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SUBJECT: Power Response Following Reactivity Additions in HRT

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ABSTRACT

Calculations have been performed relating the magnitude of an HRT power excursion to an instantaneous addition of reactivity (up to $1\% \Delta k_e$). Five delayed neutron groups as well as separate heat balances over the core and blanket were accounted for in the calculation.

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SUMMARY OF RESULTS

Following a given reactivity addition (up to $1\% \Delta k_e$), the ratio of maximum to initial powers decreases with increasing initial power level. However, the maximum power level attained increases with increasing initial power. Table 1 shows the result of adding 0.3% of reactivity to the reactor when operating at initial powers of 0.25 and 3.0 Mw.

Table 1

Power Rise Associated with 0.3% Reactivity Addition

Initial Reactor Power, Mw	0.25	3.0
Reactivity Addition, %	0.3	0.3
Ratio of Maximum to Initial Power	3.0	1.8
Maximum Power Level, Mw	0.75	5.4
Time to Maximum Power, sec	~ 6.0	~ 0.55

RESULTS

An addition of reactivity to the HRT causes a rapid increase in the power level which in turn increases the reactor temperature; because of the negative temperature coefficient of reactivity, the temperature rise causes the power to return to its initial value. The energy which is produced in the excursion (less that removed in the heat removal system) is just sufficient to increase the average reactor temperature so as to compensate for the added reactivity. Therefore, the maximum power level attained is dependent on the ratio of the temperature coefficient and the heat capacity of the system.

Figure 1 shows the ratio of maximum to initial powers for reactivity additions up to $1\% \Delta k_e$ with initial powers of 0.25, 1.0 and 3.0 Mw. Since the reactor fuel circulates, the effective heat capacity of the system depends on the time required to reach the maximum power level. For small reactivity additions and low initial power levels, the time required to reach the peak is of the same order as the core residence time, indicating that the heat capacity of the core circulating system ($\sim 500l$) is to be used. As the reactivity addition or the operating power is increased, the time needed to reach the peak power level is reduced to one second or less indicating that the proper heat capacity to use is that of the core only ($\sim 290l$). In all cases, the time required to reach the peak is small compared to the blanket residence time; therefore, the heat capacity of the blanket ($\sim 1550l$) was used.

Fig. 1. Peak Power in the HRT

PROCEDURE

Writing a neutron balance over the reactor:

$$\frac{dN}{dt} = (k-1) \frac{N}{\ell} - k \beta \frac{N}{\ell} + \sum_i \lambda_i c_i \quad (1)$$

For a given fuel loading the neutron population (N) is directly proportional to the reactor power (P); therefore eq. 1 can be written as:

$$\frac{dP}{dt} = (k-1) \frac{P}{\ell} - k \beta \frac{P}{\ell} + \sum_i \lambda_i c_i' \quad (2)$$

For an instantaneous addition of reactivity (δ), the multiplication constant (k) can be written as

$$k = \begin{cases} 1.0 & \text{at } t < 0 \\ 1.0 + \delta + \left. \frac{\partial k}{\partial T} \right|_C \Delta T_C + \left. \frac{\partial k}{\partial T} \right|_B \Delta T_B & \text{at } t \geq 0 \end{cases} \quad (3)$$

Making the approximation $k\beta \simeq \beta$ and substituting eq. 3 into eq. 2 gives:

$$\frac{dP}{dt} = \left[\delta - \beta + \left. \frac{\partial k}{\partial T} \right|_C \Delta T_C + \left. \frac{\partial k}{\partial T} \right|_B \Delta T_B \right] \frac{P}{\ell} + \sum_i \lambda_i c_i' \quad (4)$$

Writing a balance over the i_{th} delayed neutron precursor and using effective yields as given by Kasten⁽¹⁾

$$\frac{dc_i}{dt} = -\lambda_i c_i + k \beta_i \frac{N}{\ell} \quad (5)$$

Again replacing the neutron population by the power and using the approximation of $k \beta_i \simeq \beta_i$, eq. 5 becomes:

$$\frac{dc_i'}{dt} = -\lambda_i c_i' + \beta_i \frac{P}{\ell} \quad (6)$$

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(1) P. R. Kasten, "Dynamics of the HRT," ORNL-2072, June 7, 1956.

Writing heat balances around the core and blanket and assuming constant heat removal from each region:

$$S_C \frac{dT_C}{dt} = R (P - P_O) \quad (7)$$

$$S_B \frac{dT_B}{dt} = (1-R) (P - P_O) \quad (8)$$

Dividing eqs. 4, 6, 7, and 8 by P_O and defining

$$X \equiv P/P_O$$

and

$$D_i \equiv C'_i/P_O$$

the equations reduce to

$$\frac{dx}{dt} = \left[\delta - \beta + \frac{\partial k}{\partial T} \Big|_C \Delta T_C + \frac{\partial k}{\partial T} \Big|_B \Delta T_B \right] \frac{x}{\ell} + \sum_i \lambda_i D_i \quad (9)$$

$$\frac{d D_i}{dt} = - \lambda_i D_i + \frac{\beta_i}{\ell} X \quad (10)$$

$$\frac{S_C}{P_O} \frac{dT_C}{dt} = R(X-1) \quad (11)$$

$$\frac{S_B}{P_O} \frac{dT_B}{dt} = (1-R)(X-1) \quad (12)$$

If we add the last eqs. (11) and (12) and make the following definitions:

$$\omega_C^2 \equiv \frac{1}{\ell} \frac{dk}{dT} \Big|_C \frac{P_O}{S_C}$$

$$\omega_B^2 \equiv \frac{1}{\ell} \frac{dk}{dT} \Big|_B \frac{P_O}{S_B}$$

$$Y_C \equiv \frac{S_C}{P_O} \left(T_C - T_C(o) \right)$$

$$Y_B \equiv \frac{S_B}{P_O} \left(T_B - T_B(o) \right)$$

$$Y \equiv Y_C + \frac{\omega_B^2}{\omega_C^2} Y_B$$

Equations 9, 10, 11, and 12 reduce to

$$\frac{dx}{dt} = \frac{\delta - \beta}{\ell} X + \omega_C^2 YX + \sum_i \lambda_i D_i$$

$$\frac{dD_i}{dt} + \lambda_i D_i = \frac{\beta_i}{\ell} X$$

$$\frac{dY}{dt} = (X-1) \left[R + (1-R) \frac{\omega_B^2}{\omega_C^2} \right]$$

This system of seven, simultaneous, nonlinear, differential equations (five delayed neutron groups were used) was coded for the IBM-704 computer. The routine starts with the steady-state values of X, Y, and D_i and computes their values at later times as:

$$Z(t + \Delta t) = Z(t) + \left. \frac{dZ}{dt} \right|_t \Delta t$$

The values of $X(t)$, $Y(t)$ and $\int_0^t X(t)dt$ are labeled variable 1, 2, and 3, respectively, and are printed out versus time.

APPENDIX

Initial Conditions

$X(o)$	1.0
$Y(o)$	0
$D_1(o)$	23.42
$D_2(o)$	60.19
$D_3(o)$	16.10
$D_4(o)$	6.871
$D_5(o)$	0.7348

Reactor Constants

R	0.60
$\ell^{(2)}$	$7 \times 10^{-4} \text{ sec}$
$\left. \frac{dk}{dT} \right _C^{(2)}$	$- 1.21 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$
$\left. \frac{dk}{dT} \right _B^{(2)}$	$- 1.5 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$
$S_C \text{ (core only)}$	$1259 \frac{\text{kw-sec}}{^\circ\text{C}}$
$S_C \text{ (core circulating system)}$	$2170 \frac{\text{kw-sec}}{^\circ\text{C}}$
S_B	$6720 \frac{\text{kw-sec}}{^\circ\text{C}}$

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(2) P. R. Kasten, "HRT Operation with the Blanket Pressurizer Completely Filled," HRP No. 58-318, August 5, 1958.

Delayed Neutron Precursor Constants

i	$\lambda_i (\text{sec}^{-1})$	$\beta_i (\text{effective})$	$\beta_i (\text{static})$
1	0.0122	0.0002	0.00025
2	0.0315	0.001327	0.00166
3	0.154	0.001736	0.00213
4	0.456	0.002193	0.00241
5	1.61	<u>0.000828</u>	<u>0.00085</u>
		0.006284	0.0073

NOMENCLATURE

C_i	Population of i_{th} delayed neutron precursor
C'_i	Latent power associated with i_{th} delayed neutron precursor
N	Neutron population
P	Reactor Power
R	Fraction of reactor power produced in core
S	Heat capacity
T	Temperature
k	Effective multiplication constant
ℓ	Neutron lifetime
t	Time
β	Effective delayed neutron fraction
β_i	Effective delayed neutron fraction of i_{th} group
λ	Decay constant of the i_{th} delayed neutron precursor
δ	Quantity of reactivity added

Subscripts

C	Refers to core
B	Refers to blanket
i	Refers to i_{th} delayed neutron group

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