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A Proposal for Criticality Control Measurements
Using Pulsed Neutron Methods

In response to a suggestion by E. P. Blizard, consideration has been given to the possibility that in certain types of processing or storage facilities handling enriched fissionable isotopes the pulsed neutron method can give a useful measure of the subcriticality of the system. The types of systems contemplated would be arbitrarily shaped and distributed containers holding aqueous solutions of fissionable isotopes. A cell containing processing tanks or columns plus associated piping would be a typical example.

If the neutron decay rate were measured at a time when only water is present in the system and at a time when a known fuel concentration is present, then subsequent measurements on the same geometrical assembly containing solutions of unknown concentrations would give a measure of its concentration and multiplication constant. Such a measurement might be undertaken if high γ levels indicate the possibility of excessive concentrations of fissionable material.

Preliminary Experiment

A preliminary experiment was performed at the BSR in which progressively more subcritical configurations of BSR-I fuel elements were assembled, and the multiplication constant was measured both by the conventional source-and-detector method and by the pulsed-neutron method.

Fig. 1 shows the successive configurations of BSR-I elements used in the experiment. The last configuration was a 3 x 5 array.

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THE OUTLINE REPRESENTS THE CRITICAL INITIAL BSR-I CONFIGURATION. THE ELEMENT MARKED "1" WAS REMOVED FOR THE FIRST SUBCRITICAL RUN. NEXT, "2" WAS ALSO REMOVED AND A SECOND RUN MADE, AND SO ON IN SEQUENCE.

Fig. 1.

Fig. 2 is a curve of the reciprocal count-rate measured in the usual way with a Po-Be neutron source and a fission chamber detector vs the decay constant, λ , obtained by the pulsed technique.

The fact that the points fall well on a straight line shows that in the range covered by the experiment ($k = 1$ to $k \approx .85$) the pulsed method is applicable and gives results consistent with those obtained by the sub-critical multiplication method.

No difficulty is anticipated in extending this technique to arbitrarily low multiplications in the case of an aqueous system of fixed geometry. Experimental verification, however, is difficult in the BSR where reductions in multiplication must be achieved by altering the geometry of a reflected system. Further tests using bare solution systems are therefore indicated.

A Method of Criticality Control in Systems Containing Only Solutions

For a system of arbitrarily shaped coupled containers filled with pure water we may write for the neutron decay constant, λ_0 ,

$$\lambda_0 = v \Sigma_a^{(1)} + D B^2 \quad (1)$$

where v is the mean neutron velocity; $\Sigma_a^{(1)}$ is the mean absorption cross section of the entire system; D is the diffusion coefficient in water; and B^2 the effective asymptotic buckling.¹

If we now introduce a known amount of a highly enriched fuel as dissolved material we have

$$\lambda = \lambda_0 + v \sigma_F N_F \left[\nu(1-\beta) \bar{P}(B^2) - (1 + \alpha) \right] \quad (2)$$

where σ_F is the macroscopic fission cross section of the fuel; N_F is the concentration of the fuel; ν is the mean number of neutrons emitted per fission; β is the delayed neutron fraction; $\bar{P}(B^2)$ is the probability that a fission neutron be thermalized in the system; and α is the ratio of nonfission absorption cross

Fig. 2. λ_{PULSE} vs. $(1/C)_{SOURCE}$ for Various BSR-I
Core Configurations.

section per fuel atom (including other atoms in the fuel molecule) to the fission cross section.²

For enriched systems we may assume $\bar{P}(B^2)$ to be independent of fuel concentration. Thus we may rewrite eq. (2) as

$$\lambda = \lambda_0 + N_F C \quad (3)$$

where
$$C = v \sigma_F \left[\nu(1-\beta) \bar{P}(B^2) - (1 + \alpha) \right]. \quad (4)$$

By making a pulsed measurement of the system with only water in it, λ_0 is obtained. Making a second measurement, with a known amount of fuel present, C is also obtained. At prompt critical, $\lambda = 0$, and thus from eq. (3) a linear extrapolation to prompt critical may be made. However an extrapolation to delayed critical is desirable as a criticality control method. The delayed critical point on the curve is determined as follows:

From eq. (4) we have

$$\bar{P}(B^2) = \frac{C + v \sigma_F (1 + \alpha)}{v \nu \sigma_F (1 - \beta)}. \quad (5)$$

Every term on the right side is a known quantity, and thus $\bar{P}(B^2)$ is determined. We now define a quantity C' , the parameter corresponding to C, if all neutrons were prompt:

$$C' = v \sigma_F \left[\nu \bar{P}(B^2) - (1 + \alpha) \right]. \quad (6)$$

If all neutrons were prompt, then at the fuel concentration corresponding to delayed critical, $N_F^{(d.c.)}$, λ would be zero and one would have

$$0 = \lambda_0 + N_F^{(d.c.)} C' \text{ or}$$

$$N_F^{(d.c.)} = - \lambda_0 / C'. \quad (7)$$

Substituting this into eq. (3) we find the decay constant at delayed critical, $\lambda_{d.c.}$, to be:

$$\lambda_{d.c.} = \lambda_0 + C \left(\frac{-\lambda_0}{C'} \right) = \lambda_0 \left(1 - \frac{C}{C'} \right). \quad (8)$$

It must be emphasized that the simple theory outlined here applies only where effectively uniform solutions are present. If varying concentrations or precipitates are present, then such a simple absolute calibration becomes impossible. However the decay constant would still be approaching 0 at prompt critical, though not linearly with concentration.

Fig. 3 illustrates the foregoing analysis schematically:

Fig. 3 - Diagram of λ vs N_F showing location of delayed critical point.

To summarize, a measurement is made on the system containing pure water, and another when the system contains a fuel solution of known concentration, N_p . From these measurements λ_0 and C are obtained using eq. (3). Then C' is calculated from equations (5) and (6), and finally eq. (8) gives the $\lambda = \lambda_{d.c.}$ at which the system will be delayed critical. How far from this point the system is may then be determined at any time by a measurement of λ and locating its position on the line of λ vs N_p .

The recent availability of relatively low cost, compact neutron sources adds to the attractiveness of this concept. It appears that further investigation of this method for criticality control seems advisable, and, in particular, a test with solutions of known concentrations is recommended.

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