. In the event this pressure were rapidly reduced, the temperature of the boiler water would follow the equilibrium relationship for saturated steam, falling until a new stable condition was attained. During the period of pressure drop the heat transfer rate would increase due to the larger temperature driving force (assuming the heat transfer coefficient does not decrease), and the temperature of the fuel solution flowing from the exchanger would decrease. Subsequent to the steam pressure attaining a constant level, the fuel solution temperature reaches a new steady condition. Equations describing this behavior are derived in APPENDIX B.

Fig. 1. Relationship Between Maximum Core Pressure Rise, Equivalent Prompt Reactivity Addition, and Rate of Reactivity Addition for TBR

A series of calculations has been performed for the TBR heat exchanger for linear rates of decrease in shell-side temperature from 280°C to 100°C . Boiling temperature rather than pressure has been specified for ease in computation, but the results can be related to rate of pressure decrease by use of a chart of the thermodynamic properties of steam. In all calculations the initial power level has been assumed to be so low that there is negligible heat transfer and the entire system is at 280°C . The overall heat transfer coefficient and the fuel solution flow rate are assumed to remain unchanged during an event; the heat exchanger parameters used are those of the design conditions.¹

In Fig. 2 the change in exit fuel solution temperature is plotted versus elapsed time from the beginning of an incident for rates of change in shell side temperature (dT_b/dt) ranging from $-\infty$ (instantaneous fall in pressure) to $-18^{\circ}\text{C}/\text{sec.}$ For all cases the solution temperature falls 120°C to the steady state condition for an entrance temperature of 280°C and a constant boiling temperature of 100°C .

Rate of Change in Core Temperature

Addition of cold liquid to the core while the reactor is at low power results in an immediate reduction in mean core temperature. The calculated rate of temperature change is dependent on the model chosen for mixing in the core. The model of uniform residence time, or "slug flow", yields the maximum rate of change which can occur; and hence to be conservative (i.e., to insure that all errors are on the side of predicting higher pressures than will occur) it has been employed in all computations. There is a period during which the rate of change in core temperature varies with time, and conservatism here also dictates the use of the most rapid change in estimating

Fig. 2. Change in Temperature of Fuel Solution Leaving TBR Heat Exchanger vs. Time for Various Rates[∞] of Change of Steam-Side Temperature.

reactivity addition.

The time variation of the temperature of the fuel solution entering the reactor core is the same as that at the exit of the heat exchanger, displaced in time by the period required for passage through the piping in between. Hence the curves of Fig. 2 have been used with the equations for slug flow (APPENDIX C) to predict the maximum rate of decrease in core temperature which can follow a specified change in shell-side temperature. The results of these calculations are plotted as the upper curve in Fig. 3.

Relation of Reactivity Addition to Temperature Change

The rate of addition of reactivity to a reactor is equal to the product of the rate of core temperature change, dT/dt , and the temperature coefficient of reactivity, $\partial k_e / \partial T$.

$$b = \frac{\partial k_e}{\partial T} \frac{dT}{dt} \quad \text{sec}^{-1} \quad (1)$$

The parameter, ξ , employed in evaluating the effect of reactivity addition, is defined as the rate of addition divided by the mean lifetime of prompt neutrons in the core, τ_l .

$$\xi = \frac{b}{\tau_l} \quad \text{sec}^{-2} \quad (2)$$

The temperature coefficient for the TBR is $-1.5 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$ and the prompt lifetime is $7.7 \times 10^{-4} \text{ sec}$. The rate addition parameter, ξ , is thus a constant times the rate of core temperature change, as follows:

$$\begin{aligned} \xi &= - \frac{1.5 \times 10^{-3}}{7.7 \times 10^{-4}} \frac{dT}{dt} \\ &= -1.95 \frac{dT}{dt} \quad \text{sec}^{-2} \end{aligned} \quad (3)$$

Fig. 3. Maximum Rate of Change in TBR Core Temperature and Corresponding Rate of Reactivity Addition vs. Rate of Steam-Side Temperature Decrease in Heat Exchanger

Using Equation 3 the upper curve of Fig. 3 has been converted to the lower curve which relates rate of reactivity addition to rate of change of steam-side temperature.

Core Pressure Rise

The curve for ξ from Fig. 3 has been combined with values obtained from Fig. 1 to yield the maximum rise in core pressure which will be caused by a given rate of decrease in boiler water temperature. These results are presented in Fig. 4 for the two initial power levels, 1 kw and 10^{-7} kw. The values of 3300 and 670 psi indicated at the righthand ordinate are the pressure increases which would occur for an instantaneous drop of steam-side temperature from 280°C to 100°C , and thus for the initial power levels considered, these are the extreme effects of increase in rate of heat removal in the heat exchanger.

DISCUSSION

The results plotted in Fig. 4 indicate that with the reactor at source power and at normal operating temperature, sufficient reactivity can be added to the system by a rapid decrease in steam pressure to endanger the core tank but probably not the pressure vessel. At all points in the derivations and calculations where approximations are required, choices have been made which are conservative in the sense that more extreme pressure surges are predicted than would occur under actual conditions. Hence Figs. 1 and 4 may be taken as predictions of the upper limits of the pressure rises which could result from the conditions specified. At higher initial fission power levels the pressure surges are less severe. It should be noted that it is the initial

Fig. 4. Maximum Pressure Rise in Core of TBR vs. Rate of Fall of Steam-Side Temperature in Heat Exchanger

rate of fissioning which affects the power excursion, and energy released by fission-product decay has importance only in that some photoneutrons are produced by the higher energy gamma rays. At lower temperatures the rate at which reactivity can be introduced into the core is less great because the absolute value of the temperature coefficient of reactivity is smaller and the available temperature potential for cooling the solution is reduced.

A value of dT_b/dt can be converted to rate of change of pressure with time by dividing by $\partial T_b/\partial p_{sat}$. The change in saturation temperature of water with pressure is not constant but decreases rapidly with increasing temperature, as shown below.³ However, this does not imply that a rupture at low pressure is more hazardous than the same event at high pressure, since the rate of pressure decrease will be greater at higher initial levels.

T_b	p_{sat}	$\frac{\partial T_b}{\partial p_{sat}}$
200°C	226 psia	0.219 °C/psia
240	485	0.117
280	931	0.071

Using the value of $\partial T_b/\partial p_{sat}$ at 240°C to convert rate of pressure decrease to temperature decrease, the peak pressure increases listed below have been obtained from Fig. 4.

$\frac{dp_{sat}}{dt}$	$\frac{dT_b}{dt}$	Δp_{max}	
		$P_o = 10^{-7} \text{ kw}$	$P_o = 1 \text{ kw}$
200 psi/sec	23 °C/sec	190 psi	< 100 psi
500	59	560	190
1000	117	1400	370
2000	234	2300	530
∞	∞	3300	670

The relation between pressure rise and increase in reactivity is strongly dependent on the geometry of the system, particularly on the arrangement and size of the connecting line between core tank and pressurizer. An increase in the cross-section of this line or a decrease in the distance between core tank and liquid surface in the pressurizer will result in lower values of Δp_{max} than predicted for the present design. Any changes from the dimensions used in the calculations of this memorandum will alter the results and Fig. 1 will no longer apply.

The results plotted in Figs. 1 - 4 are all predicated on the assumption that the core circulating pump continues to operate throughout the duration of the period of interest. If operation of the pump were quickly interrupted following a steam pressure release, the rate of reactivity addition to the core would be reduced and the severity of the surge mitigated.

RELATIONSHIPS BETWEEN MAXIMUM CORE PRESSURE RISE,
EQUIVALENT PROMPT REACTIVITY ADDITION,
AND RATE OF REACTIVITY ADDITION

The equations which follow² predict the maximum rise in pressure in the core of a homogeneous reactor following an addition of reactivity. The model for the derivation is a circulating fuel system having a pressurizer with a finite vapor volume. Equation (4) yields the maximum pressure increase which will occur for the case of an instantaneous reactivity addition.

$$\Delta p_{\max} = \frac{m_e^2 F}{2\omega_h^2 \gamma_2} \left\{ 0.385 m_e + \alpha_1 \left(1 + \frac{m_e^2 F}{4 \gamma_3} \right) \right\} + \frac{C_2 m_e}{\gamma_2} \quad (4)$$

$$\omega_h^2 = \frac{A_r v_s^2}{V_c L_r} = 15,600 \text{ sec}^{-2} \quad (5)$$

$$\gamma_2 = \frac{144 g_c}{v_s^2 \tau_l} \frac{\partial k_e}{\partial \rho} = 0.016 \frac{\text{in}^2}{\text{sec-lb}_M} \quad (6)$$

$$\gamma_3 = \frac{U_o A_r \rho_o}{V_c \tau_l} \frac{\partial k_e}{\partial \rho} = 785 \text{ sec}^{-2} \quad (7)$$

$$\alpha_1 = \frac{\eta_f U_o}{L_r} = 5.4 \text{ sec}^{-1} \quad (8)$$

$$C_2 = \frac{144 g_c p_o V_c}{v_s^2 \rho_o V_v} = 0.057 \quad (9)$$

$$F = \frac{\omega_h^2 (1 + C_2) + \alpha_1 m_e + m_e^2}{\omega_h^2} \quad (10)$$

For reactivity addition as a rate function, an equivalent instantaneous addition which would yield the same pressure rise can be obtained from Equation (11).

$$1 + \frac{\omega}{\omega_{np}^2} = \frac{m_e^2/2 \omega_{np}^2}{\ln(m_e^2/2 \omega_{np}^2)} \quad (11)$$

(also plotted in Fig. 2 of reference 2)

$$\omega_{np}^2 = \omega_n^2 x_{pc} \quad (12)$$

$$x_{pc} = \frac{P_{pc}}{P_o} = c^{-1} M_s^2 / 2\xi + \sqrt{\pi} \frac{M_s}{2\sqrt{2\xi}} \operatorname{erf}\left(\frac{M_s}{\sqrt{2\xi}}\right) \quad (13)$$

(also plotted in Fig. 3 of reference 2)

$$\omega_n^2 = \frac{S_c P_o}{\tau_l} \left| \frac{\partial k_e}{\partial T} \right| = 2.18 \times 10^{-4} P_o \text{ sec}^{-2} \quad (14)$$

(P_o in kw)

$$M_s = \frac{\delta_{sc} + \bar{\beta}}{\tau_l} = 1.3 \times 10^3 \text{ sec}^{-1} \quad (15)$$

(taking δ_{sc} as 1.0 and $\bar{\beta}$ as 0.0024)

For the condition when the reactor is subcritical with a neutron source present, source power can be estimated from the following equation.

$$P_{os} \approx \frac{10^{-11}}{1 - k_e} S_e \quad (16)$$

APPENDIX B

EFFECT OF STEAM PRESSURE CHANGE ON FUEL SOLUTION TEMPERATURE

If heat generation is neglected, the rate of temperature change of fluid in passage through a heat exchanger can be related to the local heat transfer rate by a time dependent energy balance.

$$\rho S c_p \frac{dT_h}{dt} = -U_{ht} z [T_h(t) - T_b(t)] \quad (17)$$

Equation (17) can be simplified for constant physical properties.

$$\frac{d\Delta T_h}{dt} = -K_1 [\Delta T_h(t) - \Delta T_b(t)] \quad (18)$$

$$K_1 \equiv U_{ht} z / \rho S c_p \quad (19)$$

$$\Delta T_h \equiv T_h(t) - T_b(o)$$

$$\Delta T_b \equiv T_b(t) - T_b(o)$$

Let ΔT_b change linearly to a new value $\Delta T_b(t_b)$ with the duration of the period of change designated t_b .

$$\Delta T_b(t) = K_2 t \quad 0 \leq t \leq t_b \quad (20)$$

$$\Delta T_b(t) = \Delta T_b(t_b) \quad t \geq t_b \quad (21)$$

$$K_2 \equiv \frac{\partial T_b}{\partial t} = \frac{\partial \Delta T_b}{\partial t} \quad (22)$$

$$\frac{d\Delta T_h}{dt} = K_1 K_2 t - K_1 \Delta T_h(t) \quad 0 \leq t \leq t_b \quad (23)$$

$$\frac{d\Delta T_h}{dt} = K_1 \Delta T_b(t_b) - K_1 \Delta T_h(t) \quad t \geq t_b \quad (24)$$

Equations (23) and (24) are readily integrated for the case of zero initial power, $\Delta T_h(0) = 0$, and uniform shell-side temperature.

For the range $0 \leq t \leq t_b$

$$\frac{d\Delta T_h}{dt} + K_1 \Delta T_h = K_1 K_2 t \quad (25)$$

$$\Delta T_h e^{K_1 t} = \frac{K_2}{K_1} e^{K_1 t} (K_1 t - 1) + C \quad (26)$$

$$\Delta T_h(\theta) = 0 \quad \theta \leq t$$

$\theta \equiv$ Time at which fluid enters region of heat exchange

$$\Delta T_h = \frac{K_2}{K_1} (K_1 t - 1) - \frac{K_2}{K_1} (K_1 \theta - 1) e^{-K_1(t - \theta)} \quad \theta \leq t \quad (27)$$

For the range $t \geq t_b$

$$\frac{d\Delta T_h}{dt} + K_1 \Delta T_h = K_1 \Delta T_b(t_b) \quad (28)$$

$$\Delta T_h e^{K_1 t} = \Delta T_b(t_b) e^{K_1 t} + C \quad (29)$$

$$\Delta T_h(t_b) = \frac{K_2}{K_1} (K_1 t_b - 1) - \frac{K_2}{K_1} (K_1 \theta - 1) e^{-K_1(t_b - \theta)}$$

$$\theta \leq t_b$$

$$\Delta T_h(t_b) = 0$$

$$\theta \geq t_b$$

$$\Delta T_h = \Delta T_b(t_b) - \frac{K_2}{K_1} e^{-K_1(t - t_b)} - \frac{K_2}{K_1} (K_1 \theta - 1) e^{-K_1(t - \theta)} \quad (30)$$

$$\theta \leq t_b$$

$$\Delta T_h = \Delta T_b(t_b) \left[1 - e^{-K_1(t - \theta)} \right] \quad \theta \geq t_b \quad (31)$$

For solution at exchanger exit, L.

$$t \leq t_h, \theta = 0 \quad (32)$$

$$t \geq t_h, \theta = t - t_h \quad (33)$$

$$t_h \equiv L/V$$

Combination of the preceding relationships as appropriate yields the following equations applicable for the conditions specified.

$$\underline{0 \leq t \leq t_h \leq t_b}$$

$$\Delta T_h(L, t) = \frac{K_2}{K_1} \left[K_1 t + e^{-K_1 t} - 1 \right] \quad (34)$$

$$\underline{0 < t_b \leq t \leq t_h}$$

$$\Delta T_h(L, t) = \Delta T_b(t_b) - \frac{K_2}{K_1} \left[e^{K_1 t_b} - 1 \right] e^{-K_1 t} \quad (35)$$

$$\underline{t_b, t_h \leq t \leq t_b + t_h}$$

$$\Delta T_h(L, t) = \Delta T_b(t_b) - \frac{K_2}{K_1} e^{-K_1(t-t_b)} - \frac{K_2}{K_1} \left[K_1(t-t_h) - 1 \right] e^{-K_1 t_h} \quad (36)$$

$$\underline{t \geq t_b + t_h}$$

$$\Delta T_h(L, t) = \Delta T_b(t_b) \left[1 - e^{-K_1 t_h} \right] \quad (37)$$

$$\underline{t_h \leq t \leq t_b}$$

$$\Delta T_h(L, t) = \frac{K_2}{K_1} (K_1 t - 1) - \left[K_1(t-t_h) - 1 \right] e^{-K_1 t_h} \quad (38)$$

$$\underline{t \leq t_h, K_2 \rightarrow \infty, t_b \rightarrow 0, \Delta T_b(t_b) \text{ finite}}$$

$$\Delta T_h(L, t) = \Delta T_b(t_b) \left[1 - e^{-K_1 t} \right] \quad (39)$$

$$\frac{t \geq t_h, K_2 \rightarrow \infty, t_b \rightarrow 0, \Delta T_b(t_b) \text{ finite}}{\Delta T_h(L, t) = \Delta T_b(t_b) \left[1 - e^{-K_1 t_h} \right]} \quad (40)$$

It is useful to note that if the operating conditions of a heat exchanger are given, K_1 can be obtained by integrating equation (18) for the case of power removal at steady state, and rearranging.

$$K_1 = \frac{1}{t_h} \ln \frac{\Delta T_h(0)}{\Delta T_h(t_h)} \quad (41)$$

APPENDIX C
RELATION BETWEEN MEAN CORE TEMPERATURE AND
REACTOR INLET TEMPERATURE

For a period of interest sufficiently short that the power does not rise enough to influence the core temperature, the rate of change in mean core temperature is related to the inlet and outlet conditions by the following energy balance.

$$\frac{1}{S_c} \frac{dT}{dt} = P_o - Wc_p \left[T_2(t) - T_1(t) \right] \quad (42)$$

$$\frac{dT}{dt} = -\frac{1}{t_c} \left\{ \left[T_2(t) - T_2(0) \right] - \left[T_1(t) - T_1(0) \right] \right\} \quad (43)$$

$$P_o = Wc_p \left[T_2(0) - T_1(0) \right]$$

$$Wc_p S_c = Wc_p / \rho V_c c_p \equiv 1/t_c$$

$t_c \equiv$ Mean core residence time.

$$\frac{d\Delta T}{dt} = \frac{1}{t_c} \left[\Delta T_1(t) - \Delta T_2(t) \right] \quad (44)$$

$$\Delta T(t) \equiv T(t) - T(0)$$

$$\Delta T_1(t) \equiv T_1(t) - T_1(0)$$

$$\Delta T_2(t) \equiv T_2(t) - T_2(0)$$

For "slug flow" in core (uniform residence time)

$$\Delta T_2(t) = \Delta T_1(t - t_c) \quad (45)$$

$$\frac{d\Delta T}{dt} = \frac{1}{t_c} \left[\Delta T_1(t) - \Delta T_1(t - t_c) \right] \quad (46)$$

The applicable values of ΔT_1 in equation (46) can easily be obtained from a plot of $\Delta T_1(t)$ and $\Delta T_1(t-t_c)$ versus t . If ΔT_1 changes at a constant rate for a period longer than t_c , during a part of that period the following relationship can be used.

$$\frac{1}{t_c} [\Delta T_1(t) - \Delta T_1(t-t_c)] = \left[\frac{\partial \Delta T_1}{\partial t} \right]_c \quad (47)$$

For "complete-mixing" in core

$$\Delta T_2(t) = \Delta T(t) \quad (48)$$

$$\frac{d\Delta T}{dt} = \frac{1}{t_c} [\Delta T_1(t) - \Delta T(t)] \quad (49)$$

$$\Delta T(t) = \frac{1}{t_c} e^{-t/t_c} \int \Delta T_1(t) e^{t/t_c} dt \quad (50)$$

Equation (50) can be integrated graphically and $d\Delta T/dt$ then obtained from a plot of ΔT_1 and ΔT versus t .

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2. Kasten, P. R., "Homogeneous Reactor Safety", ORNL-CF-55-5-51, May 9, 1955.
3. Dorsey, N. E., "Properties of Ordinary Water-Substance", Reinhold Publishing Corporation, New York, 1940, Table 247.

NOMENCLATURE AND PARAMETER VALUES

A_r	Cross-sectional area of relief pipe leading from core to pressurizer, 2.3 sq. ft.
b	Rate of reactivity addition, sec^{-1} .
C_2	Dimensionless reactor parameter defined in Equation (9), 0.057.
c_p	Specific heat of fuel solution, $1.28 \text{ Btu/lb-}^\circ\text{F} = 2.43 \times 10^{-3} \text{ Mw - sec/lb-}^\circ\text{C}$.
F	Dimensionless reactor parameter defined in Equation (10).
g_c	Conversion factor, $32.2 \text{ lb. mass-ft/lb. force - sec}^2$.
K_1	Dimensional heat exchanger design parameter defined in Equation (19) and evaluated using Equation (41), 0.81 sec^{-1} .
K_2	Rate of change in boiling temperature on shell-side of heat exchanger, $\partial T_b / \partial t$.
k_e	Multiplication constant for a finite reactor; neutrons produced in one generation per neutron produced in preceding generation.
L	Length of heat exchanger tube.
L_r	Axial distance between reactor core and surface of liquid in pressurizer, 12 ft.
m_e	Equivalent prompt reactivity addition divided by the mean lifetime of prompt neutrons, sec^{-1} .
P_o	Initial fission power of reactor, kw.
P_{pc}	Power evaluated when the reactor is prompt critical, kw.
p_o	Initial pressure in pressurizer.
S	Total cross-sectional area of flow passages through heat exchanger.
S_c	Reciprocal heat capacity of reactor core, $2.12 \times 10^{-4} \text{ }^\circ\text{F/Btu} = 1.12 \times 10^{-4} \text{ }^\circ\text{C/kw - sec}$.
S_e	Source strength, $10^7 \text{ neutrons/sec}$.
T	Means temperature of reactor core; $T(o) = 280^\circ\text{C}$.

T_b	Boiling temperature on shell side of heat exchanger; $T_b(0) = 280^\circ\text{C}$; $T_b(t_b) = 100^\circ\text{C}$.
T_h	Bulk temperature of fuel solution in passage through heat exchanger; $T_h(0) = 280^\circ\text{C}$.
T_1	Temperature of fuel solution entering reactor core; $T_1(0) = 280^\circ\text{C}$.
T_2	Temperature of fuel solution leaving reactor core; $T_2(0) = 280^\circ\text{C}$.
t	Time after beginning of an event, sec.
t_b	Time required for T_b to fall to 100°C , sec.
t_c	Mean residence time of fuel solution in reactor core, 1.17 sec.
t_h	Time required for passage of fuel solution through heat exchanger, $L/U = 1.36$ sec.
U	Mean velocity of fuel solution in passage through heat exchanger.
U_{ht}	Overall heat-transfer coefficient in heat exchanger based on inside tube diameter.
U_o	Mean velocity of solution leaving reactor exit under normal conditions, 22 ft/sec.
V_c	Volume of reactor core, 65 cu. ft.
V_v	Vapor volume in pressurizer, 1,000 l. = 35 cu. ft.
v_s	Velocity of sound in core fuel solution, 2,300 ft/sec.
W	Mass flow rate of fuel solution under normal conditions.
x_{pc}	P_{pc}/P_o , reactor power at prompt critical relative to initial power.
z	Total perimeter of all passages through heat exchanger, based on inside tube surface.
α_1	Normalized friction coefficient defined by Equation (8), 5.4 sec ⁻¹ .
$\bar{\beta}$	Effective fraction of neutrons that are delayed (the delayed neutrons whose precursors decay in the reactor core).

- γ_2 Dimensional reactor parameter defined by Equation (6), $0.016 \text{ in}^2 / \text{sec} \cdot \text{lb}_M$.
- γ_3 Dimensional reactor parameter defined by Equation (7), 785 sec^{-2} .
- Δp_{max} Maximum rise in core pressure during a reactor power excursion, psi.
- ΔT $T(t) - T(0)$, change in mean core temperature from initial condition.
- ΔT_b $T_b(t) - T_b(0)$, change in boiling temperature from initial condition.
- ΔT_h $T_h(t) - T_b(0)$, difference between bulk solution temperature in heat exchanger and initial boiling temperature.
- ΔT_1 $T_1(t) - T_1(0)$, change in temperature of solution entering core from initial condition.
- ΔT_2 $T_2(t) - T_2(0)$, change in temperature of solution leaving core from initial condition.
- δ_{sc} $1 - k_e$, amount reactor is subcritical initially, taken as 1.0.
- $\partial k_e / \partial T$ Temperature coefficient of reactivity, $-1.5 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$.
- $\partial k_e / \partial \rho$ Density coefficient of reactivity, 0.014 cu.ft/lb.
- η_f Dimensionless friction parameter equal to number of velocity heads dissipated between core and pressurizer, 3.0.
- θ Time at which solution enters region of heat exchange, sec.
- ξ b/τ_1 , dimensional parameter representing rate of reactivity addition, sec^{-2} .
- ρ Density of fuel solution.
- τ_1 Mean lifetime of prompt neutrons, $7.7 \times 10^{-4} \text{ sec.}$
- ω_h^2 Dimensional reactor parameter defined by Equation (5) (square of hydraulic frequency), $15,600 \text{ sec}^{-2}$.
- ω_n^2 Dimensional reactor parameter defined by Equation (14) (square of nuclear frequency).
- ω_{np}^2 $x_{pc} \omega_n^2$, modified nuclear frequency, sec^{-2} .

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