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The Effect of Xenon on Safety of the HFBR*[†]

by

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The Effect of Xenon on Safety of the HFBR

I am sorry to report that the senior author is unable to be here today to present this paper in person. He is still hobbling around from a skiing accident last winter. In his absence, the junior author will have to do the best job he can with the material.

As you have probably read, Brookhaven's High Flux Beam Reactor was taken critical on October 31, 1965 and reached its design power level early this year. After completing its first fuel cycle, (or more correctly its first fuel half-cycle, since a two step fuel shuffling scheme is involved), its official dedication was held at Brookhaven on April 22nd of this year.

A brief description of the HFBR is that it is an under-moderated, high power density research reactor with a flux level of 10^{15} neutrons/cm²-sec with heavily loaded fuel elements of the MTR-ETR type which is cooled, reflected and moderated by high velocity D₂O. The core is a cylinder of only 88 liters from which we get out 40 MW, set in a 7-foot sphere of heavy water which acts as its external moderator. The design spatially separates the thermal and resonance components of the neutron flux to enhance the value of the reactor as a high flux research tool. It is also externally controlled.

The work which we shall report on today is only a small part of a long study of HFBR dynamics, the bulk of which was carried out by members of the Project Staff. The HFBR has a number of inherent safety features, the long neutron generation time typical of heavy water moderated reactors and strong, negative core and reflector temperature and void coefficients. On the other hand, the HFBR can gain considerable reactivity if (1) the fuel could somehow be uniformly dispersed through the core and reflector or (2) the heavy water could be replaced by ordinary water or even (3) if some fuel were removed from the core in such a way as to produce an optimum reactivity configuration.

The studies of HFBR reactor transients have generally indicated that the simple lumped parameter or "point" reactor model with conduction type temperature delays is generally satisfactory. A somewhat better model is the so-called "line" model which assumes slug flow of coolant through the reactor core and reflector and thus includes coolant transport delays. As was discussed in yesterday's session on reactor dynamics, convective effects are unstabilizing and we were interested in finding out if they might be serious in the HFBR. The equations describing the system are shown in the first figure.

Figure 1

I will allow only a brief glance at this elaborate set of equations since they will be familiar to specialists as the so-called line or slug flow model of reactor dynamics. The effect of xenon and of the fuel, core coolant and reflector

temperature coefficients are taken into account and the fuel heat transfer coefficient is taken as proportional to the 0.8 power of the coolant velocity. Although we have emphasized the reduced importance of xenon in the HFBR as against thermal reactors, it is still quite important.

Figure 2

This figure shows the transfer function of the reactor. It may be noted that at low flow rates, the transport delay through the reflector results in a number of small amplitude resonances. However, at the full flow rate of 35 ft/sec the core transit time is only 1/20 of a second and the transfer function of the reactor becomes the same as that of a point reactor with conduction delays. The adequacy of the transfer function as a guide to actual amplitudes encountered during transients is shown in the next figure.

Figure 3

The results shown here were obtained by solving the partial differential equations after initiation of an imposed reactivity oscillation at full power. The solid lines represent the linearized model, the squares represent the amplitude of the first oscillation in the nonlinear model and the circles, if any, the minimum amplitude of the response of the nonlinear model.

Because of the small size of the HFBR, compared to the large migration area typical of heavy water reactors, spatial xenon oscillations do not occur even at high power levels. However, the HFBR is unstable to xenon burnup in its fundamental mode and hence even small reactivity perturbations give rise to

an eventual increase in power.

Figure 4

This figure shows the slow upward drift in power corresponding to a 5¢ reactivity oscillation. The effect of xenon burnup becomes quite serious when one considers more severe reactivity perturbations such as short time ramp reactivity increases as is shown in the next figure.

Figure 5

The final figure shows the response of the reactor to a one second reactivity ramp at full power. On the 80¢ ramp, a peak is seen in the curve at short times when the negative reflector coefficient starts to dominate the increase in neutron yield from short-lived delayed neutron emitters. As the longer lived delayed neutron emitters come into equilibrium, the power rises again and this trend is enhanced by xenon burnup. Neglect of xenon can therefore lead to a serious underestimate of the rapidity with which the power can rise.

Fig. 1: Model Description

The mathematical equations which comprise the HFBR slug flow model are the following:

$$\text{Core: } \dot{P} = \frac{\beta}{\ell} \left[\delta_T - 1 - \alpha_f \bar{T}_f - \alpha_C \bar{T}_C - \alpha_R \bar{T}_R + \delta_X (X(0) - X)P + \sum a_i C_i \right]$$

$$\dot{C}_i = \lambda_i (P - C_i)$$

$$\bar{T}_f = \frac{P}{\epsilon} - \frac{H_f}{\epsilon} (\bar{T}_f - \bar{T}_C)$$

$$\frac{\partial T_C}{\partial t} + v_C \frac{\partial T_C}{\partial X} = \frac{H_f}{H_C} (\bar{T}_f - \bar{T}_C)$$

$$H_f = \left[H_{fo} + C_f (\bar{T}_f - \bar{T}_{fo}) \right] \left(\frac{.05}{t_C} \right)^{.8}$$

$$\bar{T}_C(t) = \frac{1}{h_C} \int_0^{h_C} T_C(X, t) dX$$

$$\dot{I} = \lambda_I (P - I)$$

$$\dot{X} + \lambda_X X = A(Y_X P + Y_I I - XP)$$

$$X(0) = AP_0 / (\lambda_X + AP_0)$$

$$\text{Reflector: } \frac{\partial T_R}{\partial t} + v_R \frac{\partial T_R}{\partial X} = 0$$

$$T_R(0, t) = T_C(h_C, t)$$

$$\bar{T}_R = \frac{1}{h_R} \int_0^{h_R} T_R(X, t) dX$$

TRANSFER FUNCTION AT 40MW FOR VARIOUS
CORE TRANSIT TIMES

FIGURE 2

FIGURE 3

FIGURE 4

RESPONSE OF HFBR AT POWER TO ONE SECOND
REACTIVITY RAMP

FIGURE 5