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# Development and Analysis of a Metal-Fueled Accelerator-Driven Burner

F. Lypsch* and R. N. Hill**

*Institute for Safety Research and Reactor Technology, Research Centre Juelich, P.O. Box 1913, 52425 Juelich, Germany

**Reactor Analysis Division, Argonne National Laboratory, Argonne, Illinois 60439

**Abstract:** The purpose of this paper is to compare the safety characteristics of an accelerator driven metal-fueled fast system to a critical core on a consistent basis to determine how these characteistics are affected solely by subcriticality of the system. To accomplish this, an accelerator proton beam/tungsten neutron source model is surrounded by a subcritical blanket using metallic fuel and sodium as coolant. The consequences of typical accident transients, namely unprotected transient overpower (TOP), loss of heat sink (LOHS), and loss of flow (LOF) were calculated for the hybrid system and compared to corresponding results for a metal-fueled fast reactor. Results indicate that the subcritical system exhibits superior performance for TOP (reactivity-induced) transients; however, only in the critical system are reactivity feedbacks able to cause passive shutdown in the LOHS and LOF events. Therefore, for a full spectrum of accident initiators considered, the overall safety behavior of accelerator-driven metal-fueled systems can neither be concluded to be worse nor to be better than advanced reactor designs which rely on passive safety features.

## INTRODUCTION

Numerous reactor research programs have focused on the transmutation of nuclear waste in order to reduce the hazards of high-level waste. An interesting variation seems to be a hybrid design consisting of a charged particle high energy accelerator, a target region making use of the spallation process, and a subcritcal blanket region [1,2].

Subcritical accelerator systems offer several potential advantages for transmutation applications. These systems can be operated with a low inventory since large fissile masses are not required for criticality. Moreover, this low inventory leads to low fuel concentrations which may allow the use of improved fuel forms, particularly for fluid fuel systems which are being investigated in current studies [3]. For the transmutation of fission products, the subcritical system is ideal because large capture rates can be tolerated; whereas, excess neutrons must be produced to offset parasitic capture in a critical system. The primary performance disadvantage of accelerator systems is the energy consumption of the accelerator, reducing the net energy production of the system.

Subcritical systems additionally differ from critical systems in their transient behavior. The reliance on extraneous source neutrons changes the worth of all temperature coefficients. For example, the large margin to any kind of criticality accident in accelerator systems has been widely recognized. However, subcriticality can also be expected to reduce the importance of the passive reactivity feedback mechanisms which have been exploited in advanced reactor designs.

The aim of this paper is to perform an overall safety performance evaluation to assess the impact of subcriticality by comparing the safety characteristics of an accelerator driven system to a critical core. In order to make the comparison as consistent as possible, the accelerator system was designed similar to a current reactor design. For this study, a metal-fueled fast reactor system proposed for transmutation [4] was chosen as the reference configuration. The development of a fast spectrum subcritical accelerator system using similar materials and geometry is described in the next section; ideally, the only difference between the two systems would be in the neutron criticality.

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## CONCEPTUAL DESIGN OF ACCELERATOR SYSTEM

The intended comparison of the subcritical design to a current reactor design greatly determined the configuration of the system. A 900 MWt IFR metal-fueled fast reactor [4] with a conversion ratio near 1 was chosen as the reference critical system. An eigenvalue of 0.95 and a cycle length of one year were targeted for the subcritical system. The eigenvalue reduction (compared to the critical system) was achieved by reducing the fuel volume fraction. The fuel parameters are enumerated in Table 1.

**Table 1:** Fuel Lattice Parameters

| Fuel parameters | Inner Blanket | Outer Blanket | Critical Core |
|---|---|---|---|
| Height [cm] | 200.0 | 200.0 | 96.5 |
| Pin Diameter [cm] | 0.508 | 0.546 | 0.724 |
| Pin Pitch [cm] | 0.838 | 0.846 | 0.854 |
| Volume Fractions [%]: | | | |
| Fuel | 20.0 | 23.0 | 38.5 |
| Structure | 25.3 | 25.3 | 25.6 |
| Coolant | 54.7 | 51.7 | 35.9 |
| TRU/HM Enrichment [%] | 20.5 | 20.5 | 24.6 |

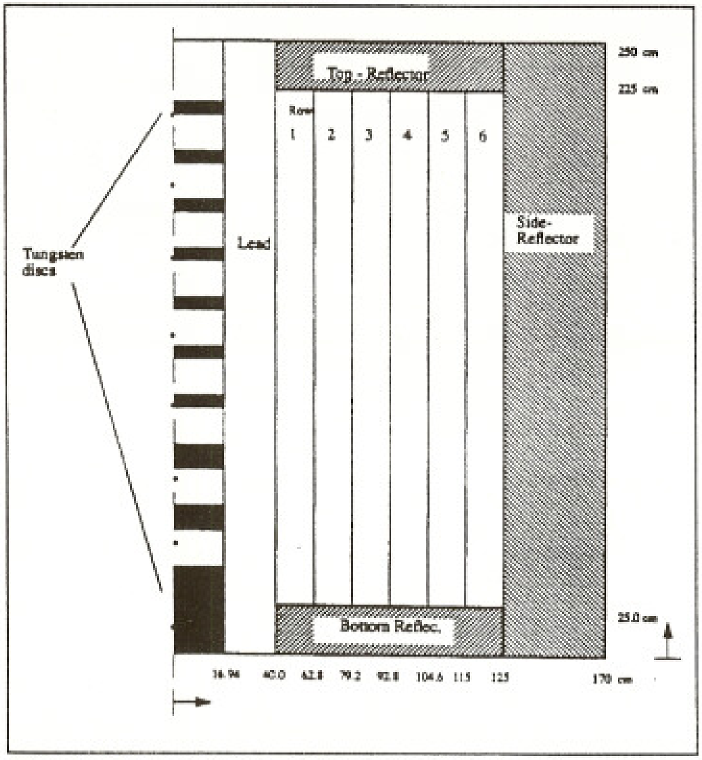

Fig. 1: Cross section of the subcritical system

The accelerator/target design resembles that of [5] and was only slightly adapted to our purposes. The main difference was the exchange of the heavy water coolant for sodium coolant in the target region. This modification should not change the overall conclusions of this study. The blanket region was configured to efficiently utilize the spallation neutrons. As shown in Fig.1, the height to diameter ratio of the blanket is nearly 1. The height was dictated by the axial size of the target design; and the radial dimension was scaled to provide adequate power production even in the outer rows. If the inner blanket zone is operated at power densities similar to a reactor system, the resulting power level of the entire blanket region is 1950 MWt. This power corresponds to a proton beam voltage of 1600 MeV and a current of 39 mA. The core was subdivided into two zones with a slightly higher fuel volume fraction in the outer regions to reduce the neutron flux gradient and to smooth the power density distribution. Finally, the fuel residence times were spatially varied to roughly conserve the discharge burnup at 100 MWd/kg; the row 1 fuel resides three cycles, and the row 6 fuel resides seven cycles.

## THE NEUTRONICS OF THE STEADY STATE SYSTEM

The 1.6 GeV protons enter the target region from above (Fig. 1) and produce spallation neutrons in the various tungsten discs. The high energy reactions are modeled by HETC-KFA 2

[6] transporting protons and neutrons down to 14.2 MeV. Neutrons falling below that boundary form the source neutrons for the ensuing 9-group fixed source DIF3D calculations which compute the overall neutron balance and the flux distribution in the different regions [7]. Fuel burnup was modeled by the REBUS depletion code employing DIF3D and batch-averaged compositions [8].

Fig. 2 compares the flux distribution of the hybrid design to that of a 900 MWth metal-fueled fast reactor [4]. As expected, the source-driven flux distribution decreases with penetration into the blanket region; whereas, the flux is relatively constant in the fueled region of the reactor system. In addition, the subcritical flux decreases considerably during a fuel cycle. The average flux, that is to say the power, decreases considerably during a fuel cycle due to a change of the eigenvalue from 0.95 to 0.93. If the accelerator current is maintained at a constant level, the flux decrease with depletion results in a corresponding 33 % power decrease at EOEC.

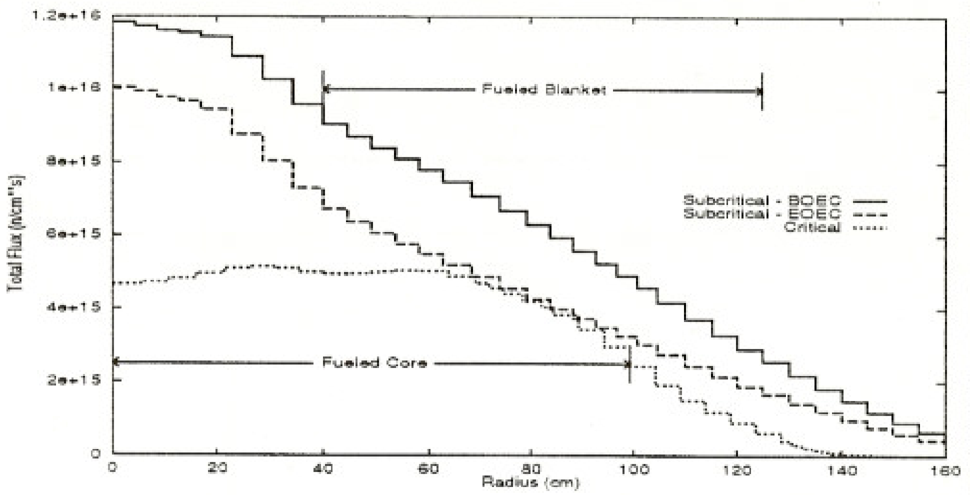


Fig. 2:Radial Flux Distribution of Subcritical Assembly and Typical Reactor

## ANALYSIS OF THE SAFETY BEHAVIOR

Because the eigenvalue flux solution represents a non-physical situation (where the only source of neutrons is fission), changes in the eigenvalue are not useful for the evaluation of reactivity effects. Instead, a multiplication factor, k, is introduced to quantify neutron production:

$$k = \frac{\text{Prod.rate}}{\text{Absorp.rate} + \text{Leak.rate}}$$

**Table 2:** Reactivity Feedback Coefficients

| | Accelerator | Core |
|---|---|---|
| Delayed Neutron Fraction | $3.31 \cdot 10^{-3}$ | $3.53 \cdot 10^{-3}$ |
| Prompt Neutron Lifetime [s] | $9.05 \cdot 10^{-7}$ | $2.49 \cdot 10^{-7}$ |
| Axial Expansion[cents/K] | -0.095 | -0.11 |
| Radial Expansion [cents/K] | -0.22 | -0.22 |
| Fuel Doppler [cents/K] | -0.099[a] | -0.099 |
| Coolant Density. [cents/K] | +0.58 | +0.18 |

[a]assumed equal to reactor values

where the reaction rates are determined using the fixed-source flux distribution. This multiplication factor also determines the correlation between the accelerator parameters (proton current and neutron yield per proton) and the power level.

Reactivity effects were calculated by evaluating changes in the multiplication factor for perturbations causing changes in radial dimensions, axial dimensions, and coolant density. The results are summarized in Table 2. The feedback coefficients are similar to those computed for the critical reactor system.

Using these reactivity feedback coefficients, the modeling of transient performance was conducted using a simplified version of the SASSYS code [9]. This code couples the neutronic behavior in each of the six fueled rows to the thermal behavior of the primary and secondary systems. Point kinetics are used to model the nuclear dynamics. This is sufficient for small perturbations where the flux shape does not change considerably; the modeling of transient behavior beyond the onset of sodium boiling (with large reactivity and thermal feedbacks) is beyond the scope of this calculational procedure. In the following section, results obtained for the high power region of the accelerator system (Row 1 in Fig. 1) are compared to typical reactor results for a variety of transient situations.

## COMPUTATION OF THE TRANSIENTS

The accident analyses for both the critical and subcritical systems concentrated on three pertinent accidents generally investigated for reactor licensing,

- the TOP scenario (transient overpower) assumes a control rod failure and is simulated in the program by inserting an excess reactivity over a reasonable timescale. In a subcritical design control rods are not necessary, but they may be allocated to reduce the power drop between BOEC and EOEC
- the LOHS (Loss of Heat Sink) scenario is caused by failures in the steam generator system. All cooling in the secondary system is lost over a very short time period resulting in a temperature rise in the primary coolant.
- the LOF scenario (Loss of Flow) has its origin in the primary circuit due to a failure of all of the pumps, as the flow is reduced to zero after a certain amount of time depending on the pump inertial forces. A conceivable reason for this accident is an overall power failure accompanied by a general failure of the on-site auxiliary systems.

As expected, the subcritical system exhibits favorable responses to TOP (reactivity-induced) transients. As shown in Fig. 3, the subcritical system does not experience the rapid power rise exhibited by the critical system which activates the reactivity feedbacks; and the total power increase for a reactivity insertion of 1 $ is less than 10%. The secondary systems can readily discharge this additional heat and temperatures stabilize approximately 20 K higher than initial operational values.

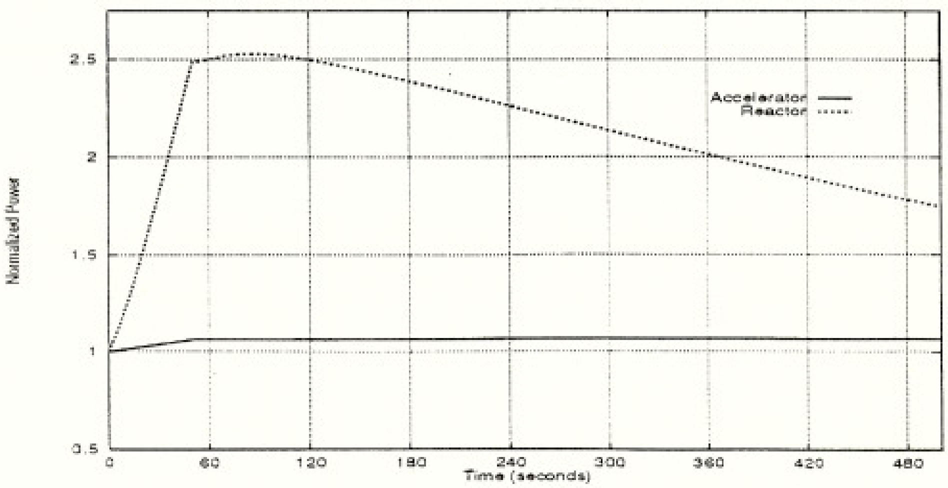


Fig. 3: Comparision of Power Transients for $1 TOP

The outcome of the LOHS event is shown in Fig. 4. The power increase in the subcritical system is caused by the large positive coolant density coefficient, which introduces significant reactivity as the system temperature rises; the relative contribution of the reactivity coefficients is illustrated in Fig. 5. The outlet temperature of the primary circuit is depicted in Fig. 6. Sodium boiling occurs in less than 350 seconds when the power of the system has already tripled. Since our design was not configured to minimize the sodium void coefficient, a case with a zeroed sodium coefficient was also run. In this case, the net reactivity effect is negative and the power decreases slightly with rising temperature (see Fig. 4). However, due to the constant number of extraneous source neutrons, the system continues to produce nearly full power unlike the critical system where the reactivity feedbacks effectively shut the system down (reduce to decay heat). As shown in Fig. 6, the lower power level of the zero-void-worth subcritical system does not prevent coolant boiling; but, the time to boiling is extended to beyond 1000 seconds. Conversely, the metal-fueled fast reactor avoids coolant boiling as long as adequate decay heat removal is provided.

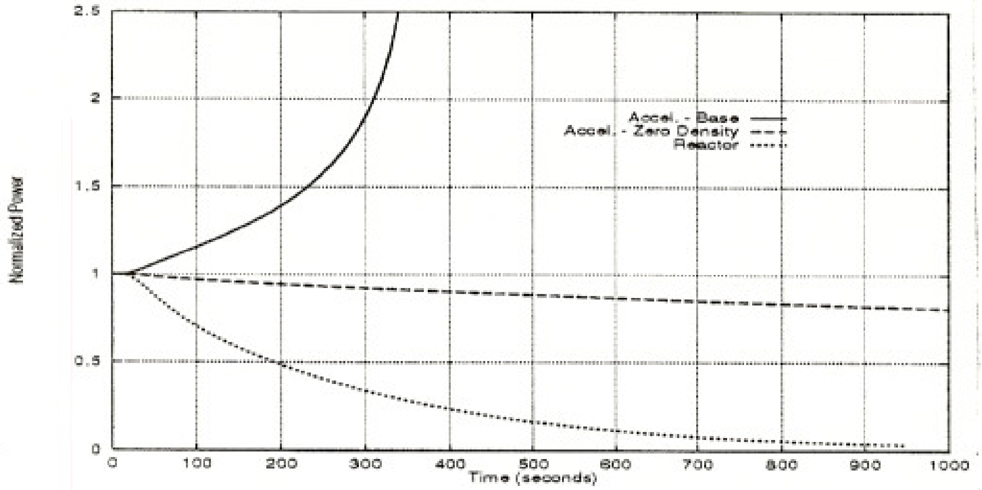


Fig 4:Comparision of Power Transients for LOHS

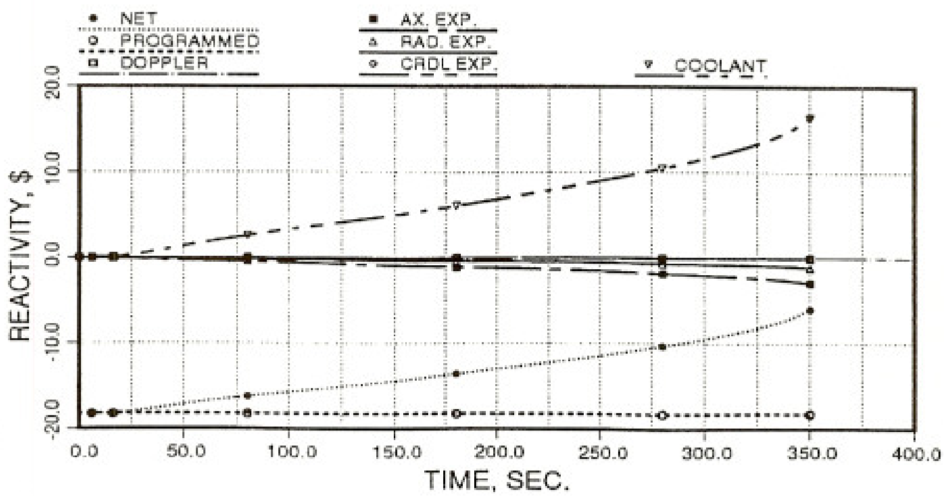


Fig 5: Reactivity Transients for Subcritical Assembly with Computed Sodium Coefficient (LOHS)

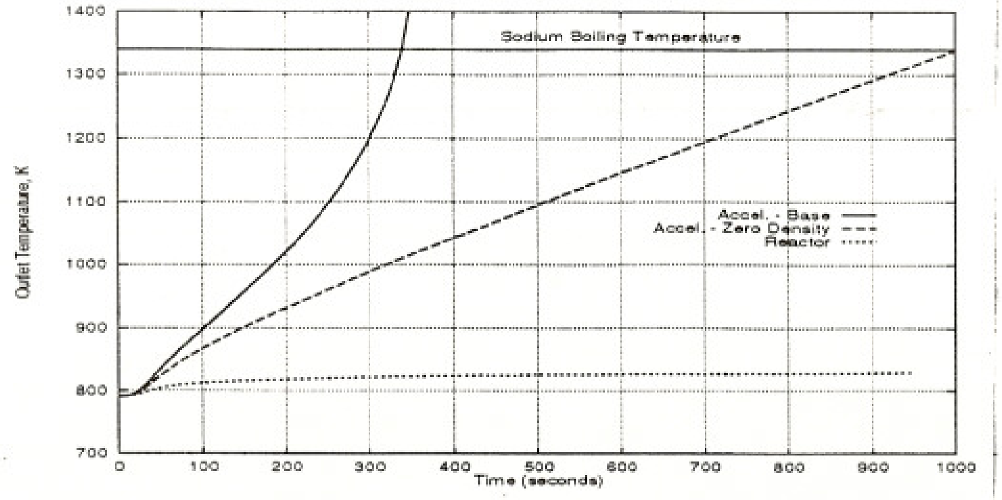


Fig 6: Comparison of Temperature Transients for LOHS

Because the power/flow mismatch is more severe in LOF events, the transient behavior is worse than in LOHS events. In Fig. 7, the response of subcritical and critical systems to a flow coastdown with a halving time of 6 seconds is shown. For the metal-fueled fast reactor, the initial coolant temperature rise is rapidly offset by reactivity feedbacks again leading to a passive shutdown after a short-lived temperature spike. A maximum coolant temperature of 950K is attained leaving a safety margin to boiling of 300K. In the subcritical system even with a zeroed sodium coefficient, the coolant temperature rises rapidly because reactivity effects do not sufficiently reduce the power level, and the outlet temperature reaches boiling only 20 seconds into the transient. However, this transient scenario is easily avoided for most initiating events. The principal initiating event for a rapid loss-of-flow is the general failure of offsite power; and this failure would imply an automatic shut-down of the accelerator if it is directly hooked into the grid. Thus, loss of offsite power instantaneously stops the production of source neutrons which zeroes the neutron flux and power density in the source-driven blanket. According to Fig. 7 the transient response is benign when accelerator operation ceases.

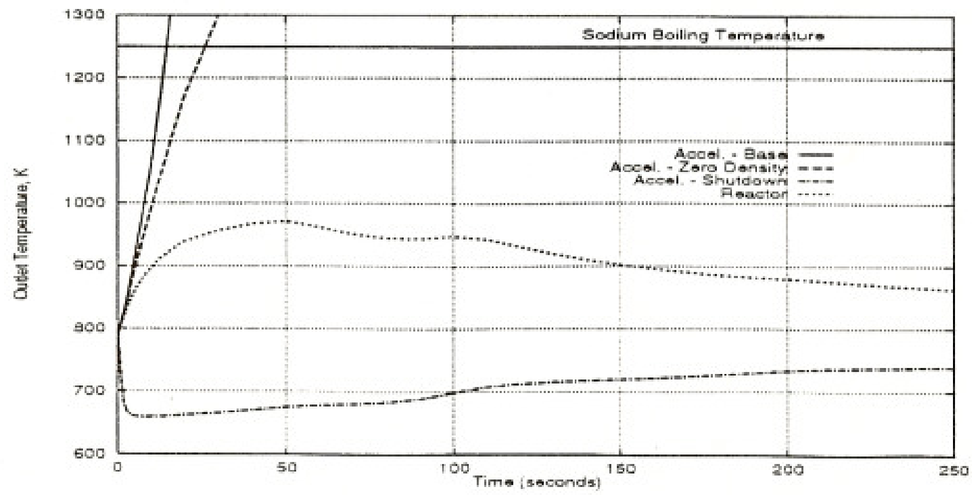


Fig 7: Comparison of Temperature Transients for LOF

## SUMMARY AND CONCLUSIONS

The purpose of this paper was to compare a metal-fueled fast reactor design to an accelerator driven unit on a consistent basis with special regard to the safety issues. To accomplish this, a subcritical blanket using metallic fuel and sodium coolant was developed by modifying the lattice design of the reactor system (lower fuel volume fraction). The subcritical system is operated at a similar power density and fuel burnup; and identical heat removal systems are employed. Thus, performance differences between the two systems can be primarily attributed to the deviation from criticality.

Several nuclear performance issues were identified for the source-driven subcritical system. Large spatial gradients are observed in the neutron flux; thus, material zoning and/or residence time variation are needed to achieve favorable power shaping and depletion characteristics. In addition, subcritical operation leads to a decreasing flux level with depletion; in this study, the power decreased by 1/3 over a one year cycle. This depletion behavior could be compensated by either varying the accelerator current or controlling the neutron balance (e.g., insert poison material at BOEC).

The behavior of the subcritical system was analyzed for typical reactor accident scenarios, namely unprotected transient overpower (TOP), loss of heat sink (LOHS), and loss of flow (LOF) events. With regard to the TOP transient, the subcritical system exhibited much better performance than a critical system; even large reactivity insertions (up to 1$) lead to only small (<10%) power increases. However, the subcritical system does not passively shutdown for loss-of-cooling events. Some active measure (e.g., switching off the accelerator) is required. Otherwise, sodium boiling will occur in less than twenty minutes in the LOHS sequence, and less than one minute in the LOF event. In principal, these LOF events can be largely avoided by connecting the accelerator directly to the same power source as the coolant pumps.

In summary the overall safety behavior of this accelerator-driven metal-fueled system can not be considered to be obviously worse nor better than advanced metal-fueled reactor designs. The behavior of the subcritical system indicates different inherent strengths and weaknesses compared to a similar critical system. Reactivity-induced transients are particularly benign in the subcritical system. However, appropriate response to loss-of-cooling events is a more prominent issue for subcritical systems.

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