MASTER

A METHOD OF ESTIMATING
THE KINETIC EFFECTS OF SCRAM RODS

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SUMMARY

A simple algebraic equation is extrapolated from the space independent kinetics equations to describe reactor power as a function of time during a power reduction. This equation,

$$\frac{n}{n_0} = \frac{1}{1 - \frac{\rho(t)}{\beta}},$$

necessitates an approximate knowledge of the reactivity-time function causing the power reduction.

As proof of this method a comparison was made to an ETR scram. The calculated power was within 3% of the actual measured power which is sufficient for safety purposes.

Most high power reactors have several modes of power reduction, which must, for safety reasons, meet certain minimum power-time specifications. The equation developed in this report can be used to verify that the actual scram transients are within the minimum specifications.

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I. Introduction

Evaluation of ETR scram transients has resulted in an approximation method where the transient can be calculated using conventional algebraic equations. The error, within the stipulated limits, of the power calculated by the approximation differs by less than 3% from the power as calculated by the normal reactor kinetics equations. The following is a description of this approximation and an actual comparison to experimental data from the ETR.

II. Kinetic Solution

The basic space independent kinetics equations are

$$\frac{dn}{dt} = \frac{k(t)(1-\beta) - 1}{\ell} n + \sum \lambda_i C_i \quad (1)$$

$$\frac{dC_i}{dt} = \frac{k(t)\beta_i}{\ell} n - \lambda_i C_i, \quad i = 1, 2, \dots, 6 \quad (2)$$

where n represents neutron concentration, β is the delayed neutron fraction from the emitters, C_i , whose decay constants are λ_i , ℓ is the mean neutron lifetime, and $k(t)$ is the neutron multiplication factor.

These equations can be solved on the Electronic Differential Analyzer if $k(t)$ can be generated, although when this work was performed only a power series for $k(t)$ could be generated on the Analyzer (as used here this means a step, ramp, or accelerated reactivity input).

An approximation to these equations was deduced from the one delayed group - step reactivity solution. The step solution is

$$\frac{n}{n_0} = \frac{\beta}{\beta - \rho} e^{\frac{\bar{\lambda} \rho}{\beta - \rho} t} - \frac{\rho}{\beta - \rho} e^{-\frac{(\beta - \rho)}{\ell} t}, \quad (3)$$

where $\bar{\lambda}$ is a weighted mean decay constant. This equation predicts the overall magnitude of the prompt drop fairly well, but is applicable only for step reactivities. That is, the prompt drop from equation (3) is

$$\frac{n}{n_0} = \frac{\beta}{\beta - \rho}. \quad (4)$$

To calculate the transient produced by a time dependent reactivity it was postulated that ρ could be replaced by $\rho(t)$ in the prompt drop equation. Thus,

$$\frac{n}{n_0} = \frac{1}{1 - \frac{\rho(t)}{\beta}}. \quad (5)$$

The restraints on equation (5) are $\rho_{\max} > \beta$, t must be small, and $\rho(t)$ cannot be a constant. In the rod drop case, it is obvious that after the rods are completely inserted (i.e. $\rho(t)$ becomes $\rho_{\max}$), equation (5) becomes invalid.

These assumptions and the accuracy of the solution compared to the actual 6 group theory would be very difficult to prove mathematically. The accuracy of equation (5) was determined by a direct comparison to known solutions of the exact equations (1) and (2). This was done analytically by using the Electronic Differential Analyzer where known functions of reactivity were used to calculate short time transients. The schematic diagrams and scaling for the EDA are shown in Fig. 1. A point wise comparison of the power as calculated by these two methods differed by less than 3% for ramp and accelerated reactivity inputs. This small error is applicable only when large negative reactivities are inserted within a time that is small in comparison to the mean delayed neutron half-life. For this study, the smallest reactivity used is 1% and solutions are limited to less than 0.250 sec.

As additional experimental proof of this method, an actual ETR scram transient using a rod worth $\sim 3\%$ was compared to the above equation.

FIG. 1
EDA DIAGRAM

Figure 2 is a reproduction of the experimental transient, biased 65 milliseconds, compared to the transient obtained by hand computations. The recorded signal $t = 0$ of the experimental transient actually began when a scram signal was generated in the reactor control system. The subsequent shim rod release occurred a short time later due to the delays inherent in relay switching and magnetic release mechanisms. The delay in this case was approximately 65 milliseconds, which is reasonable for a manual scram. The time scale in Fig. 2 begins where the actual rod drop starts.

For the calculated curve, reactivity is assumed to be¹

$$\rho = \rho_m \left[\frac{x}{x_m} - \frac{\sin 2\pi \frac{x}{x_m}}{2\pi} \right] \quad (6)$$

and

$$x = \frac{3g}{2} t^2, \quad (7)$$

where x is the shim rod position, ρ_m is the maximum worth of the rod, and the acceleration is $3g$.

The long delay (~ 60 milliseconds) before any appreciable power reduction occurs is due to zero initial condition on both the rod position and velocity. In a gravity-water pressure system the rod must start with zero velocity. With scram rods completely withdrawn it takes a considerable length of time after the rod is released before any detectable reactivity is introduced. This time can be reduced by operating with the scram rods partially inserted.

The last portion of Fig. 2 from 175 to 200 milliseconds shows the basic error of equation (5). This equation shows that the reactivity and thus the power level becomes constant when the rod is completely inserted at 250 milliseconds. At this point the calculated curve has a slope of zero when in the actual case the slope should be somewhat negative and after a long time it should approach the familiar - 80 sec period.

1. Murray, R. L., Nuclear Reactor Physics, Prentice Hall, 1957.

FIG. 2
COMPARISON OF MEASURED AND CALCULATED ETR SCRAMS

FIG. 3
CALCULATED ETR SCRAM TRANSIENTS

FIG. 4
ENERGY RELEASE vs. ROD WORTH FOR ETR CALCULATED SCRAMS

III. ETR Rod Drop Case

It is common to use one of 2 rods in the ETR for a junior scram (No. 13 worth $\sim -2\%$ and No. 10 worth $\sim -3\%$). The choice between the rods will depend on which one is not in use in the reactor servo system. The problem encountered through this choice is whether the 2% rod will provide adequate protection when dropped on a junior scram signal. This was answered by calculating a set of transients using equation (5) with ρ_m as the parameter.

Combining (5) thru (7) yields

$$\frac{n}{n_0} = \frac{1}{1 - \frac{\rho_m}{\beta} \left[\frac{3g t^2}{2x_m} - \sin\left(\frac{3\pi g t^2}{x_m}\right) \right]}, \quad t < \frac{1}{4} \text{ sec.} \quad (8)$$

where $|\rho_m| > 1\%$ (ρ_m is negative), $x_m = 3$ ft, $x(0) = 0$, $\dot{x}(0) = 0$, $\beta = 0.00755$, and $g = 32.2$ ft/sec². The limit, $t < \frac{1}{4}$ sec, is imposed since the scram rod is completely inserted at that time.

Figure 3 shows a set of calculated power-time curves with $\rho_{\max}$ as the parameter. The largest effect on the power level is produced by relatively small reactivities of 1% and 2% . As the reactivity of the scram rod is increased in 1% increments, the transients become closer together with the result that there is no practical difference between a rod worth 9% compared to one worth 10% .

Figure 4 combines the parameter study of Fig. 3 into a single curve of energy release vs total rod worth where the scram acceleration and total drop distance remains constant. Basically, this curve gives the same information as Fig. 3, that is, the most important reductions of energy release during a scram is accomplished by a 1% to 2% rod. As can be seen from Fig. 4 the energy release for -2% insertion is ~ 31 Mw-sec and for -3% is ~ 27 Mw-sec. This energy difference is probably negligible for a junior scram. The difference in the "prompt drop", 28% for the $2\% \rho_{\max}$ and 20% for $3\% \rho_{\max}$, is also small on a practical scale. If the ETR were operating at normal power level of 175 Mw, the "prompt drop" would reduce the power to 49 and 35 Mw respectively.