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SUBJECT: HFIR Response to Void Swept into Flux Trap

TO: HFIR Distribution

FROM: R. S. Stone

ABSTRACT

Flux excursions in the HFIR and the response of its safety system have been examined for the situations arising from voids swept into the flux trap with the cooling water. It was found that by limiting the addition of void reactivity to $1.00 or less, temperature coefficients alone can handle the excursion without damage to the core.

Curves are given which show the safety system response necessary for larger additions of void reactivity.

DISCLAIMER

Introduction

The High Flux Isotope Reactor has a positive void coefficient in the central flux trap region, involving about 2-1/2 per cent in reactivity. Cooling water flows through this region with a velocity of 30 ft/sec, presenting the possibility of inserting a water-borne void worth several per cent of reactivity within approximately 25 milliseconds. The analysis described in this report was undertaken to determine how large such a void insertion could be before the reactor suffered a damaging transient, given various speeds of response of the safety system. The results could then be used to determine the best compromise between a fast safety system to cut an excursion short, and permanent displacement of part of the water in the flux trap, to limit the total reactivity which could be added by itinerant voids.

Method of Calculation

The HFIR system was simulated on the ORNL Reactor Controls Analog Facility with a 20:1 expanded time scale. The principal assumptions made in the model are detailed below.

a) Reactor kinetics

The conventional reactor kinetics equations were used, assuming a single-region, one-group reactor.

$$\ell\dot{\varphi} = (1-\beta)k\varphi - \varphi + \sum_{i=1}^{n} \ell\lambda_i X_i \qquad (1)$$

$$\ell\lambda_i\dot{X}_i = \beta_i\lambda_i k\varphi - \ell\lambda_i^2 X_i \qquad (2)$$

Here φ is power, and X_i is the potential power stored in delayed neutron precursors of type i.

The "neutron lifetime," ℓ, varies from 50μ seconds at startup to 100μ seconds in old age, the variation coming from the long neutron time constant of the Be reflector, which is increasingly exposed by the shim plates as burnup progresses.

Rather than use the nominal startup lifetime of 50μ seconds, which is an average of core lifetime and (water) reflector lifetime, the decision was made to use a lifetime of ℓ = 23μ seconds to represent the lifetime in the core itself,[1] and to create a seventh group of delayed neutrons,[2] with β_7 = 0.3000 (worth of the unreflected reactor is 70 per cent), and $\tau_7 = \frac{1}{\lambda_7}$ = 113μ seconds.[3]

For the fission product delayed neutron groups, $\sum_{i=1}^{6}\beta_i = 0.0064$.[4]
The 2 longest period groups were lumped together in the simulation.

b) Heat Transfer

Heat transfer equations were written for the flux trap, for the fuel region, and for the shim region, since each of these regions has an appreciable temperature coefficient. The fuel is the region to be watched for possible damaging temperatures.

Because the heat transfer coefficient within the metal sections is much higher than the corresponding oxide to water coefficient, the metal in each region is assumed to have the same temperature throughout.

The bulk water temperature in each region is also assumed to be uniform. Turbulent mixing should help to make this the case.

Using the fuel region as an example, the equations used were of the form

$$\dot{T}_{mf} = \frac{P_{mf}}{C_{mf}} - \frac{h_f A_f (T_{mf} - T_{wf})}{C_{mf}} \tag{3}$$

$$\dot{T}_{wf} = \frac{P_{wf}}{C_{wf}} + \frac{h_f A_f (T_{mf} - T_{wf})}{C_{wf}} - \frac{(T_{wf_2} - T_{wf_0})}{C_{wf}} \tag{4}$$

$$T_{of} = T_{mf} - \frac{h_f}{h_{of}} (T_{mf} - T_{wf}) \tag{5}$$

In these equations, the subscript "f" denotes a parameter from the fuel region.

T_{mf} = mean metal temperature

T_{wf} = bulk water temperature

T_{wf_0} = inlet water temperature = 120°F

T_{wf_2} = outlet water temperature $\simeq 2T_{wf} - T_{wf_0}$

T_{of} = oxide film temperature

A_f = heat transfer area between metal and water = 380 ft^2

h_f = over-all heat transfer coefficient between metal and water = $(h_{of}^{-1} + h_{wf}^{-1})^{-1}$.

h_{of} = oxide film heat transfer coefficient = 11.1 BTU/sec ft^2 °F.

h_{wf} = water film heat transfer coefficient
= $4287 + 39.00\, T_{wf} - 4.536 \times 10^{-2}\, T_{wf}^{2.5}$

Similar sets of equations were written for the flux trap and shim regions, except that in those locations the metal-water heat transfer coefficients were assumed constant. (Water temperature is less subject to change in those locations.)

c) Reactivity

With the reactor critical, and at design point power, reactivity additions of from 1/2 per cent to 2-1/2 per cent were ramped into the reactor in 25 milliseconds. In some runs these additions were left in the reactor at their maximum value, in other runs they were ramped out again in 25 milliseconds, to simulate a void which passes through. Other runs were made with step inputs.

The level safety was set to trip at 110 per cent of rated power, or at 110 Mw. After the trip, there was a variable time lag, followed by insertion of rods worth 10 per cent/foot at some acceleration between 1/6 g and 10 g. These lag times and accelerations were programmed to cover a wide range of possible safety systems. The situation where no safety action is taken was also simulated.

Temperature coefficients used[6] were + 1.04 x $10^{-4}/^{\circ}F$ for the flux trap, -1.71 x $10^{-4}/^{\circ}F$ for the fuel region, and + 3.12 x $10^{-5}/^{\circ}F$ for the shim region. Since these are primarily moderator temperature coefficients, all were tied to water temperatures in the regions concerned. The temperature coefficient in the reflector is very small (+ 8.3 x $10^{-6}/^{\circ}F$), and so was neglected.

The computer flow sheet is available as ORNL Drawing C-RC-204.

Results

Eighty-six separate excursions were examined, with variations in the reactivity addition, and in the time response of the safety system. Metal-oxide and oxide-water temperatures in the fuel region were monitored for each of these runs. Temperatures used in the simulation were mean temperatures, with the initial fuel region metal surface temperature, $T_{mf}(o)$ = 269.4°F, and the initial oxide surface temperature = 248.1°F.

For the metal, failure was presumed to occur when the metal temperature reached the melting point, taken to be 1100°F. This represents a temperature rise of 1100-270 = 830°F. If we assume the hot spot has twice the temperature rise of the mean, we must limit T_{mf} to 270 + 415 = 685°F.

For the oxide, failure was presumed to be imminent when its temperature reached the boiling point, taken to be 545° in the pressurized system.[7] This represents a temperature rise of 545-248 = 297°F, and if we assume the hot spot has twice the temperature rise of the mean, we must limit T_{of} to 248 + 149 $\simeq$ 400°F. This condition proved to be the most difficult to meet.

For each safety system response, and each type of reactivity insertion (a single ended step; a void ramping in at water velocity and sticking; and a void ramping in-and-out at water velocity), peak T_{mf} and T_{of} were measured for increasing values of Δk in the input. The Δk's were recorded where each T_{mf} curve crossed the 685^{o} mark, and where T_{of} crossed the 400^{o} mark, and these maximum allowable Δk's were then plotted vs safety system delay time for a family of safety rod accelerations, for each of the various input regimes. These sets of curves are shown in Figures 1 through 3.

Conclusions

From these curves it is apparent that no presently conceivable safety system could turn an excursion occasioned by the full 2-1/2 per cent void reactivity swept in at water velocity. Under the most optimistic conditions, i.e., neglecting the possibility of trouble from film boiling, it would seem imperative to permanently displace enough water in the reactor island to limit the possible void insertion to less than 2 per cent.

On the other hand, if this permanent displacement of island water is carried to the point where the maximum possible void coefficient insertion is around 0.75 per cent, the reactor will shut itself down from the maximum possible void coefficient accident without damage, and no safety system action is necessary.

The sacrifice in flux which must be made when island water is displaced, will to a large extent determine how far this displacement should be taken.

Consideration is currently being given to the idea of holding the maximum possible void reactivity increase to about $1.00.[8] Should this objective be carried through, the necessity for speed in the safety system would no longer be tied to the void insertion accident, but could be determined by startup speed requirements, cold slugging, or whatever other accident is determined to then present the greatest hazard.

Notes and References

1. If we calculate neutron lifetime on the basis of thermal absorption cross-section in the fuel, we find

$$\ell = \frac{1}{\Sigma a V} = \frac{1}{0.2024 \times 2.2 \times 10^5} \cong 23 \times 10^{-6} \text{ sec.}$$

2. D. L. Hetrick and D. P. Gamble; "Transient Reactivity During Power Excursions in a Water Boiler Reactor;" Transactions of the American Nuclear Society, 1-2, 48 (Dec., 1948).

3. The value of τ_7 = 113μ sec was chosen to satisfy the relation

$$0.70 \times 23\mu \text{ sec} + 0.30 \times \tau_7 = 50\mu \text{ sec},$$

where 50μ seconds is the required "average" lifetime at startup.

At the end of reactor life, τ_7 must = 280μ sec, so as to satisfy the relation

$$0.70 \times 23\mu \text{ sec} + 0.30 \times \tau_7 = 100\mu \text{ seconds}.$$

4. G. R. Keepin, T. R. Wimett, and R. K. Ziegler; "Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium, and Thorium;" Journal of Nuclear Energy 6, 1-21 (1958).

5. From formula fitted to experimental values of W. R. Gambill by R. D. Cheverton (Private communication).

6. Taken from curves prepared by R. D. Cheverton (Private communication).

7. This restriction was made because of the fear that should film boiling occur at a hot spot, heat transfer to the water would be cut off at that point, and local burnout take place.

8. HFIR meeting of July 20, 1960.

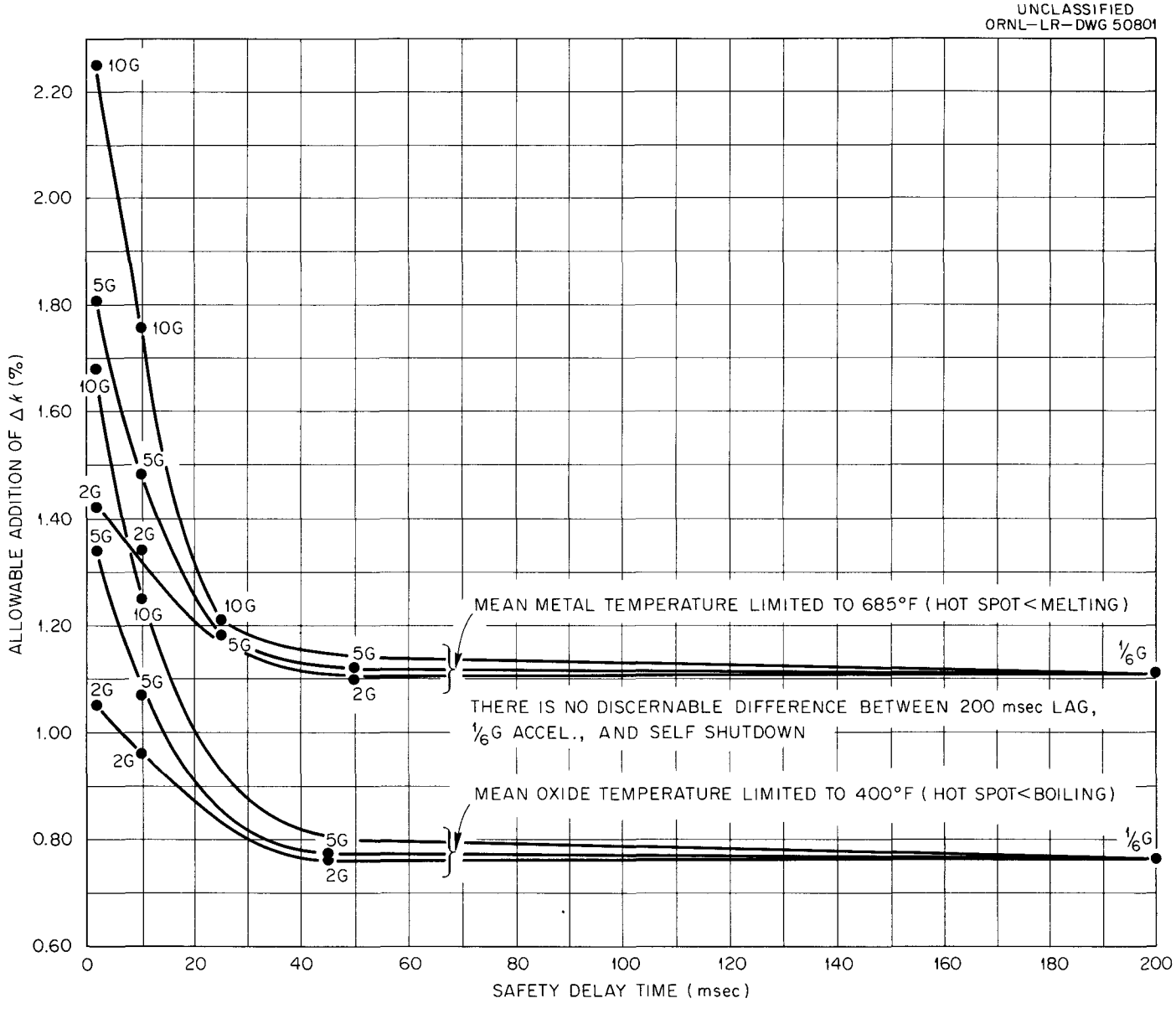

Fig. 1. Allowable addition of Δk in HFIR for Regime where Δk is Ramped in over 25 msec, and Remains in Core.

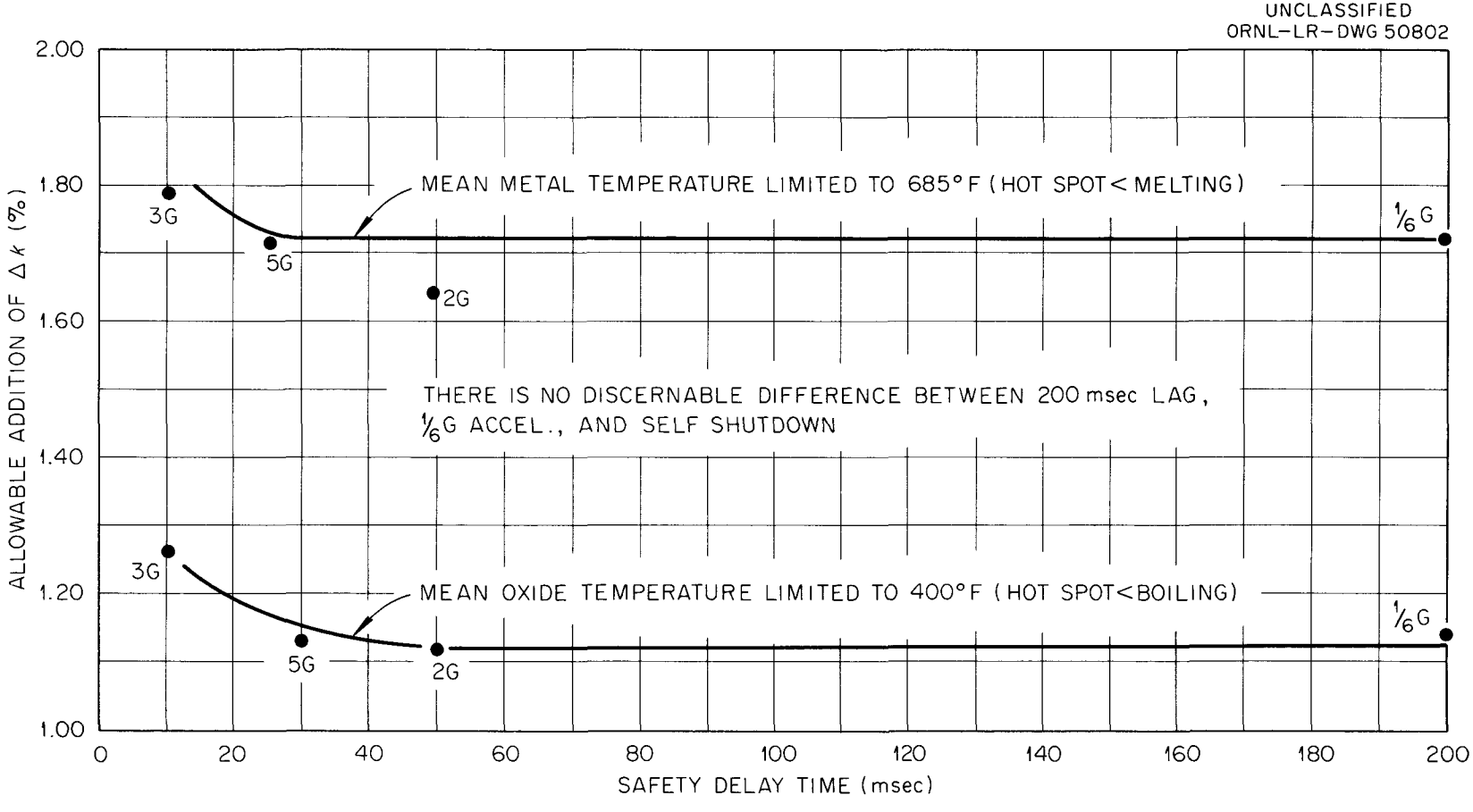

Fig. 2. Allowable Addition of Δk in HFIR for Regime where Δk is Ramped in over 25 msec, and Ramped out over the next 25 msec.

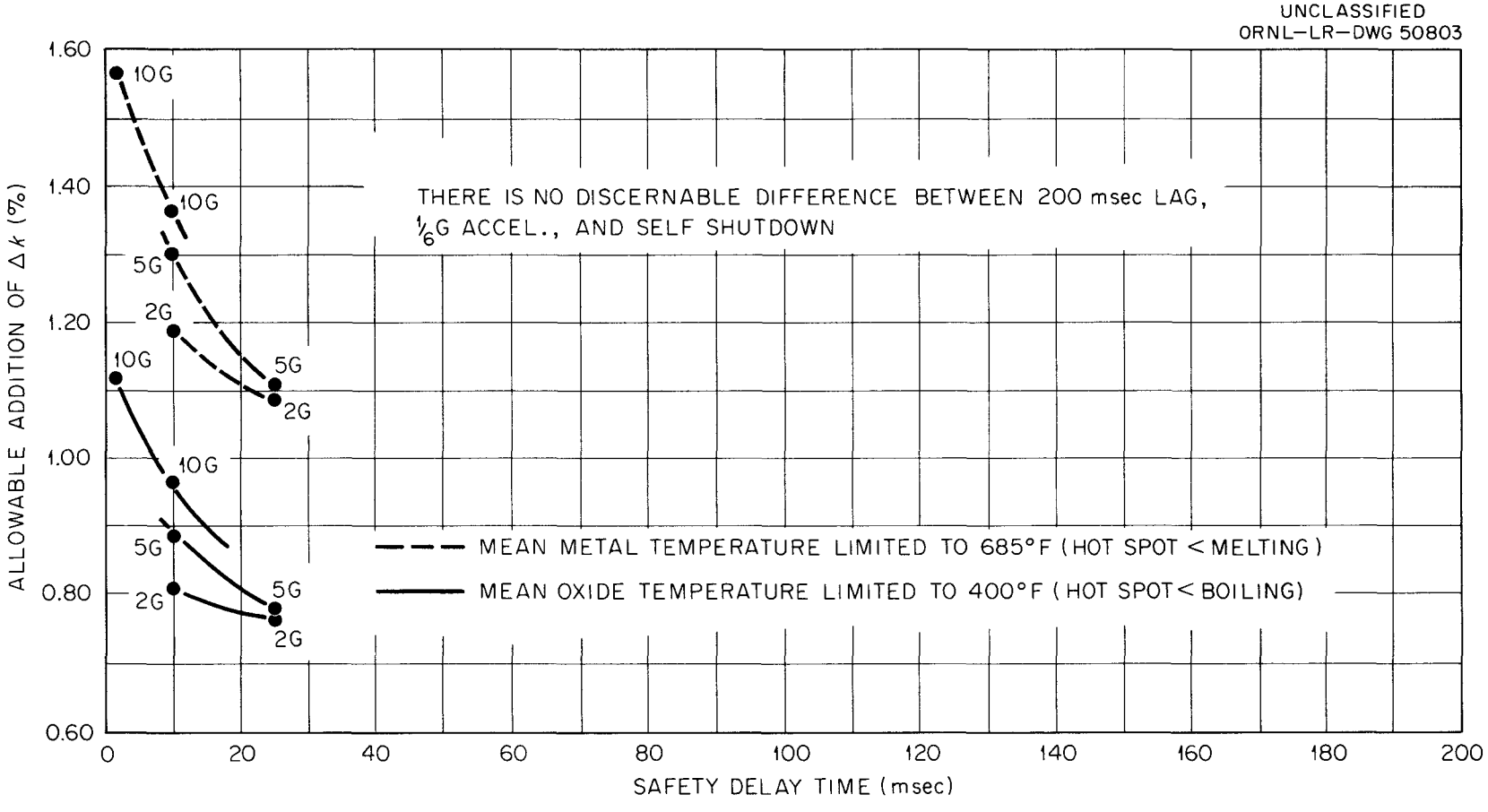

Fig. 3. Allowable Addition of Δk in HFIR for Regime where Δk is Stepped in, and Remains in Core.

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