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LOSS-OF-COOLANT ACCIDENT ANALYSES OF THE ADVANCED NEUTRON SOURCE REACTOR*

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INTRODUCTION

Currently in the conceptual design stage, the Advanced Neutron Source Reactor (ANSR) will operate at a high heat flux, a high mass flux, and a high degree of coolant subcooling. Loss-of-coolant accident (LOCA) analyses using RELAP5 have been performed as part of an early evaluation of ANSR safety issues. This paper discusses the RELAP5 ANSR conceptual design system model and preliminary LOCA simulation results. Some previous studies were conducted for the preconceptual design[1-3].

The ANSR design features an axially split and offset core cooled by upward flowing heavy water and is assembled from thin involute-shaped aluminum clad fuel plates and cylindrical aluminum side plates. The core central region contains control rods cooled by a portion of the heavy-water coolant flow. The core assembly is contained within an aluminum core pressure boundary tube surrounded by a heavy water moderator tank. The core inlet and outlet piping and the moderator tank are submerged in a light-water pool.

The reactor cooling system features a single hot leg and multiple cold legs between the reactor and the hot and cold leg distribution headers. Four coolant loops, three active and one standby, are connected in parallel across the distribution headers. Each loop consists of hot leg piping, a horizontal U-tube main heat exchanger, a horizontal U-tube emergency heat exchanger, a centrifugal main coolant pump, and cold leg piping.

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Emergency heat exchangers, cooled by natural circulation of pool water on the secondary side, are placed in series with the primary heat exchangers. Primary coolant in both heat exchangers circulates through the shell side for easier maintenance. Additionally, three accumulators (gas pressurized liquid volumes), one per loop, are located between the main circulation pumps and the emergency heat exchangers to decrease the system depressurization rate in the event of depressurization transients.

Primary coolant system pressure is modulated through letdown valves and a pressurizing pump system. Monitored by the core inlet pressure, the letdown flow is removed from each of the heat exchanger inlet sides and circulated through a clean-up system and returned to the pressurizing system by high head pumps. The injection point is located at the common hot leg upstream of the hot leg distribution header.

A spectrum of LOCAs (76 mm-, 152 mm-, and 203 mm-breaks located between the core inlet and the cold leg distribution header) was performed to understand thermal hydraulic behavior and determine limiting break sizes. For the largest break, hot spot thermal limits are encounted very early in the event before the accumulator can be activated, reactor can be scramed, and main circulation pump begins coastdown. Because the closest approach to burnout occurs within 30 ms after break initiation, results are presented only in the first 200 ms and events which take place after that time are not discussed.

MODEL DESCRIPTION

The ANSR RELAP5 system model includes three major regions (see Fig. 1). The core model (region 1) consists of the core halves, coolant bypasses, and a central hole region. Core power is calculated using a point kinetics model with reactivity feedback from coolant density change and control rod movement. Distributions of core power among the various metal and fluid regions and uncertainty multipliers for the hot streak (1.14) and the hot spot (1.31) are based on the preconceptual core design. Relative axial power profiles in the average and hot channels are based on the I3 fuel loading design (an internal designation representing a particular radial and axial distribution of fissile material within the active fuel region) at the end of the cycle, which is the limiting condition under steady-state operations[4,5]. A uniform aluminum oxide thickness of 13.17 μm is assumed to be present on the fuel plates by selecting the maximum oxide layer present within the hot channel after 14 days of operation.

The loop model contains four independent heat exchanger loops, three active and one standby (region 2). The main and emergency heat exchanger models are adjusted to provide correct flow rates and pressure drop characteristics at design conditions. The single-phase homologous curve of the main circulation pumps was developed from three-quadrant Byron Jackson design curves[6] (model Ns 1840) and two-phase corrections were based on Semiscale data[7].

An open-loop representation of the letdown and pressurizing system (region 3) is included in the model. In the design, primary system pressure is controlled through modulation of the letdown valves. This is modeled using a specified letdown flow velocity. Trip sensor locations, setpoints, and delay times remain the same as in the preconceptual design. The accumulator model assumes a 2 m^3 tank volume filled with 1.95 m^3 of heavy water and a 0.05 m^3 nitrogen cover gas initially at the pool water temperature. These assumptions are made so that an isothermal expansion of the gas bubble from the initial state to atmospheric pressure would not result in emptying accumulator tanks.

In developing the model, each component within the primary loop was first calibrated independently and then all were combined to form the full core/loop model. A steady-state full power operating condition was established by iterative reinitialization until the heat addition balanced heat rejection and all nominal operating conditions (such as core power, core inlet temperature/pressure, and core pressure drop) are met. This steady state was used as a starting point for the LOCA transients.

Execution of the system model was made with the RELAP5/MOD2 computer code[8] on an IBM RISC system 6000, model 320 workstation. The critical heat flux (CHF) correlations existing in this version of RELAP5 were modified. For high mass flux (above 200 kg/m^2 -s), the Costa flow excursion model[9] (used when subcooling is larger than 5 °C) is incorporated with the Biasi CHF correlation[10] (used when subcooling is less than 5 °C); for low mass flux (below 100 kg/m^2 -s), the modified Zuber correlation[11,12] is applied.

RESULTS AND DISCUSSION

When the break opened at 10 s, a depressurization wave propagated around the primary coolant system from the break location. The depressurization (Fig. 2) wave reached the core outlet within 15 ms. This delay agrees reasonably with the 10 ms required for a wave to travel the 15.6 m from the break point to the core outlet at an approximate sound speed of 1540 m/s. The declining core outlet pressure first resulted in accumulator injection at about 14 ms. The letdown flow was isolated at roughly 17 ms upon a low core inlet pressure trip. For the 203 mm break, the CHF was exceeded at about 26 ms. A reactor trip signal on low core exit pressure (1.68 MPa) was generated at about 20 ms but scram rod insertion did not start until 80 ms because of a 60 ms delay due to sensor and mechanical factors.

Events taking place after 200 ms for the 152 mm break are included for completeness.

The main circulation pump began coastdown at 5 seconds, the accumulator drained at 7 seconds, and the pump reached pony motor speed (15% of normal pump speed) at 15 seconds after the break opened.

The rate of pressure change within the break volume is determined by the sum of incoming and outgoing mass flow rates across the volume boundaries. For this volume, the incoming mass flows include three pump flows and three accumulator flows and the outgoing mass flows are core inlet flow and the break flow. When the incoming flow is less than the outgoing flow, the pressure in the volume decreases. When the reverse is true, the volume pressure increases. Immediately after the break is initiated, the break flow overwhelms the accumulators injection flows and a rapid depressurization results. Soon after, the depressurization wave reaches the pump discharges and pump flow increases. As a result, the cold leg pressure recovers, the break flow increases, and the cycle is repeated until the oscillations are damped.

Break and total accumulator mass flows are compared in Fig. 3. For each break, the accumulators do not become active rapidly enough to significantly slow the rapid depressurization early in the transients. It takes about 14 ms after break initiation to begin injecting flow into the system, while break flow begins immediately upon break initiation. Consequently, it is suggested that relocation of accumulators closer to the break, rather than increasing accumulator size alone, would shorten the reaction time and thereby improve the system depressurization rate.

Temperature transients at the hot spot, located at the hot channel exit of the upper core, are shown in Figs. 4 and 5. For the 152 mm break, wall temperatures exceed saturation temperatures by a maximum of only 30 °C at the times of 26 ms and 140 ms where insignificant voiding occurred as seen in Fig. 6. On the contrary, for the 203 mm break, the hot spot wall temperatures exceed saturation temperatures at about 26 ms and continue to rise sharply when the CHF limit is exceeded by the local heat flux (Fig. 7). During the post-CHF period, significant void generation at the hot spot occurs as shown in Fig. 6. Interested readers should refer to the report by Fletcher and Ghan[2] for discussions of processes of void growth and collapse in the hot channel bounded by fuel- and side-plates.

The hot spot heat flux, expressed as a fraction of Costa-flow-excursion-predicted values, is plotted verses time in Fig. 7. The Costa correlation is linearly proportional to coolant subcooling and the square root of velocity. For the 76 mm break, the fraction is calculated to be relatively small, fluctuating around a mean of about 0.25. For the 152 mm break, two peaks were observed with considerably greater values. The first and second peaks with values of 0.75 and 0.95 occurring at times of 26 and 140 ms correspond closely to the first and second core outlet pressure minima (see Fig. 2). The second peak shows a higher value because a lower pressure leads to a lower saturation temperature, and consequently a lower Costa prediction. This latter peak significantly reduces core thermal margin. Contrary to the other two breaks, the 203 mm break displays a fraction exceeding unity at 26 ms. At that time, the local heat flux exceeds the flow excursion limit and film boiling is indicated by the rapid drop in surface heat flux and resulting sharp surface temperature rise. Values above unity are not captured because of the sparse data plotting frequency.

CONCLUSIONS

Three transient simulations, starting from 350-MW full-power conditions, were completed for 76 mm-, 152 mm-, and 203 mm-breaks located between the core inlet and cold leg distribution header. These calculations indicate that the ANSR conceptual design can survive both 76 mm- and 152 mm- breaks, but flow excursion would be exceeded for a 203 mm break. This fuel damage occurs at about 26 ms, early in the transient before scram insertion (initiated at about 80 ms) can reduce core power. Design modifications to accelerate scram reactivity insertion or slow the depressurization rate by accumulator relocation may eliminate the early fuel damage. Other design modifications involving elimination of the cold leg distribution header, preferred direction flow orificing at the cold leg connection to the core pressure boundary tube, larger accumulator surge lines, and larger accumulators are under consideration and may also help to eliminate early fuel damage.

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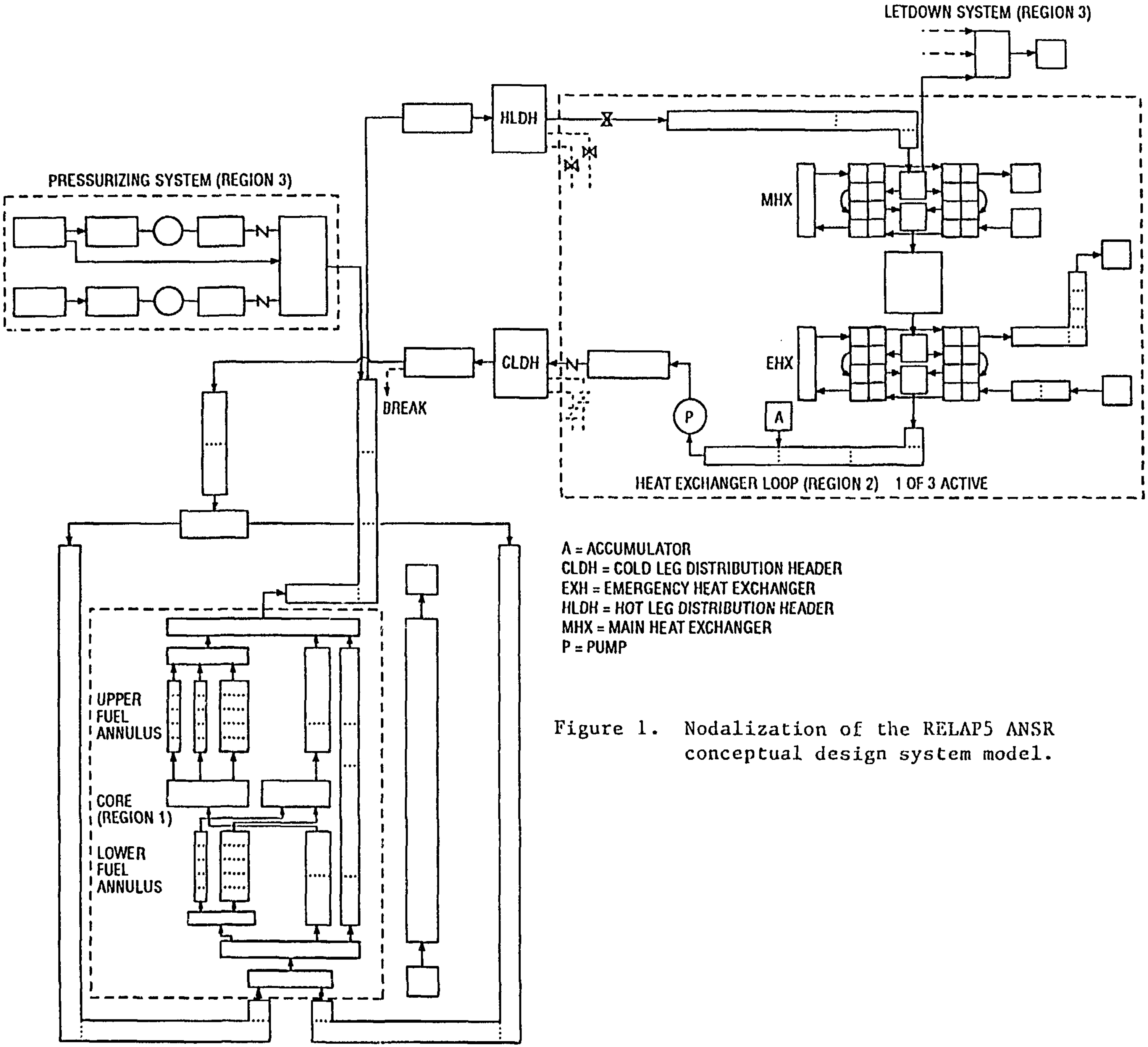

A = ACCUMULATOR
CLDH = COLD LEG DISTRIBUTION HEADER
EXH = EMERGENCY HEAT EXCHANGER
HLDH = HOT LEG DISTRIBUTION HEADER
MHX = MAIN HEAT EXCHANGER
P = PUMP

Figure 1. Nodalization of the RELAP5 ANSR conceptual design system model.

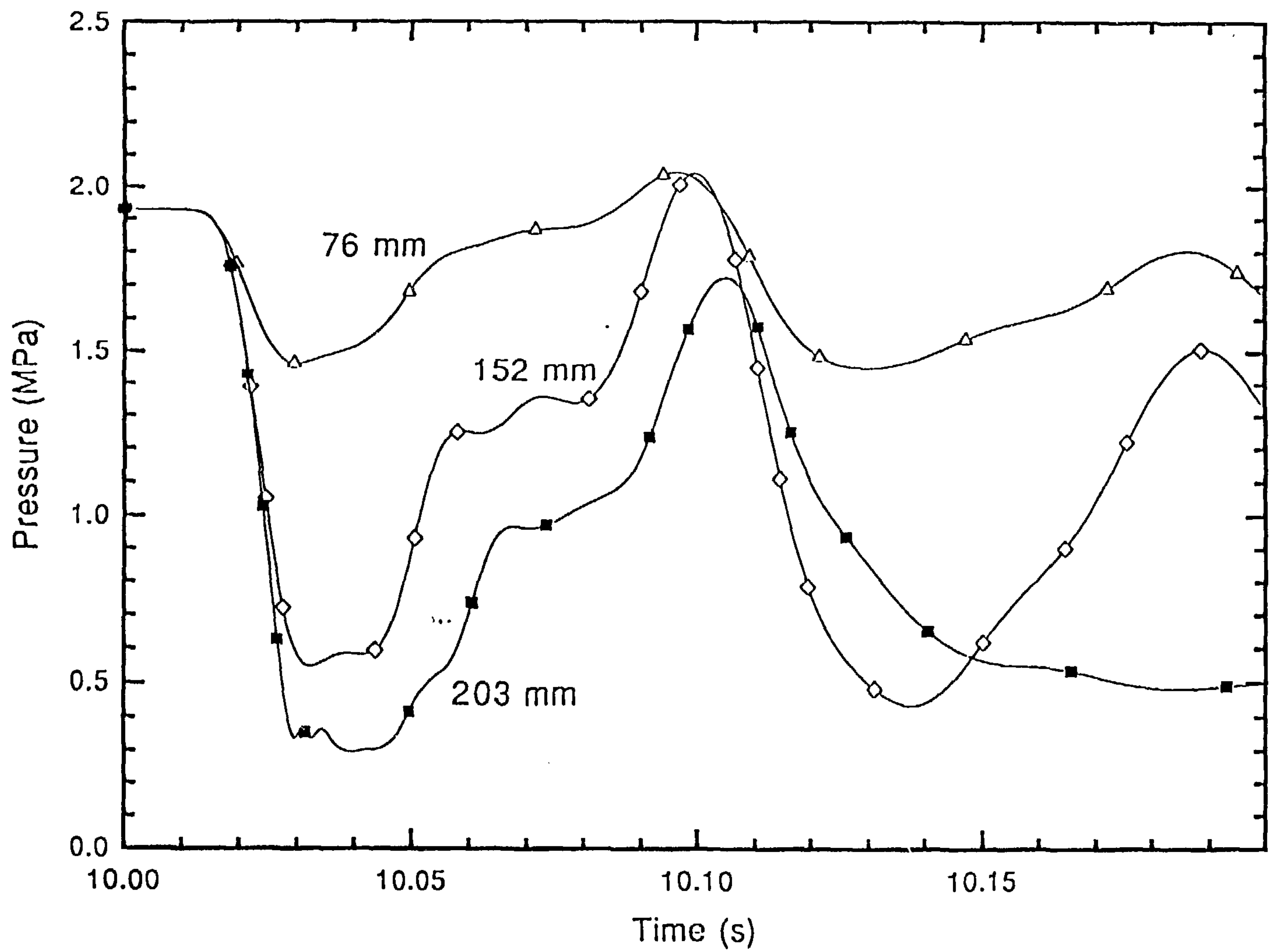

Figure 2. Core Outlet Pressure Response.

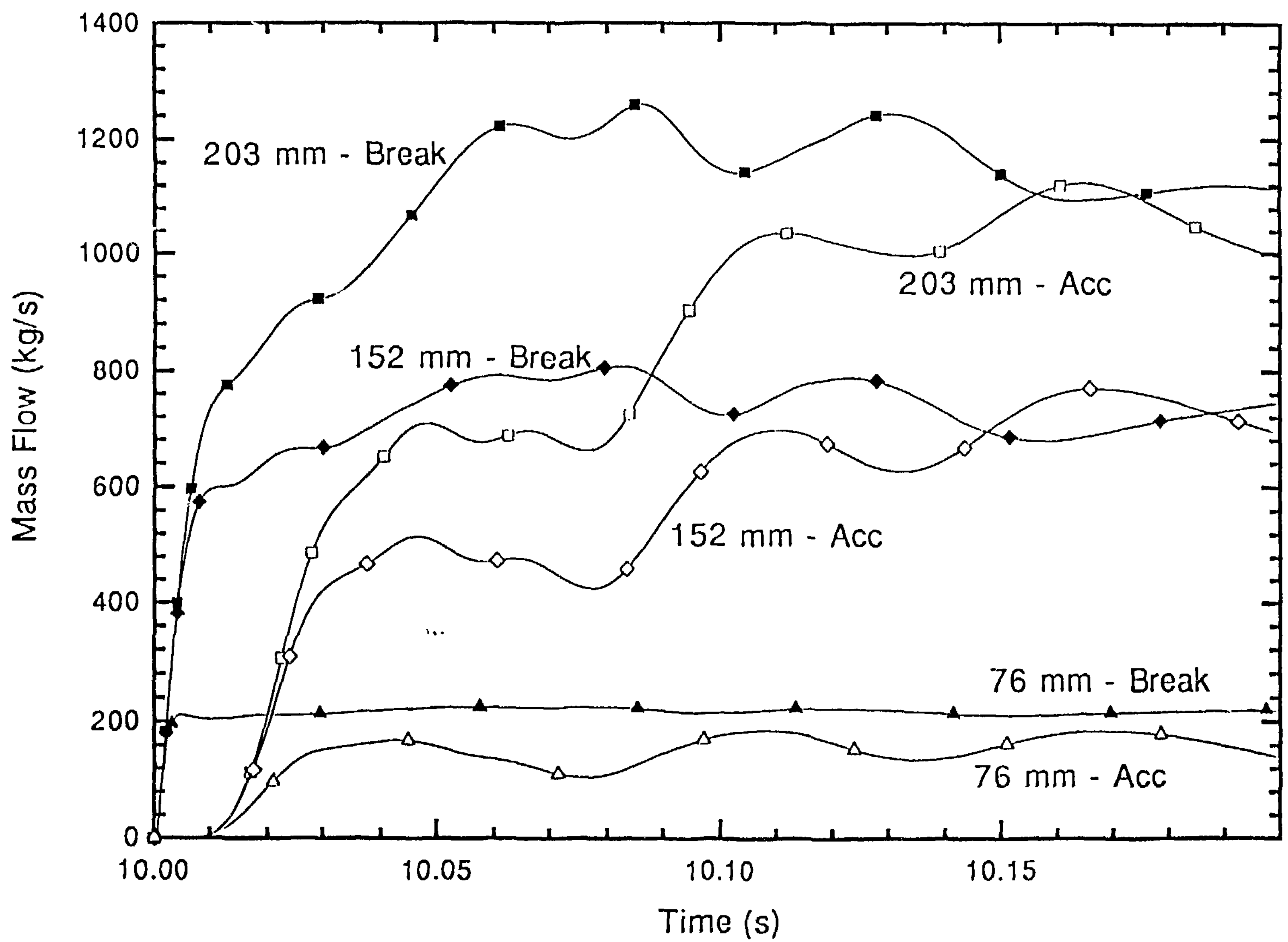

Figure 3. Accumulator and Break Flow Rates.

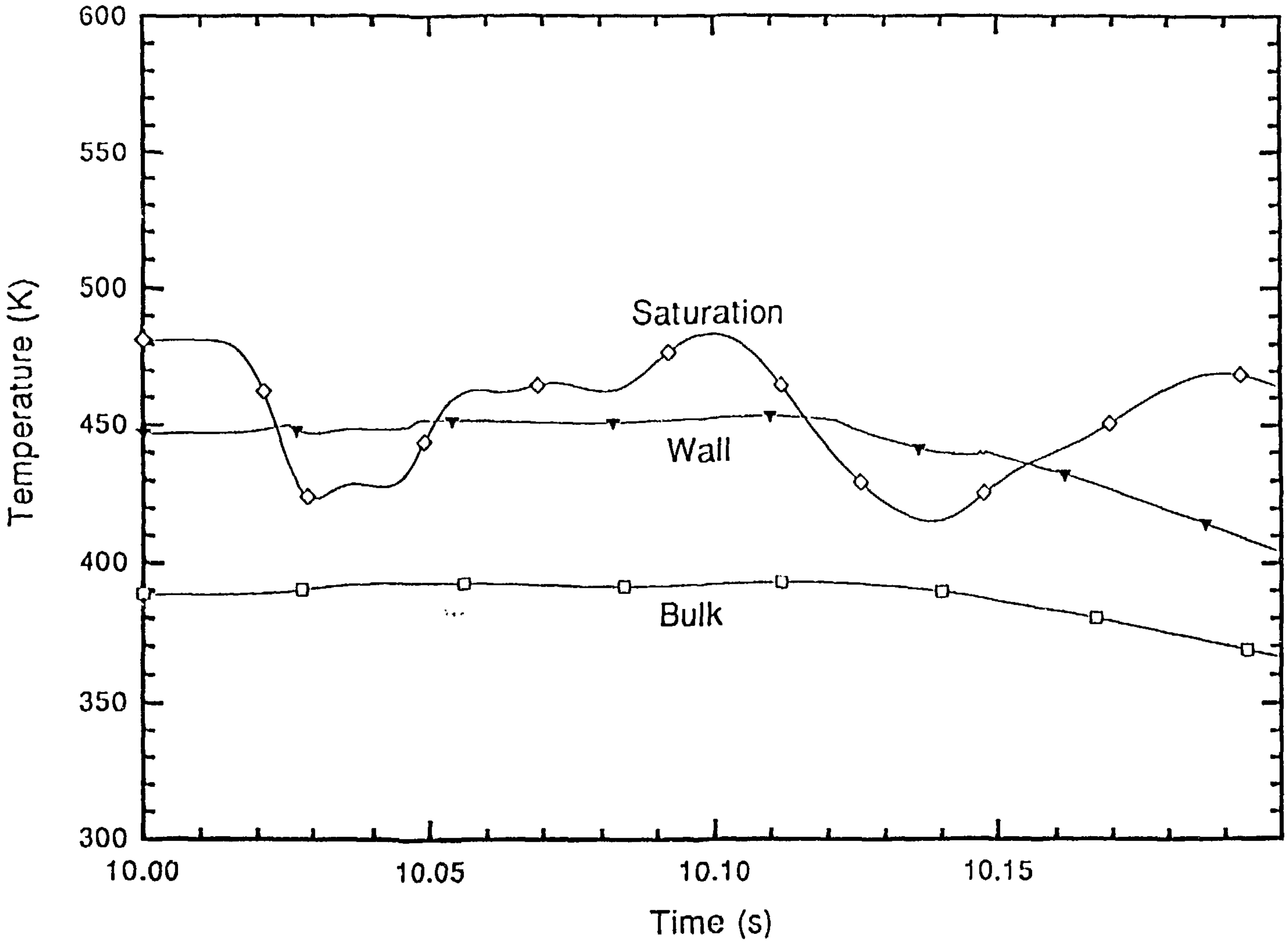

Figure 4. Hot Spot Temperature Response - 152 mm break.

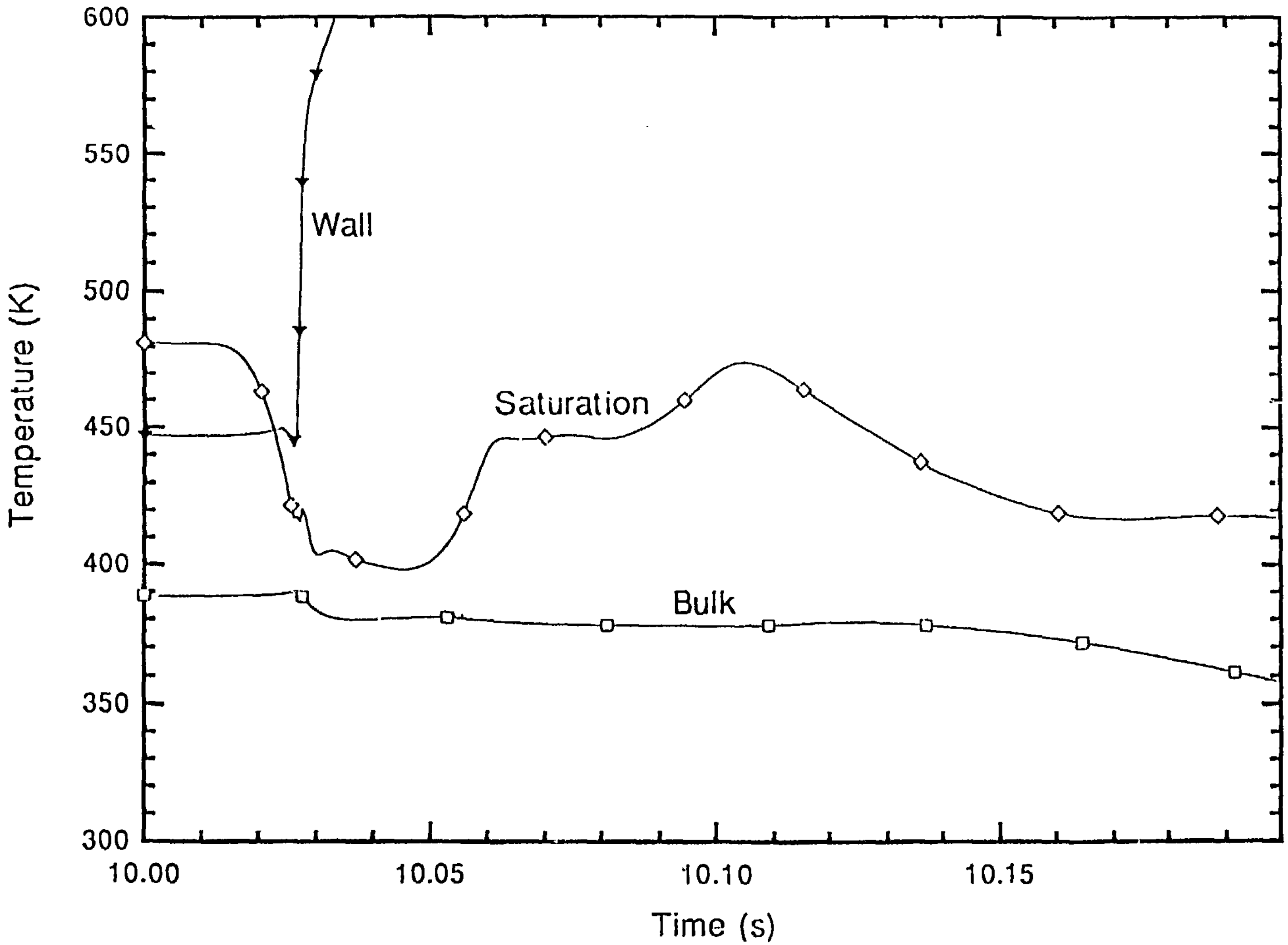

Figure 5. Hot Spot Temperature Response - 203 mm break.

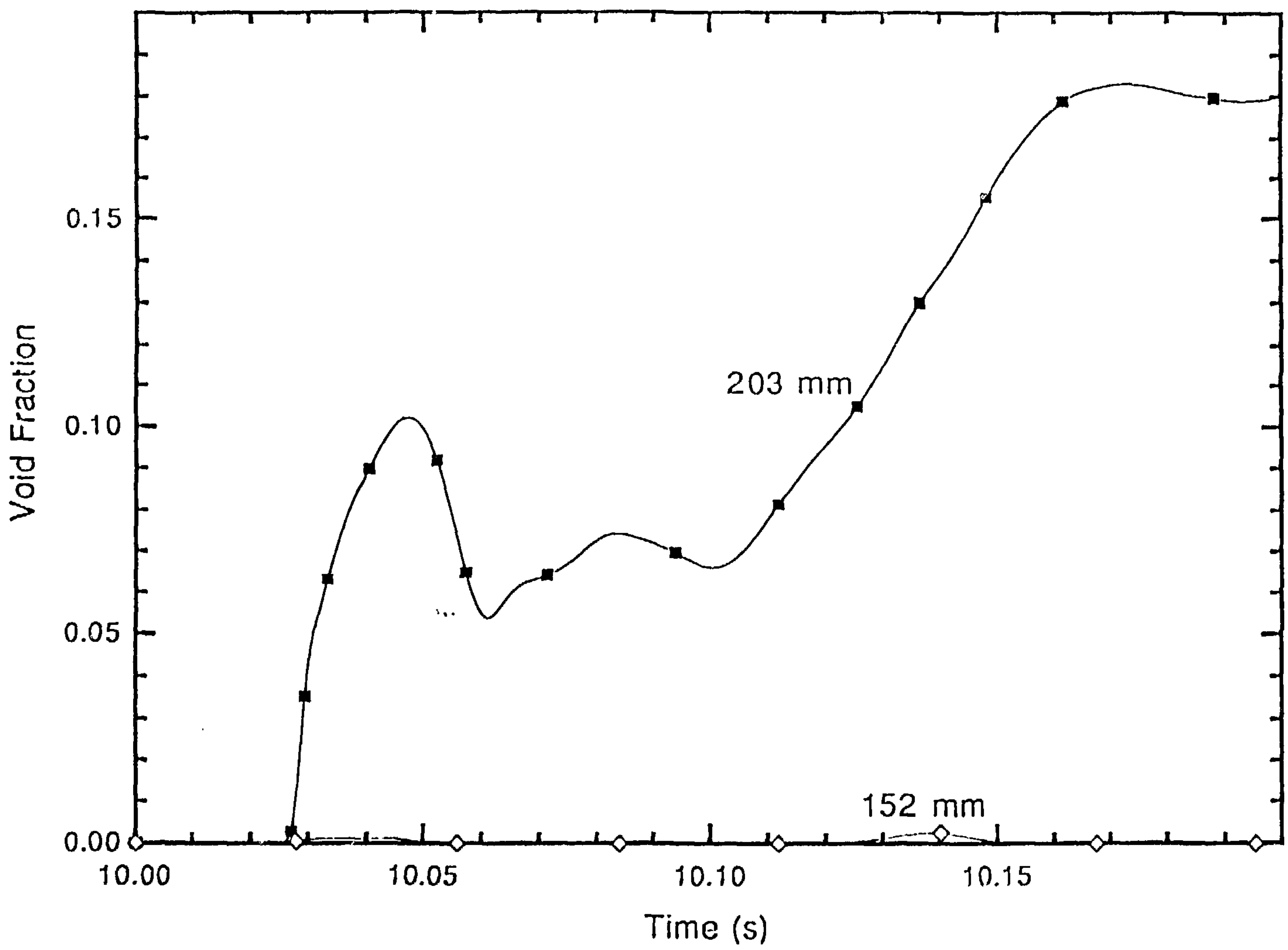

Figure 6. Local Void Fraction at the Hot Spot.

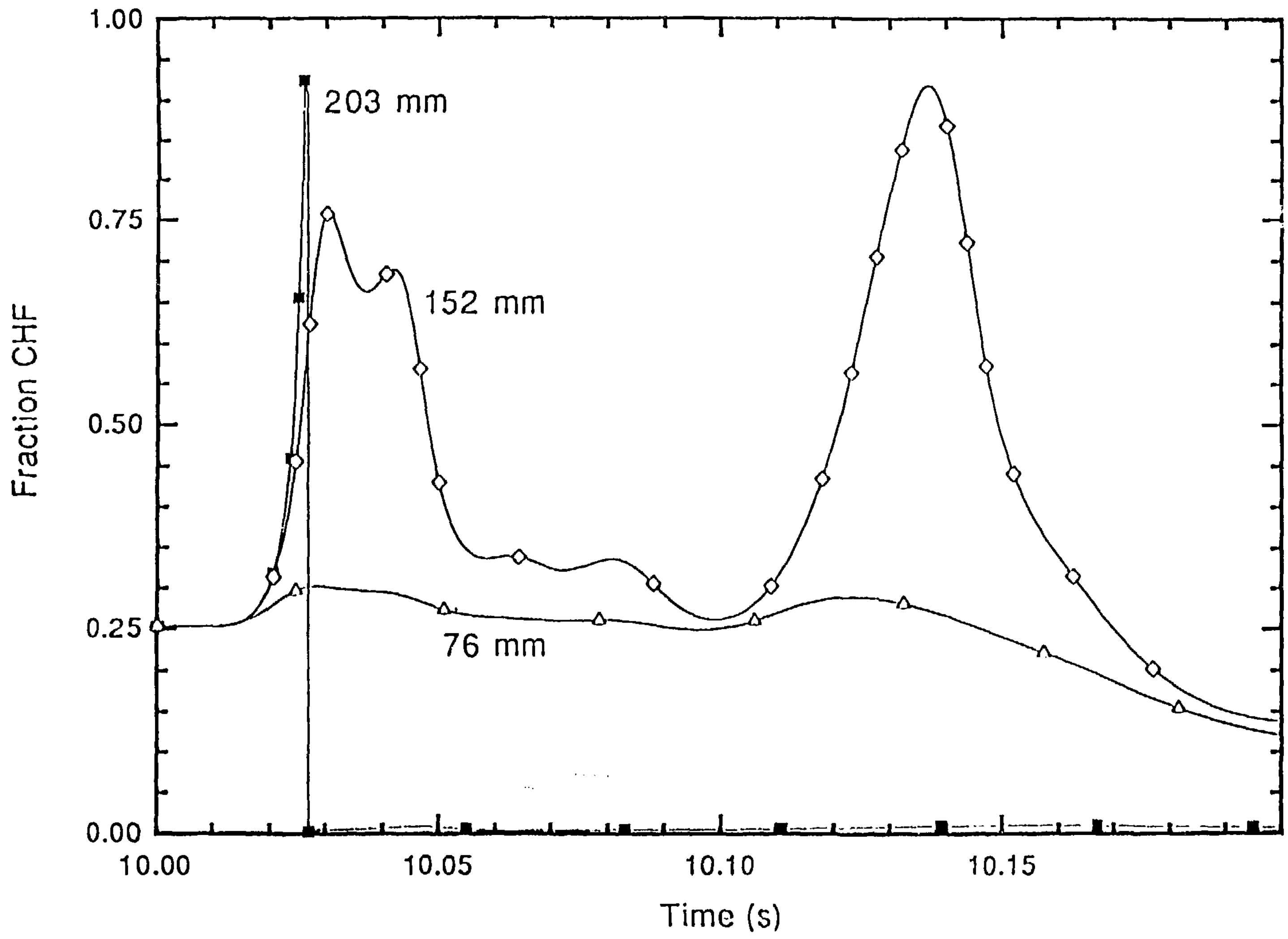

Figure 7. Local Heat Flux normalized by the Costa CHF at the Hot Spot.