Modelling of HIFAR Thermal-Hydraulics Using RELAP5/MOD2

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Abstract In this paper, a thermal-hydraulic computational model of HIFAR (**H**igh **F**lux **A**ustralian **R**eactor), using a computer program called RELAP5/MOD2 (**R**eactor **L**oss of **C**oolant **A**nalysis **P**rogram, version **5/MOD2**), is described. The purpose of the model is to provide a state-of-the-art thermal-hydraulic simulation tool for analysing selected hypothetical accident scenarios in HIFAR. The current model includes (1) a primary cooling system with three heat exchangers using heavy water coolant; (2) a secondary coolant system using light water (with less detail than the primary system). In the present modelling stage, our attention has been focused on the distribution of coolant flow and on cooling of the core under steady-state conditions. Some preliminary results of HIFAR thermal-hydraulic analyses are presented.

1. INTRODUCTION

Analysis has played a unique role in nuclear reactor safety because full-scale demonstration experiments (or actual events) normally available to evaluate the accident behaviour of industrial products (e.g., automobiles and aircraft) are not available nor practical to obtain in the case of nuclear reactors. The diversity of reactor system designs and the numerous potential events to be considered make the required large number of full-scale experiments prohibitively expensive. Consequently, a greater than usual responsibility has been placed on the reactor safety analyst to be rigorous and accurate in the development and testing of analysis tools.

HIFAR is a heavy water moderated and cooled, materials testing and research reactor producing a maximum thermal neutron flux of 10^{14} neutrons per square centimetre per second at a heat output of 10 megawatts. To make the nuclear reactor safer and more reliable, comprehensive analyses of various emergency situations in it are required. Many scenarios are possible. However, if we stop to consider only one of them, specifically, reduction of the flow rate of the coolant in the reactor, this process in itself will involve many problems of thermal-hydraulics.

A number of advanced computer codes now are available to carry out reactor thermal-hydraulic analyses. One of them is RELAP5/MOD2 which was originally developed in Idaho National Engineering Laboratory, US and was originally designed to analyse the thermal-hydraulic behaviour of light water and pressurised power reactor systems in which operating conditions are normally at high-pressures and high-temperatures. In the present work, the RELAP5/MOD2 program has been used for thermal-hydraulic analysis of our research reactor, HIFAR at ANSTO, under the operational condition of low-pressure and low-temperature with heavy water as coolant in the primary cooling system. The development of analytical tools for reactor safety analysis will continue to be a very challenging task. The physical phenomena that can exist under postulated accident conditions have required the development of new analytical models and associated numerical solution methods. The large number of components and the complexity of accident phenomena have necessitated innovative application of even the most sophisticated modern computers to achieve the desired results in practical computation times.

The requirement to model two-phase flow conditions has either directly or indirectly accounted for the greatest part of the technical development effort. Under Loss of Flow Accident (LOFA) conditions, such as possible in HIFAR, nonhomogeneous, nonequilibrium and multidimensional flow effects can be important. New hydrodynamic models have to be developed to account for these phenomena. The presence of two-phase flow also influences the performance of pumps, the flow through valves, orifices, and postulated breaks.

The present work attempts to build a computational model of HIFAR, using the RELAP5/MOD2 program and to provide a state-of-the-art thermal-hydraulic simulation tool for analysing selected hypothetical accident scenarios in HIFAR. Currently, the HIFAR model including a primary cooling system with three heat exchangers using heavy water coolant coupled to a secondary coolant system using light water, has been developed. The coolant flows in both the primary and secondary systems with heat transfer through three heat exchangers have been simulated under the designed operating condition. Some preliminary calculated results using the developed model are presented.

2. RELAP5/MOD2 COMPUTER PROGRAM

The RELAP5 family of codes was developed at the Idaho National Engineering Laboratory with U.S. Nuclear Regulatory Commission support for best estimate transient simulation of water nuclear reactors and associated systems. The RELAP5/MOD2 code is a one-dimensional, transient analysis code for thermal-hydraulic systems, and it employs a nonhomogeneous and nonequilibrium flow model for two-phase regions to predict pressures, temperatures, void fractions and flow rates. The code available at ANSTO is the ATR (Advanced Test Reactor) specific version, which incorporates aluminium type fuel, and D_2O coolant properties.

A series of benchmark calculations were performed to validate the installation of the code at ANSTO. The benchmarks were selected from the assessment problems developed previously at Idaho National Engineering Laboratory.

The assessment problems performed using the installed version of RELAP5/MOD2 at ANSTO include: Nine-Volume Water Over Steam, Branch Tee Problem, Crossflow Tee Problem, Edwards Pipe Problem with Extras, A Three-Dimensional Flow Problem, Bennett's Heated Tube Experiments, ORNL Bundle CHF Tests, Wyle Small Break Test and a Workshop Problem. The computed results were compared with those presented in RELAP5 Code Manual Volume 3 (Carlson, 1990). All results are in reasonably good agreement with the previous ones.

3. HIFAR MODEL

3.1 HIFAR Primary Cooling System Model

A flow diagram of the HIFAR primary cooling system is shown in Figure 1. Heavy water (D_2O) is used as both moderator and primary coolant in the primary cooling system. Essentially, the system consists of the Reactor Aluminium Tank (RAT) and the external piping, pumps, heat exchangers, etc. in a shielded plant room beneath the biological shield. It is designed for a 240 kPa plus working pressure. Of the ten tonnes of heavy water in the system, six tonnes are in the RAT. The compact system minimises heavy water investment; similar economic reasons require a high standard of system cleanliness and integrity.

Heavy water flows from the RAT through four 180 mm bore pipes incorporating Dall flow measuring elements into a 254 mm bore suction header for the circulating pumps. The main circulators are 52.2 kW Hayward Tyler totally submersible mixed-flow pumps, which have a squirrel cage motor and pump impeller in the same casing. If operated singly each main pump would deliver 270 kg s^{-1} of heavy water at 120 kPa. Two pumps must be running during normal operation, providing a flow of 400 kg s^{-1} at 258 kPa.

The pumps deliver heavy water to a discharge header connected to the tube sides of three heat exchangers which are all normally in service and are cooled on the shell side by light water. The secondary cooling system will be discussed in the next section. The cooled heavy water enters the RAT plenum chamber, where it is distributed to the 25 fuel elements through the nozzles on which the elements are seated. The coolant flows through the fuel element coolant passages and discharges into the RAT through ports in the fuel elements immediately above the fuel tubes.

The RELAP5 nodal diagram of the HIFAR primary coolant system model is shown in Figure 2. The RELAP5 model of the HIFAR primary coolant system is composed of the following main hydrodynamic components: two pumps, three heat exchangers, core component, suction and discharge headers, low plenum, reactor tank and upper pool model, and a number of valves and pipes.

The model consists of hydrodynamic volumes (fluid control volumes, here each rectangular box in the nodal diagram represents a single control volume (node) in the RELAP5 model), hydrodynamic junctions (momentum control volumes, here lines that link the boxes indicate the connectivity of the volumes using the various junctions such as single junctions, branch junctions and time-dependent junctions), and heat structures (here the shaded areas represent the heat structures).

Three pipe components, 150, 160 and 170, with heat structures represent three heat exchangers in the side of the primary cooling system. Each heat exchanger is discretized into three hydrodynamic control volumes and is cooled through heat structures by light water in the secondary side. In the current model, the core is modelled by the pipe component (110) and will provide heat power as a function of time to reach a steady-state condition. A sink model is specified in the top of the upper pool in order to get a reference pressure for the circulating system.

3.2 HIFAR Secondary Cooling System Model

The secondary cooling system circulates light water to transport heat from the main heat exchangers and dissipate it to the atmosphere in cooling towers. The system comprises four main and two shut down circulators in the pump house, drawing water from a pond and delivering it to an inlet header in the Reactor Containment Building (RCB). The header distributes it to the heat exchangers, from whence it flows to a discharge header. The water leaves the RCB and is distributed to six cooling towers. The cooled water flows from the tower basins to the pond. The circuit is shown in Figure 3.

The main circulators are three horizontal shaft centrifugal pumps, each delivering 133 kg s^{-1} at 150 kPa. The cooling towers are of evaporative counter flow design. When the reactor is operating at high power there is full flow through the main heat exchangers and the reactor temperature is controlled by varying the secondary coolant temperature. The towers can dissipate 13 MW from 360 kg s^{-1} water at an inlet temperature of 30°C with an ambient wet bulb temperature of 20°C.

The RELAP5 nodal diagram of the HIFAR secondary coolant system model is shown in Figure 4. Three pipe components, 250, 260 and 270, with heat structures represent three heat exchangers in the secondary cooling system side. Each heat exchanger is discretized into three hydrodynamics control volumes. The heat transfer coupling between the secondary and primary cooling system is carried on through the heat exchangers, 150, 160, and 170 in the primary cooling system side.

The suction, inlet and outlet headers are modelled by three branch components (203, 204, 205), respectively. The cooling tower model is composed of a branch component (206), two time-dependent volumes (208, 209) and a time-dependent junction (229).

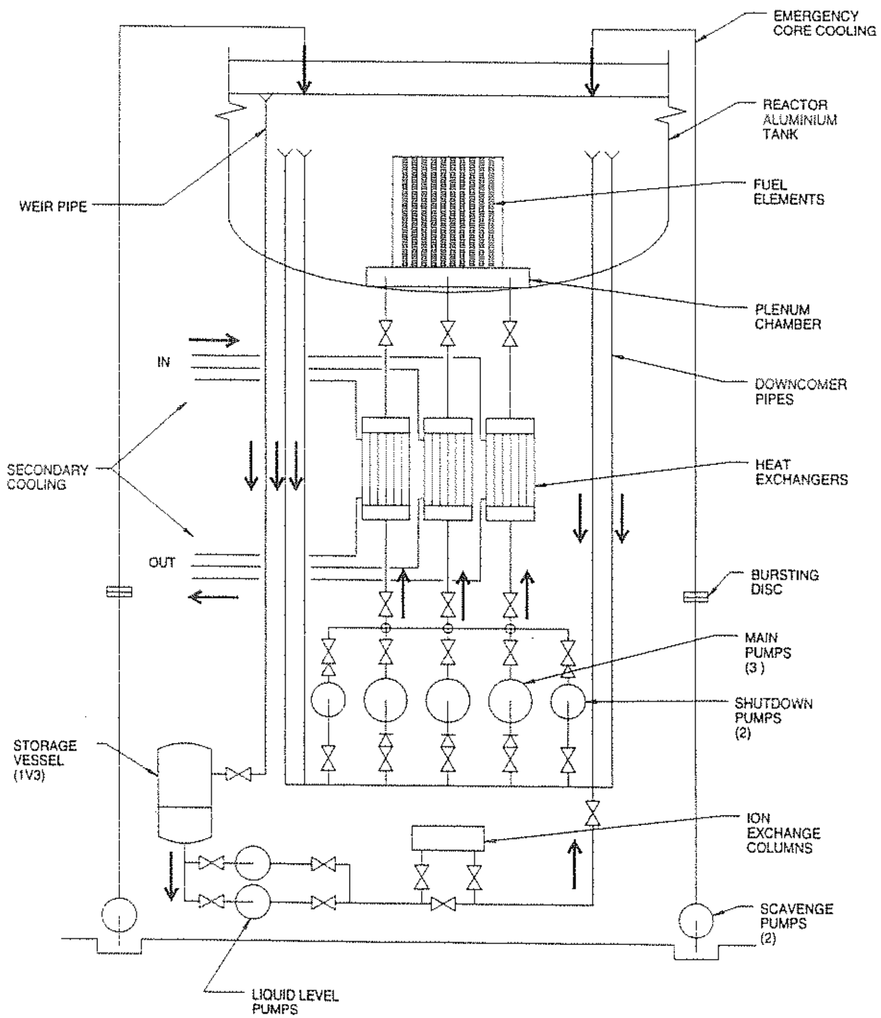

Figure 1 Diagram of HIFAR primary cooling system

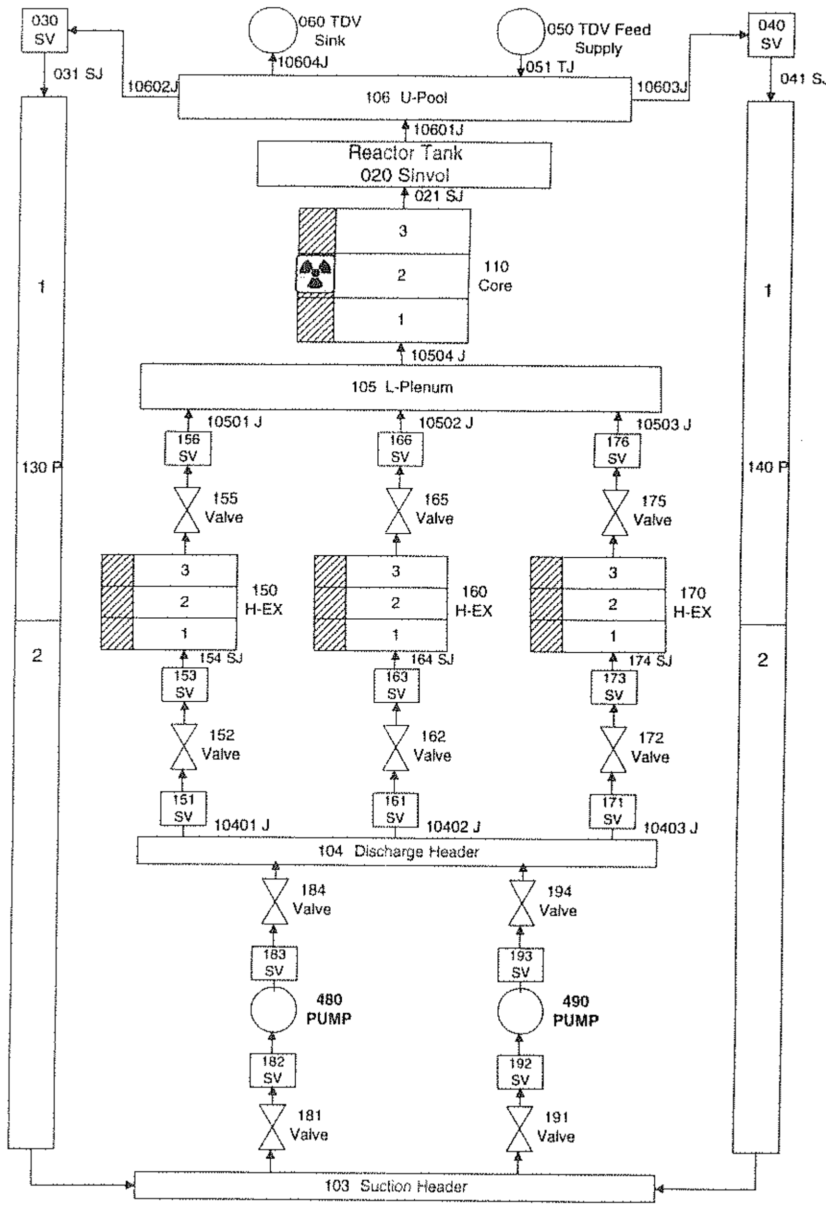

Figure 2 RELAP5 model of HIFAR primary cooling system

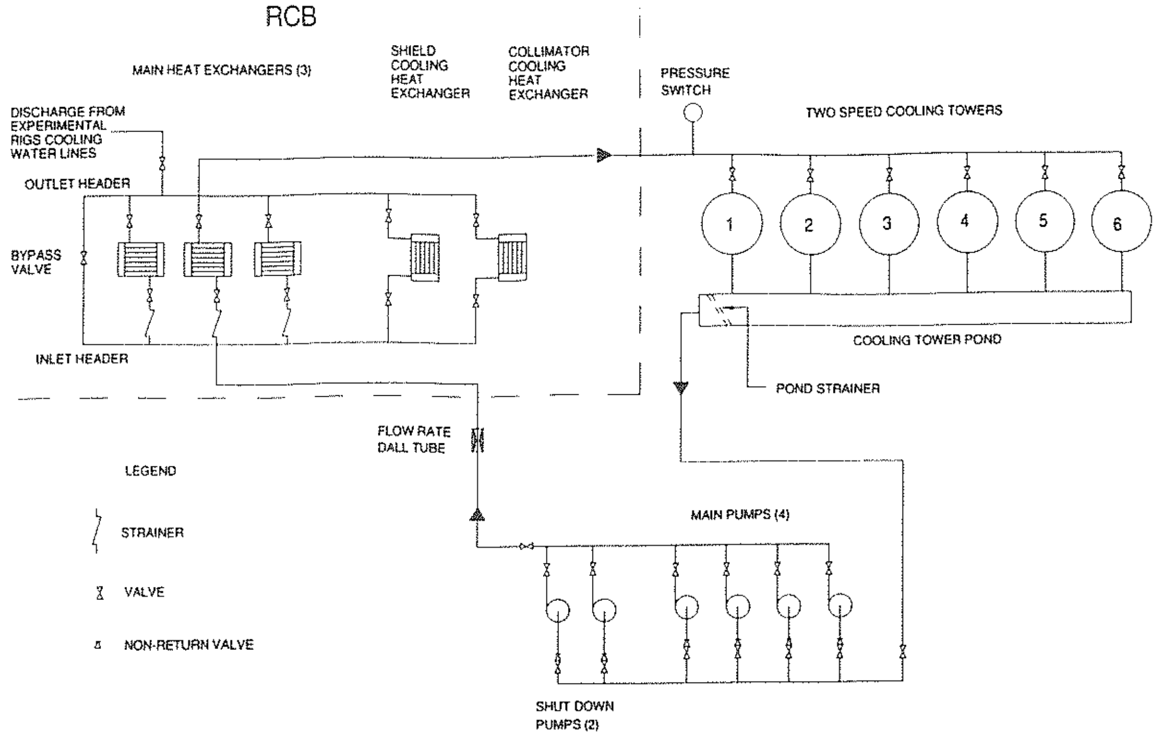

Figure 3 Diagram of HIFAR secondary cooling system

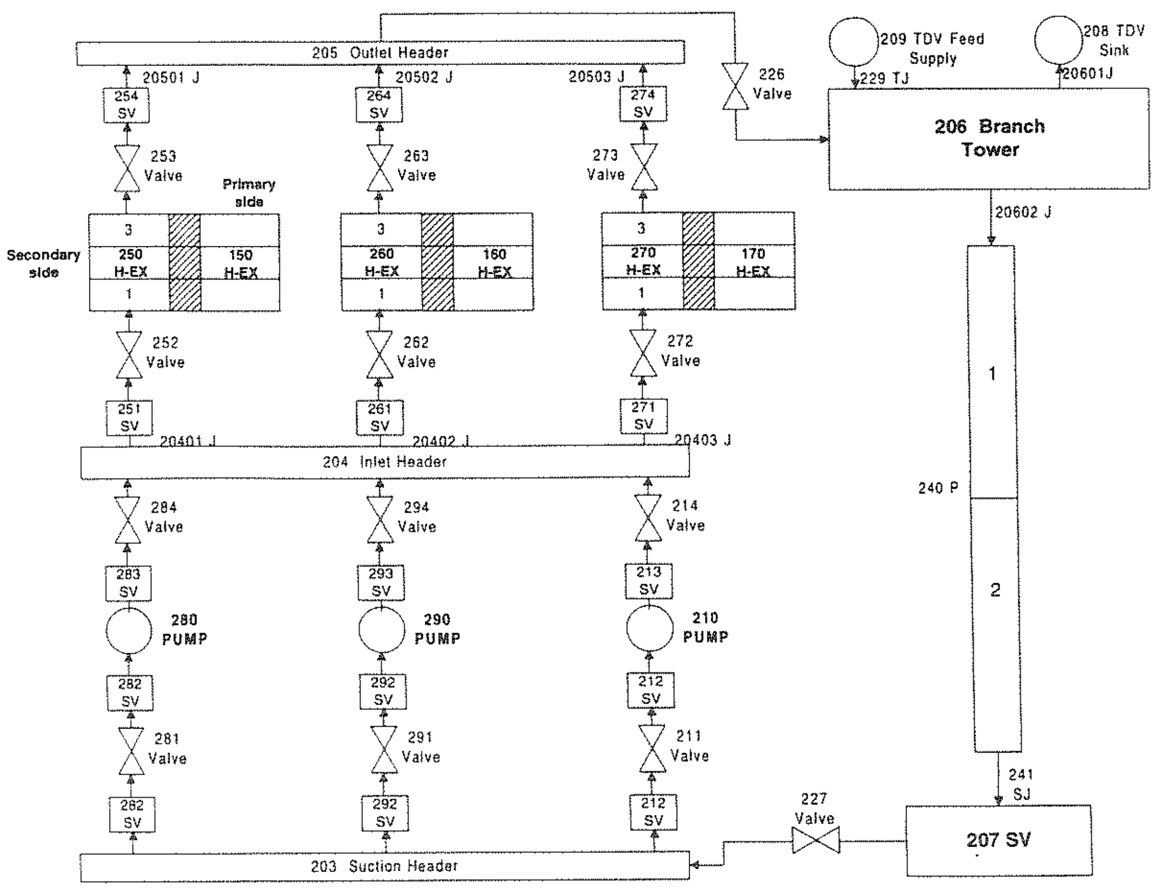

Figure 4 RELAP5 model of HIFAR secondary cooling system

4. RESULTS

In order to model the transient phenomena of HIFAR, it is necessary to calculate the steady state conditions. The initial temperature in the reactor core is 313 K (about 40°C) with an initial power 1MW increasing to 10MW in 200 seconds. A total flow rate driven by two pumps in the reactor core is 400 kg/s. The pressure in the top of reactor tank is atmospheric. This reference pressure was achieved by modelling a sink and supply in upper pool. The steady state was implemented by using the steady state option in RELAP5/MOD2.

Figure 5 shows the calculated approach to steady state of HIFAR temperatures in the reactor core and two heat exchangers in the primary and secondary cooling systems. It took about 1500 seconds to achieve a steady state by removing 10MW heat from the primary side to secondary cooling system. An increment of temperature 5.9K on the heavy water coolant in the reactor core was calculated. This result is in agreement with the theoretical analysis and experimental observation in HIFAR.

One transient condition was simulated by suddenly reducing the flow rate in both the primary and secondary sides. Figure 6 shows the history of the pump flow rates reduced in the primary and secondary sides. The total flow rate in the primary cooling system was decreased from 400 kg/s in the normal operating condition to about 40 kg/s in an accident situation (this flow rate is due to the buoyant effect). The temperature rise in the reactor core due to the reduction of coolant flow is shown in Figure 7. The maximum temperature rising in the reactor core was about 47k (or 47°C) in 650 seconds and the solution started oscillating. This is because the fluid void fraction was changing dramatically and started oscillating (see Figure 8).

In the future, the current HIFAR model will be further developed and refined. More analyses of postulated small-break and large-break LOCAs in HIFAR will be carried out.

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REFERENCE

Carlson, K.E., et al., RELAP5/MOD3 Code Manual Volume III: *Developmental Assessment Problems*, 1990.

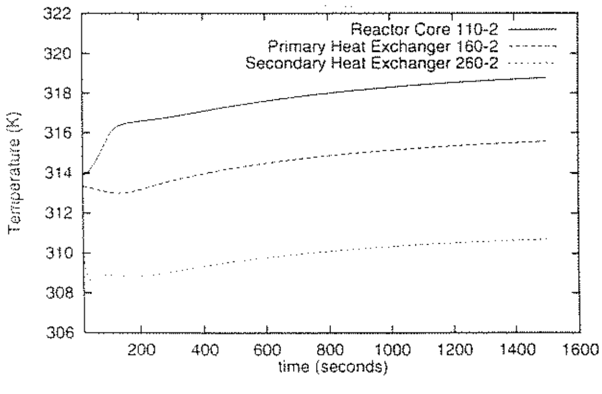

Figure 5 Calculated fluid temperature

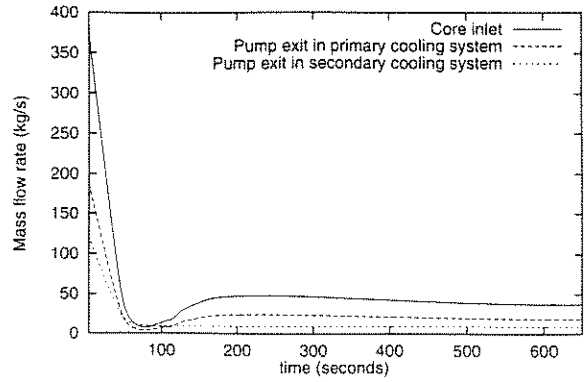

Figure 6 Coolant flow rate

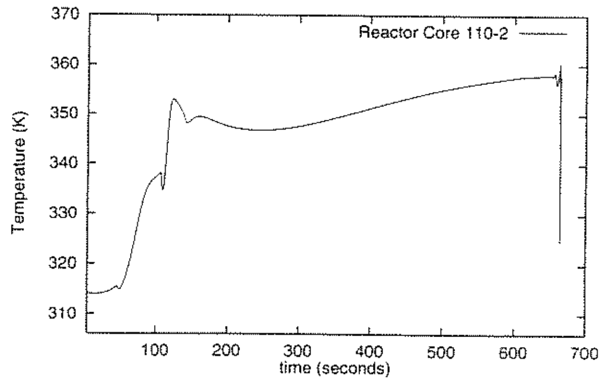

Figure 7 History of calculated fluid temperature

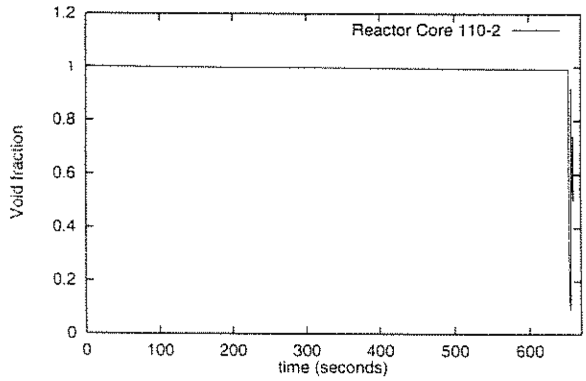

Figure 8 Calculated fluid void fraction