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Phenomena and Scenarios Related to a Loss-of-Heat-Sink Accident (with Scram) in an LMFBR*

R. A. Bari and W. T. Pratt
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

J. F. Meyer
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

ABSTRACT

Several key phenomena and alternative scenarios which may follow a loss-of-heat-sink event, with scram, in an LMFBR are discussed. An event tree procedure is used to highlight the major branching points as they relate to controlling phenomena in the accident progression. For each of these branching points, a discussion of results of analyses carried out at BNL is presented. These discussions focus on the inherent safety capability features of the LMFBR concept as well as on particular design features of the Clinch River Breeder Reactor and of the Fast Flux Test Facility.

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The purpose of this paper is to discuss several key phenomena and alternative scenarios which may follow a loss-of-heat-sink (LOHS) event, with scram, in a liquid metal fast breeder reactor (LMFBR). An event tree procedure is used to highlight the major branching points as they relate to controlling phenomena in the accident progression. For each of these branching points, a dicussion of results of analyses carried out at BNL is presented. These discussions focus on the inherent safety capability features of the LMFBR concept as well as on particular design features of the Clinch River Breeder Reactor (CRBR) and of the Fast Flux Test Facility (FFTF).

A LOHS accident may be postulated to occur with or without reactor scram. The present analysis considers the accident to occur with scram (one particular LOHS accident without scram has been presented in the literature).[1] The loss of shutdown heat removal capability has been considered from a probabilistic point of view for the Clinch River Breeder Reactor.[2] From these studies, it can be concluded that the LOHS accident is of sufficiently high probability that its consequences warrant investigation. In addition, during the "operating licensing" review of the FFTF by the Advisory Committee on Reactor Safeguards[3], both the FFTF Project and the NRC Staff were requested by the Committee to address the consequences of a LOHS.

In our analysis, for the purpose of clarity, we have divided the LOHS into two categories. In the first category, we consider LOHS events (L-I) which include an initial breach of the primary heat transport system (PHTS) pressure boundary. The second category includes those LOHS events (L-II) for which there is not an initial breach of the PHTS pressure boundary. Category L-I LOHS events may include PHTS pipe ruptures and events initiated by natural phenomena which lead to vessel, piping or component damage in the PHTS. Category L-II LOHS events may include loss of feedwater supplies, loss of air blast heat exchangers and pipe ruptures in the secondary heat transport system. A total loss of electric power can be associated with either category and, in the absence of a demonstrated natural convection heat removal capability, presents a severe limitation to the reliability[2] of the shutdown heat removal system. In Figures 1 and 2, we present the events for the category L-I LOHS and L-II LOHS, respectively. From Figure 1, it can be seen that three events control the L-I scenarios. These are:

1. NA BOILS = the event that sodium in the PHTS reaches the boiling point and vapor is produced.
2. BOIL-OFF TO CORE LEVEL = the event that the sodium inventory in the vessel boils off until its level reaches the top of the active core.
3. CLAD DRYOUT = the event that there is no longer a liquid film of sodium on the cladding wall and that this situation is sustained such that clad melting follows.

The event trees, as presented in these figures, are reduced event trees in the sense that irrelevant or illogical branches are not considered. For example, if sodium never boils, it is expected that clad will not melt, and similarly if the core is no longer covered by sodium, then the clad is expected to melt. The event trees presented here are given for a certain time span. For example, Event 2 (BOIL-OFF TO CORE LEVEL) may not have occurred simply because not enough time has elapsed. The ordering of events is not unique but, rather, represents the most logical structure for the discussion of the scenarios.

The first branch point, (A) in Figure 1, asks the question: can decay heat be removed from the sodium via heat losses to the vessel and piping walls such that the sodium will not boil? In terms of addressing a LOHS event, this may be a question of semantics. On the other hand, it may be a question of reactor design practices. For the CRBR and the FFTF, thermal insulation is provided on the vessel and piping in order to minimize thermal losses during normal operation. For the LOHS event, the presence of this insulation forces the assignment of an extremely low probability to the lower path from branch A in Figure 1.

If sodium does boil in the reactor vessel, then two related questions can be asked:

Branch Point B: Does the sodium boil-off from the vessel inventory such that the core is uncovered?

Branch Point C: Does the clad dry out before the core is uncovered?

As the sodium boils-off from the vessel and to the reactor containment cells and/or the reactor containment building via the breach in the PHTS, several physical processes come into play. These processes include the condensation of sodium vapor on structures (e.g., the reactor vessel head) and the exothermic chemical reaction of sodium in the containment building atmosphere. An analysis of the containment pressurization for FFTF has been carried out[4] with the CACECO[5] computer code. It was found that the time to uncover the core was 175 hours.

We note that, for FFTF, significant reactor containment building (RCB) pressurization would occur (10 psig after 80 hours) long before the sodium level in the reactor vessel dropped (by virtue of sodium boil-off) to the elevation of the active core. It has been suggested[6], however, that the RCB would provide sufficient condensation surfaces to prevent such pressurization and indeed the analytical model (the CACECO code[5]) was considered overly conservative. A simple energy balance obtained from CACECO at 80 hours will demonstrate that this is not the case. At 80 hours, CACECO predicts that approximately 170 x 10^6 Btu of energy would be transferred to the RCB from the vessel by escaping gases. Approximately 50,000 lb of sodium vapor would have reached the RCB together with ∿20,000 lb of water vapor from dehydrating concrete. The subsequent $Na\text{-}O_2$ and $Na_2O\text{-}H_2O$ reactions release an additional ∿380 x 10^6 Btu in the RCB. CACECO predicts that the vast majority of this energy input into the RCB would be absorbed by the structures or lost to the outside environment. Only ∿40 x 10^6 Btu or ∿7% of the available energy is predicted to increase the internal energy of the atmosphere. Such an energy balance is not overly conservative.

During the boil-off of sodium from the vessel, before the sodium level drops to the level of the core region, the possibility arises that the clad will dry out. In-vessel natural circulation will tend to remove heat from the core, but for the low heat flux, low flow regime only limited experimental and analytical information exists on the conditions needed to prevent dryout. Based on two-phase pressure drop calculations carried out in this regime[7], and also on experimental information on critical heat fluxes in this regime[8], we conclude that dryout cannot be ruled out under conditions of low heat flux and low flow.

Category L-II LOHS events follows similar event tree paths (see Figure 2) as do Category L-I events, except that an additional event must be added to the event tree. This event is:

PHTS PRESS. AND BREACH = the event that pressurization of the PHTS pressure boundary as a result of sodium vapor production within the primary system sodium inventory causes a failure of PHTS pressure boundary (e.g., the vessel head seals or the PHTS piping fails due to stress).

This event will inevitably occur for an isolated system which is not rejecting sufficient heat. The branching, (P) in Figure 2, is associated with the time at which the question is asked. It is instructive to consider that accident progression, which includes the events, NA BOIL (yes), PHTS PRESS. AND BREACH (no), CLAD DRYOUT (yes). The meltdown progression has been assessed[9] using the CRBR geometry at a decay power level of 1% of nominal. It was determined that fuel and control materials would melt approximately 20 minutes after sustained dryout. During this period, sodium vapor produced in the core region would pass through the upper plenum sodium without condensation (the bulk of the in-vessel sodium would be close to saturation) and be released into the cover gas space. Condensation of the sodium vapor would subsequently occur at the relatively cool reactor head preventing significant pressurization of the primary system until the surface temperature of the head approaches the sodium saturation temperature.

Pressurization of the FFTF primary system has been estimated at BNL.[4] It was determined that 10 hours (from the beginning of sodium boiling) would be required to heat-up the reactor head and pressurize the primary system to

10 psig. A similar calculation has not been carried out for the proposed CRBR design, however, pressurization would be expected on the order of hours. Clearly, if dryout is assumed to occur shortly after the sodium starts to boil, then the subsequent meltdown (time-scale of minutes) would not be influenced by primary system pressurization (time-scale of several hours). After fuel or control material relocation begins, recriticality is predicted[9] to occur in the presence of a large body of liquid sodium in the upper plenum. For the L-I events, there are two paths to meltdown, and for the L-II events there are three paths to meltdown. For these five scenarios, the meltdown progression, material relocation, and the potential for recriticality are similar[9] (the differences are mainly associated with time scale).

In summary, this work has provided, within the context of an event tree scheme, a survey of alternative LOHS events and an assessment of their consequences. Uncertainties in our current knowledge have been highlighted, and the needs for future experimental and analytical studies have been indicated.

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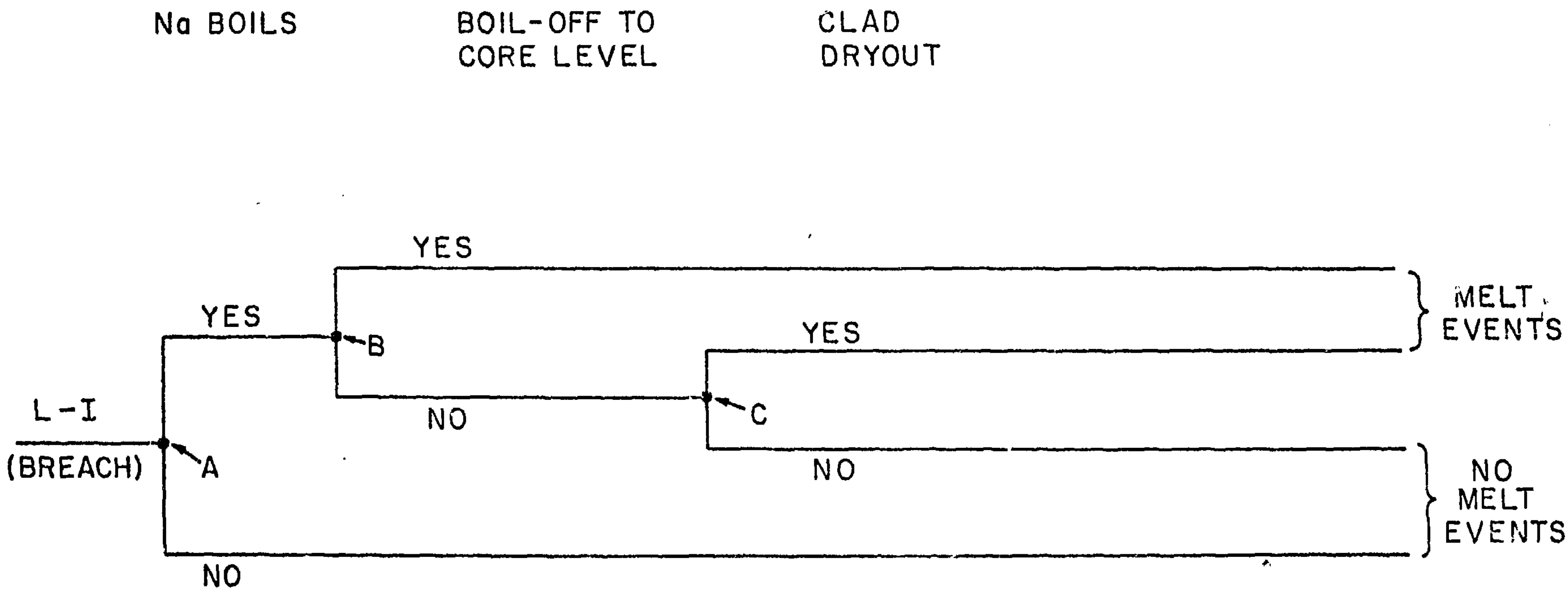

Figure 1: Event Tree for LOHS Scenarios for which there is an Initial Breach of the PHTS Pressure Boundary.

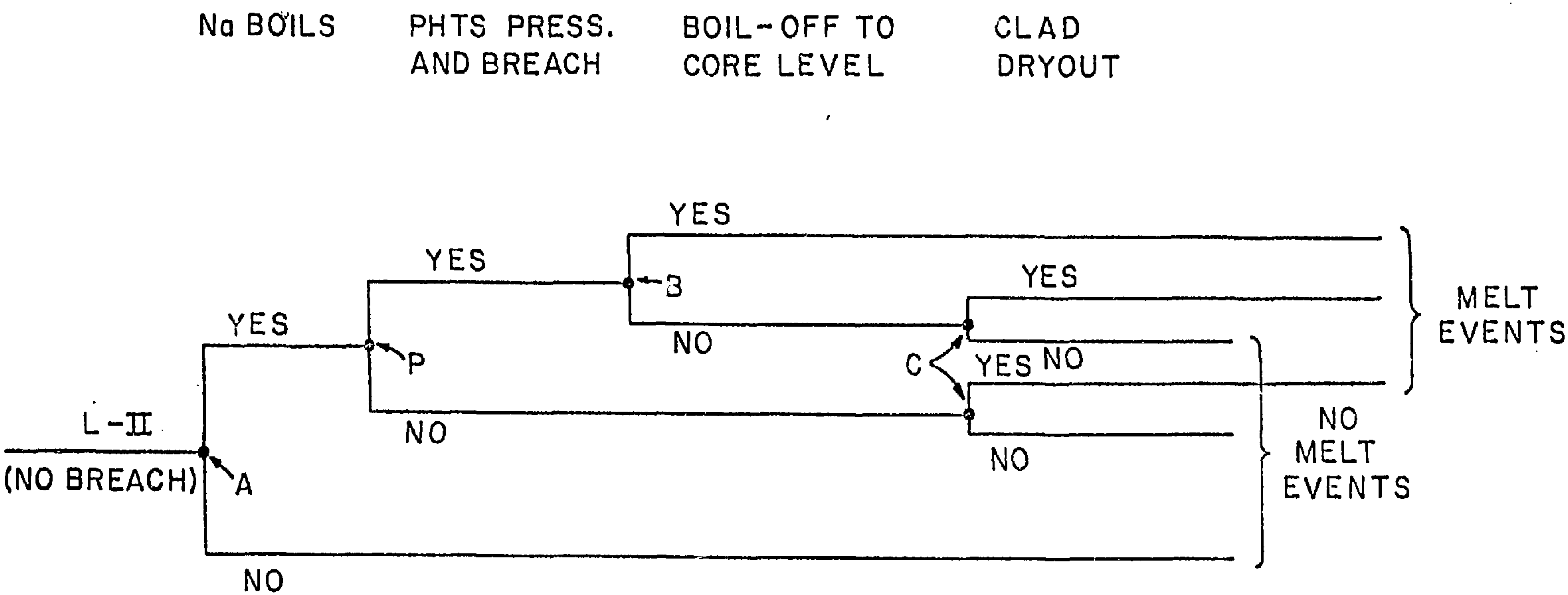

Figure 2: Event Tree for LOHS Scenarios for which there is not an Initial Breach of the PHTS Pressure Boundary.