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Loss-of-Coolant Accident Mitigation for the Advanced Neutron Source Reactor

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ABSTRACT

A RELAP5 Advanced Neutron Source Reactor system model has been developed for the conceptual design safety analysis. Three major regions modeled are the core, the heat exchanger loops, and letdown/pressurizing system. The model has been used to examine design alternatives for mitigation of loss-of-coolant accident (LOCA) transients. The safety margins to the flow excursion limit and critical heat flux are presented. The results show that the core can survive an instantaneous double-ended guillotine of the core outlet piping break (610 mm-diameter) provided a cavitating venturi is employed. RELAP5 calculations were also used to determine the effects of using a non-instantaneous break opening times. Both break opening time and break formation characteristics were included in these parametric calculations. Accumulator optimization studies were also performed which suggest that an optimum accumulator bubble size exists which improves system performance under some break scenarios.

INTRODUCTION

Presently in the conceptual design stage, the Advanced Neutron Source Reactor[1] (ANSR) is a high heat flux, high mass flux, and high coolant subcooling research reactor to be built at the Oak Ridge National Laboratory. The ANSR features upflow of D_2O coolant through the core to facilitate natural circulation after shutdown, submerged coolant loop configuration, and passive gas-pressurized accumulators to improve the depressurization behavior. The ANSR does not have a LOCA in the conventional sense due to the use of submerged piping, water-filled accumulator, and limited volume air cells. Nevertheless, the reactor core must be protected against the rapid depressurization that would follow a breach of the primary coolant pressure boundary.

As part of the Conceptual Safety Analysis Report (CSAR), LOCA analyses were performed using RELAP5 to assess core survivability using appropriate mitigation schemes. The CSAR studied several depressurization events[2] including a double-ended guillotine (DEG) core inlet break, a DEG core outlet break, the rupture of the Core Pressure Boundary Tube (CPBT) outer wall, several station

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blackout scenarios and reactivity insertion accidents. This paper focuses on the loss of pressure mitigation schemes developed for the CSAR and subsequent studies regarding various break formation characteristics and effects of accumulator bubble sizes on the safety margin. Figure 1 shows the break locations examined in this study.

MODEL DESCRIPTION

An ANSR RELAP5 system model has been developed based on the conceptual design. The model includes three major regions as shown in Fig. 2. The core model (region 1) consists of two core halves, core bypass channels, and a central control rod region. The core is surrounded by the CPBT, which separates the high-pressure primary system and the low-pressure reflector tank.

Core power is calculated using a point kinetics model with reactivity feedback based on coolant density and control rod position. Power is distributed among the various metal and fluid regions and is distributed axially within the fueled region based on a specific fuel loading design.

Each of the two fuel elements is modeled as an average channel (which incorporates all but two of the fuel plates) and two hot channels representing the most limiting axial relative power density profile in each core half. For each fuel element, one of these hot channels reflects 95% probability uncertainty levels (for analysis of unlikely events), and one represents 99.9% probability uncertainty levels (for analysis of anticipated events). The purpose of the hot channels is to calculate the most severe axial bulk temperature profile within the core. Within each of these channels, correlations are compared at hot spot conditions. The magnitude of these spots are defined using uncertainties which effect local heat flux conditions, but do not effect bulk coolant conditions because they are so localized.

The loop model (region 2) contains three independent heat exchanger loops. Each loop consists of an isolation valve, a hot/cold leg, an accumulator, horizontal U-tube main and emergency heat exchangers, a centrifugal main circulating pump, and an inertial flow diode (a preferred flow direction device). Both heat exchanger models are calibrated to design specification. The single-phase homologous curves defining the performance of the main circulation pumps was developed from three-quadrant Byron Jackson design curves,[3] and two-phase corrections were based on Semiscale data.[4]

An open-loop representation of the letdown and pressurizing system (region 3) is included in the model. Letdown flow is extracted from the inlet plena of the three main heat exchangers. In the design, primary system core outlet pressure is controlled through modulation of the letdown valves. This is modeled by establishing the nominal valve opening size required to allow a nominal flow during normal conditions and controlling about that point.

A main pressurizing pump provides injection flow through a makeup line located at the hot leg distribution header. Injection flow is drawn from a constant temperature heavy-water source by the main pressurizing pump. Following letdown isolation, flow through the pressurizing pumps is assumed to continue until the integrated injected flow reaches the makeup tank capacity.

RESULTS AND DISCUSSION

For conservatism, the initial conditions for all events have been modified from nominal by the amount necessary to account for measurement error and routine control variations: increasing reactor power by 4.2%, decreasing primary pressure by 5%, raising the core inlet temperature by 0.6°C. Consequently, the steady-state margin to FE and CHF is decreased. A coincident loss of off-site power, in which the pressurizing pump and the secondary coolant loop pump were tripped at the time of break, has been assumed for LOCA events.

1. Core Outlet Break with Venturi

The objective of this calculation was to determine if a cavitating venturi located immediately downstream of the core region would mitigate core damage resulting from core outlet breaks (see Fig. 1). A venturi was so designed that no flashing would occur under normal operating conditions, but would reach saturation and cause flashing and choking at the throat during breaks. Because of choking, the pressure waves propagating from the break toward the core exit were attenuated. As a result, the initial rapid depressurization at the core exit was improved, preventing core damage.

This accident scenario simulated a 610-mm-diam instantaneous DEG break at the core outlet, immediately downstream of the venturi. This break was modeled as two independent in-line junctions (one for each end of the broken pipe), connected to separate time-dependent volumes representing the light water pool at the time of break. In the model, a venturi was placed within the upper pressure boundary assembly within volumes of 640-01, -02, and -03 (Fig. 2). A throat of 234-mm-diam was found to be effective in preventing fuel damage during the break.

The safety margin is measured by thermal limit ratios. The ratios are defined as the calculated limiting heat flux for flow excursion (FE) or critical heat flux[5] (CHF) divided by the local fuel surface heat flux. The Costa FE correlation,[6] representing the onset of the significant void generation, along with the CHF, were calculated at the channel hot spots. A minimum ratio greater than one indicates that the limit has not been exceeded, and that no fuel damage would be predicted; if the minimum ratio is less than one, the possibility of fuel damage exists.

The pressure response at the exit of lower core (the lower core is the most limiting) is displayed in Fig. 3. After the break initiation at 10s with the venturi in place, a much smoother and higher pressure was maintained due to flashing at the throat, limiting the break flow and attenuating pressure wave oscillations. Without the venturi, a rapid depressurization accompanied with high frequency oscillations causes the core exit to reach saturation, leading to possible fuel damage.

The effectiveness of the venturi is further demonstrated in the thermal limit ratio comparison (Fig. 4). The departure in the FE thermal limit between cases with and without the venturi is most pronounced because the FE ratio is highly sensitive to pressure. The CHF limit is less sensitive to pressure. As indicated, both the thermal limits are exceeded without the venturi in place while a significant margin for both FE and CHF of about 1.7 and 1.5, respectively, is calculated with the venturi in place.

2. Core Inlet Break with a Finite Time Opening

Break opening comparisons and optimal initial accumulator bubble size studies were performed for the DEG core inlet breaks at the primary supply vessel adapter weldment (PSVAW) with an opening time of 1.1s (see Fig. 1). The PSVAW is the component where the four cold legs combine and flow is routed into the core region.

2.1 Break Opening Comparisons

Equation (1), the lower curve in Fig. 5, represents a power-law model and simulates the expected behavior- small leakage area associated with initial cracking with area increasing rapidly as the crack propagates.

$$d(t)/d_o = 2^{t/\tau} - 1 \qquad (1)$$

where d(t) is the instantaneous break diameter, d_o is the fully open break diameter, t is the time from the initiation of the break, and τ is the time constant for the break.

Equation (2), the middle curve of Fig. 5, represents a linear model and assumes that the crack diameter linearly increases with time.

$$d(t)/d_o = t/\tau \qquad (2)$$

Equation (3), the upper curve of Fig. 5, represents a second power-law model with a more rapid opening rate than Eq. (1).

$$d(t)/d_o = 2(1 - 2^{-t/\tau}) \qquad (3)$$

All of these break models satisfy the same initial and final conditions (fully closed initially and fully opened at 1.1 s). The calculations in this section all utilize the same accumulator parameters (e.g., a tank volume of 5 m^3 and an initial bubble size of 0.1 m^3).

The thermal limit ratios for the FE and CHF as a function of time are shown in Figs. 6 and 7, respectively. The results confirm that formation rates that are initially slow then increase rapidly lead to greater safety margins. Although the slower opening power-law model results indicate thermal limits greater than 1.0 for a break formation time of 1.1s, faster break progression rates (both the linear and more rapid opening power-law models) result in violation of the thermal limits. Obviously, the development of an appropriate break opening model based on data is needed.

2.2 Optimal Initial Accumulator Bubble Sizes

With the accumulators located on the hot leg, an optimum accumulator bubble size exists which trades off the desirability of maintaining system pressure with the time required to trip the reactor on low pressure (the longer the time to trip, the less the core flow due to increasing flow out of the break).

The objective was to determine an optimum bubble size for a given accumulator design. In this study, the accumulator tank volume was assumed to be 7.52 m^3, and the break opening time was 1.1 seconds using the break opening model of Eq. (1).

The calculated thermal limit ratio for the FE is shown in Fig. 8. For the 0.52 m^3 bubble, after the break opens at 10s, the ratio declines due to system depressurization until the low pressure scram setpoint is reached. Soon after the reactor scram, the ratio reaches the minimum and then recovers rapidly because of the increasing coolant subcooling.

As the bubble size is decreased, the minimum FE limit first improves and then worsens. For a large bubble, the accumulator injection is strong enough to keep the core exit pressure high and therefore delay the reactor scram. A delay in reactor scram coupled with the decreasing core flow results in a smaller minimum FE ratio. In the limit of no bubble, the accumulator injection is not enough to improve the core exit pressure. Rapid depressurization causes boiling and dryout. As a result, the core cannot survive. Somewhere in between exists an optimal bubble size. The results indicate a very small optimum bubble size in the accumulator for core inlet breaks. For the 1.1 s time constant, it is less than 0.065 m^3, corresponding to a 50 cm-diam bubble.

These results indicate that there are possible improvements which can be made in the current system design by altering the accumulator configuration because presently the accumulator tends to delay the reactor trip. Modifications to the safety system are being considered.

CONCLUSIONS

In summary, for the ANSR conceptual design, the core can withstand an instantaneous 610 mm-diam double-ended guillotine break of the hot leg piping if a cavitating venturi is placed downstream of the core exit. During this break, when the pressure at the throat drops below saturation conditions, the coolant chokes, thereby becoming an effective flow and pressure limiter.

Safety margin is highly sensitive to the break opening model. The RELAP5 results confirm that for non-instantaneous breaks, formation rates that are initially slow and then increase rapidly lead to greater safety margins for the DEG core inlet breaks. The choice of any model must be based on data.

RELAP5 calculated an optimal bubble size less than 0.065 m^3 for the 7.52 m^3 accumulator, hence a smaller accumulator than is presently used in the design would be sufficient to mitigate the effects of a DEG core inlet break. These results suggest possible improvements in safety system design because the accumulator tends to delay the reactor trip. Modifications to the safety system are being considered.

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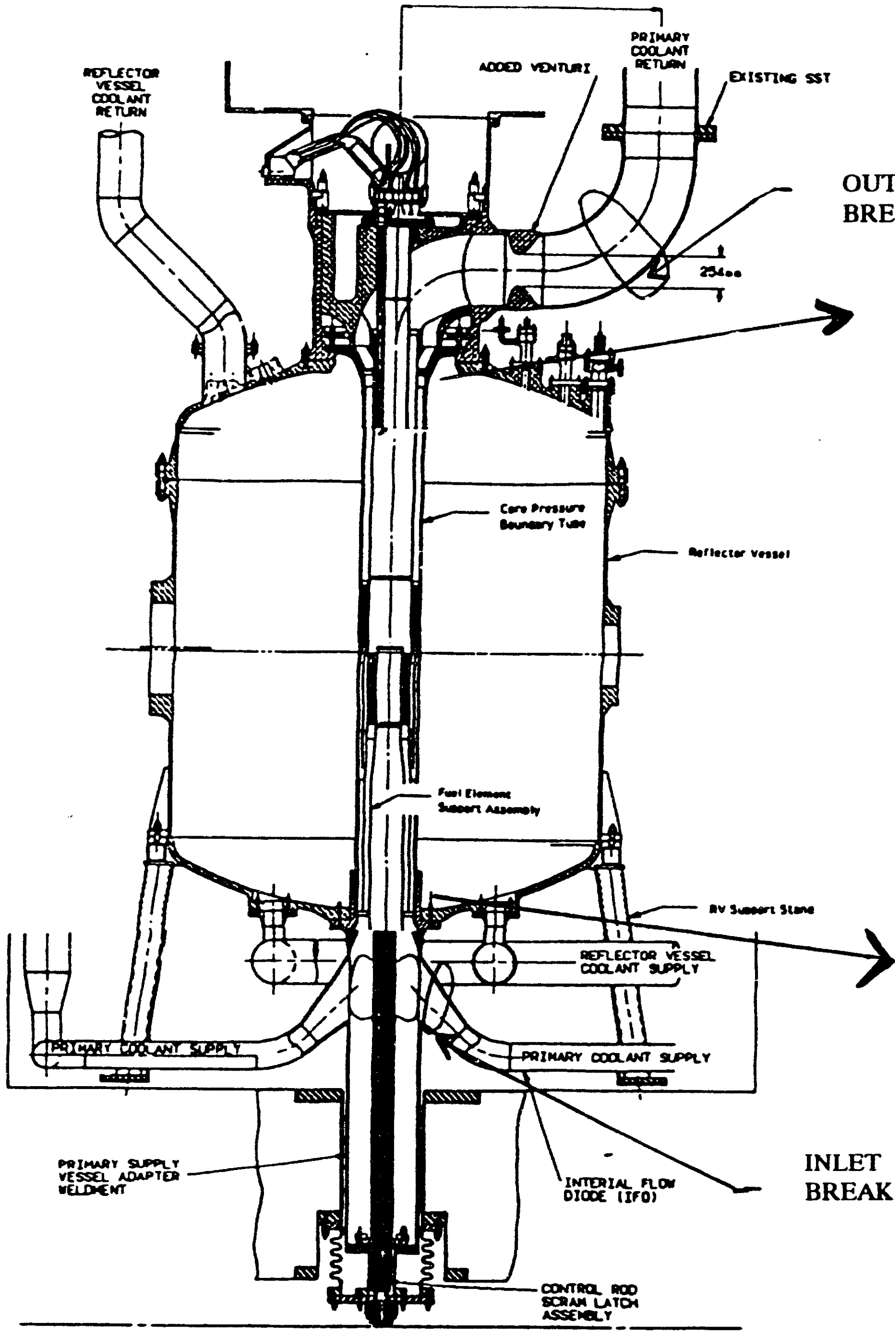

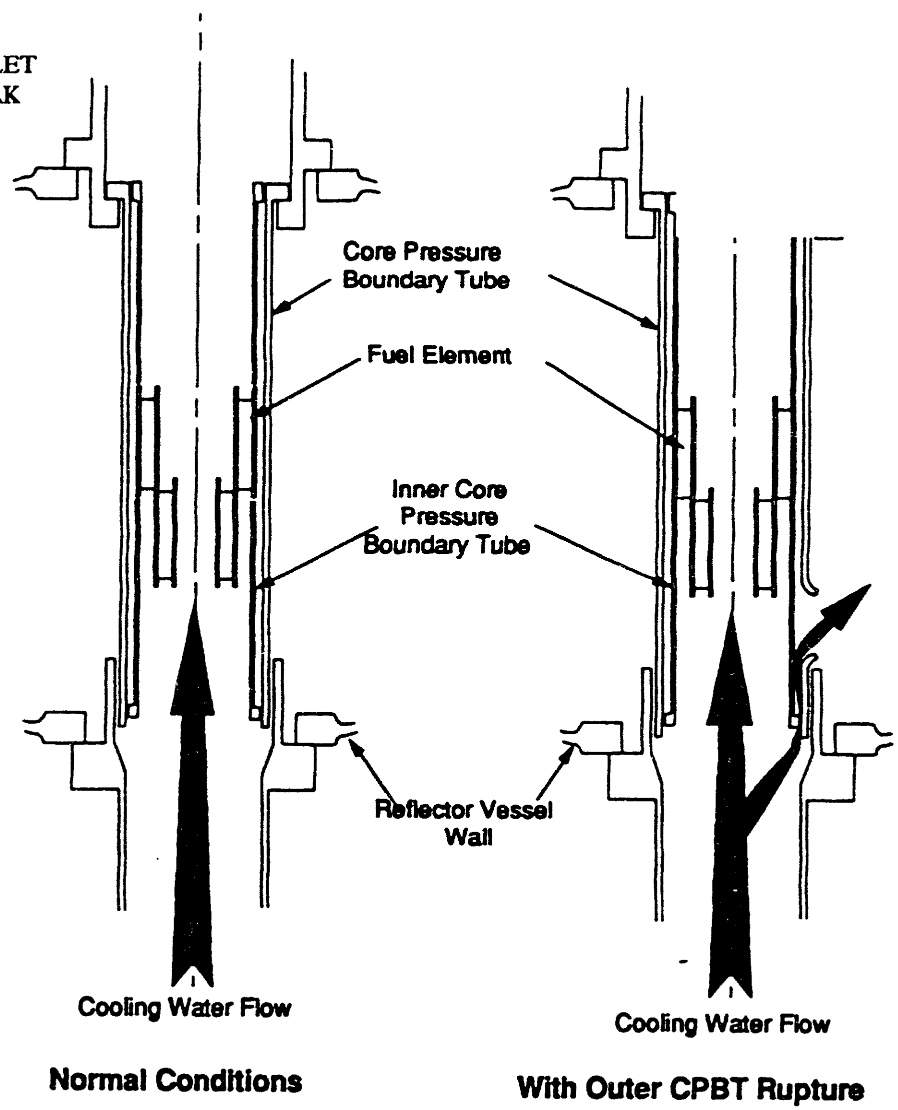

Illustration of double-walled CPBT before and after outer wall rupture.

Fig. 1. Advanced Neutron Source Reactor core region showing core inlet and outlet break locations.

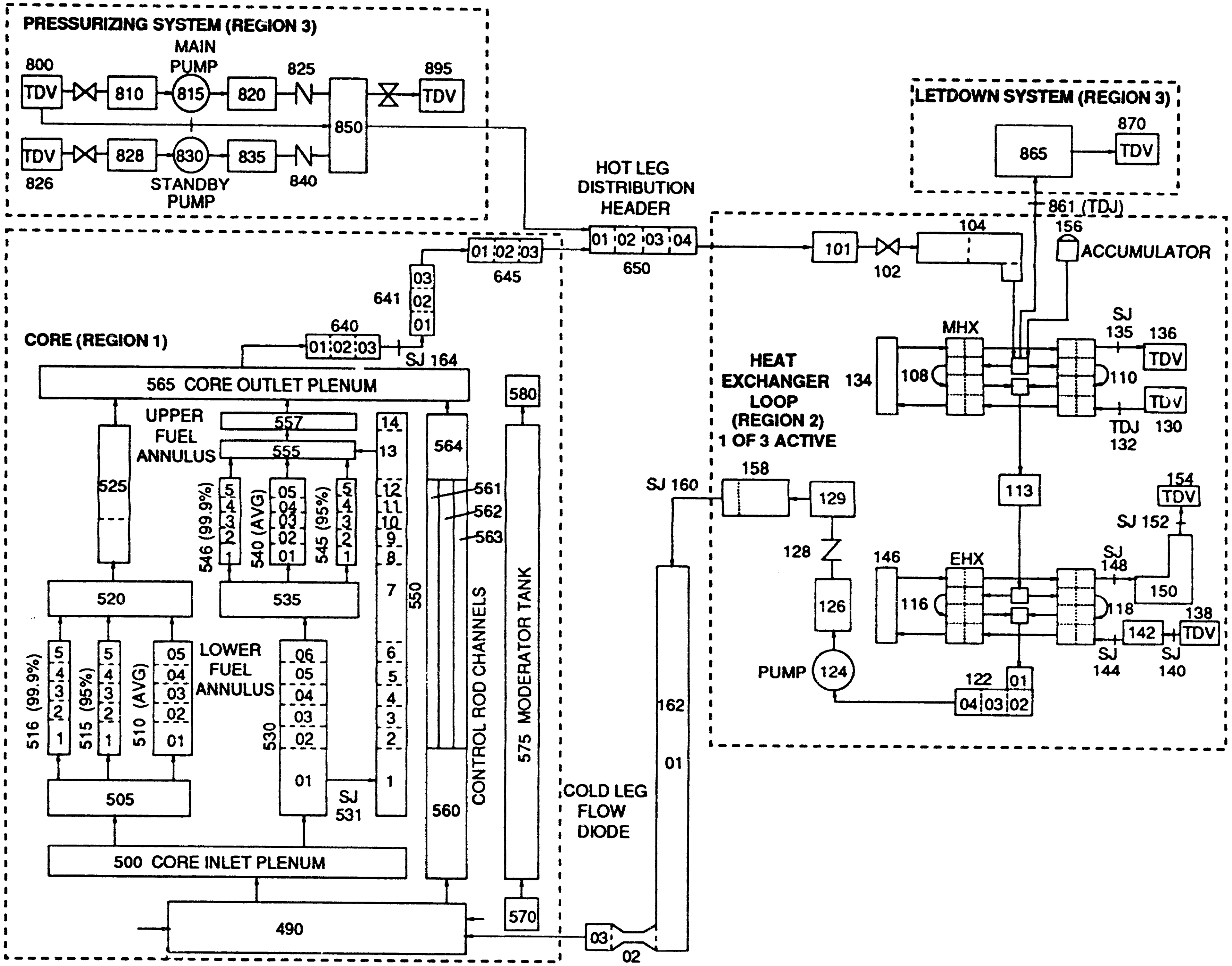

Fig. 2. Nodalization of the conceptual design ANS RELAP5 system model.

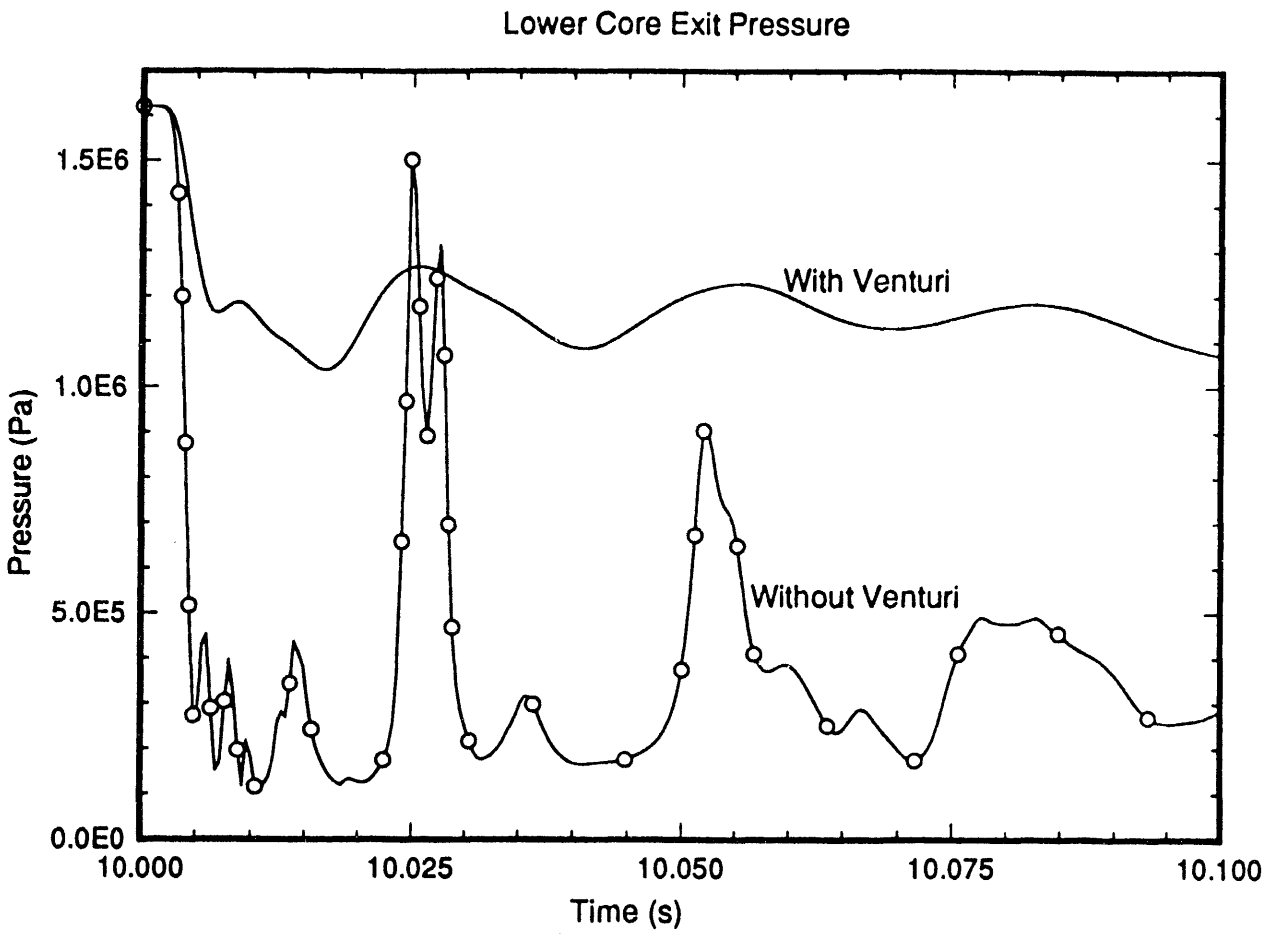

Fig. 3. Comparison of lower core exit pressure with and without a cavitating venturi in place downstream of the core during a double-ended hot leg break.

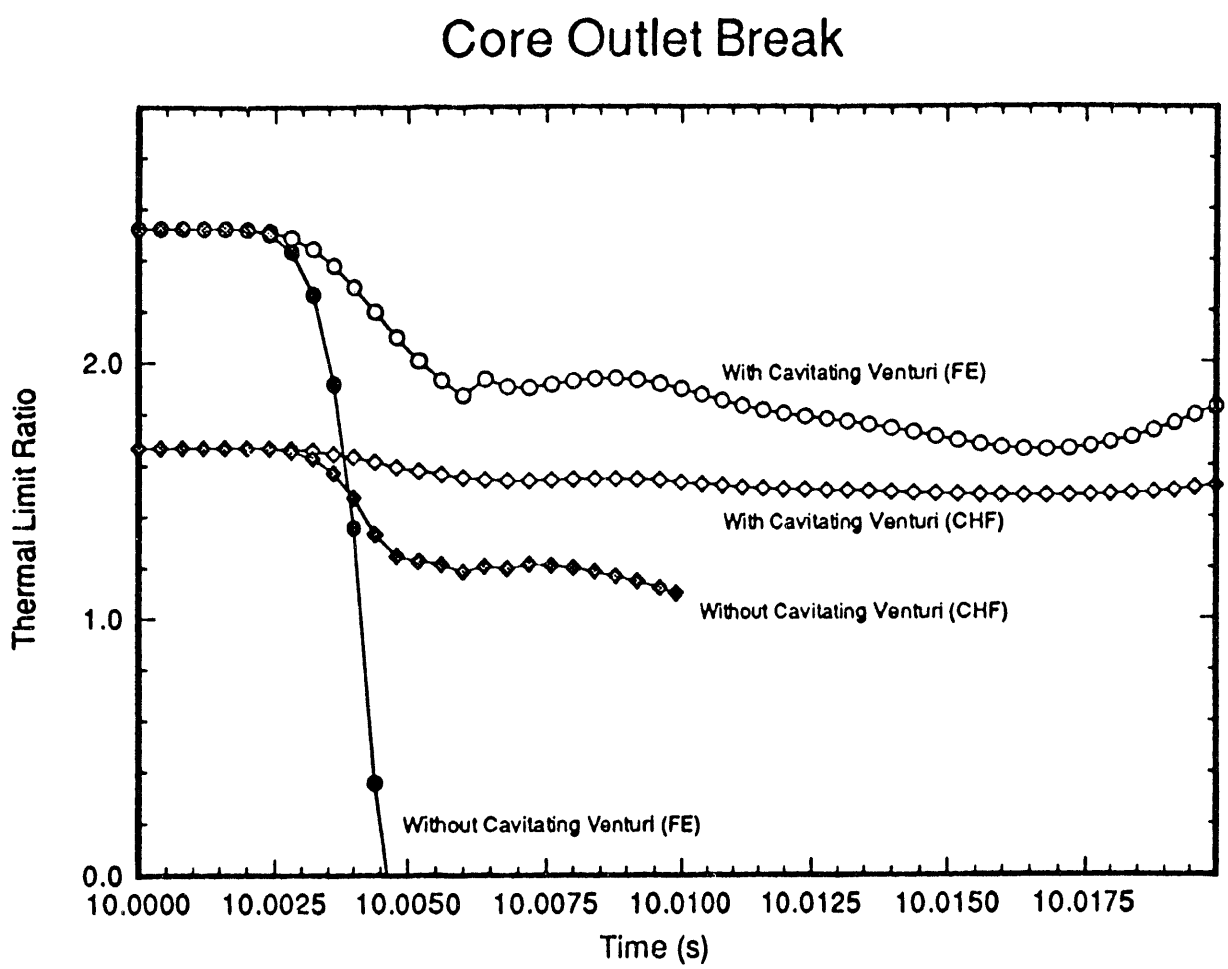

Fig. 4. Comparison of thermal limit ratios with and without a cavitating venturi in place downstream of the core during a double-ended hot leg break.

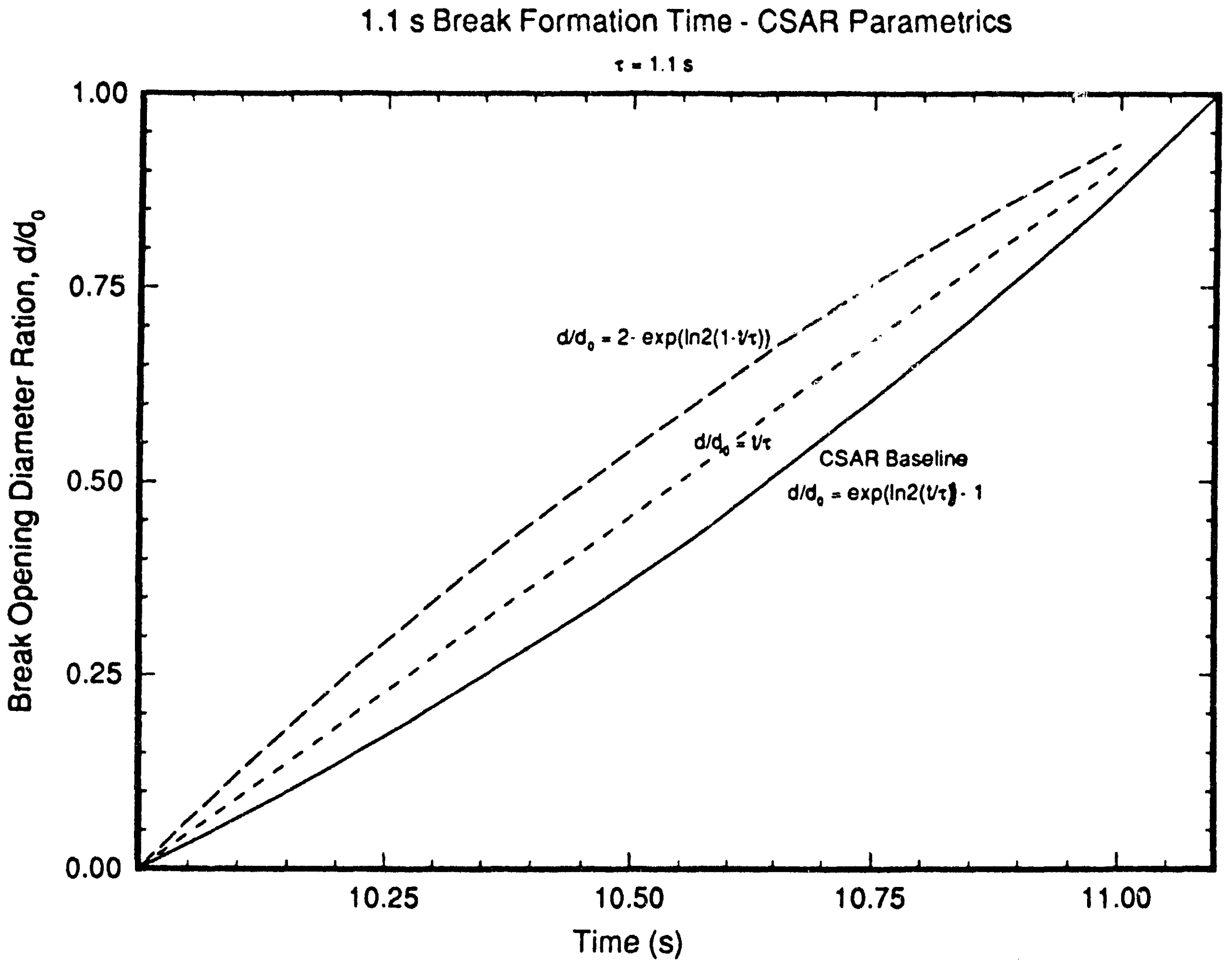

Fig. 5. Comparison of three different assumptions for the rate at which the diameter of the break orifice increases during a double-ended core inlet break.

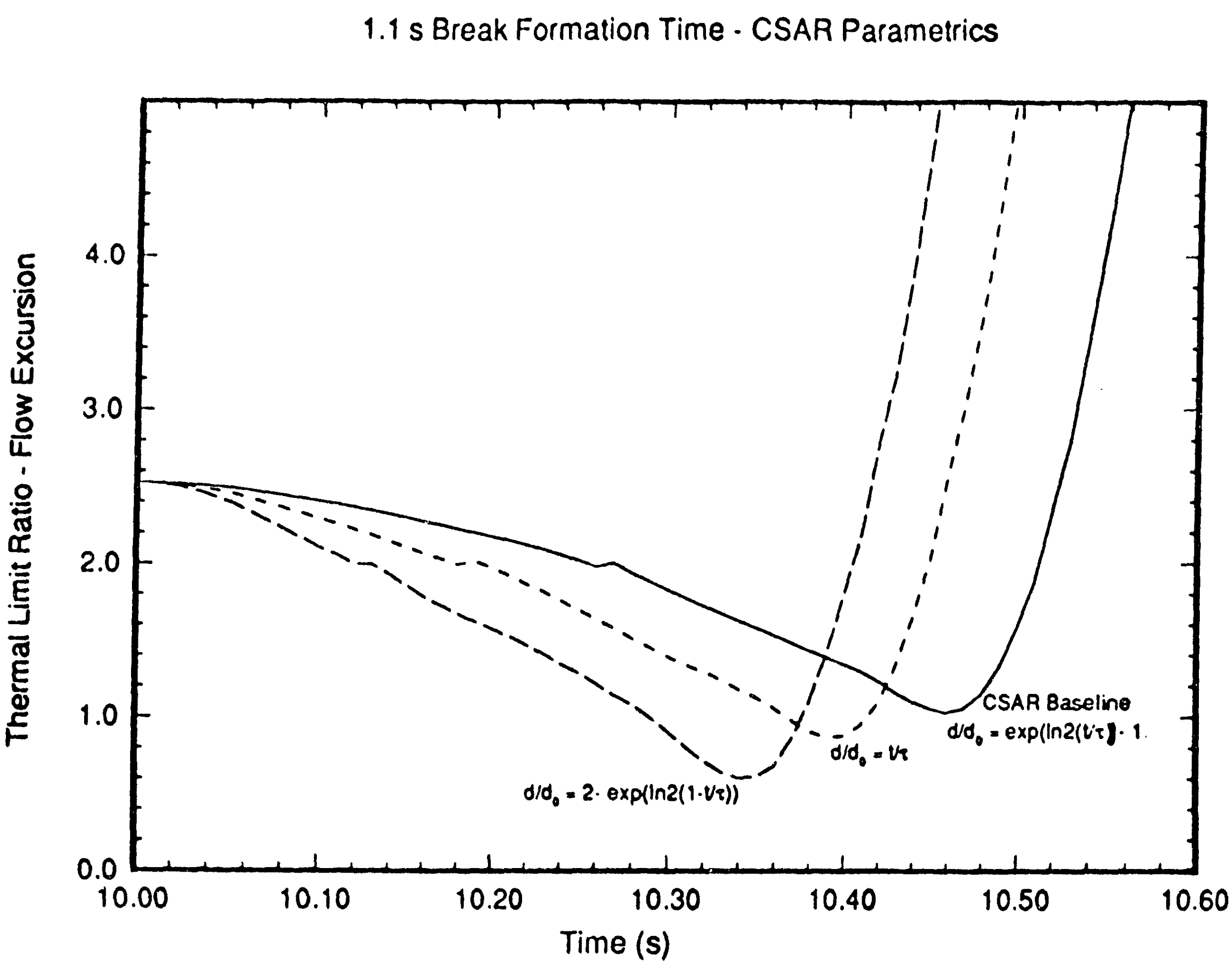

Fig. 6. Thermal limit ratios (FE) for three different assumptions for the rate of break formation.

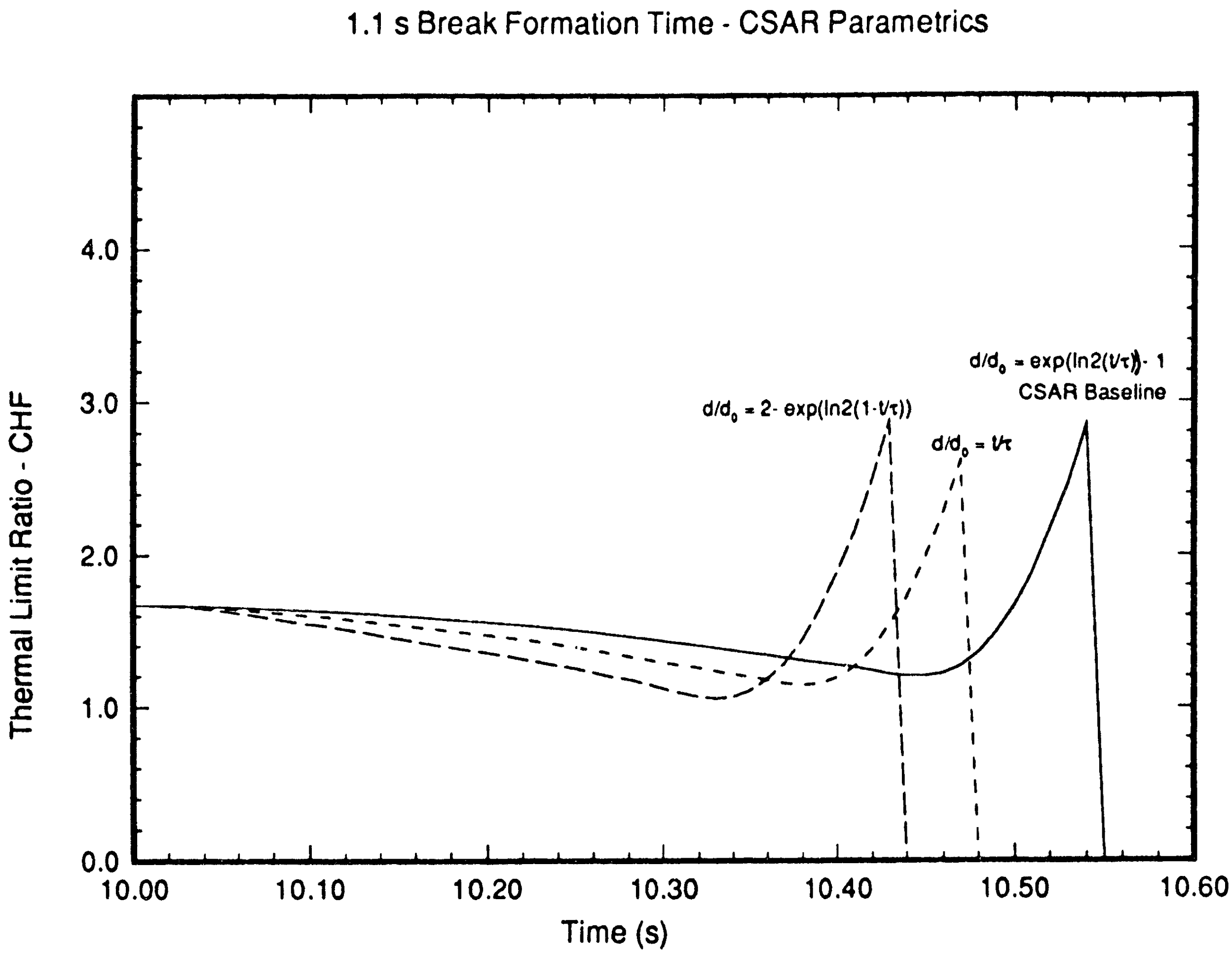

Fig. 7. Thermal limit ratios (CHF) for three different assumptions for the rate of break formation.

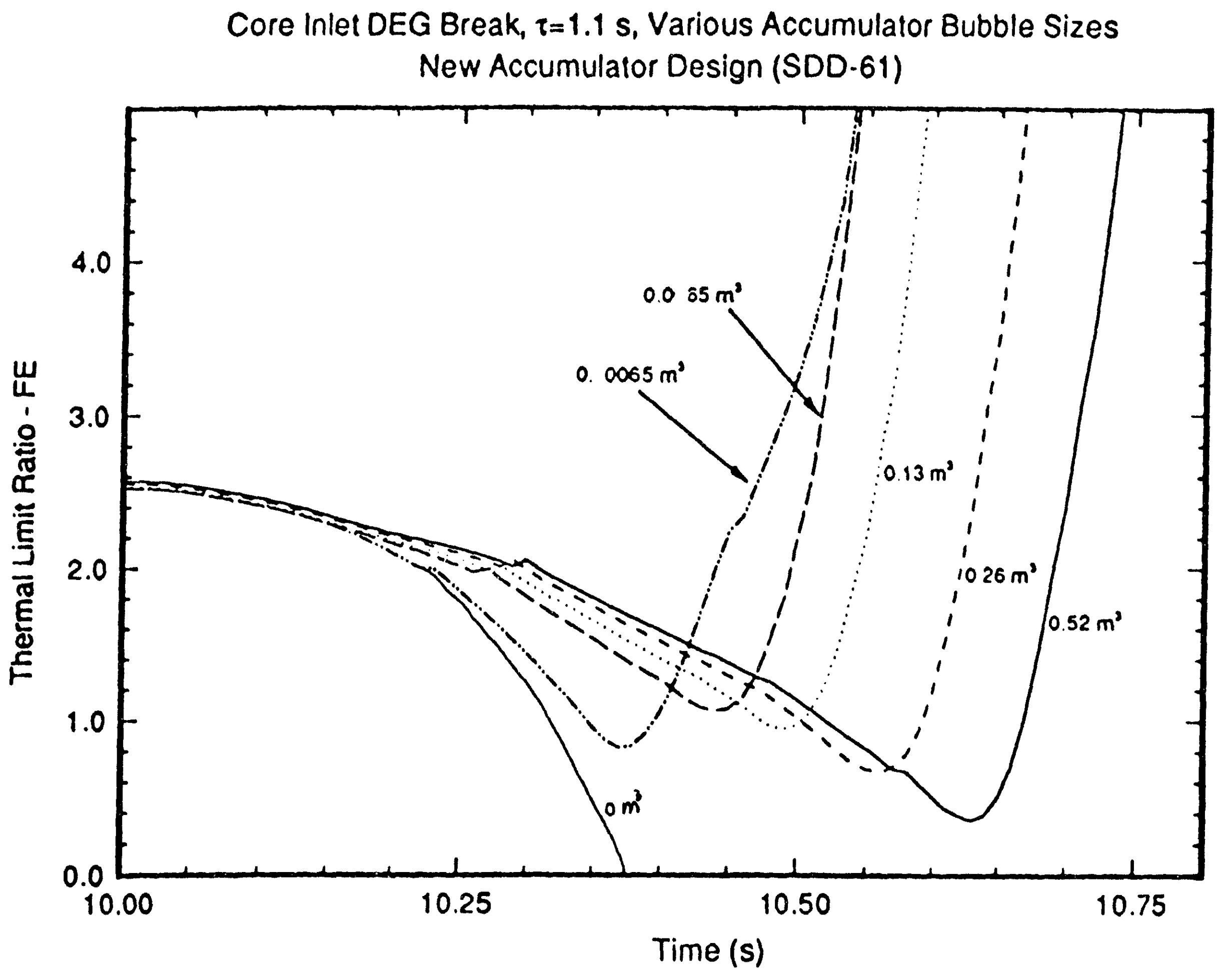

Fig. 8. FE thermal limit ratio for various accumulator bubble sizes during a double-ended core inlet break.

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