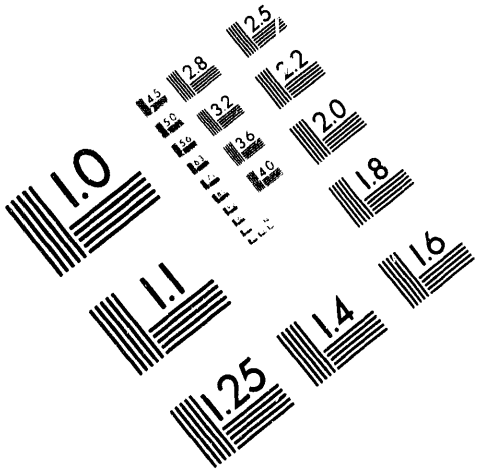

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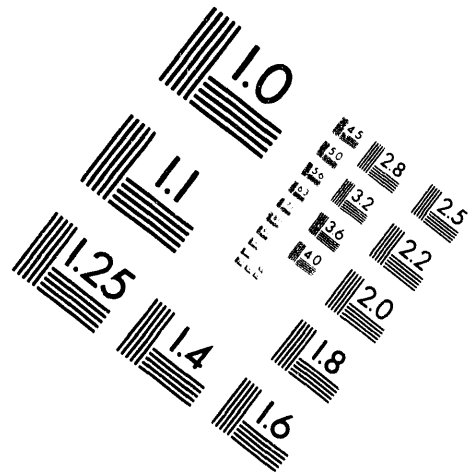

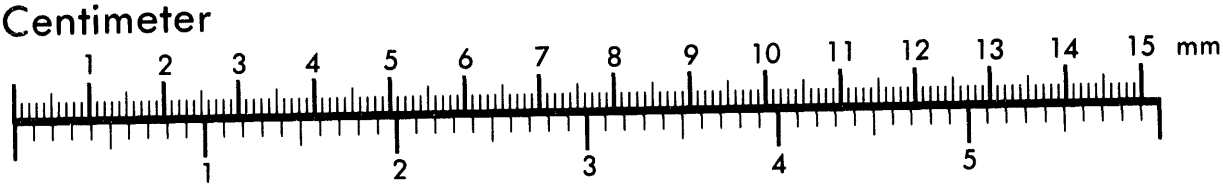

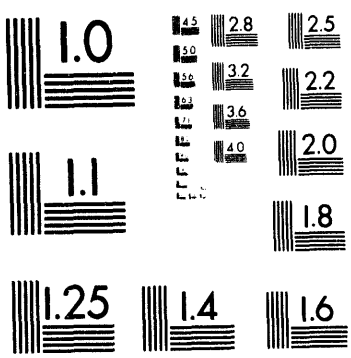

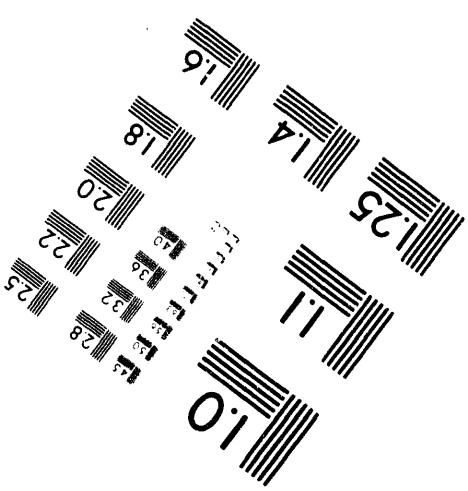

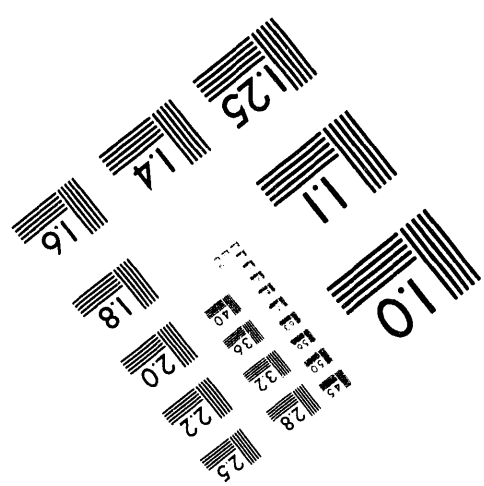

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Kinetics Of Accelerator Driven Devices

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Abstract. Kinetic calculations were made to show that subcritical accelerator driven devices are robust and stable. The calculations show that large changes in reactivity that would lead to an uncontrollable excursion in a reactor would lead only to a new power level in a subcritical device. Calculations were also made to show the rate of power changes resulting from startup and shutdown, and that methods also exist for continuously monitoring the reactivity of a subcritical system.

INTRODUCTION

Any device containing fissile material will be in one of four operating regimes: subcritical, critical, delayed critical, or prompt critical. Both delayed and prompt critical are referred to as "supercritical." In the absence of an external source, the power of a subcritical device always decreases. In a critical device, the power is constant. If a device is delayed critical, the power is increasing with the rate of increase limited by the time constants, on the order of minutes, that are associated with the delayed neutrons. A prompt critical device has time constants associated with the prompt neutron lifetime, which is on the order of milli- to microseconds. The time behavior of any of these devices can be approximated by the point reactor kinetics equations.

The point reactor kinetics equations are given below:

$$\begin{aligned} dn/dt &= ((\rho(t) - \beta) / \Lambda)\, n(t) + \sum \lambda_i C_i(t) + S, \\ dC_i/dt &= (\beta_i/\Lambda)\, n(t) - \lambda_i C_i(t), \\ \rho(t) &= (k(t) - 1) / k(t). \end{aligned} \tag{1}$$

where:

- $n(t)$ = neutron population as a function of time - note that it is proportional to power
- t = time
- β = fractional yield of delayed neutrons per fission neutron
- β_i = fractional yield of the ith group of delayed neutrons
- Λ = prompt neutron lifetime
- λ_i = decay constant of the ith group of delayed neutron group
- $C_i(t)$ = the concentration of the ith group of delayed neutron precursors as a function of time
- S = fixed source - here neutrons produced from the accelerator protons, and
- $k(t)$ = reactivity of the reactor as a function of time.

The neutrons born in a fissile material containing device will have two separate origins. The prompt neutrons are born of fission and comprise a fraction greater than 0.99, i.e. $(1-\beta)$, of these neutrons. The prompt neutron lifetime, Λ, refers to the time it takes from the neutrons birth to the fission resulting from its capture. The delayed neutrons are born from the decay of a fission fragment and appear seconds to minutes following the fission in which the fission fragment was born. Source neutrons from protons are independent of these prompt and delayed neutrons.

An examination of the kinetics equations delineates the various operating regimes. The prompt critical regimes occur when ρ is greater than β. The rate of change of power is positive independent of contributions from delayed neutrons. The time constant, Λ, is on the order of micro- to milliseconds. The doubling times are such that the reactor could not be controlled.

When ρ is positive, but less than β, the reactor is in the delayed critical regime, and the rate of change of power is positive only with contributions from the delayed neutron term with the time constants, $1/\lambda_i$, being on the order of seconds to minutes. The power doubling times are much longer, and the device is clearly controllable. The critical reactor is the regime where ρ is zero. Each fission will subsequently produce only one fission, thus the power is constant, i.e. $dn/dt=0$.

If the device is capable of maintaining constant power or increasing in power, without a external source of neutrons, it is a reactor. If the device requires a external source to maintain constant power, then it is referred to as a subcritical reactor. The reactivity, ρ, of a subcritical reactor is negative. Note that in the absence of a source, the power of a subcritical reactor decreases indefinitely with time constants $1/\lambda_i$. In the subcritical regime, the larger portion of a power change resulting from a change in the external source or a change in reactivity occur with the time constant, Λ, associated with the prompt neutrons. The delayed neutrons which follow, slowly increase the power slightly by adding a tail to the major power change.

The power of a subcritical reactor results from a multiplication of the neutrons from the external source, S. The source multiplication is described by the following equation:

$$M = 1/(1-k) \tag{2}$$

where:

M = multiplication factor
k = reactivity.

The power of a subcritical accelerator driven reactor then is determined by the reactivity of the device and the proton beam strength that produces the neutrons.

Thus, an important safety feature of accelerator driven devices is that they cannot undergo unlimited power excursions. The maximum power is limited to the subcritical multiplication of the source. In this paper we demonstrate this with our initial calculations describing the kinetic behavior of an accelerator driven device. Comparisons are also made between the power changes in a critical reactor and an accelerator driven device resulting from the same ramp input of reactivity.

It is important in accelerator driven devices to constantly monitor the reactivity of the system to ensure that it remains in the subcritical mode and to design the system in such a way that deposition or precipitation of fissile material does not lead to a supercritical system. Kinetic calculations are then made to demonstrate that the time rate of change of the power as a function of reactivity and source strengths give a clear indication of the reactivity the blanket (1).

Kinetic calculations are also made to describe the startup and shutdown of accelerator driven devices. These calculations show the rapid initial rise or drop in power followed by a slowly changing power level.

METHODS

A modified version of the kinetics code AIREK III [1] was used to make the calculations. Among the important input parameters to a kinetic codes are reactivity, prompt neutron lifetime, and the delayed neutron fraction. Note that parameters such as geometry, materials, or fissile enrichment are not included. Thus, a given set of input parameters could describe a large envelope of devices. The startup and shutdown cases used parameters consistent with a system containing fissile uranium. The remaining cases used parameters consistent with a blanket utilizing a ^{239}Pu containing salt, e.g., (65%LiF / 29%BeF_2 / 5%ZrF_4 / x%PuF_3) where percents

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1) George Lawrence, Los Alamos National Laboratory, suggested these calculations be made and that they could possibly provide a method for measuring the reactivity of subcritical devices.

are mole percent and "x" represents 1% or less. The Li is 99.99 a/o ^7Li.

Parameters were established as reasonable through a set of k calculations using one- and two-dimensional S_n transport codes in which subcritical devices with salt containing blankets were modeled. In these calculations, it was established that in highly thermal systems, small changes in Pu concentration lead to large changes in reactivity. For example, a change of 0.1 mole percent of Pu lead to a reactivity change of greater than 1$ (ρ / β = reactivity in units of dollars) in a blanket containing 5% salt and 95% carbon. These calculations indicate that in certain reactor systems, large accidental excursions are possible.

CALCULATIONS / RESULTS

The first calculations demonstrated a startup, shutdown, and steady state case for a subcritical device. These cases were run with β of 6.1e-03, Λ of 1.e-04 s, and initial k for the subcritical device of 0.95 The steady state subcritical reactor power is 3000 MW.

In Fig. 1, these startup, shutdown and steady state cases are shown. The shutdown occurs form turning off the source while the device is at steady state power. The startup occurs when the source is turned on when the device is at a low power level. The initial time rate of change of the power for startup or shutdown is related to the prompt neutron lifetime and the tail to the decay constants of the delayed neutrons.

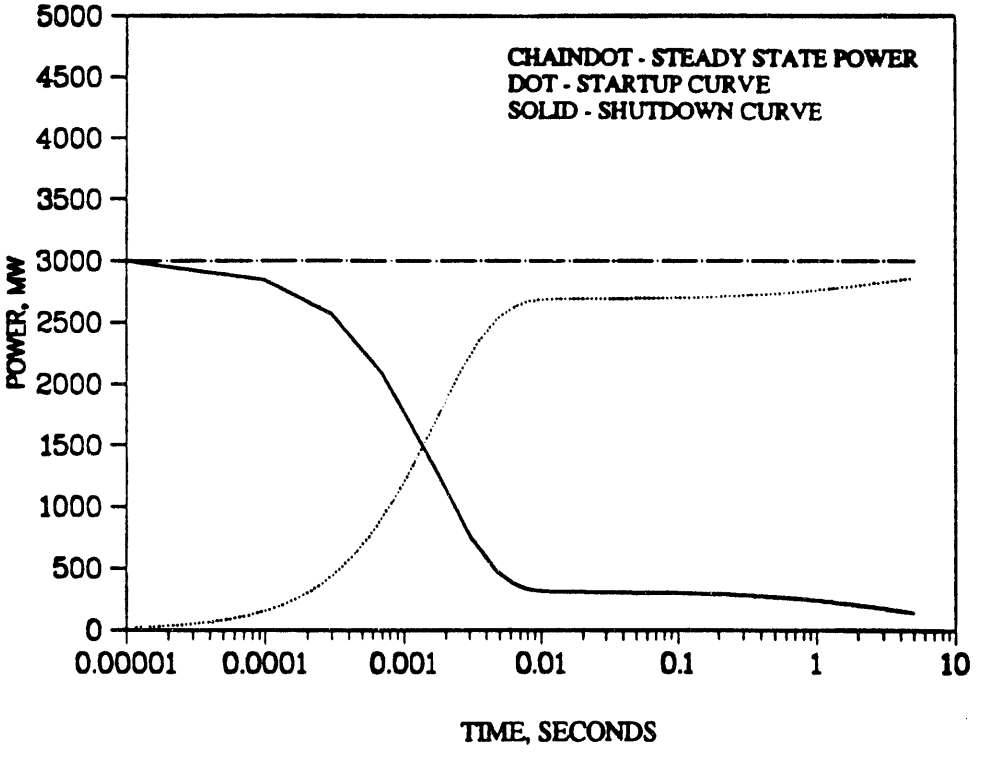

Fig. 1. Startup, Shutdown and Steady State Power

These calculations were followed by a comparison of the power change of a subcritical device to that of a reactor both having a 1$/s reactivity ramp insertion with a maximum insertion of 1$, i.e. $\rho = \beta$. These cases were run with β of 2.18e-03 and Λ of 1.e-04 s. The initial k for the subcritical device was 0.96 and initial k of the reactor was 1 (critical). The steady state reactor power was 500 MW. The source strength for the subcritical device is such that it operated at a steady state power of 500 MW.

In Fig. 2, the results of the calculations are shown. The reactor goes prompt critical one second into the excursion while the subcritical device's power is only increased by approximately 5% . This power change for the subcritical system can hardly be seen in Fig. 2, but is clearly noted in Fig. 3. In this scenario, the reactors become uncontrollable, while the accelerator driven device simply levels off at a new, higher power level.

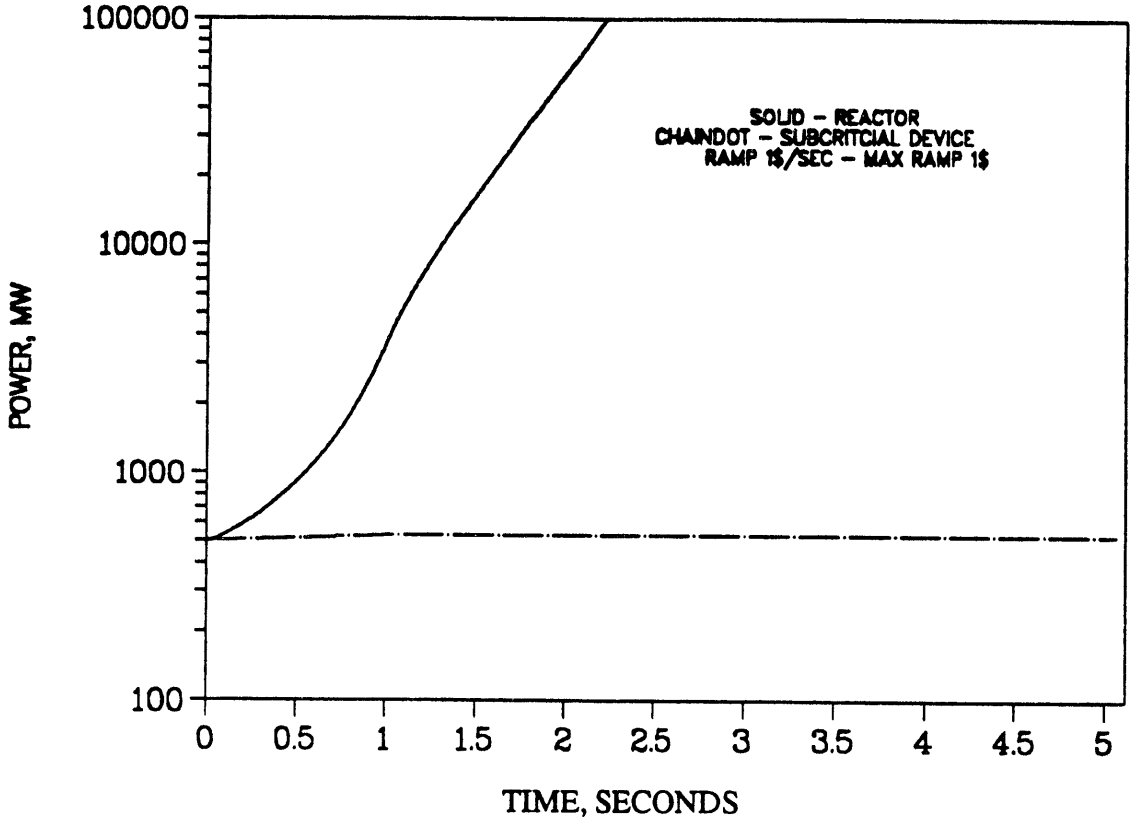

Fig. 2. Ramp Reactivity Input Into Critical Reactor and Subcritical Device

Next, shutdown calculations for several initial values of k for a 500 MW reactor were made. For these calculations β of 2.18e-03 and Λ of 1.e-04 s were used. These results are shown in Fig. 4. Note that the k at which the reactor was operating clearly determines the shape of the shutdown curve, which may be measured. Note also that the source needs to be turned off only very short periods of time to establish the curve shape. Such measurements could clearly establish the reactivity of the device and could be used to ensure the subcritical status of the system.

CONCLUSION

Clearly, subcritical systems are robust devices. Calculations show that large changes in reactivity that would lead to an uncontrollable excursion in a reactor would lead only to a power change in a subcritical device. Methods also exist for continuously monitoring the reactivity of a subcritical system. Thus, a subcritical device may have several advantages over a critical device in the areas of safety and operability.

REFERENCES

[1] L.R. Blue and M. Hoffman "AIREK-III," Atomics International document AMTD-131 (1963)

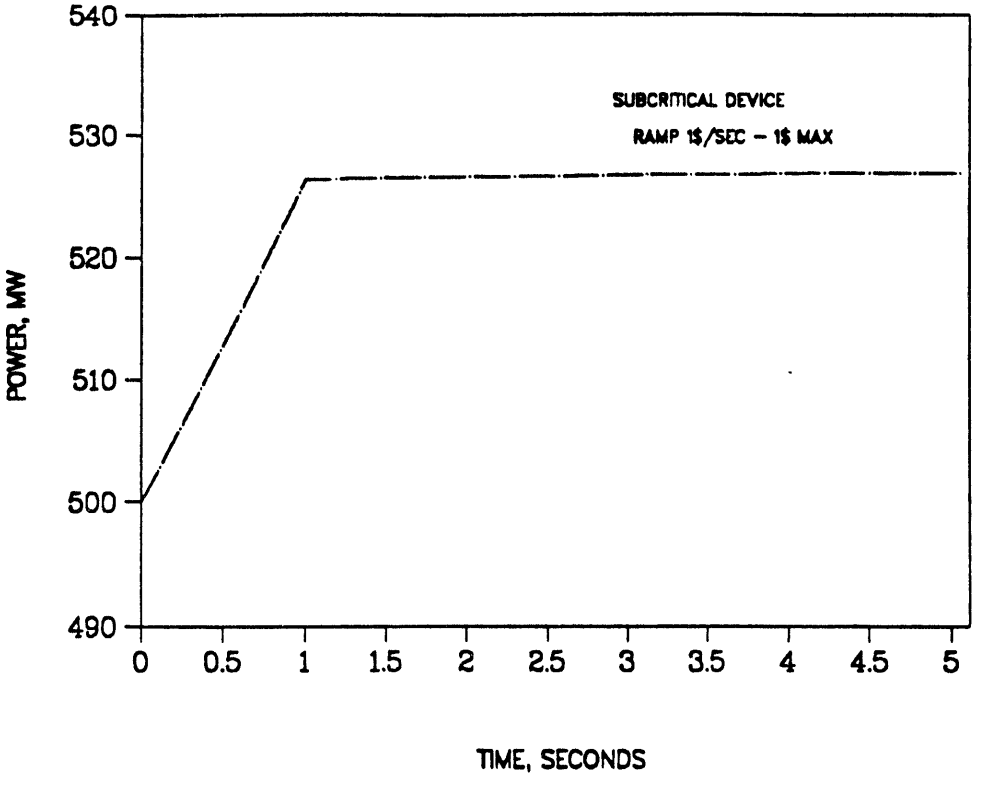

Fig. 3. Ramp Reactivity Input Into Subcritical Device

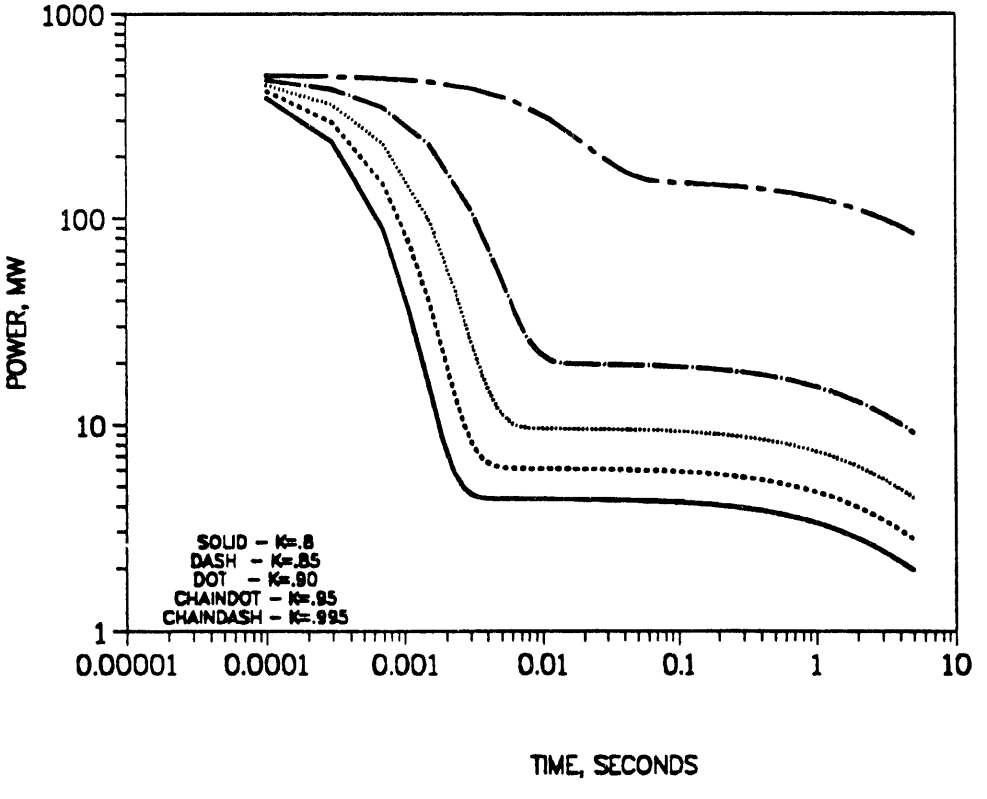

Fig. 4. Shutdown curves for blankets with various values of k.

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