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RELAP5/MOD.2 ANALYSIS OF THE HFBR
FOR A LOSS OF POWER AND COOLANT ACCIDENT

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Formal Report

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ABSTRACT

A set of postulated accidents were evaluated for the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. A loss of power accident (LOPA) and a loss of coolant accident (LOCA) were analyzed. This work was performed in response to a DOE review that wanted to update the understanding of the thermal hydraulic behavior of the HFBR during these transients. These calculations were used to determine the margins to fuel damage at the 60 MW power level.

The LOPA assumes all the backup power systems fail (although this event is highly unlikely). The reactor scrams, the depressurization valve opens, and the pumps coast down. The HFBR has down flow through the core during normal operation. To avoid fuel damage, the core normally goes through an extended period of forced down flow after a scram before natural circulation is allowed. During a LOPA, the core will go into flow reversal once the buoyancy force are larger than the friction forces produced in the core during the pump coast down. The flow will stagnate, reverse direction, and establish a buoyancy driven (natural circulation) flow around the core. Fuel damage would probably occur if the critical heat flux (CHF) limit is reached during the flow reversal event.

The RELAP5/MOD2.5 code, with an option for heavy water, was used to model the HFBR and perform the LOPA calculation. The code was used to predict the time when the buoyancy forces overcome the friction forces and produce upward directed flow in the core. The Monde CHF correlation and experimental data taken for the HFBR during the design verification phase in 1963 were used to determine the fuel damage margin.

The RELAP5 code predicted flow reversal 68 s after the scram. A very conservative peak heat flux (i.e., much higher than actually expected) of $1.4425 \times 10^5 \text{ W/m}^2$ (45,750 Btu/hr-ft²) was predicted to be in the HFBR at the time of flow reversal. The 1963 experiments established that CHF would occur between $1.472 \times 10^5 \text{ W/m}^2$ (46,700 Btu/hr-ft²) and $1.513 \times 10^5 \text{ W/m}^2$ (48,000 Btu/hr-ft²) after the complete depressurization of the cover gas in the reactor vessel. A safe flow reversal limit of $1.472 \times 10^5 \text{ W/m}^2$ was adopted by the Reactor Division. This is an ultra conservative approach since the flow reversal occurs at higher pressures in the cover gas than atmospheric pressure, and this would result in higher CHF values. The Monde correlation, evaluated at the conditions in the core during flow reversal, predicted the CHF limit would be at $3.041 \times 10^5 \text{ W/m}^2$ (96,400 Btu/hr-ft²). The predicted peak heat flux of $1.4425 \times 10^5 \text{ W/m}^2$ in the HFBR is well below the experimental data and the Monde correlation. Consequently, the HFBR should be able to sustain a LOPA event without fuel damage from the 60 MW power level. Furthermore, application of the Monde CHF correlation to the transient showed that the flow reversal should occur at least 34 s after a scram to avoid any fuel damage.

The LOCA transient was a beam tube rupture event initiated from the 60 MW power level (no mechanism for this event has been identified). RELAP5 was used to predict the timing of the events after the beam tube rupture and the water level history. The reactor was predicted to trip 12.3 s after the break opening. The depressurization valve and syphon break valve opened at 42 s. The peak power assembly went into flow reversal at 39 s (very conservative estimate) after the scram, and since this is greater than the minimum time required to avoid fuel damage, no fuel damage would be expected. The depressurization valve was able

to keep the cover gas pressure from overpressurizing and forcing the water level down into the core. Thus, about 0.61 m (2 ft.) of water was predicted to be over the transition plate, and to be in equilibrium with the water level in the thermal shield volume outside the reactor vessel. This would allow for a natural circulation pathway to be established around the core, and keep the core covered and in a coolable state.

EXECUTIVE SUMMARY

The HFBR reactor has been modeled by the RELAP5 computer code. This advanced two phase, six equation, nonequilibrium thermal hydraulic code can now be used by the HFBR staff to help in the understanding of the thermal hydraulic behavior of the reactor.

The improved code and newly created input deck have been applied to two transients of concern for the 60 MW power level. One was the loss of power accident (LOPA) and the other was a loss of coolant accident (LOCA) where a beam tube is assumed to rupture. The plant model developed for the HFBR was based on many conservative assumptions and simplifications. The analysis is therefore not best estimate but very conservative.

The results of the analysis for the LOPA was that the HFBR at 60 MW can safely undergo a flow reversal without fuel damage. The safety limit chosen by the HFBR staff to ensure no fuel damage is that the peak heat flux in the core must remain below the critical heat flux (CHF) limit. During a series of tests performed earlier [Tichler, 1963] at atmospheric pressure, it was experimentally determined that the lowest CHF limit for the HFBR was between $1.47\text{E}5\text{ W/m}^2$ ($46,700\text{ BTU/hr-ft}^2$) and $1.513\text{E}5\text{ W/m}^2$ ($48,000\text{ BTU/hr-ft}^2$). These values straddle the highest level of safe flow reversal and the lowest CHF limit. This series of experiments has been shown to be conservative [Rohatgi and Slovik, 1990]. A further margin of safety is used since the HFBR staff has selected the safe flow reversal criteria of $1.472\text{E}5\text{ W/m}^2$ ($46,700\text{ BTU/hr-ft}^2$) as the safety limit although experimentally this heat flux did not go into CHF. Additional confirmation of this limit, as discussed in this report, is obtained by utilizing a more recent correlation [Monde, 1982]. Applying this correlation to the test data at atmospheric pressure lead to a CHF limit value of $1.686\text{E}5\text{ W/m}^2$ ($53,487\text{ BTU/hr-ft}^2$). This represents a 13% difference between the Monde data and the experiment data which could be accounted for in the equipment uncertainties used back in 1963. The RELAP5 computer code determined the peak heat flux in the core to be 1.4425105 W/m^2 ($45,750\text{ BTU/hr-ft}^2$) at the time of flow reversal initiation (68 seconds). This estimate is based on 98% of the decay heat being deposited in the fuel plate while the actual peak plate would have an 18% reduction from gamma smearing.

It must be further recognized that the HFBR selected limit of $46,700\text{ BTU/hr-ft}^2$ is very conservative, since the CHF limit data is pressure-dependent. The cell fluid conditions calculated by RELAP5 for the peak location at the point of flow reversal show that the local pressure is .34 MPa (50 psia). Evaluating the Monde correlation at this pressure leads to a CHF limit of 3.04105 W/m^2 ($96,400\text{ BTU/hr-ft}^2$), or about double that calculated at atmospheric pressure. This demonstrates that the HFBR has a large inherent safety margin to CHF during a LOPA event from experimental data and the most recent correlations for CHF. Also, the extended time to flow reversal allowed the vessel to depressurize to about 2.86105 Pa (42 psia) and would have expelled about 90% of the dissolved helium in the system. The remaining helium gas in the vessel would be in micro bubbles and would not have any major significance to the CHF determination.

The second transient analyzed was a loss of coolant accident (LOCA) at 60 MW where a beam tube is assumed to rupture and coolant is allowed to escape into the thermal shield and biological shield cavity volume surrounding the reactor vessel. The reactor tripped 12.3 s after the break occurred. The

depressurization valve and syphon break valve opened at 42 s. The pump was lost at about the same time because the syphon break line injected gas from the cover gas region into the vessel exit pipe (or top of reflector) and sent two phase flow into the pump. The pump lost its head and the reactor vessel was isolated. The syphon break line performed as designed by breaking the syphoning effect from the rest of the loop. The hot channel was conservatively predicted to go into flow reversal at 39 s after the scram while the other channel followed at 225 s. No CHF limit, or fuel damage, was reached since the LOPA analysis showed that a minimum of 34 s is required for the peak plate in the core to pass the CHF limit. The timings of the event are conservative as the peak assembly modeled in RELAP5 was about 40% over powered. The analysis at 60 MW did not show any fuel damage during the transient.

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1. INTRODUCTION

At Brookhaven National Laboratory (BNL) the High Flux Beam Reactor (HFBR) has been undergoing a safety review by the Department of Energy (DOE). Several transients have been identified to study the thermal hydraulic behavior of the HFBR in various hypothetical off normal conditions and to predict its inherent safety margins. The National Research Council, which is a DOE review team, has recommended that the HFBR be analyzed with one of the advanced computer codes. This would not only provide a better understanding of the thermal hydraulic behavior during transients like the flow reversal event, but also develop a computer tool to analyze thermal hydraulic issues as they arise in the future. A generic beam tube rupture event has been identified as an important transient to be analyzed for the purpose of determining the timing of the events (i.e. fluid levels, pump trip, reactor scram, etc.) when the HFBR is under going a loss of coolant accident (LOCA). The purpose of this report will be to document the effort to develop a plant model for the HFBR for an advanced computer code and to present the results for a loss of power accident (LOPA); and a beam tube rupture event.

To simulate the HFBR with an advanced thermal hydraulic system code, the first effort was to choose an appropriate code. After a review of the available codes, and the work being performed at other facilities, the RELAP5 computer code was selected. This choice was made because RELAP5/MOD2.5 had been modified to include heavy water properties and was used by several other DOE facilities. A major consideration was that any modifications to the code to model the other DOE reactors would be appropriate to the HFBR. Essentially, a large user group for the code was created which could pool information and speedup the code improvement effort.

Once the code was chosen, the HFBR system was modeled. This task involved reviewing the blue prints of the facility to determine the geometrical parameters, such as areas, lengths, and elevations associated with the piping and reactor internals. The reactor protection system also had to be defined. This information along with nominal operating conditions were combined to create an input deck for the HFBR. The model was then adjusted to duplicate the known plant data for pump coast down and cover gas depressurization. The final version of the input deck was used to simulate the transients of interest.

This report will give a brief description of the HFBR facility and a discussion on the transients of interest. The input deck preparation will be discussed along with the results.

2. DESCRIPTION OF THE HFBR

The High Flux Beam Reactor (HFBR) is a small research reactor that produces neutron beams for experiments in many areas of study where cold, thermal, and epithermal neutrons are needed. The HFBR has been operational since 1964 when it first went into service as a 40 MWt facility [Hendrie, 1964]. By 1978 it was recognized that the margins to safety were very large and the HFBR staff requested and received approval to operate the facility at 60 MWt [Addendum to Final Safety, 1978]. A brief review of the normal operation of the HFBR is discussed below to provide information pertinent to the transients analyzed. For a detailed discussion of all components of the HFBR, the reader is referred to the plant description manual [Plant Description Manual, 1984].

A schematic of the HFBR piping system can be seen in Figure 2.1. The entrance to the primary loop piping is at the outlet of the vessel (EL 125 ft. 4 in.). A reducing elbow 0.7366 m (29 in. diameter) connects the vessel outlet into a pipe 0.508 m (20 in. diameter) which ends at an elevation of 95 ft. 6 in. At this point, the flow of heavy water splits into two branches from a Tee joint. The subsequent two loops are identical and are available for operating the HFBR in a single or double loop configuration. Downstream of the tee joint, a pipe 0.4572 m (18 in. diameter) brings the fluid from the elevation of 95 ft. 6 in. to a primary pump. The discharge of the pump passes through a check valve and the hot fluid enters a heat exchanger. The check valve prohibits reverse flow in the loop and allows the operation of the HFBR in a single loop configuration. Cold fluid leaves the heat exchanger at an elevation of 103 ft. and returns to another Tee joint which combines both loops into a single 0.508 m (20 in. diameter) pipe to return the fluid back into the reactor vessel. At an elevation of 128 ft. 10 in. the vertical pipe merges into an expansion elbow which connects into the reactor vessel (diameter of 0.7366 m (29 in.)).

In Figures 2.2 and 2.3 the HFBR reactor internals are shown. Flow entering the vessel is directed downward into the reactor shroud. (The shroud is the pipe that directs the fluid into the core and separates the cold flow entering the core and the hot flow leaving it.) Above the entrance area is the helium expansion space which is normally maintained at a pressure around 1.655 MPa (240 psia). The helium is constantly being cycled by passing through a demister and is then recombined to maintain radiolytically produced deuterium gas at acceptably low concentrations. During a depressurization, the helium is expelled through the demister and about 21.3 m (70 ft.) of piping through the depressurization valve which exhausts into the flue stack and vents into the atmosphere. The stack release is filtered by HIPA filters and charcoal beds.

In Figure 2.3 it is shown that the flow shroud directs the cold fluid into the core. There are many penetrations through the transition plate which are shown in Figure 2.4.

About 88% of the flow passes through the core region while about 12% bypasses directly into the reflector region. About half of the bypass flow pass through the inserts for the main control blade (49% of bypass) penetrations and through the control blades themselves. The position of these control blades during several operating conditions are shown in Figure 2.5. Several orifices at the top of the control blades allow water to pass inside and cool the absorbing material. This allows a direct flow path from above the core directly into the reflector (19% of bypass). Just below the auxiliary coupling (see

Figure 2.1 Isometric Drawing of the Primary System and the Shutdown Cooling System
(taken from the 40 MW FSAR)

FIGURE 2.2 HFBR Flow Pattern at Normal Operation

Figure 2.3 HFBR Internals

FIGURE 2.4 Isometric View of the Lower Ends of the Control Rod Mechanism in the Reactor Vessel

FULL-IN POSITION

**CRITICAL POSITION EARLY
IN OPERATING CYCLE**

**FULL-OUT POSITION
END OF OPERATING CYCLE**

FIGURE 2.5 Control Rod Blade Positions Around the Core at Shutdown (full-in position) and during Operation

Figure 2.4), flow enters the auxiliary control rod blade shaft and passes through the shaft and into and out the auxiliary control blade (32% of bypass). The auxiliary blades are located close to the grid plate during normal operation. The only other bypass into the reflector is by the opening of the flow reversal valves as seen in Figure 2.4. The four flow reversal valves spaced around the core are held closed during normal operation by a pilot line which directs pressure off the pumps. During a normal pump coast down, the shutdown cooling system pump also holds these valves shut to direct the flow through the core. However, if this system is not available, the flow reversal valves begin to open when the pressure across the transition plate is less than 20.68 k Pa (3 psia) which provides a path for natural circulation.

A majority of the flow (88%) passes through the 28 fuel assemblies in the core as shown in Figure 2.6. A top view of the transition plate and the core region is shown in Figure 2.7. A diagram of a typical fuel assembly is shown in Figure 2.8. It can be seen in Figure 2.8 that there are 18 fuel plates in an assembly with an aluminum restraint around the fueled region. The plate is impregnated with uranium in 0.05715 m (2.25 in.) of the arc length while the plate has a total arc length of 0.0610 m (2.4 in.) exposed to the coolant. The periphery channels are in direct contact with the reflector and offer a heat sink to them during any event. The high thermal diffusivity of aluminum [$8.59 \text{ m}^2/\text{s}$ ($3.33 \text{ ft}^2/\text{hr}$)] and the interconnection of the plates to the aluminum restraint around the assembly, offers a significant heat sink with excellent thermal diffusion properties within the assembly. The effect would be to flatten any temperature peaks within the assembly. It should be noted that this reactor has its peak power assemblies on the periphery since the design of this small core leads to the leakage of a large fraction of fast neutrons. The reactor relies on the back reflected thermal neutrons to preserve criticality. The end plates of the assembly have larger flow channels to minimize dimensional changes while the internal channels are about 2.44 mm (0.096 in.). A non-heated inlet tube section of 0.35 m (13.8 in.) brings the fluid from the transition plate into the fueled region. The fuel region is 0.578 m (22.75 in.) long while the total length of the plates are 0.603 m (23.75 in.). The bottom 0.45 m (18 in.) of the assembly is a support structure to hold the assemblies in position while offering no obstruction to the flow exiting the core. Note that the lower part of the assembly is well vented to allow easy radial movement of the fluid and that the end inserts into a slot in the grid plate. Once the flow exits the core, it turns up into the annulus and out of the reactor vessel. A summary of the operating parameters of this facility and general geometric data are shown in Tables 2.1 and 2.1a.

2.1 Shutdown Cooling System

The Shutdown Cooling System is an independent system in the HFBR. It has two independent pumps and a heat exchanger. Each pump can deliver about $0.067 \text{ m}^3/\text{s}$ (1060 gpm). The system takes suction from the vessel discharge and re-enters the reactor vessel at an elevation of 133 ft. 1 in. which is about 1.5 m (60 in.) above the center line of the inlet pipe to the reactor vessel, as shown on Figure 2.1.

The Shutdown System is required to be on when the HFBR is operating. One pump is continuously running with the other on standby. During reactor operation, the head developed by both primary pumps exceeds that of the shutdown pump so that discharge check valves on the shutdown pump are held closed and no

Figure 2.6 Elevation of the HFBR Core

Figure 2.7 Transition Plate Details

Figure 2.8 HFBR Fuel Element (all dimensions are in inches)

Table 2.1 HFBR Characteristics

	<u>Parameter</u>
Power, MWt	60
<u>Materials</u>	
Coolant, moderator, and reflector	D ₂ O
Fuel (U-235)	U ₃ O ₈ cermet
Core structure, beam tubes	6061 Al
Reactor vessel	6061 Al
Primary pipes and process equipment	stainless steel
<u>Fuel Element and Core</u>	
Type	MTR-ETR curved plates
Uranium concentration in fueled section, wt%	37 (U ₃ O ₈)
Fuel section thickness, mm (in.)	0.58 (.02228)
Cladding thickness, mm (in.)	0.34 (.0136)
Standard plate thickness, mm (in.)	1.27 (.05 in.)
End plate thickness, mm (in.)	2.54 (.100)
Plates per element	18 std.
Uranium enrichment, %	93
U-235 loading per element, gm	351
Element length, m (in.)	1.454 (57.25)
Number of fuel elements in core	28
Active core height, m (in.)	0.578 (22.75)
Active core volume, liters	96.8
Internal irradiation volume, liters	6.3
Reflector thickness, m (in.)	0.803 (31.6)
<u>Control Rods</u>	
Number of main rods	8
Number of auxiliary rods	8

Table 2.1 (continued)

Water Flow Data

Water channel flow area per element, m ² (ft ²)	2.99E-3 (0.0322)
Water channel flow area, core, m ² (ft ²)	8.36E-2 (0.900)
Water velocity in channels, m/s ft/sec	11.67 (38.3)
Fuel element flow rate, kg/s (gpm)	
One element	37.91 (553)
28 elements	1061.21 (15,480)
Bypass flow rates, kg/s (gpm)	
Between fuel elements	11.10 (162)
Control rod cooling, main rods (8)	28.10 (410)
Control rod cooling, auxiliary rods (8)	47.30 (690)
Control rod bypass (16)	70.95 (1,035)
In-core facility (2)	4.45 (65)
Core edge facility	2.94 (43)
Total reactor vessel flow rate, kg/s (gpm)	1227.11 (17,900)
Core pressure loss, Pa (psia)	2.79 E5 (40.6)
Other vessel losses, Pa (psia)	1.72 E4 (2.5)
External primary system losses, Pa (psia)	1.37 E5 (20)
Total primary system losses, Pa (psia)	4.35 E5 (63.1)
Available pump head, Pa (psia)	4.67 E5 (67.8)

Process System Design

Maximum operating pressure, MPa (psig)	1.724 (250)
Normal operating pressure, MPa (psig)	1.379 (200)
Vessel design pressure, MPa (psig)	1.896 (275)
Vessel design temperature, K (°F)	394.26 (250)
Beam tube design temperature, K (°F)	477.59 (400)

Table 2.1a Nominal Operating Pressures and Temperatures in the Primary System
at 1.227E3 kg/s (18,000 gpm)

<u>Location</u>	<u>Pressure MPa (psia)</u>	<u>Temperature K (°F)</u>
Vessel outlet	1.48 (184)	339.2 (151)
Pump section	1.27 (194)	339.2 (151)
Pump Discharge	1.34 (262)	339.2 (151)
Heat exchanger discharge	1.76 (256)	327.6 (130)
Vessel inlet	1.57 (228)	327.6 (130)

shutdown cooling flow is permitted. To avoid overheating the shutdown pumps are provided with a low flow bypass for cooling.

When the primary pump motors are tripped, the head developed by the pump decrease as the pumps coast down. A point is reached in the coast down when the shutdown pump head dominates and the shutdown pump discharge check valve opens. By the time the primary flow decreases to $0.125 \text{ m}^3/\text{s}$ (2000 gpm), the shutdown pump begins operating and delivering about $0.0625 \text{ m}^3/\text{s}$ (1000 gpm). Only one pump operates at a time. Furthermore, the pressure from the shutdown pumps keep the flow reversal valves closed so that all downward directed flow goes through the core.

The power supply to the shutdown system is commercial AC through a rectifier. If there is a 0.5s disruption in power, the system automatically switches to DC power and the diesels in the emergency power room are started. The shutdown pump would be manually switched back to the AC power generated by the diesels.

2.2 Pony Motors

The coupling of a small DC motor called a pony motor to each main pump permits a safe transition to flow reversal cooling in the event commercial power is lost and the emergency power supply to the primary pumps fails. After an emergency shutdown from 60 Mwt operation, the decay heat levels are such that a period of forced downward flow is necessary to ensure a safe flow reversal event. It should be noted that this period of forced downward flow is not necessitated by the typical power in the assemblies, but by the core hot spots.

The DC motors are coupled to the main pump motor flywheel through a gear unit and over running clutch. The gear unit reduces the motor output speed to 180 rpm and the clutch is designed to engage and drive the pump only when the output speed of the gear unit exceeds the speed of the pump. The pony motor will be running when the reactor is operating and will couple to the pump when the main motor loses power and its speed falls below 180 rpm. At 180 rpm each primary pump will circulate $0.107 \text{ m}^3/\text{s}$ (1700 gpm). About 16% of the total pump flow bypasses the core through the open flow reversal valves. With the shutdown pumps not running, the flow reversal valves will open since there is insufficient head developed by the primary pump when operating at 180 rpm to keep the flow reversal valves closed.

The DC batteries are designed to power the pony motors for two hours, but could last up to six.

2.3 Syphon Break line

The syphon break valve opens a line between the cover gas volume and the outlet pipe of the reactor vessel to preclude the fluid in the vessel from being syphoned out during a loss of coolant event when the break is located in the loop piping at an elevation below the reactor vessel. The valve opens with a 2.6 s delay when the water level reaches the low-low level of 197 in. (EL 130 ft. 6 in.), see Figure 2.1. By equalizing the pressure above the core with the outlet leg, the fluid is held in the lower part of the vessel. This will maintain a level high enough to allow a natural circulation path.

2.4 The Primary Pumps

The characteristics of the primary pumps are shown in Table 2.2. The normal coast down of a pump of this size is about 15 s; however, the pumps in the HFBR have flywheels added to them to achieve a coast down of about 80 s. The actual flow coast down generated by these pumps is shown in Figure 2.9. The flywheels were added to the pumps to provide protection in case of an unaided coast down event occurring in the HFBR. It was known from the 1963 Experiments [Tichler, 1963] that the maximum heat flux at HFBR operating conditions would require forced down flow for a short period of time between the reactor scram and the flow reversal event to assure a safe outcome to the event. Thus, the pumps were designed to have an extended coast down to provide a large safety margin during a flow reversal event with the hardware in the plant.

Table 2.2 Data on Primary System Pumps

Manufacturer	Pacific Pumps, Inc.
Flow capacity:	
Design	9,000 gpm at 128 ft head
Test	9,000 pgm at 142 ft head
Number of stages:	One
Impeller:	19-1/4 in. diameter enclosed-type
RPM:	1190
Motor:	Louis Allis, 400 hp, 2300 volts, 3 phase, 60 Hz
NPSH at rated flow:	32 ft
Materials of construction:	
Casing, impeller, inner base, parts, shaft	Stainless steel
Number of seals:	One

FIGURE 2.9 Flow Coastdown in Primary System with Shutdown Pump Not Running

3. TRANSIENT DESCRIPTION AND SCENARIOS

Two classes of events have been identified for study because of their impact on safety. The first type of accident is the loss of forced downflow in the core after a scram. The flow automatically switches to upflow by the process of natural circulation after the loss of the pumps. The concern is the time required for the flow reversal event to occur. The time to flow reversal defines the power level, which directly determines whether fuel damage will occur. The hypothetical loss of power accident (LOPA) event is used to demonstrate the thermal hydraulic response of the HFBR during a flow reversal event. The second transient was a beam tube rupture event where a break in a beam tube is assumed. No mechanistic procedure identified this break size 8.974 E-4 m^2 (1.39 in^2) or even if a break is possible at this location. This type of transient is a Loss of Coolant Accident (LOCA) and is evaluated for the HFBR to predict the fluid levels in the reactor vessel after the initiation of the event. The calculation will be used to determine if the core remains covered and coolable. The following is a detailed discussion of the events.

3.1 Loss of Power Accident (LOPA)

The LOPA is a hypothetical event where all the electrical power is assumed to be lost in the HFBR facility. This would automatically scram the reactor, open the depressurization valve, and trip the reactors pumps. Two independent systems must fail for this event to occur (i.e., the shutdown pumps and the pony motors). The primary pumps have flywheels added to their shafts to extend the flow coastdown. A DC motor, called a pony motor, is coupled to the main pump motor flywheel through a gear unit and over running clutch and is required to be on-line during plant operation. The gear unit reduces the motor output speed to 180 rpm, and the clutch is designed to engage the drive pump only when the output speed of the gear unit exceeds the speed of the pump. The pony motor is running when the reactor is operating and will couple to the pump when the main motor loses power and its speed falls below 180 rpm. At 180 rpm, each primary pump will circulate $0.107 \text{ m}^3/\text{s}$ (1700 gpm). The batteries have the capacity to run the motor at rated conditions for about six hours. The pony motor backup battery system is assumed to fail during this event. Another independent backup pumping system, designated the Shutdown Cooling System, is also assumed to fail. It has its own heat exchanger and piping system and is designed to be the primary source of driving head when the primary reactor pumps are accidentally lost. A pilot tube from these pumps will continue to keep the flow reversal valves closed, forcing all downward directed flow through the fuel assemblies. This is the main backup system when the primary pumps lose power. The shutdown pump merges into the primary pump coast down to deliver about $0.063 \text{ m}^3/\text{s}$ (1000 gpm). The power for the shutdown system is from the Emergency Motor Control Center that is supplied by local diesel motors, or DC batteries. However, for this LOPA event the Shutdown Cooling System is also assumed to fail (see Plant Description Manual for details).

As noted from the above description, many failures must happen simultaneously for the LOPA to occur. However, by assuming the event to take place, a scenario is established to review the thermal hydraulic behavior of the HFBR during an unaided loss of downflow and the subsequent upflow from natural circulation caused from the decay heat in the fuel.

3.1.1 LOPA Scenario

The initiation event for a LOPA is the loss of all power to the HFBR. The alternate power supplies to the Shutdown Cooling System and the pony motors are assumed to fail. Only the extended coast down from the flywheels added to the primary pumps will provide the forced downward flow in the core until the buoyancy forces turn the flow direction.

At the loss of AC power, the reactor is scrammed, the pumps are simultaneously tripped, and the solenoid to the depressurization valve de-energizes and opens 1.5 s later.

3.2 Beam Tube Rupture

A beam tube rupture event has been postulated for the HFBR reactor. No mechanistic event has been identified to cause any cracking (i.e. material failure) or any stress loading on a beam tube that could result in a rupture, but this hypothetical event is being analyzed to look at the timing of the event and fluid levels in the reactor.

The crucial parameter associated with this event is the liquid level in the reactor. Once the beam tube is considered open, the heavy water leaving the reactor vessel begins filling up the thermal shield and biological shield cavity surrounding the reactor vessel. This volume essentially forms a cup around the reactor vessel which has its rim at EL 121 ft. 9 in. (see Figure 3.1). Any water that passes this elevation spills over and onto the shutdown cell floor. If the level inside and outside the vessel were able to stop at the rim elevation, the transition plate would have 0.63 m (25 in.) of water above it and would be able to establish a path for natural circulation. Of course, the only way the two levels can maintain the same height is for both surfaces to be at atmospheric pressure (since the thermal shield volume is exposed to the atmosphere). The concern is that the level in the vessel will continue to drop until the core is exposed because of the cover gas pressurization. This would occur if the vapor volume continued to pressurize from steam production in the core, and it was greater than what the depressurization valve could expel. The water level would continue dropping into the core region and the end result would be fuel damage. However, this could be avoided if the cover gas pressure reached atmospheric conditions soon after the depressurization valve opened and the liquid level slowly approached the 121 ft. 9 in. elevation point. The analysis was made to determine whether the level in the vessel would expose the core or stop at some point above the transition plate and maintain a coolable state.

3.2.1 Beam tube Rupture Scenario

The initiation of the event is the opening of the beam tube. The behavior of the reactor and its response is governed by the reactor protection system as seen in Table 3.1. The evolution of the event is dictated by the activation of the set points.

FIGURE 3.1 Location of Thermal Shield

Table 3.1 Reactor Protection System Set Points

<u>System</u>	<u>Set Points</u>
Reactor trip (0.5 s delay)	Cover gas press < 1.24 MPa (180 psig)
Reactor trip (2.6 s delay)	Level < 209 in. (EL 131 ft. 6 in.)
Primary pump trip (2.6 s delay)	Level < 197 in. (EL 130 ft. 6 in.)
Primary pump trip (0.5 s delay)	Cover gas press < 0.827 MPa (120 psig)
Auto-depress (2.6 s delay)	Level < 197 in. (EL 130 ft. 6 in.)
Syphon break valve (2.6 s delay)	Level < 197 in. (EL 130 ft. 6 in.)

4. RELAP5/MOD 2.5/V3a3 APPLICABILITY TO THE HFBR

The RELAP5 [Ransom, 1987] series of codes has been developed for the U. S. Nuclear Regulatory Commission (NRC) by INEL to analyze the PWR and BWR power plants in the United States. The application of RELAP5 to the HFBR does require modifications since the code was developed for high pressure, light water, commercial systems with rod bundles for the fuel assemblies. The HFBR facility is a low pressure, small, research reactor with narrow gap plate fuel. The geometry, operating conditions, and piping arrangements of this type of reactor system is usually quite different from the large commercial reactors designed to produce power. This is true for most of the DOE facilities. Areas for RELAP5 improvement had already been identified and some work has been performed since other facilities, including Savannah River, Advanced Neutron Source (ANS), and HFIR had been using the code prior to the computational needs identified at BNL. (Savannah River fuel assemblies consist of narrow annular tubes with ribs. They are expected to behave very similar to flat plate fuel.) Consequently, low pressure corrections, heavy water property constitutive relationships, along with many other corrections needed for the smaller research reactor had been installed into RELAP5.

To perform the analysis of the HFBR, the Reactor Division staff contracted with INEL to provide the same version of the code used by the other DOE facilities and to have access to the correction sets generated for RELAP5 under any of the DOE contracts (i.e. Savannah River Plant, ANS, and HFIR). This contract permitted BNL to use RELAP5/MOD2.5/V3a3 for the analysis. This approach allowed the BNL analysis to take advantage of the code improvements already completed and focus on more immediate tasks. Also, BNL is in position to receive corrections as soon as they are released. An essential part of using any code for an analysis is to understand the limitations inherently built into it. The following will give a brief description of RELAP5 and what information the code is to supply to the HFBR analysis, with a discussion on some of the known deficiencies which would have a direct impact on the calculations. RELAP had also shown it could simulate the flow reversal event by application to the 1963 test data for the HFBR [Horak, 1990].

Another system code which has some capacity to model the plant is the TRAC code. However, the HFBR has a unique geometry and codes like TRAC, which have hard wired components for LWR reactors, are not in a position to model this unique geometry. RELAP5 uses the volume and junction approach which allows more flexibility.

4.1 Brief Description of RELAP5

RELAP5 code [Ransom, 1987] was developed at the Idaho National Engineering Laboratory (INEL) for the NRC, with the objective of producing an economical best-estimate analysis code for transients in LWR systems. The code includes component models for pipes, branches, abrupt flow area changes, pumps, valves, control systems, etc. to represent a reactor system or test facility. Special components such as time dependent volumes and time dependent junctions are used to provide boundary conditions. Heat structures are available to model heat transfer between solids and fluids. The code also includes a point kinetic model with activity feedbacks.

The principal features of the code is the use of the two fluid, nonequilibrium, nonhomogeneous, hydrodynamic model for transient simulations of two phase system behavior. RELAP5 employs a full nonequilibrium, six equation, two fluid model. A seventh equation to track the mass of a noncondensable in a system is also available.

The present application of RELAP5 to HFBR is to determine the timing of events. Most of the analysis is performed to determine the combined effects of several competing phenomena on the reactor protection system. Thus, the use of RELAP5 to predict the timing of an event is to use the code within its capabilities. The area of weakness is in predicting the temperatures of the plates within the assemblies.

RELAP5 is not a fuel assembly code and could only supply a first approximation to the predicted behavior of an assembly. It is routine practice to use a fuel bundle code to analyze the behavior of an assembly within a reactor and to use the flow and pressures boundaries determined by a code such as RELAP5. It was not the purpose of this effort to provide a detailed analysis of the fuel assemblies behavior during the transients reported in the work, but to determine the timing of the events and to leave the final determination of the fuel plate temperature to side calculations using boundary conditions. However, when appropriate, the results predicted by the code can be reviewed and accepted as approximate. The following are the more significant areas that need clarification or should be noted as needing code improvement for the application of RELAP5 to the HFBR.

4.2 Flow Regime Map

The flow regime maps in a two phase code determines the distribution of phases and selection of appropriate correlations for interfacial transfer terms such as interfacial area density, interfacial shear and heat transfer coefficients. There are three maps [Dimenna, et al., 1988] for two phase flow in RELAP5: (a) horizontal map, (b) vertical map, (c) high mixing map for flow through pumps. An example of a flow regime in RELAP5 is shown in Figure 4.1. The wall heat transfer depends on the flow regime map in a less direct way. This weakness is restricted only to the core region analyzed by RELAP5 and these maps are correct for all the other regions in the HFBR system.

The flow regime maps in the code were developed from the data based on pipe experiments. The void fraction when a narrow gap channel goes from bubbly to slug, or to some type of disk flow, has not been experimentally determined. However, it can be stated that RELAP5 is phenomenologically correct with void fractions below 10%, i.e., three bubbles of the gap diameter, and a high void fraction condition.

4.3 RELAP5 Two Phase Friction

RELAP5 uses the H.T.F.S. two phase friction multiplier correlation [Dimenna, et al., 1988] in estimating friction losses. A literature search yielded only one specific correlation for rectangular channels [Friedel, 1979]. This differed from the RELAP5 correlation, but was dropped from review since the data base was small and the latest H.T.F.S. correlation (different from the one used in RELAP5) was reported as having the smallest average error over a very large data base. The RELAP5 correlation was compared with the latest H.T.F.S and

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Figure 4.1 Schematic of Horizontal Flow Regime Map with Hatchings, Indicating Transition Regions

was found to be within 30% in the 30% to 70% void fraction range. There was much better agreement for the low and high void fraction range at the mass flux of interest (see Fig. 4.2). This indicates that the two phase friction predictions in RELAP5 are reasonable for these calculations. However, a larger data base is needed for a more accurate two phase friction pressure drop description of narrow gap rectangular channels.

4.4 QCHF Correlations

The CHF correlations in RELAP5 do not apply to thin, narrow gap, flat plate fuel found in the HFBR. The code uses two correlations, one for high flow rate and one for a very low flow rate. The high flow rate CHF correlations were developed by Biasi [Biasi, et al., 1967] and consist of two equations, one for high quality and one for low quality. The equations are

$$q_{\text{CHF-B}} = \frac{1.883 \times 10^7}{D_h^n G^{1/6}} \left(\frac{f(P)}{G^{1/6}} - X \right) \quad (4.1)$$

for the low-quality region, and

$$q_{\text{CHF-B}} = \frac{3.78 \times 10^7 h(P)}{D_h^n G^{0.6}} [1-X] \quad (4.2)$$

for the high-quality region,

where

D_h	=	hydraulic diameter
n	=	0.4, for $D_h \geq 1$ cm 0.6, for $D_h < 1$ cm
X	=	quality
$f(P)$	=	$0.7249 + 0.099 P e^{(-0.032P)}$
$h(P)$	=	$-1.159 + 0.149 P e^{(-0.019P)} + 8.99P/(10 + P^2)$
G	=	mass flux
P	=	pressure (bar) (minimum pressure is 2.7 bar)

The correlation is applied whenever the mass flux is equal to or greater than 200 kg/m²-s. For $G > 300$ kg/m²-s, the maximum of Eqs. 4.1 and 4.2 is applied. For $G < 300$ kg/m²-s, the high quality correlation, Eq. 4.2, is applied.

FIGURE 4.2 Relative Percent Error Between RELAP5/MOD2 and the HTFS Mark II Correlation for Two Phase Friction Multipliers

The low flow rate CHF correlation is based on a modified Zuber correlation [Smith and Griffith, 1976] for horizontal pool boiling of a saturated liquid on a flat plate. The form of the equation is

$$q_{CHF} = (1-\alpha) 0.131 h_{fg} \rho_g^{1/2} [\sigma g (\rho_f - \rho_g)]^{1/4} . \quad (4.3)$$

where

h_{fg} = heat of evaporation

ρ_g = vapor density

ρ_f = liquid density

σ = surface tension

g = gravity constant

The correlation of the modified Zuber is applied to low flow situations where $G < 100 \text{ kg/m}^2\text{-s}$. For G between $100 \text{ kg/m}^2\text{s}$ and $200 \text{ kg/m}^2\text{s}$, a linear interpolation with G is performed between Eq. 4.2 and 4.3.

The above correlations are for tube data, and CHF correlations for narrow rectangular channels are quite different. Comparisons with the Monde correlation for rectangular channels, for example, showed that the RELAP5 QCHF predicted heat flux levels about three times greater. RELAP5 will not be able to accurately predict QCHF in the calculations and the heat flux to this occurrence will have to be predicted by a side calculation until the code is updated for rectangular channels. The $(1-\alpha)$ term in Eq. 4.3 would allow RELAP5 to predict a reasonable CHF under a high void condition for the rectangular channel.

A literature search on CHF correlations in rectangular channels with a narrow gap revealed two past efforts that had any bearing on this work. These were by Monde [Monde, 1982] and Mishima [Mishima et al., 1985]. While both CHF equations showed very similar results, the Monde correlation was chosen for the analysis since its experimental conditions were similar to one expected in the HFBR. The CHF correlation was for natural convection in a vertical rectangular channel submerged in saturated liquid. This is the phenomenon of concern since it has been determined [Rohatgi and Slovik, 1990] that the flow reversal process occurs under 40 ms. Thus, the flow coast down phase does not play a dominant role in predicting CHF. The form of the equation is

$$q_c = \frac{0.16 h_{fg} \rho_g (\sigma g \Delta \rho / \rho_g^2)^{1/4}}{1 + 6.7 \times 10^{-4} (\rho_\ell / \rho_g)^{0.6} (L_H / s)} . \quad (4.4)$$

where

h_{fg} = heat of evaporation

ρ_ℓ = liquid density

ρ_g = vapor density

g = gravity

$\Delta\rho = \rho_\ell - \rho_g$

L_H = heated length

s = gap size

This equation suggests that the CHF at very low flow rates becomes independent of the flow rate and approaches a value which is generally much smaller than pool boiling CHF.

To demonstrate the differences between the tube CHF correlations and those proposed for rectangular channels, a comparison was made between CHF predicted Monde correlation and RELAP5 calculation for conditions near the flow reversal event ($P = 3.37\text{E}5$ Pa, $X = 5.0\text{E}-5$, $G = 330.0$ kg/m²-s). The CHF prediction by Monde correlation and the RELAP5 model are $3.0\text{E}5$ W/m² and $9.5\text{E}6$ W/m², respectively. RELAP5 overpredicted CHF and the code would not be able to switch to transition film boiling heat transfer packages without modifications to the code for rectangular channels.

4.5 RELAP5 Application

RELAP5 limitations are restricted to a core analysis. The code was not created to be a fuel bundle analysis code and would provide only an approximation to the core behavior. The fuel plate temperatures would be reasonable for low quality and high quality flow since the phenomena are modeled correctly in the code. With this in mind, RELAP5 can be used to simulate the reactor vessel and internal flow paths with accuracy and has been used to predict the timing of the events.

It should be noted that RELAP5 uses a consistent set of wall and interfacial heat transfer models, friction models, and solves the correct energy balance equations. The above statements do not indicate that the code should not be used, but that once its limitations are understood, the code can be applied in the correct way.

5. RELAP5 REPRESENTATION

In a RELAP5 representation, a system is constructed from pipes and heat slabs with specialty models for valves, pumps, and control systems. These elementary building blocks can be assembled to create vessels or heat exchangers, etc. A heat slab either generates heat (i.e. fuel plates), absorbs (i.e. vessel walls) or conducts it from one hydraulic cell to another (tubes in a heat exchanger). The temperature distribution within the heat slab is determined each time step. The heat flow between two systems can be modeled by identifying two hydrodynamic volumes as sharing a common heat slab which conducts heat from one cell to the other according to the temperature gradient. The HFBR model was constructed as shown in Figure 5.1.

The first step in the generation of the input deck for the HFBR plant was collecting information about all the significant lengths, volumes, and elevations [Hendrie, 1964]. The volumes and elevations were preserved with the area being modified to represent the average area found in the length. The hydraulic diameters were based on the average or smallest diameter found in the section. Loss coefficients were used to correct the pressure losses around the loop piping and through the reactor vessel to match the friction drop in the system at rated flow conditions, as shown in Table 2.1. In Table 5.1, the pertinent data used in the input deck can be found in order of the component numbers indicated in Figure 5.1. A copy of the input deck used for the LOPA calculation is in Appendix A. Several of the components in the deck deserve special mention and will be discussed below.

5.1 Decay Heat and the Power Distribution

The decay heat level and the power distributions in the HFBR are well documented. The decay levels are shown in Table 5.2 [Tichler, 1989] and have been multiplied by 1.05 to compensate for the 1 sigma uncertainty (4%) in the values.

The power distribution analysis calculated previously [Mallen, 1977] within the core has shown that the peak plate relative power density is 2.032 while the peak assembly relative power density is 1.261. These two values represent the highest power densities determined in the fuel cycle. To be conservative in heat flux, the peak assembly modeled (i.e. heat slab 1008000000) in RELAP5 used an assembly constructed of 18 peak plates. That gives the hot channel assembly a peak to average value of 2.032 which is 61% higher than that actually expected within a peak assembly in the actual HFBR core. The 14 periphery assemblies are the locations of the highest power densities and, contain the peak power assembly. By reviewing the power distributions [Mallen, 1977], it was found that the core power densities can be grouped into two power levels. One for the periphery and one for the interior channels with the peak channel being taken for the periphery. The most skewed power distribution possible put 57.8% of the power in the periphery assemblies with 7.2% (i.e. peak to average of 2.032) for the peak assembly. The 14 remaining interior channels contribute the other 42.2% of the power. The axial power (see Table 5.1) distribution used for the calculation was also the most severe condition in the fuel cycle.

- J29 BREAK LOCATION
- J20 DEPRESSURIZATION VALVE
- J30 CHECK VALVE
- J12 FLOW REVERSAL VALVES
- J11 CORE BYPASS
- J52 HELIUM INJECTION
- HS8 HEAT STRUCTURE, HOT ASSEMBLY
- HS9 HEAT STRUCTURE, PERIPHERY ASSEMBLIES
- HS10 HEAT STRUCTURE, INTERIOR ASSEMBLIES
- HS2025 HEAT STRUCTURE, HEAT EXCHANGER

FIGURE 5.1 RELAP5 HFBR Representation

TABLE 5.1

HFBR DATA USED IN RELAP5

COMPONENT: 1

VOLUMES: 9

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Transition plate to vessel outlet (annulus section)	.782	.18	0.30	1.73355	36.47	38.20		339.3	36.47	38.2
2 Pipe at vessel outlet (OD=30" Reducing Elbow)	.737	.199	0.74	1.4478	38.2	37.53	1.267	339.3	38.2	
3-5 Downward ID=22 1/4" pipe	.564	.199	0.565	3*(.25085)	37.53	33.08		339.3		
6 ID=19.546" pipe above bifurcation	.497	.199	0.497	1.7462715	30.85	29.1084		339.3		29.1084
7 Bifurcation connection	.703	.199	0.497	2.37702	29.1084	29.1084		339.3	29.1084	29.1084
8-9 Turn after pump suction valve OD=18"	.56	.199	0.448	2*(2.0955)	29.1084	29.1084	(Pump Suction) 1.336	339.3	29.1084	29.1084

COMPONENT: 2

VOLUMES:

TYPE: PUMP

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet Outlet	
Pump	.633	0		2.032	29.1084	29.1084	$P_{IN} = 1.334$	339.3	29.1084	29.1084
Coast Down Controlled by RPM vs. Time [Code mass flow match to junction 00105 where venturi meter and data recorded]	<u>Valves Used During LOPA</u>									
	<u>Time</u>	<u>Rads/s</u>								
	0	130.5								
	75.0	130.5 (Start Transient)								
	76.0	75.5								
	77.0	67.5								
	78.0	55.1								
	80.0	44.9								
	85.0	24.03								
	89.0	20.5								
	95.0	16.51								
	105.0	12.56								
	115.0	10.08								
	125.0	8.23								
	135.0	5.60								
	145.0	2.75								
160.0	.0001									
Pump Stop at 160 s										

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Pipe before heat Exchanger	.63	1.4	0.45	0.7874	29.1084	29.1084		339.3	29.1084	29.1084
2 HE Inlet	2.33	1.4	1.65	1.0499	29.1084	30.1583		339.3		
3, 4, 5, 6 HE Pipe in Contact with 2nd Side	1.319	1.4	0.016	4(.6477)	30.1583	30.1583				
7 Section that Bends up in HE	1.319	1.4	0.016	.3895	30.1583	30.5478				
8, 9, 10, 11 HE pipes in contact with 2nd side	1.319	1.4	0.016	4(.6477)	30.5478	30.5478		327.6		
12 He Outlet	1.95	1.1	1.39	0.8467	30.5478	31.3945	1.763MPa	327.6		
13, 14 ID=17,624 pipe returning to the single inlet to reactor	.633	1.1	0.45	2(1.8669)	31.3945	31.3945			31.3945	31.3945
15 Centerline of tee to centerline of elbow	.197	1.1	0.497	2.3114	31.3945	31.3945			31.3945	31.3945
16, 17, 18 Two loops combine and start up to vessel	.565	1.1	0.565	3(2.62467)	31.3945	39.2685			31.3945	
19 Reducing elbow between rising pipe and vessel	.65	1.1	0.65	1.4478	39.2685	39.2685	1.57MPa	327.6		39.2685

COMPONENT: 4

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Centerline of inlet pipe down into the shroud area	1.0974	0.0	0.936	.96582	39.2685	38.7732		327.6	39.2685	39.2685
a) Outlet of C3*	<u>Branch Components have Multiple Connections</u> Connects to inlet of C4									
b) Outlet of C4										
c) Inlet of C4										

*C3 means component 3

COMPONENT: 5

VOLUMES: 3

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Centerline of inlet pipe going toward cover gas	1.109	0.0		.49532	39.2685	39.7638		327.6		
2 Volume of water in contact with cover gas	1.153	0.0		.9525	39.7638	40.7163		327.6		
3 Cover gas region	1.153	0.0		.4826	40.7163	41.1989	1.48			41.1988

COMPONENT: 6

VOLUMES: 2

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Section inside shroud	1.63	0.8	1.45	.56832	38.7732	38.2049		327.6		
2 Section in shroud	.793	0.8	0.63	.985308	38.2049	37.2196		327.6		

COMPONENT: 7

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Bottom elevation of volume represents the transition plate	.794	0.8	0.63	.75164	37.2232	36.4749		327.6		
This volume represents the space above the transition plate. Several other flow paths connect at the transition plate are:										
a) Outlet C7* to inlet C8 Area = $4.44959\text{E-}3 \text{ m}^2$ Loss Coefficient = 0.0 b) Outlet C7 to inlet C9 Area = $5.78447\text{E-}3 \text{ m}^2$ Loss Coefficient = 0.0 c) Outlet C7 to inlet C10 Area = $6.229\text{E-}2 \text{ m}^2$ Loss Coefficient = 0.0 d) Outlet C6 to inlet C7										

*C7 means component 7

COMPONENT: 8

(Peak Assembly)

VOLUMES: 4

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Non-heated inlet section	.07527	.266	0.075	.352425	36.4681	36.1156		327.6	36.4681	
2, 3, 4 Fuel plate region divided into 3 equal volumes	.0617	.266	0.0048	3(.2010833)	36.1156	35.5124				35.5124
				-HEAT STRUCTURE 0080 transfers heat into Volumes 2, 3, 4 - see heat structure for power input						

COMPONENT: 9

(13 Periphery Channels)

VOLUMES: 4

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Non-heated inlet section	.271	.266	0.075	.352425	36.4681	36.156		327.6	36.4681	
2, 3, 4 Fuel plate region divided into 3 equal volumes	.222	.266	0.0048	3(.2010833)	36.1156	35.5124				35.5124
				-HEAT STRUCTURE 0090 transfers heat into Volumes 2, 3, 4 - see heat structure for power input						

COMPONENT: 10

(14 Assemblies)

VOLUMES: 4

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Non-heated inlet section	.2816	.266	0.075	.352425	36.4681	36.156		327.6		
2, 3, 4 Fuel plate region divided into 3 equal volumes	.2307	.266	0.0048	3(.2010833)	36.1156	35.5124				
				- HEAT STRUCTURE 0100 transfer heat into Volumes 2, 3, 4 - see heat structure for power input						

COMPONENT: 11

VOLUMES: JUNCTION

TYPE: SNGLJUN

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Models flow bypassing core	.115	2.5		----		36.4681				
	- Area based on clearance in Y shaped openings for control blades in transition plate - Mass flow is total bypass at normal operating conditions - Loss coefficient adjusted for full bypass flow references to Y shape clearance									

COMPONENT: 12

VOLUMES: JUNCTION

TYPE: VALVE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Flow Reversal Valves (4 Valves combine to act as one)	0.1616	5.3		----		36.4681	---	---		36.4681
	- Area proportional to the pressure drop across transition plate* - Valve completely open when $\Delta p=0$ and closed when $\Delta p=2.15 \text{ E4 Pa (3.12 psi)}$ - Equation to describe area is $\text{Area Fraction} = 1 - 3.16 \text{ E-5 } \Delta p - 2.785 \text{ E-9 } \Delta p^2 + 9.74 \text{ E-14 } \Delta p^3$ - Δp calculated between C7 and C14 - Modeled as servo value which means it will always open and close according to the pressure calculated each time step - The following control variables are associated with Component 12: 20500100 to calculate (Δp) 20500200 to calculate (Δp^2) 205003 to calculate (Δp^3) 205004 to calculate equation of area fraction open									

* Reference 27 June 89 Memorandum from L. Cheng to G. Slovik and U. S. Rohatgi, "Modeling of Flow Reversal Valve".

** Reference Memorandum dated 18 June 62 from John R. Pozzato, "Additional Test Results from Prototype Flow Reversal Valve". Valve determined from this experimental data.

COMPONENT: 13

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Volume below core exit (lower head of reactor vessel)	1.39	0.0	0.075	0.739715	35.7726	34.7726		339.3	35.5124	34.7726
				- Fuel assemblies flow pass into this volume - Inlet of C13 is connected to Inlet of C24						

COMPONENT: 14

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Vol. in reflector be- tween bottom of transi- tion plate and core centerline	1.848	0	1.711	.6540499	35.8140	36.4681		339.3	35.8144	36.468
				- Flow reversal valves (J12) communicate between C7 and C14 - Bypass flow (J11) goes between C7 and C14 - Loss coefficient of 0.1 between C24 and C14 - Loss coefficient of 0.1 between C1 and C14						

COMPONENT: 15

SHELL SIDE HEAT EXCHANGER
VOLUMES: 11

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1, 5 Shell side in lower baffle region	1.66	0.0		.6477	0.0	0.0				
6 Lower to upper part of baffle	1.66			.3895	0.0	0.0				
7-11 Upper baffled region	1.66			.6477	0.0	0.0				
				- Exact dimensions of heat exchange not important for transients of the LOPA and LOCA class - Heat loss to match steady state operation only necessary since flow through HE ends early in transient						

COMPONENT: 17

TYPE: TMDPJUN

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet Outlet	
Mass injection for shell side of heat exchanger	1.66									
					- Supplied secondary mass flow which balance the heat rejection at normal operation					
					- Pump assumed to trip with loss of power or trip (TRIP 501)					
					- C16 and C17 supply mass flow into shell side of heat exchanger					
					<u>Time</u>					<u>Mass Flow (kg/s)</u>
					0.0					10.07 (time after trip)
					2.0					70.7 (delay)
					32.0					22.0
180.0					1.0					
400.0					1.0					

COMPONENT: 18

TYPE: SNGL JUN

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Supplied pressure boundary for heat exchanger							0.36			
				- C18 and C19 supplied pressure boundary at one exit of heat exchanger - C16 and C17 supplied mass flow boundary at entrance to shell side of heat exchanger ($t_{in} = 289 \text{ K}$)						

COMPONENT: 20

TYPE: VALVE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Depressurization Valve He102	0.015	5.0*	---	---	42.1093	42.1093				

*Determined from plant blowdown data

COMPONENT: 24

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 Volume in reflector between core outlet and core centerline	1.848	0.0	1.711	.301625	35.5124	35.8140		339.3	35.5124	35.814
				- Inlet of C13 connected to Inlet of C24 - Outlet of C24 connected to Inlet of C14 (upper reflector region) - Reflector split in preparation for the beam tube rupture analysis						

COMPONENT: 25

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Volume in thermal shield, below core centerline	1.834	0.0	1.34	1.0414	35.8140 bottom of shield	34.7726				
					- Inlet oc C25 is connected to inlet of C26					

COMPONENT: 26

VOLUMES: 7

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Model volume above core centerline in thermal shield										
1	1.07	0.0	1.0	.10054	35.8140	37.109			35.8140	37.109
2	1.09	0.0	1.0	.10054		- The volume as a function of height as to volume in thimbles and shutter volumes - Details needed to predict correct static head - Top of thermal shield volume is atmospheric				
3	1.15	0.0	1.0	.10054						
4	1.388	0.0	1.0	.35243						
5	1.781	0.0	1.0	0.2096						
6	2.04	0.0	1.0	0.2794						
7	0.258	0.0	1.0	0.1524						

COMPONENT: 27

JUNCTION

TYPE: SINGLJUN

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Connects top of thermal shield to atmospheric pressure										
					- Connects C26 to C28 - C28 models the atmospheric pressure					

COMPONENT: 29

TYPE: VALVE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Models the break at EL 117'6" (central beam)	0.0338*	0.0			35.8140	35.8140			35.8140	35.8140
					- Trip 509 opens the break on time					

*Area = $8.963\text{E-}4 \text{ m}^2$ (1.39 in²)

CHECK VALVE

COMPONENT: 30

VOLUMES:

TYPE: VALVE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet Outlet	
	.633	2.184 ($\Delta p = 1.537$) E4 Pa at operat- ing con- ditions		Abrupt Area Change	29.1084	29.1084	1.8	339.3	29.1084	29.1084
Area Changed as Function of Flow					- Area of check valve modeled as flow vs. area - Flow in 001020 is reference for area of check valve (location where pump coast down data taken) - The following control variables are used: a) 205030000 defines flow in 0010200 b) 205031 uses flow to find area c) Table 20203100 has normalized flow versus area					
Mass Flow		Area Fraction								
1227.0 (kg/s)		1.0								
549.0		1.0								
411.5		0.93								
274.4		0.9								
137.2		0.6								
54.0		0.3								
11.0		0.0*								

*(Reference: BNL Memorandum dated 23 August 89, "Relationship Between Flow Area and Pressure Drop for the Primary System Check Valve," by Lap Y. Cheng, used to extrapolate to valve closing.)

COMPONENT: 31

VOLUMES: 1

TYPE: SinglVol

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m)	
1 Section of pipe needed to be between pump model and valve	.633	0.0	.448	0.7874	29.1084	29.1084	1.804	339.3	29.1084	29.1084

COMPONENT: 40

VOLUMES: 2

TYPE: PIPE

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1,2 Represents piping from demister to depressuri- zation valve He/02	0.028	70.0	0.028	7.620	42.1093	42.1083				
				- Exact length and configuration not needed since components adjusted to reproduce plant data for a depressurization (see L. Cheng memo to File 22.39, dated 23 Jan 89, Figure 1)						

COMPONENT: 41

VOLUMES: 1

TYPE: BRANCH

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
1 This component represents the demister. (The piping between the cover gas and demister are not modeled.)	1.534		1.168	.9104	41.1989	42.1093				
- Elevations not important for a gas - Component connects cover gas (C5) to demister (C4) and helium injection (J52)										

COMPONENT: 52

TYPE: TMDP JUN

Volume # & Description	ID (m)	Loss Coeff.	Hyd. Diameter (m)	Length (m)	ELEVATION (m)		P L A N T D A T A			
					Inlet	Outlet	Press (MPa)	T (K)	Elevation (m) Inlet	Outlet
Junction to supply He that comes from dissolution during the depressurization	1.33	0		---	42.1093	42.1093				
					- Trip 520 (depressurization valve opening) initiates He injection - C51 and J52 combine to make up for He injection system (only in cover gas) - The components have been benchmark against plant data* - The following control variables are used:					
					a) 20503700 Define present time b) 20503800 Define Δt c) 20503900 Define present pressure in 006010000 d) 20504000 Subtract off secondary mass from total mass in problem (leaves only primary) e) 20504100 Defines Δp [i.e., $P(NOW)-P(Post)$] f) 20504200 Mass of He (i.e., mass * Δp * coefficient) g) 20505200 Defines He mass injection (from solution)/Δt h) 20505300 Add up mass released during depressurization i) 20505400 Remember last He total injection j) 20505500 Remember last time k) 20505600 Remember last pressure					

* Reference: BNL Memorandum dated 23 Jan 89, "Depressurization of HFBR Due to Opening of the Depressurized Valve He102," to File 22.39.

HEAT SLAB STRUCTURE, HOT ASSEMBLY

COMPONENT: 10080

TYPE: HEAT SLAB

Volume # & Description	Area	Hyd. Diameter	Length	E L E V A T I O N		P L A N T D A T A			
				Inlet	Outlet	Press	T	Inlet	Outlet
Fuel divided into 3 equal lengths	3(0.4416)	0.0048	3(.2010833)						
Heat Slab Hydraulic Connector 100801 100802 100803 00802 00803 00804 - Fuel plate modeled with rectangular geometry insulated center line, and right boundary connected to hydraulic volume									

HEAT STRUCTURE, PERIPHERY ASSEMBLIES (13)

COMPONENT: 10090

TYPE: HEAT SLAB

Volume # & Description	Area	Hyd. Diameter	Length	E L E V A T I O N		P L A N T D A T A			
				Inlet	Outlet	Press	T	Elevation Inlet	Outlet
Fuel divided into 3 equal lengths	3(5.7408)	0.0048	3(.2010833)						
Heat Slab Hydraulic Connector 1009001 1009002 1009003 00902 00903 00904 - Fuel plate modeled with rectangular geometry, insulated center line, and right boundary connected to hydraulic volumes									

COMPONENT: 10100

HEAT STRUCTURE, INTERIOR ASSEMBLIES (14)

TYPE: HEAT SLAB

Volume # & Description	Area	Hyd. Diameter	Length	E L E V A T I O N		P L A N T D A T A			
				Inlet	Outlet	Press	T	Elevation Inlet	Outlet
Fuel divided into 3 equal lengths	3(6.1824)	0.0048	3(.2010833						
Heat Slab Hydraulic Connector 1010001 1010002 1010003 01002 01003 01004 - Fuel plate modeled with rectangular geometry, insulated center line, and right boundary connected to hydraulic volume									

Table 5.2
60 MW Decay Heat Data

<u>Time After Shutdown</u> <u>sec</u>	<u>Decay Heat,</u> <u>MW</u>
0.5	8.93
1.0	6.28
5.0	5.00
10	4.05
20	3.27
30	2.86
40	2.61
50	2.45
60	2.31
70	2.19
80	2.09
100	1.96
200	1.62
300	1.47
400	1.38
500	1.31
600	1.26
700	1.20
800	1.16
1000	1.09
2000	0.880
3000	0.762
4000	0.686
5000	0.632
6000	0.591
7000	0.557

5.2 Flow Reversal Valves

Four flow reversal valves are positioned on the transition plate and remain closed during the normal operation. A pilot line from the primary and shutdown pumps keep the valves closed during normal pump trips to direct the flow into the core when the shutdown pumps take over cooling the core. However, during an accident where both the primary pumps, the pony motors, and shutdown pumps are not available, the flow reversal valves open during the pump coast down phase and direct some of the fluid into the reflector lowering the reflector temperature. Eventually, the down flow through the core stops and the heat in the core produces bubbles and reduces the coolant density in the core. This results in an increase in the buoyancy forces of the fluid, which causes flow reversal in the core and upward directed flow. The natural circulation pathway around the core is completed by the opening of the flow reversal valves.

Figure 5.2 is a diagram of a flow reversal valve. The data on the prototype [Pozzato, 1961] was used to determine the value of the loss coefficient to be 5.315. The area of an open valve is determined by the pressure across the valve body. In the RELAP5 model the pressure difference is defined as the difference in pressure between C7 (hydraulic cell above the core) and C14 (hydraulic cell below transition plate in the reflector). The valve is completely open when the pressure difference is zero and closed at 21.55 k Pa (3.125 psi). The equation used with the control variables defined in the deck was

$$\begin{aligned} \text{Area fraction} = & 1 - 3.1622\text{E-}5\Delta p - 2.78495\text{E-}9(\Delta p)^2 \\ & + 9.7397\text{E-}14(\Delta p)^3 \end{aligned} \quad (5.1)$$

The area of one of the eight holes in each flow reversal valve is $6.027\text{E-}4 \text{ m}^2$ (0.9336 in^2) [Cheng, June 1989] and the total flow area for each valve is $4.822\text{E-}3 \text{ m}^2$ (7.469 in^2). This is slightly less than the full size of the holes since the piston blocks $8.07\text{E-}5 \text{ m}^2$ (0.125 in^2) of each. This component was modeled as a valve (C12) in the input deck with control variables 20100100, 20500200, and 20500300 being the pressure difference, the pressure difference squared, and tripled, respectively. The area fraction of the valves is defined in control variable 20500400. These components are also in Table 5.1.

5.3 Reactor Vessel Depressurization and Plant Data

Several years ago the HFBR underwent blowdown experiments where the pressure in the cover gas was measured after the valve (He-102) was opened. The results are shown in Figure 5.3 [Cheng, January 1989]. The RELAP5 model geometrically reproduced the necessary volumes but was unable to reproduce the blowdown characteristics of the reactor vessel. It was subsequently determined that the RELAP5 model depressurized too quickly since it was not accounting for the helium coming out of solution. The solubility of the helium is computed using Henry's law (i.e., equilibrium dissolution model).

$$P = H * X \quad (5.2)$$

FIGURE 5.2 Flow Reversal Valve Details

FIGURE 5.3 Cover Gas Pressure Following Opening of Valve HCe-102

where P = partial pressure of helium, Pa

H = Henry's constant $(1.2159016 \times 10^{10} \text{ Pa } (12 \times 10^4 \text{ atm}) \text{ for D2O})$

X = mole of He/moles of solution

In RELAP5, a control variable (20504100) was used to define the decrease in pressure from the last time step and this was multiplied by the primary system mass and the inverse of Henry's constant. Henry's constant is also multiplied by the mass fraction to convert the equation into the mass of He coming out of solution (i.e. $20 \text{ kg/mole-D2O} \times \text{mole-He}/4 \text{ kg}$). The equation used in RELAP5 is

$$\text{Mass of He} = (4/20 \times 1.2159016 \times 10^4) \times (P^{N+1} - P^N) \times (\text{mass of primary system}) \quad (5.3)$$

where P^{N+1} = pressure at present time step

P^N = pressure at previous time step

This calculation was performed in control variable 20504200. The helium mass flow was determined in control variable 20505200 where the mass is divided by the time between the two pressure points, which is approximately equal to the mass flow rate of helium coming out of solution. The prediction of this model applied to the data is shown in Figure 5.3. The results indicate that RELAP5 should be able to make a good estimate of the helium dissolution rate.

5.4 Pump Model

The RELAP5 model of the pump used the rpm vs. time option. The rpms given in the deck were adjusted by trial and error until the coastdown of the plant (Figure 2.9) was duplicated by the code. (The behavior of the pump in the beam tube rupture case is not important since its effect become negligible very early in the transient, as discussed in Chapter 7.) The data is available for 50 seconds of coast down. The curve beyond 50 s was extended by extrapolating to zero pump speed. This occurs at about 100 s after a pump trip. However, the exact behavior is not necessary to model since a check valve in the primary loop closes when the flow drops below 11 kg/s. This has been found to occur after flow reversal has begun which makes the tail end of the pump coast down irrelevant.

5.5 HFBR Model Conservatism

The following are the assumptions, or modeling adjustments, made in the analysis to achieve conservative results (i.e., these are not best estimate calculations).

1. The metal mass of the reactor vessel was not modeled. This will cause the temperature of the water in the vessel to rise more rapidly than would actually occur.

2. Gamma ray smearing is not accounted for in the analysis. This effect reduces the peak power locations and increases the lower power ones in the decay heat operation. In BWR assemblies, this effect has been known to reduce the peak

location power density by as much as 10%. This occurs because the gamma rays have a large mean free path in the core. Their effect is evenly spread throughout the core. It should be remembered that in the decay heat mode of heating, about 50% of the heat is produced by betas while the remaining 50% is produced by the gammas; but, the betas are absorbed where they are created while the gammas disperse throughout the whole system.

Recent calculations [Todosow, 1989] indicate that 35.3% of the gammas are absorbed outside the core which implies that 18% of the total decay heat is deposited outside of the fuel region. Thus, 82% of the total decay heat remains in the core region. This energy deposition breaks down into 5% being deposited directly into the coolant where the fuel plates receive about 77% of the total decay heat produced. In the RELAP5 model, 98% of the decay heat is produced in the plates and only 2% is deposited in the coolant. By neglecting the gamma smearing effect and assuming a 10% increase in the peak heat flux, about 40% more energy is deposited in the RELAP5 fuel plates than expected in the actual HFBR. This assumption makes the heat flux predictions in RELAP5 very conservative. This will also reduce the time to flow reversal for the peak assembly in RELAP5.

3. The fuel plates are modeled as having an insulated centerline while in reality each plate is cooled on both sides. The peak plate would have cooler neighbors which would increase the temperature gradients within the plates and subsequently would reduce the maximum temperature. It should be noted that aluminum has a very high thermal diffusivity, $8.6\text{E-}5 \text{ m}^2/\text{s}$ ($3.33\text{ft}^2/\text{s}$). This will result in fuel temperatures being over predicted in RELAP5.

4. The heat transfer between the periphery channels (the hottest in the core) and the reflector is not modeled. This will result in higher in-channel fluid temperatures and associated plate temperatures. This will reduce the time to flow reversal.

5. The HFBR fuel channel box [approximately $7.6 \times 7.6 \text{ cm}$ ($3 \text{ in.} \times 3 \text{ in.}$)] is of unfueled aluminum (Al) construction. Inside are slightly curved plates with enriched uranium impregnated into the Al plates. The interconnecting plate to channel box arrangement cannot be modeled in the code. This leaves a large thermal heat sink unaccounted for. The effect of not modeling these characteristics will cause an increase in fuel plate heat up rates and higher predicted plate temperatures.

6. The peak assembly in RELAP5 is built up of 18 plates with the highest single plate power density found in the entire fuel cycle [Mallen, 1977]. The axial power shape was the most skewed condition found to give the largest possible heat flux. The effect of this assumption will be that the heat flux will be over predicted in RELAP5.

All of the above assumptions will make the analysis more demanding than what would physically be possible at the facility. These effects will cause the HFBR analysis to be a conservative calculation rather than a best estimate.

6. FLOW REVERSAL EXPERIMENTAL DATA

A separate effects test was performed in 1963 [Tichler, 1963] to demonstrate the thermal hydraulic behavior of the HFBR during a flow reversal event and to determine the heat flux limits (i.e., CHF conditions) where flow reversal can safely be experienced. The test facility has been recently re-assessed [Rohatgi and Slovik, 1990] for similarity to the HFBR and it was concluded that it was more difficult to achieve flow reversal in the test than in the HFBR core. The test data demonstrated that a safe flow reversal (i.e., no CHF) would occur at $1.47 \times 10^5 \text{ W/m}^2$ (46,700 Btu/hr-ft²) and burnout would occur at $1.51 \times 10^5 \text{ W/m}^2$ (48,000 Btu/hr-ft²). The conditions of the experiment applied to the Monde [Monde, 1982] correlation would predict a CHF level of $1.686 \times 10^5 \text{ W/m}^2$ (53,487 Btu/hr-ft²), which indicates that the experimental results are reasonable and conservative. Data collected from ORNL for HFIR [Gambill, 1965] using a gap of about half of the gap in the HFBR's test facility (length of 24 in.) predicted a CHF of $2.05 \times 10^5 \text{ W/m}^2$ (65,000 Btu/hr-ft²) which implies that the HFBR's test generated conservative values within the correct range.

These tests were performed with the cover gas at atmospheric conditions and a water level high enough to give about 1.58 Pa (23 psia) at the core center. This test gives the CHF at atmospheric conditions, but as shown in Figure 5.3, the reactor vessel cover gas doesn't reach atmospheric conditions until about 100 s after a depressurization. The criteria of safe flow reversal (i.e., the CHF level) is also a function of pressure and its limit increases with pressure. In Table 6.1, the decay heat power level of the HFBR is compared with the Monde correlation [Monde, 1982] where the surrounding fluid is assumed to be saturated (the subcooling that actually surrounds the HFBR core will increase the CHF limit). The pressure history comes from the LOPA calculation with a plate peaking factor of 2.032. The use of the 1963 experimental results for safe flow reversal is essentially using the long term CHF limit (i.e., after depressurization) for the flow reversal point which occurs at a higher pressure. This makes the $1.47 \times 10^5 \text{ W/m}^2$ (46,700 BTU/hr ft²) limit used by the HFBR staff very conservative.

The HFBR staff has been using the safe flow reversal limit of $1.47 \times 10^5 \text{ W/m}^2$ (46,700 Btu/hr-ft²) as a matter of policy. In this report the lower burnout limit of $1.51 \times 10^5 \text{ W/m}^2$ (48,000 Btu/hr-ft²) will be used for discussion, and it has been shown to be conservative, Table 6.1. The following is a description of the test.

A small-scale separate effects test facility [Tichler, 1963], shown in Figure 6.1, was set up to simulate the flows expected during a flow reversal event in the HFBR. The facility had full height fuel channels with electrically heated nickel plates representing fuel. Pipe sections were used to represent the core inlet section, core outlet, and side reflector. The heated channel in the test (0.098 in. x 2 in. x 22 in.) was very similar to the channels (0.096 in. x 2.46 in. x 22.75 in.) in the HFBR. The flow reversal bypass valves were modeled by a ball valve while the friction loss in the bypass valve was simulated by an orifice. The ratio of bypass path area to core area varied from 0.22 to 0.75 in the test. The HFBR ratio is 0.36. A pump and heat exchanger representing the external loop in the HFBR was also provided for in the facility.

Two types of tests were performed in this facility. The first part assessed the transient flow reversal phenomena in the HFBR. These tests were

Table 6.1 CHF Limits As A Function of Pressure for the HFBR

TIME (s) (After Scram)	Decay Power Levels MW	Pressure* (Core Center) MPa	Heat Flux ($\times 10^{-5}$) W/m ²		
			HFBR Average	HFBR Peak	Monde CHF Correlation
10 s	4.05	1.428	1.092	2.22	9.1
20 s	3.27	1.228	0.881	1.79	8.3
30 s	2.86	1.009	0.771	1.57	7.0
40 s	2.61	0.779	0.703	1.43	5.7
50 s	2.45	0.590	0.660	1.34	4.7
60 s	2.31	0.443	0.622	1.26	3.8
70 s	2.19	0.339	0.590	1.20	3.0
80 s	2.09	0.266	0.563	1.14	2.3
95 s	1.99	0.199	0.536	1.09	1.7

*From the RELAP5 LOPA calculation

Figure 6.1 Schematic of the 1963 Test Facility

performed with two configurations, namely, single and three channel test sections. The channel velocities varied from 1 ft/sec to 9 ft/sec and the heat flux varied from 9000 BTU/hr-ft² to 50,000 Btu/hr-ft². The velocities covered the HFBR loop flow rates from 400 gpm to 3600 gpm. Hence, all tests were begun below the flow rate of 4900 gpm where the flow reversal valves open in the HFBR when the pumps are no longer keeping them closed. The heat flux range in the test covers the range expected in the HFBR. The HFBR power near the time of flow reversal is about 2000 KW, which is equivalent to the average core heat flux of 19000 Btu/hr-ft².

The tests were begun with the pump running and the bypass valve open until the system achieved a steady-state condition. The transient was initiated by tripping the pump. It was observed that there was voiding and flow reversal in all the runs with heat flux exceeding 12,000 Btu/hr-ft². There were no flow measurements and the conclusions about flow reversal were made on the basis of visual observation of voiding, pressure, and temperature. The plate temperature at the top of the core was close to the boiling point (240°F) after the flow reversal event. Brief periods of rapid temperature increase of 7 to 15°F/sec were observed, but the total temperature increase was on the order of 100°F. Only two tests with the single channel test section (29 and 30) showed burnout and a rapid temperature rise of 40°F/sec. Test 28 had a single channel and was the highest heat flux test for which no burnout was observed. The heat flux was 46,700 Btu/hr-ft². This heat flux became the basis for a safe flow reversal and safety procedures in the HFBR.

The second set of tests were performed to assess the stable natural circulation phase after the flow reversal event was established. These tests were performed for low and high subcoolings for the fluid in the reflector. The test report states that a stable natural circulation was established for several different conditions and no damage to the plate was observed. The heat flux varied from 10,400 Btu/hr-ft² to 59,400 Btu/hr ft² depending on inlet conditions.

These tests demonstrated the flow reversal phenomenon in the HFBR and found that the CHF heat flux limit was at 1.51×10^5 W/m² (48,000 Btu/hr-ft²) for atmospheric cover gas conditions. The highest, safe, flow reversal test had a heat flux of 1.47×10^5 W/m² (46,700 Btu/hr-ft²). The actual CHF limit is between 1.5×10^5 W/m² and 1.47×10^5 W/m²; however, no refinement was made in 1963 to determine the exact value. By policy this was used to design the pump coast down and as the safe flow reversal heat flux (i.e., no CHF). Recent experimental work [Monde, 1982] has shown their results are consistent with the 1963 experimental data. The Monde correlation would have predicted the experimental test facility of 1963 to have gone into CHF around 1.686×10^5 W/m² (53,487 Btu/hr-ft²). The 1.47×10^5 W/m² limit used by the HFBR staff is conservative since the plant will go through flow reversal at a much higher pressure (around 3.4E5Pa (50 psi), and as demonstrated in Table 6.1, the CHF correlations has a pressure effect to it. The HFBR staff has been using the after depressurization QCHF limit for their criteria of safe flow reversal. This report will use 1.51×10^5 (which also is conservative) since it was the lowest actual CHF level experimentally determined.

7. TRANSIENT CALCULATIONS AND DISCUSSION OF RESULTS

The RELAP5 model developed in this report was applied to two transients at the 60 MW power level. The first was the loss of power accident (LOPA). This highly unlikely event was analyzed for the purpose of studying the thermal hydraulic behavior of the core during a flow reversal in the core. The second transient was a loss of coolant accident (LOCA) where a break in a beam tube was assumed (i.e. no mechanism identified). The following will be a discussion of the RELAP5 calculations.

7.1 The Loss of Power Accident (LOPA)

The LOPA is a hypothetical event where all the power is assumed to be lost in the HFBR facility (see Section 3 for a complete discussion). This would automatically scram the reactor, open the depressurization valve, and trip the reactor's primary pumps. The shutdown pumps are assumed to be unavailable which allows the opening of the depressurization valve. DC back up batteries are used to power the pony motors for a minimum of two hours, are assumed to be unavailable. The purpose of the pony motors are to maintain a forced downward flow in the core until the decay power level in the fuel plates is low enough that a flow reversal in the core would not cause fuel damage. The analysis of the LOPA will assess the capability of the core to undergo flow reversal safely, and, unassisted.

7.1.1 LOPA Results

The initial conditions for the transient are presented in Table 7.1. The pressure drop in the loop was adjusted to match the plant data found in Table 2.1.

Table 7.1 Initial Conditions

Power Level	60 MWt
Water Level	EL 133 ft 7 in.
Loop Flow	1226 kg/s (~17900 GPM)
Cover Gas	1.54749E6 (224 psia)

The calculation was run for 75 s to establish a steady state. The transient was initiated at 75 s. The sequence of events are listed in Table 7.2. The results are presented in Figures 7.1 through 7.14.

In Figure 7.1, the cover gas reaches atmospheric pressure 100 s after the power loss. From Table 7.2, the flow reversal event first occurred 68.2 s after the scram with the cover gas pressure at 2.868×10^5 Pa (42 psia) and the center of the hottest channel having a pressure of 3.3879×10^5 Pa (49 psia). The system pressure decreased from 1.547×10^6 Pa (224 psia) down to 2.868×10^5 Pa (42 psia) during a period of 68.2 s. In Figure 7.2 the helium released from the primary system by the RELAP5 equilibrium dissolution model is shown. The abundance of nucleation sites within the reactor and the long duration of the pressure decrease, implies that the event is reasonably simulated by an equilibrium model. The figure shows that about 90% of the initial 1 kg of helium in the system has been expelled by the time of the flow reversal. The effect of

Table 7.2 Sequence of Events

	<u>Relative Time (s)</u>
Power loss t = 75.0 s	0.0
Pump trip t = 75.0 s	0.0
SCRAM t = 75.0 s	0.0
Depressurization	
Valve opens t = 76.5 s	1.5
Flow reversal valves (FRV)	
Open t = 81.0 s	6.9
Flow reversal in	
Hot channel t = 143.2	68.2
Average channels t = 144.8	69.8
(average power)	
Internal channels t = 145.8	70.8
(colder power channels)	
Check valve closed t = 143.8	68.8
Stable natural circ. t = 170.5	95.5

FIGURE 7.1 LOPA Cover Gas Prediction

FIGURE 7.2 LOPA Helium Released from Equilibrium Dissolution

FIGURE 7.3 LOPA Loop Flow

FIGURE 7.4 LOPA Mass Flow in Flow Reversal Valves

FIGURE 7.5 LOPA Bypass Mass through the Transition Plate

FIGURE 7.6 LOPA Pressure in Unheated Tube Area of the Hot Channel (Core Entrance)

FIGURE 7.7 LOPA Pressure in Cell Below Core Outlet

FIGURE 7.8 LOPA Liquid Temperature of Fluid Above the Transition Plate (Fluid Leaving the Core)

FIGURE 7.9 LOPA Liquid Temperature of Cell Below Core Outlet

FIGURE 7.10 LOPA Mass Flow in the Hot Channel (1 Assembly)

FIGURE 7.11 LOPA Mass Flow in the Average (i.e., power) Channels (13 assemblies)

bnl
at

FIGURE 7.12 LOPA Mass Flow in the 14 Internal Assemblies

FIGURE 7.13 LOPA Void in Hottest Node of Peak Assembly

FIGURE 7.14 LOPA Fuel Plate Centerline Temperature of Hottest Node in Peak Assembly

the remaining helium in the primary system, which is probably suspended in the heavy water as micro bubbles, would be insignificant since they would stay entrained in solution. These bubbles represent a vessel void fraction below 2% and would not significantly alter the prediction of CHF. The check valve in the exterior loop closed at 68.8 s and isolated the reactor vessel from the rest of the loop (Figure 7.3).

Inside the vessel, the flow reversal valves (Figure 7.4) began to open about 6 s after the pump trip since the pilot line no longer provided a pressure head to keep the valves closed (see Section 2). The valves opened according to the pressure across the transition plate. Zero pressure drop across the transition plate opens them fully while 2.155×10^5 Pa (3.125 psia) closes them completely. The mass flow through the valves (which goes from above the core into the reflector region) is the largest during the pump coast down and reverses momentarily to upflow after the check valve closure. The pressure wave generated by the check valve closure momentarily decreases the pressure above the core causing the reversal of flow direction. The natural circulation flow through the flow reversal valves are about 6.91 kg/s. Figure 7.5 shows the bypass flow around the core which is mainly from the clearances in the control blade penetrations through the transition plate. It allows a flow of about 3.2 kg/s during natural circulation.

The pressure history around the core region is shown in Figure 7.6 where the pressure at the top of the core is shown with the hydraulic cell just below the core in Figure 7.7. The fluid temperature above the core and below it are shown in Figures 7.8 and 7.9, respectively. Fluid exiting the core is reaching saturation conditions (has not mixed with the water in the shroud yet) while the water in the reflector, which is the water at the core entrance in natural circulation, is highly subcooled. The higher density fluid in the reflector, relative to the hot fluid in the core, causes an increase in the buoyancy forces within the core. The buoyancy driven flows predicted are presented in Figures 7.10 through 7.12. The hottest assembly stabilizes around -0.71 kg/s (negative means upflow) while the average powered assemblies draw about -5.1 kg/s (these are the 13 peripheral assemblies). The cooler interior assemblies generate a flow of -4.3 kg/s.

7.1.1a LOPA Core Analysis

RELAP5 has predicted the earliest flow reversal to occur 68.2 s after the scram. (This timing is conservative since it depends on the total heat load in the assembly. The peak assembly is about 40% higher in power than it should be.) The power level in the core from decay heat is 2.2116 MW. The power distribution was skewed to maximize the predicted heat flux. The maximum heat flux (i.e. internal heat generation/area) is 1.442×10^5 W/m² (45,753 BTU/hr-ft²) which is below the experimental derived CHF flux limit of 1.513×10^5 W/m² (48,000 BTU/hr-ft²). This is even below the safe flow reversal policy limit of 1.472×10^5 W/m² (46,700 BTU/hr-ft²) used by the HFBR staff. The hydraulic conditions predicted by RELAP5 were used in the Monde correlation which predicted the CHF limit to be 3.04×10^5 W/m² (96,432 BTU/hr-ft²). The heat flux predicted by RELAP5 is compared to CHF limits predicted by the Monde correlation using the hydraulic conditions in the central node of the hottest channel from the RELAP5 calculation and are shown in Table 7.3. On the basis of the Monde correlation, it can be concluded that the CHF condition was not reached in the flow reversal event. Also, the 1.47×10^5 W/m² safe flow reversal policy limit used by the HFBR staff

Table 7.3 CHF Evaluation

	(W/m ²)	(W/m ²)
<u>Time</u>	<u>HTPNR*</u>	<u>Monde</u>
60 s	1.439E5	3.993E5
65 s	1.296E5	3.458E5
68 s	1.289E5	3.04E5
70 s	1.4219E5	2.964E5
75 s	1.406E5	2.672E5
80 s	1.3801E5	2.377E5
85 s	1.358E5	2.142E5
450 s	0.9587E5	1.364E5

*Heat flux predicted by RELAP5

can be seen to be a factor of two conservative to the actual limit.

The above-mentioned comparison indicates a significant margin to CHF as predicted by the 1963 HFBR experiment. The margins are even larger on the basis of recent CHF correlations of Monde (see Table 6.1). Also, it should be noted that the peak heat flux used in the RELAP5 analysis was very skewed by using high peaking factors. The most significant is the deposition of 98% of the decay heat remaining in the plate while recent analysis demonstrated that about 80% would remain in the plate. This would place the actual peak plate (i.e. the core average plate multiplied by 2.032 for the maximum plate and by 0.8 for the actual heat deposited) heat flux in the HFBR at $9.692 \times 10^4 \text{ W/m}^2$ (30,745 BTU/hr-ft²) which is three times smaller than the CHF limited predicted by Monde. Thus, the experimental data collected for the HFBR in 1963 and the Monde correlation confirm that the HFBR can successfully negotiate a flow reversal without fuel damage for the conditions of a LOPA with a factor of 2 in the CHF limit at 60 Mwt.

If the heat flux of $1.513 \times 10^5 \text{ W/m}^2$ (48,000 BTU/hr-ft²) is used as the HFBR safe limit, this implies that a peak plate of 2.032 can sustain a safe reversal any time after 34 s. The average plate in the core will pass through its critical time after 3 s. These times can be met with the extended coast down supplied by the flywheels added to the pumps (see Figure 2.9).

7.1.1b RELAP5 Fuel Plate Evaluation

As discussed in Section 5, RELAP5 is not a fuel assembly code. Under reasonable conditions, it can give a good approximation to the fuel temperatures. One of the reasons for the uncertainties in the temperature prediction is the flow regime map in the code is for pipe flows rather than the narrow, rectangular channels that exist in the HFBR. However, it was also recognized that the regions where the code would be phenomenology correct are the bubbly flow or high void regimes. The void fraction in the hot channel predicted by RELAP5, is shown in Figure 7.13. The other channels had voids of much lower values since they are cooler. About 3 to 4 bubbles of a diameter equal to the gap size in the channel would probably be the end of the bubbly regime and transition point to the disk flow regime. The range of the void fraction would be between 9.4 to 12.6% for bubbly flow, and for any void fraction below this range, the results from RELAP5 should be reasonable. From Figure 7.13, the void fraction is below 10% during the transient which implies that the fuel temperature in Figure 7.14 is reasonable. The figure also shows that the temperatures reach the operating level at the flow reversal point, but drop to a relatively cool temperature afterwards. It should be noted that the void fraction at the flow reversal point actually goes up to about 80%; however, the transient was characteristically fast and was difficult to capture on the plot file. This behavior is consistent with the results from the scaling study [Rohatgi and Slovik, 1990] which determined the flow reversal event would occur on the order of 0.04 s once a void was generated in a channel. The results from the fuel temperature predictions show that the temperatures would return to the operating conditions during a flow reversal and would not be a challenge to the fuel integrity.

7.2 Beam Tube Rupture

A beam tube rupture event (although no mechanism for it has been identified) has been postulated for the HFBR reactor. A brief description is

provided here (for a detailed discussion, see Section 3). The lowest elevation where a beam tube is positioned is in the center of the core (EL 117 ft 6 in.). The flow leaving the rupture would fill up the thermal shield volume to its maximum level of 92 in. (EL 121 ft 9 in.) above the bottom of the vessel and then overflow onto the shutdown cell floor. This type of transient is a loss of coolant accident (LOCA). If the level inside and outside the vessel remain at the top of the thermal shield, the transition plate (EL 119 ft, 7 3/4 in.) would have 2 ft, 5 in. of water above it. This would allow the core to have a natural circulation path. The core could continue in this coolable state indefinitely, that is, as long as make up water for the evaporation loss was available.

However, if the pressure inside the shroud volume (i.e. volume above the core) continues to increase, the level might continue to drop and expose the core. This would lead to fuel damage and a radioactive release into the building. The RELAP5 code was used to predict the liquid levels in the vessel and the timing of the events.

7.2.1 Beam Tube Rupture LOCA

The reactor set points are given in Table 3.1 and the initial conditions are the same as those in Table 7.1. The event was started at 25 s when the 8.9710^{-4} m^2 (1.39 in.²) break in the system was opened. The timing of the events predicted by RELAP5 are shown in Table 7.4.

From Table 7.4, the reactor trip is the first event to occur at 12.31 s caused by the drop in system pressure. In Figure 7.15 the depressurization curve is shown. The volume of vapor above the core reached atmospheric conditions about 210 s after the initiation of the event. Over pressurization of the cover gas area did not push the level into the core and expose the fuel plates. The break mass flow rate started out at 29 kg/s but dropped below 5 kg/s by 500 s, as seen in Figure 7.16. The sudden increase in mass flow around 67 s is from the syphon break line opening which pressurized the top of the reflector and increased the static pressure head at the break. The opening in the syphon break equalized the higher pressure in the cover gas with the volume at the top of the reflector when the valve opened and injected vapor from the cover gas into the vessel exit pipe area which resulted in breaking the syphoning effect. Opening the syphon break valve isolated the reactor vessel from the loop (Figure 7.17). The sudden increase in voids at the vessel exit, and therefore, at the pump suction caused loss of pump head due to two phase degradation at about 42 s. The level in the vessel shroud also increased since the increase in pressure at the top of the reflector pushed the fluid back into the vessel, as seen in Figure 7.18. This can be seen in Figure 7.15 where the pressure curve changes slope. The top of the transition plate is at 67 in. in Figure 7.18 which demonstrates that plenty of water is still left in the vessel after 500 s. The level is slowly dropping to the top of the thermal shield level (i.e. 92 in.). The water level in the thermal shield volume is shown in Figure 7.19.

The flow reversal valves (Figure 7.20) opened at 48 s since the pumps were lost at 42 s and the pressure drop across the transition plate was not large enough to keep them closed. The associated bypass flow is shown in Figure 7.21. The core's hottest channel went through a flow reversal at 52 s which means flow reversal occurred at 39.7 s after the scram. (This is a highly conservative time since the power in a channel determines this behavior and the peak channel in RELAP5 was about 40% higher than what was expected in the actual plant.) No CHF

Table 7.4 Sequence of Events for the Beam Tube Rupture

<u>Event</u>	<u>Time (s)</u>	<u>Relative Time (s)</u>
Reactor trip	37.31	12.31
Pump trip, depressurization		
Valve open, syphon break valve open	67.4	42.4
Flow reversal valve opens	73.0	48.0
Flow reversal in hot channel	77.0	52.0
Check valve closed	77.23	52.23

FIGURE 7.15 SBLOCA Cover Gas Prediction

FIGURE 7.16 SBLOCA Mass Flow through Break

FIGURE 7.17 SBLOCA Mass Flow in Exit Piping from Vessel

FIGURE 7.18 SBLOCA Level of Fluid in the Vessel Shroud Area

FIGURE 7.19 SBLOCA Level of Fluid in Thermal Shield Volume

FIGURE 7.20 SBLOCA Mass Flow through the 4 Flow Reversal Valves

FIGURE 7.21 SBLOCA Bypass Flow Around Transition Plate

would be expected since 34 s was established in the LOPA event as the minimum time required after a scram that a flow reversal could safely occur. [Even the $1.47 \times 10^5 \text{ W/m}^2$ (46,700 BTU/hr-ft²) limit, which is the current HFBR criteria of safe flow reversal, requires only 35 s.] In Figures 7.22 through 7.24 the flow rates through the core channels are shown. While the hottest channel goes through a flow reversal at 52 s, the other two remain as down flow because the pressure drop caused by the break is stronger than the buoyancy forces in those channels. It isn't until about 225 s that they finally go into flow reversal when the break flow decreases.

The calculation by RELAP5 predicts that the cover gas region will not overpressurize and that the core will be in a coolable state. No fuel damage is expected since flow reversal would occur about 39 s after the scram, while only 34 s are required for a safe flow reversal.

FIGURE 7.22 SBLOCA Mass Flow through the Hottest Channel

FIGURE 7.23 SBLOCA Mass through the Other 13 Assemblies on the Periphery

FIGURE 7.24 SBLOCA Mass Flow through the 14 Interior Assemblies (Coolest in the Core)

8. SUMMARY

The HFBR reactor has been modeled by the RELAP5 computer code. This advanced two phase, six equation, nonequilibrium thermal hydraulic code can now be used by the HFBR staff to help in the understanding of the thermal hydraulic behavior of the reactor.

The improved code and newly created input deck have been applied to two transients of concern for the 60 MW power level. One was the loss of power accident (LOPA) and the other was a loss of coolant accident (LOCA) where a beam tube is assumed to rupture. The plant model developed for the HFBR was based on many conservative assumptions and simplifications. The analysis is therefore not best estimate but very conservative.

The results of the analysis for the LOPA was that the HFBR at 60 MW can safely undergo a flow reversal without fuel damage. The safety limit chosen by the HFBR staff to ensure no fuel damage is that the peak heat flux in the core must remain below the critical heat flux (CHF) limit. During a series of tests performed earlier [Tichler, 1963] at atmospheric pressure, it was experimentally determined that the lowest CHF limit for the HFBR was between $1.47\text{E}5\text{ W/m}^2$ ($46,700\text{ BTU/hr-ft}^2$) and $1.513\text{E}5\text{ W/m}^2$ ($48,000\text{ BTU/hr-ft}^2$). These values straddle the highest level of safe flow reversal and the lowest CHF limit. This series of experiments has been shown to be conservative [Rohatgi and Slovik, 1990]. A further margin of safety is used since the HFBR staff has selected the safe flow reversal criteria of $1.472\text{E}5\text{ W/m}^2$ ($46,700\text{ BTU/hr-ft}^2$) as the safety limit although experimentally this heat flux did not go into CHF. Additional confirmation of this limit, as discussed in this report, is obtained by utilizing a more recent correlation [Monde, 1982]. Applying this correlation to the test data at atmospheric pressure lead to a CHF limit value of $1.686\text{E}5\text{ W/m}^2$ ($53,487\text{ BTU/hr-ft}^2$). This represents a 13% difference between the Monde data and the experiment data which could be accounted for in the equipment uncertainties used back in 1963. The RELAP5 computer code determined the peak heat flux in the core to be 1.4425105 W/m^2 ($45,750\text{ BTU/hr-ft}^2$) at the time of flow reversal initiation (68 seconds). This estimate is based on 98% of the decay heat being deposited in the fuel plate while the actual peak plate would have an 18% reduction from gamma smearing.

It must be further recognized that the HFBR selected limit of $46,700\text{ BTU/hr-ft}^2$ is very conservative, since the CHF limit data is pressure-dependent. The cell fluid conditions calculated by RELAP5 for the peak location at the point of flow reversal show that the local pressure is .34 MPa (50 psia). Evaluating the Monde correlation at this pressure leads to a CHF limit of 3.04105 W/m^2 ($96,400\text{ BTU/hr-ft}^2$), or about double that calculated at atmospheric pressure. This demonstrates that the HFBR has a large inherent safety margin to CHF during a LOPA event from experimental data and the most recent correlations for CHF. Also, the extended time to flow reversal allowed the vessel to depressurize to about 2.86105 Pa (42 psia) and would have expelled about 90% of the dissolved helium in the system. The remaining helium gas in the vessel would be in micro bubbles and would not have any major significance to the CHF determination.

The second transient analyzed was a loss of coolant accident (LOCA) at 60 MW where a beam tube is assumed to rupture and coolant is allowed to escape into the thermal shield and biological shield cavity volume surrounding the reactor vessel. The reactor tripped 12.3 s after the break occurred. The

depressurization valve and syphon break valve opened at 42 s. The pump was lost at about the same time because the syphon break line injected gas from the cover gas region into the vessel exit pipe (or top of reflector) and sent two phase flow into the pump. The pump lost its head and the reactor vessel was isolated. The syphon break line performed as designed by breaking the syphoning effect from the rest of the loop. The hot channel was conservatively predicted to go into flow reversal at 39 s after the scram while the other channel followed at 225 s. No CHF limit, or fuel damage, was reached since the LOPA analysis showed that a minimum of 34 s is required for the peak plate in the core to pass the CHF limit. The timings of the event are conservative as the peak assembly modeled in RELAP5 was about 40% over powered. The analysis at 60 MW did not show any fuel damage during the transient.

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APPENDIX A

RELAP5 LOPA INPUT DECK

```

=====
*                               relap5/mod2                               *
*                               hfbr                                    *
*                               *                                       *
*                               *                                       *
*                               *                                       *
=====
* title card                                                            *
=====
*
=hfbr system model
*
=====
* problem type and option                                              *
=====
*
*crdno      problem type      option
100                new      transnt
101 run
*unit
*
=====
* cpu time remaining card                                             *
=====
*
*crdno      time1      time2
105          5.0      6.0
*
=====
* time step control cards                                             *
=====
*
* helium is present as the cover gas                                  *
=====
*
110 helium
*crd vol.      elev.      fluid      name
120 1090000    29.1084    d2o       none
121 15060000   0.0       water      none
*
*crdno end time min dt      max dt      control  minor ed  major ed  restart
201      74.0  1.0-7      0.05          2          20          200      1000
*
=====
*                               trips                                  *
=====
*
* 501 is for the 101a & b pumps
* no left variable rel rt variable + const      function
501  time      0      gt      null 0      75.0      1      *pump
*
*
* trip 520 is the depressurization valve for the reactor vessel
* to model hce-102, p-102,p-300. opens when primary and 2nd pumps trip
*
520  time      0      gt      null 0      76.5      1      *depress valves
*
=====
*                               component data                          *
=====
*
* 001 annulus section above trans plate and piping to pump

```

*					
*crdno	name			type	
0010000	vesoutlt			pipe	
*					
*crdno	no.vols.				
0010001	9				
*					
*crdno	area			vol.no.	
0010101	0.4800			1	
0010102	0.426141			2	
0010103	0.250852			5	
0010104	0.193942			6	
0010105	0.387884			7	
0010106	0.314772			9	
*					
*crdno	length			vol.no.	
0010301	1.73355			1	
0010302	1.4478			2	
0010303	2.2236			5	
0010304	1.7462715			6	
0010305	2.37702			7	
0010306	2.0955			9	
*					
*crdno	v-ang			vol.no.	
0010601	90.0			1	
0010602	-27.84			2	
0010603	-90.0			6	
0010604	0.0			9	
*					
*crdno	rough	dhy			vol.no.
0010801	0	0.3000			1
0010802	0	0.7366			2
0010803	0	0.5652			5
0010804	0	0.4969			7
0010805	0	0.4476			9
*					
*					
*					
*crdno	ff	rf			jun.no.
0010901	0.18	0.18			1
0010902	0.199	0.199			8
*					
*crdno	ctl			vol.no.	
0011001	0			9	
*					
*crdno	ctl			jun.no.	
0011101	0			8	
*					
*crdno	ctl	pressure	temp	vol.no.	
0011201	003	1.2365e6	339.3 0 0 0	1	
0011202	003	1.2210e6	339.3 0 0 0	2	
0011203	003	1.2274e6	339.3 0 0 0	3	
0011204	003	1.2490e6	339.3 0 0 0	4	
0011205	003	1.2707e6	339.3 0 0 0	5	
0011206	003	1.2812e6	339.3 0 0 0	6	
0011207	003	1.3013e6	339.4 0 0 0	7	
0011208	003	1.2975e6	339.4 0 0 0	8	
0011209	003	1.2961e6	339.4 0 0 0	9	
*					
*crdno	i.c.				

```

0011300      1
*
*crdno      flowf      flowg      velj      jun.no.
0011301      1227.113      0.0      0      8
*
* The pump model
*
*crdno      name      type
0020000      gal01ab      pump
*
*crdno      area      length      volume      h-ang      v-ang      delz      ctl
0020101      0.314772      2.032      0      0      0      0      0
*
*crdno      from      area      floss      rloss      flag
0020108      001010000      0      0      0      0
*
*crdno      to      area      floss      rloss      flag
0020109      031000000      0      0      0      0
*
*crdno      ctl      pressure      temp
0020200      3      1.5314e6      339.3      0 0 0
*
*crdno      ctl      flowf      flowg      velj
0020201      1      1227.113      0.0      0
0020202      1      1227.113      0.0      0
*
* pump trip is 501
*crdno      id      2faz      2fazd      tork      pvel      ptrip      rvrs
0020301      -2      -1      -2      -1      0      501      0
*
*crdno      rpvel      initv      rflo      rhead      rtork      momi      rdens
*0020302      125.0      1.0      1.08      43.9      2105.12      64.0      1087.0
*0020302      128.0      1.0      1.09      43.9      2105.12      114.0      1087.0
0020302      130.5      1.0      1.102      43.9      2105.12      80.0      1087.0
*
*crdno      rmotk      tf2      tf0      tf1      tf3
0020303      0      0      21.04      197.5      0
*
*crdno      el tm      stop motor      max frd v      max rev v
0020310      160.0      0      -1.0e-5
*
*crdno      trip      alpha      num
0026100      0
*
*crdno      time      pumpvel(rad/s)
0026101      0.0      130.5
0026102      75.0      130.5
0026103      76.0      75.5
0026104      77.0      67.5
0026105      78.0      55.10
0026106      80.0      44.9
0026107      85.0      24.03
0026108      89.0      20.50
0026109      95.0      16.51
0026110      105.0      12.56
0026111      115.0      10.08
0026112      125.0      8.23
0026113      135.0      5.60
0026114      145.0      2.75
0026115      160.0      0.0001

```

```

*
*
* 031 piece of pipe coming out of pump to put check valve in front
* (cut this off the front of 003 to put check valve between)
*
*crdno      name      type
0310000     bfchv     snglvol
*
*crdno      area      length vol  h-ang  v-ang delz  rgh  dhy  ctl
0310101     0.314772  0.7874  0    0    0    0.0  0  .4476  00
*
*crdno      ctl      pressure      temp
0310200     3        1.767e6      339.33
*
* 030 check valve at pump discharge that closes when flow below
* 400 gpm (page 20, section 3.6.4 chapter 5)
*
*crdno      name      type
0300000     deprvl    valve
*
* Lap supplied K values for the check valve
*crdno      from      to      area      floss      rloss      flag
0300101     031010000  003000000  0.314772  2.184  2.184  100
*
*crdno      ctl      flowf      flowg      velj
0300201     1        1227.113  0.0        0
*
*crdno      type
0300300     srvvlv
*
*crdno      cntrl no.  vlv tab n0.
0300301     31
*
* Check valve in front of pump (for one pump operation)
* control variable 30 is used
*crdno      nam type scale initval flag cntrl min max
20503000    vldp sum 1.0 1227.0 1 3 0.0 2.0e3
*crdno      a0 al nam code
20503001    0.0 1.0 mflowj 001020000
*
*crdno      nam type scale initval flag cntrl min max
20503100    vla function 1.0 1.0 1 3 0.0 1.0
*crdno      nam code table
20503101    cntrlvar 30 31
*
*
*
***** General Table for the control variable***
* define area of check valve as a function of
* mass flow. See memo supplied by Lap
*crdno      name trip factor,time factor,power
20203100    normarea
*
*crdno      mass flow area of check valve
20203101    11.0 0.0
20203102    54.0 0.3
20203103    137.2 0.6
20203104    274.4 0.9
20203105    411.5 0.93
20203106    549.0 1.0
20203107    1227.0 1.0

```

*

*

* 003 pipe from outlet of pump to vessel inlet

*

*crdno	name	type
0030000	hep	pipe

*

*crdno	no.vols.
0030001	19

*

*crdno	area	vol.no.
0030101	0.314772	1
0030102	4.277096	2
0030103	1.3673	11
0030104	2.993966	12
0030105	0.314772	14
0030106	0.193922	15
0030107	0.250852	18
0030108	0.332725	19

*

*crdno	length	vol.no.
0030301	0.7874	1
0030302	1.0499	2
0030303	0.6477	6
0030304	0.3895	7
0030305	0.6477	11
0030306	0.8467	12
0030307	1.8669	14
0030308	2.3114	15
0030309	2.62467	18
0030310	1.4478	19

*

*crdno	v-ang	vol.no.
0030601	0.0	1
0030602	90.0	2
0030603	0.0	6
0030604	90.0	7
0030605	0.0	11
0030606	90.0	12
0030607	0.0	15
0030608	90.0	18
0030609	0.0	19

*

*crdno	rough	dhy	vol.no.
0030801	0	0.4476	1
0030802	0	1.65	2
0030803	0	0.015748	11
0030804	0	1.3857	12
0030805	0	0.4476	14
0030806	0	0.4969	15
0030807	0	0.56515	18
0030808	0	0.6509	19

* adjust to pressure drop in system

*crdno	ff	rf	jun.no.
0030901	1.40	1.40	11
0030902	1.10	1.10	18

*

*crdno	ctl	vol.no.


```

0031001      00                      19
*
*crdno      ctl                      jun.no.
0031101      00000                      18
*
*crdno      ctl      pres (pa)      temp(k)      vol.no.
0031201      3      1.766e6      339.4      0 0 0      2
0031202      3      1.748e6      336.0      0 0 0      4
0031203      3      1.739e6      333.6      0 0 0      6
0031204      3      1.729e6      330.5      0 0 0      8
0031205      3      1.727e6      328.5      0 0 0     10
0031206      3      1.720e6      327.5      0 0 0     12
0031207      3      1.693e6      327.5      0 0 0     14
0031208      3      1.633e6      327.47     0 0 0     16
0031209      3      1.529e6      327.46     0 0 0     18
0031210      3      1.569e6      327.47     0 0 0     19
*
*crdno      i.c.
0031300      1
*
*crdno      flowf      flowg      velj      jun.no.
0031301  1.227113e3      0.0      0      18

```

* 004 cell adjacent to incoming pipe to vessel

```

*
*crdno      name      type
0040000      vesin      branch
*
*crdno      no.juns.      ctl
0040001      3      1
*
*crdno      area      length vol h-ang v-ang delz rough dhy ctl
0040101  .96986 .4953  0  0  -90.0  -.4953  0.0  0.936  00
*
*crdno      ctl      pressure      temp
0040200      3      1.5179e6      327.77
*
*crdno      from      to      area      floss      rloss      flag
0041101  003010000      004000000      0      0      0      100
0042101  004010000      006000000      0      0.8      0.8      100
0043101  004000000      005000000      0      0      0      100
*
*crdno      flowf      flowg      velj
0041201  1227.113      0.      0.
0042201  1227.113      0.      0.
0043201  0.0      0.      0.

```

* 005 top of reactor vessel / cover gas present here

```

*
*crdno      name      type
0050000      rctpt      pipe
*
*crdno      no.vols.
0050001      3
*
*crdno      area      vol.no.
0050101  0.96986      1

```

```

0050102      1.0448989                      3
*
*crdno      length                      vol.no.
0050301      0.4953                      1
0050302      0.9525                      2
0050303      0.4826                      3
*
*crdno      v-ang                      vol.no.
0050601      90.00                      3
*
*crdno      rough      dhy                      vol.no.
0050801      0      0.936                      1
0050802      0      1.1684                      3
*
*crdno      ff      rf                      jun.no.
0050901      0.0      0.0                      2
*
*crdno      ctl                      vol.no.
0051001      00                      3
*
*crdno      ctl                      jun.no.
0051101      000000                      2
*
*crdno      ctl  press      uf      ug      vg      ncv      vol.no.
0051201      3  1.550e6  327.6      0      0      0      1
0051202      3  1.541e6  327.6      0      0      0      2
0051203      6  1.540e6  2.276e5  1.150e6  1.0  0.999  3
*
*crdno      i.c.
0051300      1
*
*crdno      flowf      flowg      velj      jun.no.
0051301      0.001      0.0      0      2
*
* 041 demister
*
*crdno      name      type
0410000      demster      branch
*
*crdno      no.juns      ctl
0410001      2      1
*
*crdno      area  lngth  vol  h-a  v-ang  delz  rgh  dhy  ctl
0410101  1.0448989  .9104  0   0   90.  .9104  0  1.1684  00000
*
*crdno      ctl      pressure      uf      ug      vg      ncv
0410200      6      1.535e6  2.276e5  1.150e6  1.0  0.999
*
*crdno      from      to      area  floss  rloss  flag
0411101  005010000  041000000  0   0   0   000000
0412101  041010000  040000000  0   0   0   000000
*
*crdno      flowf  flowg  velj
0411201  0.   0.   0.
0412201  0.   0.   0.
*
* steamline to dep valve
*
*crdno      name      type
0400000      stmlne      pipe

```

```

*
*crdno      no.vols.
0400001      2
*
*crdno      area                      vol.no.
0400101      6.0983e-4                2
*
*crdno      length                    vol.no.
0400301      7.620                    2
*
*crdno      v-ang                     vol.no.
0400601      0.0                      2
*
*crdno      rough      dhy             vol.no.
0400801      0         0.027865       2
*
*crdno      ff      rf                 jun.no.
0400901      70.0    70.0             1
*
*crdno      ctl                      vol.no.
0401001      00000                  2
*
*crdno      ctl                      jun.no.
0401101      0                      1
*
*crdno      ctl  press      uf      ug      vg      ncv      vol.no.
0401201      006  1.535e6  2.276e5  1.15e6  1.0  0.999    2
*
*crdno      i.c.
0401300      1
*
*crdno      flowf      flowg      velj      jun.no.
0401301      0.0      0.0      0          1
*
* 051 helium injection
*
*crdno      name      type
0510000      heinjv    tmdpvol
*
*crdno      area      lngth vol h-ang  v-ang  delz  rgh  dhy  ctl
0510101      1.0448989 .9104  0    0    0.  0.0  0  0  00000
*
*crdno      ctl
0510200      6
*
*crdno      time      press      uf      ug      void  ncn
0510201      0.0      1.0e5    25000.0  1.15e6  1.0  1.0
*
* 052 helium injection junction
*
*crdno      name      type
0520000      heinjv    tmdpjv
*
*crdno      from      to      area
0520101      051000000  041000000  0.0
*
*crdno      ctl      trip.no.      alph code      num.code
0520200      1      520      cntrlvar      52
*

```

```

*crdno    time    flowf    flowg    velj
0520201   -1.0     0.0     0.0     0.0
0520202    0.0     0.0     0.0     0.0
0520203  1000.0    0.0   1000.0    0.0
*
* Helium injection control variables which determine how much
* helium is injected into volume 41 (models He coming out of
* solution)
*
20503700   timenew    sum    1.0    0.0    1
20503701    0.0     1.0    time        0
*
20503800   dtime     sum    1.0    0.05    0
20503801    0.0     1.0   cntrlvar   37
20503802   -1.0    -1.0   cntrlvar   55
*
20503900   pnnew     sum    1.0    0.0    1
20503901    0.0     1.0    p        041010000
*
20504000   md2o      sum    1.0    0.0    1
20504001  -8870.2    1.0   tmass        0
*
20504100   delp      sum    1.0    0.0    1    1    0.0
20504101    0.0     1.0   cntrlvar   56
20504102   -1.0    -1.0   cntrlvar   39
*
20504200   delmhe    mult    1.644872e-11    0.0    1
20504201                                     cntrlvar 40
20504202                                     cntrlvar 41
*
20505200   mhedot    div    1.0    0.0    1    1    0.0
20505201                                     cntrlvar   38
20505202                                     cntrlvar   42
*
20505300   tmhinj    sum    1.0    0.0    1
20505301    0.0     1.0   cntrlvar   54
20505302    1.0     1.0   cntrlvar   42
*
20505400   tmhinj0   sum    1.0    0.0    0
20505401    0.0     1.0   cntrlvar   53
*
20505500   timeold   sum    1.0   -0.05    0
20505501    0.0     1.0   cntrlvar   37
*
20505600   pold      sum    1.0    0.0    1
20505601    0.0     1.0   cntrlvar   39
*
* end control variable for helium injection
*
* 006 shroud pipe going to transition plate
*
*crdno      name      type
0060000     shrdt     pipe
*
*crdno      no.vols.
0060001         2
*
*crdno      area      vol.no.
0060101    2.0905        1
0060102    0.4944        2

```

```

*
*crdno      length      vol.no.
0060301      0.5683      1
0060302      0.985308    2
*
*crdno      v-ang      vol.no.
0060601     -90.00      2
*
*crdno      rough      dhy      vol.no.
0060801      0      1.4523      1
0060802      0      0.6320      2
*
*crdno      ff      rf      jun.no.
0060901      0.8      0.8      1
*
*crdno      ctl      vol.no.
0061001      00      2
*
*crdno      ctl      jun.no.
0061101      0      1
*
*crdno      ctl      pressure      temp      vol.no.
0061201      003      1.5400e6      327.72      0 0 0      1
0061202      003      1.5370e6      327.72      0 0 0      2
*
*crdno      i.c.
0061300      1
*
*crdno      flowf      flowg      velj      jun.no.
0061301      1227.113      0.0      0      1

```

* 007 node above trans plate to fuel chan.,bypass,flow rvrl valves

```

*
*crdno      name      type
0070000      ttran      branch
*
*crdno      no.juns.      ctl
0070001      4      1
*
*crdno      area      length      vol      h-ang      v-ang      delz      rough      dhy      ctl
0070101      0.4948      .75164      0 0      -90.0      -.75164      0.0      0.6314      00
*
*crdno      ctl      pressure      temp
0070200      3      1.547e6      327.72
*
*crdno      from      to      area      floss      rloss      flag
0071101      007010000      008000000      4.449599e-3      0      0      100
0072101      007010000      009000000      5.7844709e-2      0      0      100
0073101      007010000      010000000      6.229439e-2      0      0      100
0076101      006010000      007000000      0      0      0      100
*
*crdno      flowf      flowg      velj
0071201      37.91      0.      0.
0072201      492.7      0.      0.
0073201      530.6      0.      0.
0076201      1227.113      0.      0.

```

* 008 peak assembly - one peak assembly on the periphery

```

*
*crdno      name      type
0080000     pasc      pipe
*
*crdno      no.vols.
0080001         4
*
*crdno      area      vol.no.
0080101     4.449599e-3      1
0080102     2.987284e-3      4
*
*crdno      length    vol.no.
0080301     0.352425      1
0080302     0.2010833     4
*
*crdno      v-ang     vol.no.
0080601     -90.0        4
*
*crdno      rough     dhy      vol.no.
0080801     0         0.07527      1
0080802     0         0.004826     4
*
*crdno      ff        rf        jun.no.
0080901     0.266     0.266        3
*
*crdno      ctl       vol.no.
0081001     00        4
*
*crdno      ctl       jun.no.
0081101     00000     3
*
*crdno      ctl       pressure  temp      vol.no.
0081201     3         1.51e6    327.5    0 0 0      1
0081202     3         1.42e6    335.3    0 0 0      2
0081203     3         1.34e6    346.0    0 0 0      3
0081204     3         1.27e6    354.3    0 0 0      4
*
*crdno      i.c.
0081300     1
*
*crdno      flowf     flowg     velj     jun.no.
0081301     37.9     0.0       0        3

```

* 009 Average assembly - 13 other assemblies on periphery

```

*
*crdno      name      type
0090000     averp     pipe
*
*crdno      no.vols.
0090001         4
*
*crdno      area      vol.no.
0090101     5.7844709e-2      1
0090102     3.8834696e-2      4
*
*crdno      length    vol.no.
0090301     0.352425      1

```

0090302	0.2010833		4
*			
*crdno	v-ang		vol.no.
0090601	-90.0		4
*			
*crdno	rough	dhy	vol.no.
0090801	0	0.07527	1
0090802	0	0.004826	4
*			
*crdno	ff	rf	jun.no.
0090901	0.266	0.266	3
*			
*crdno	ctl		vol.no.
0091001	00		4
*			
*crdno	ctl		jun.no.
0091101	00000		3
*			
*crdno	ctl	pressure	temp
0091201	3	1.51e6	327.5
0091202	3	1.42e6	332.3
0091203	3	1.35e6	337.6
0091204	3	1.27e6	342.4
*			
*crdno	i.c.		
0091300	1		
*			
*crdno	flowf	flowg	velj
0091301	492.7	0.0	0

* 010 internal fuel assemblies - 14 assemblies

*			
*crdno	name	type	
0100000	averi	pipe	
*			
*crdno	no.vols.		
0100001	4		
*			
*crdno	area		vol.no.
0100101	6.229439e-2		1
0100102	4.182198e-2		4
*			
*crdno	length		vol.no.
0100301	0.352425		1
0100302	0.2010833		4
*			
*crdno	v-ang		vol.no.
0100601	-90.0		4
*			
*crdno	rough	dhy	vol.no.
0100801	0	0.07527	1
0100802	0	0.004826	4
*			
*crdno	ff	rf	jun.no.
0100901	0.266	0.266	3
*			
*crdno	ctl		vol.no.
0101001	00		4

```

*
*crdno      ctl      jun.no.
0101101     00000      3
*
*crdno      ctl      pressure      temp      vol.no.
0101201     3          1.51e6      327.5    0 0 0      1
0101202     3          1.42e6      331.0    0 0 0      2
0101203     3          1.35e6      335.0    0 0 0      3
0101204     3          1.27e6      339.0    0 0 0      4
*
*crdno      i.c.
0101300     1
*
*crdno      flowf      flowg      velj      jun.no.
0101301     530.6      0.0          0          3

* 011 bypass flow thru trans plate, models 8 main, 8 aux, fuel byp, thimb
*
*crdno      name      type
0110000     byptrn     sngljun
*
*crdno      from      to      area      floss      rloss      flag
0110101     007010000    014010000    1.045e-2    2.25      2.25      100
*
*crdno      ctl      flowf      flowg      velj
0110201     1      165.9      0          0

* 012 this is the flow reversal valves
*
*crdno      name      type
0120000     frvalv      valve
*
*crdno      from      to      area      floss      rloss      flag
0120101     007010000    014010000    2.052165e-2    5.3      5.3      100
*
*crdno      ctl      flowf      flowg      velj
0120201     1      0.0      0.0      0
*
*crdno      name
0120300     srvvlv
*
* flow reversal valve opens when del p across trans plt lt 3 psia
*crdno      cntrl vari number
0120301     4

* Control variable below first find the delta press across the
* the transition plate and uses the delta press as a variable
* to correlate the normalized area of the flow reversal valves
* (memo L.Y.Cheng,27 JUNE 89, Modeling of Flow Reversal Valve)
*
* Control Variable 1 define the pressure drop across the
* Transition plate
*crdno      nam type scale initval flag cntrl min max
20500100    dpc sum 1.0 0.0 1 3 0.0 2.1546225e4
*crdno      a0 a1 nam code
20500101    0.0 1.0 p 007010000

```



```

*crdno      a2      nam      code
20500102    -1.0      p      014010000
*
* Variable 2 defines delta p squared to build polynomial
*crdno      nam      type      scale      initval      flag      cntrl      min      max
20500200    co      mult      1.0      0.0      1
*crdno      alph code      var code
20500201      cntrlvar      1
*crdno      alph code      var code
20500202      cntrlvar      1
*
* Variable 3 defines delat p cubed to build polynomial
*crdno      nam      type      scale      initval      flag      cntrl      min      max
20500300    ct      mult      1.0      0.0      1
*crdno      alph code      var code
20500301      cntrlvar      2
*crdno      alph code      var code
20500302      cntrlvar      1
*
* Variable 4 defines the polynomial that is the normalized area
* as a function of delta p across the transition plate
* if delta p greater than 3.125 psi, set to 0 (valve closed)
* if delta p less than 0.0, set to 1 (fully opened)
* in between, area fraction calculated
*crdno      nam      type      scale      initval      flag      cntrl      min      max
20500400    nav      sum      1.0      0.0      1      3      0.0      1.0
*crdno      a0      a1      nam      code
20500401    1.0      -3.1622562e-5      cntrlvar      1
*crdno      a2      nam      code
20500402      -2.7849533e-9      cntrlvar      2
*crdno      a3      nam      code
20500403      9.7397822e-14      cntrlvar      3
*
* 0013 this is the section below the fuel region in the shperical section
* of the reactor vessel
*
*crdno      name      type
0130000      lplnm      branch
*
*crdno      no.juns.      ctl
0130001      3      1
*
*crdno      area      length      vol      h-ang      v-ang      delz      rgh      dhy      ctl
0130101    1.518      0.739775      0      0      -90.0      -.739775      0.0      0.0752      00
*
*crdno      ctl      pressure      temp
0130200      3      1.264e6      341.3
*
*crdno      from      to      area      floss      rloss      flag
0131101    008010000      013000000      0      0      0      100
0132101    009010000      013000000      0      0      0      100
0133101    010010000      013000000      0      0      0      100
*
*crdno      flowf      flowg      velj
0131201    37.91      0.      0.
0132201    492.7      0.      0.
0133201    530.6      0.      0.
*
* 0014 this is the section up to core centerline in the shperical

```

* part of the reactor vessel

```

*
*crdno      name      type
0140000      uplrm      branch
*
*crdno  no.juns.  ctl
0140001      2      1
*
*crdno  area  length  vol h-ang v-ang  delz  rgh  dhy  ctl
0140101  2.6819 .6540499 0  0  90.0 .6540499 0.0  1.711  00
*
*crdno  ctl  pressure  temp
0140200   3    1.253e6   339.3
*
*crdno  from      to      area  floss  rloss  flag
0141101 024010000 014000000  0    0.1    0.1   100
0142101 014010000 001000000  0    0.1    0.1   100
*
*crdno  flowf  flowg  velj
0141201 1227.11  0.    0.
0142201 1227.11  0.    0.

```

* Component 24 represents the section above the core centerline
 * to the transition plate. The branch here is needed to model
 * the beam tube rupture which occurs at the core centerline

```

*crdno      name      type
0240000      lupln      branch
*
*crdno  no.juns.  ctl
0240001      2      1
*
*crdno  area  length  vol h-ang v-ang  delz  rgh  dhy  ctl
0240101  2.6819 .301625 0  0  90.0 .301625 0.0  1.711  00
*
*crdno  ctl  pressure  temp
0240200   3    1.258e6   341.3
*
*crdno  from      to      area  floss  rloss  flag
0241101 013000000 024000000  0    0.1    0.1   100
0242101 024010000 014000000  0    0.1    0.1   100
*
*crdno  flowf  flowg  velj
0241201 1227.11  0.    0.
0242201 1227.11  0.    0.

```

*** secondary loop of the hfbr (this is the h2o loop)

* 016 feed water inlet flow to heat exchanger

```

*
*crdno      name      type
0160000      hefwr      tmdpvcl
*
*crdno  area  length  volume h-ang v-ang  delz  rough  dhy  ctl
0160101  1.3019  1.0    0  0  00.  0.0    0    0    0
*
*crdno  ctl
0160200   3
*
*crdno  time  press  temp

```

0160201 0.0 4.137e5 289.0

* 017 feedwater inlet junction to the heat exchanger

```

*
*crdno      name      type
0170000    hefwj      tmdpjun
*
*crdno      from      to      area
0170101    016000000  015000000  0.0
*
*crdno      ctl      trip.no.  alph code  num.code
0170200      1        501
*
*crdno      time     flowf      flowg      velj
0170201      0.0     370.7      0.0        0.0
0170202      2.0     370.7      0.0        0.0
0170203     32.0     22.0       0.0        0.0

0170204    180.0       1.0       0.0        0.0
0170205    400.0       1.0       0.0        0.0

```

*015 heat exchanger secondary shell side

```

*
*crdno      name      type
0150000      phe      pipe
*
*crdno      no.vols.
0150001        11
*
*crdno      area      vol.no.
0150101    1.3019        11
*
*crdno      length     vol.no.
0150301    .6477         5
0150302    .3895         6
0150303    .6477        11
*
*crdno      v-ang      vol.no.
0150601    00.0        11
*
*crdno      rough      dhy      vol.no.
0150801      0      .0098        11
*
*crdno      floss      rloss     jun.no.
0150901    0.0      0.0         10
*
*crdno      ctl      vol.no.
0151001      0        11
*
*crdno      ctl      jun.no.
0151101      0         10
*
*crdno      ctl      pressure  temp      qual      vol.no.
0151201      3      4.136e5  307.9      0 0 0      11
*
*crdno      i.c.
0151300      1

```

```

*
*crdno      flowf      flowg      velj      jun.no.
0151301      722.0      0.0          0          10

* 018 heat exchanger outlet junction
*
*crdno      name      type
0180000      heoutj      sngljun
*
*crdno      from      to      area      floss      rloss      flag
0180101      015010000      019000000      0          0          0          100
*
*crdno      ctl      flowf      flowg      velj
0180201      1          722.0      0.0          0

* 019 outlet of the heat exchanger on the water side
*
*crdno      name      type
0190000      sgslb      tmdpvol
*
*crdno      area      length      volume      h-ang      v-ang      delz      rough      dhy      ctl
0190101      1.3019      1.00          0          0          00.          0.0          0          0          0
*
*crdno      ctl
0190200      2
*
*crdno      time      press      quals
0190201      0.0          3.619e5      0.0

* 020 depress valve on top of reactor vess to model he-102,p-102,p-300
*
*crdno      name      type
0200000      deprvl      valve
*
*crdno      from      to      area      floss      rloss      flag
0200101      040010000      021000000      1.70e-4      5.0          5.0          000120
*
*crdno      ctl      flowf      flowg      velj
0200201      1          0.0          0.0          0
*
*crdno      type
0200300      trpvlv
*
*crdno      trip no
0200301      520

* 021 set outlet deprss valve to atmosphere
*
*crdno      name      type
0210000      atm      tmdpvol
*
*crdno      area      lngth      vol      h-a      v-ang      delz      rgh      dhy      ctl
0210101      1.04489      1.393      0          0          0.          0.0          0          0          00000
*
*crdno      ctl

```

0210200 6

*

*crdno	time	press	uf	ug	void	ncon
0210201	0.0	1.000e5	25000.	1.15e6	1.0	1.0

=====*

* heat structures *

=====*

* heat structure 008

* core fuel plates in the peak assembly of hydr component 008

*

*crdno	no.h.s	no.m.p	geo	s.s.flg	left	reflood	by	ax.int.
10080000	3	3	1	1	0.0	0	1	8

*

*crdno	mesh flg	fmt
10080100	0	1

*

*crdno	intvl	rt.cor
10080101	1	2.8956e-4
10080102	1	6.35e-4

*

* comp 3 is the fuel region

* comp 4 is the 6061 al clad region

*crdno	comp	intvl
10080201	3	1
10080202	4	2

*

*crdno	source	intvl
10080301	1.0	1
10080302	0	2

*

*crdno	temp	mesh p.
10080401	395.0	3

*

*crdno	left vol	incr	b.c	sacode	safac	h.s.no
10080501	0	0	0	1	0.4416	1
10080502	0	0	0	1	0.4416	2
10080503	0	0	0	1	0.4416	3

*

*crdno	rt vol	incr	b.c	sacode	safac	h.s.no
10080601	008020000	0	1	1	0.4416	1
10080602	008030000	0	1	1	0.4416	2
10080603	008040000	0	1	1	0.4416	3

*

* general table 8 holds the power information

*

*crdno	s.type	mult	dir.left	dir.rt	h.s.no
10080701	8	0.300	0	0	1
10080702	8	0.400	0	0	2
10080703	8	0.300	0	0	3

*

*crdno	chf	dhy	dht	c.length	h.s.no
10080901	0	0.0	0.0	0.0	3

-----*

* heat structure 009

* core fuel plates in the periphery assemblies of hydr component 009

```

*
*crdno    no.h.s    no.m.p    geo    s.s.flg    left reflood by    ax.int.
10090000      3      3      1      1      0.0      0      1      8
*
*crdno    mesh flg    fmt
10090100      0      1
*
*crdno    intvl    rt.cor
10090101      1      2.8956e-4
10090102      1      6.35e-4
*
*      comp 3 is the fuel region
*      comp 4 is the 6061 al clad region
*crdno    comp    intvl
10090201      3      1
10090202      4      2
*
*crdno    source    intvl
10090301      1.0      1
10090302      0      2
*
*crdno    temp    mesh p.
10090401    389.0      3
*
*crdno    left vol    incr    b.c    sacode    safac    h.s.no
10090501      0      0      0      1    5.7408      1
10090502      0      0      0      1    5.7408      2
10090503      0      0      0      1    5.7408      3
*
*crdno    rt vol    incr    b.c    sacode    safac    h.s.no
10090601    009020000      0      1      1    5.7408      1
10090602    009030000      0      1      1    5.7408      2
10090603    009040000      0      1      1    5.7408      3
*
*      general table 9 holds the power information
*
*crdno    s.type    mult    dir.left    dir.rt    h.s.no
10090701      9    0.300      0      0      1
10090702      9    0.400      0      0      2
10090703      9    0.300      0      0      3
*
*crdno    chf    dhy    dht    c.length    h.s.no
10090901      0    0.0    0.0      0.0      3
*-----*

*
*      heat structure 010
* core fuel plates in the interior assemblies of hydr component 010
*
*crdno    no.h.s    no.m.p    geo    s.s.flg    left reflood by    ax.int.
10100000      3      3      1      1      0.0      0      1      8
*
*crdno    mesh flg    fmt
10100100      0      1
*
*crdno    intvl    rt.cor
10100101      1      2.8956e-4
10100102      1      6.35e-4
*
*      comp 3 is the fuel region

```

* comp 4 is the 6061 al clad region

*crdno	comp	intvl
10100201	3	1
10100202	4	2

*crdno	source	intvl
10100301	1.0	1
10100302	0	2

*crdno	temp	mesh p.
10100401	389.0	3

*crdno	left vol	incr	b.c	sacode	safac	h.s.no
10100501	0	0	0	1	6.1824	1
10100502	0	0	0	1	6.1824	2
10100503	0	0	0	1	6.1824	3

*crdno	rt vol	incr	b.c	sacode	safac	h.s.no
10100601	010020000	0	1	1	6.1824	1
10100602	010030000	0	1	1	6.1824	2
10100603	010040000	0	1	1	6.1824	3

* general table 10 holds the power information

*crdno	s.type	mult	dir.left	dir.rt	h.s.no
10100701	10	0.300	0	0	1
10100702	10	0.400	0	0	2
10100703	10	0.300	0	0	3

*crdno	chf	dhy	dht	c.length	h.s.no
10100901	0	0.0	0.0	0.0	3

* heat structure 015

* secondary loop heat exch. tube sheet between components 003 and 015.

*crdno	no.h.s	no.m.p	geo	s.s.flg	left
12025000	9	3	2	1	0.007874

*crdno	mesh flg	fmt
12025100	0	1

*crdno	intvl	rt.cor
12025101	2	0.009525

*crdno	comp	intvl
12025201	6	2

*crdno	source	intvl
12025301	0	2

*crdno	temp	mesh p.
12025401	318.0	3

*crdno	left vol	incr	b.c	sacode	safac	h.s.no
12025501	003030000	10000	1	1	4546.854	4
12025502	003070000	10000	1	1	2734.29	5
12025503	003080000	10000	1	1	4546.854	9

*crdno	rt vol	incr	b.c	sacode	safac	h.s.no

12025601	015100000	-10000	1	1	4546.854	4
12025602	015060000	10000	1	1	2734.29	5
12025603	015050000	-10000	1	1	4546.854	9

*

*crdno	s.type	mult	dir.left	dir.rt	h.s.no
12025701	0	0	0	0	9 * left side
12025801	C	0	0	0	9 * rt side

*

*crdno	chf	dhy	dht	c.length	h.s.no
12025901	0	0	0	0	9

=====*

* general tables *

=====*

* table of time, core power peak assembly (near mid thumbles) table 8

* 1 assembly

*crdno	name	trip	factor,time	factor,power
20200800	power	501	1.0	.072

*

*crdno	time	watts
20200801	0.0	60.0e6
20200802	0.5	8.93e6
20200803	1.0	6.28e6
20200804	5.0	5.00e6
20200805	10.0	4.05e6
20200806	20.0	3.27e6
20200807	30.0	2.86e6
20200808	40.0	2.61e6
20200809	50.0	2.45e6
20200810	60.0	2.31e6
20200811	70.0	2.19e6
20200812	80.0	2.09e6
20200813	100.0	1.96e6
20200814	200.0	1.62e6
20200815	300.0	1.47e6

* table of time, core power periphery assemblies (13) table 9

*

*crdno	name	trip	factor,time	factor,power
20200900	power	501	1.0	.506

*

*crdno	time	watts
20200901	0.0	60.0e6
20200902	0.5	8.93e6
20200903	1.0	6.28e6
20200904	5.0	5.00e6
20200905	10.0	4.05e6
20200906	20.0	3.27e6
20200907	30.0	2.86e6
20200908	40.0	2.61e6
20200909	50.0	2.45e6
20200910	60.0	2.31e6
20200911	70.0	2.19e6
20200912	80.0	2.09e6
20200913	100.0	1.96e6

20200914	200.0	1.62e6
20200915	300.0	1.47e6

* table of time, core power periphery assemblies table 10
 * (14 assemblies)

*crdno	name	trip	factor,time	factor,power
20201000	power	501	1.0	.422

*

*crdno	time	watts
20201001	0.0	60.0e6
20201002	0.5	8.93e6
20201003	1.0	6.28e6
20201004	5.0	5.00e6
20201005	10.0	4.05e6
20201006	20.0	3.27e6
20201007	30.0	2.86e6
20201008	40.0	2.61e6
20201009	50.0	2.45e6
20201010	60.0	2.31e6
20201011	70.0	2.19e6
20201012	80.0	2.09e6
20201013	100.0	1.96e6
20201014	200.0	1.62e6
20201015	300.0	1.47e6

=====*

* heat structure thermal property data *

=====*

*

*crdno	mtl.type	th.con	ht.cap	
20100600	tbl/fctn	1	1	* s steel in he tubes
20100300	tbl/fctn	1	1	* fuel cermet in core
20100400	tbl/fctn	1	1	* fuel cladding al6061

=====*

* table 003 is the fuel cemert material

*crdno	temp	thm cond
20100301	260.0	200.0
20100302	1367.0	200.0
*crdno	temp	rowcp
20100351	260.0	5.7275e6
20100352	1367.0	5.7275e6

* table 004 is the aluminum cladding for the fuel

*crdno	temp	thm cond
20100401	260.0	155.0
20100402	1367.0	155.0
*crdno	temp	rowcp
20100451	260.0	2.6e6
20100452	1367.0	2.6e6

* table 006 is the s-steel in the heat exchanger tubes

* taken from relap5 sample problem "typical pwr model"

*crdno	temp	thm cond (w/(m*k))
20100601	273.15	12.98
20100602	1199.8	25.11
*crdno	temp	rowcp (j/(m**3 * k))
20100651	273.15	3.383e6
20100652	330.48	3.383e6
20100653	386.04	3.964e6

20100654	441.59	4.100e6
20100655	497.15	4.234e6
20100656	552.71	4.334e6
20100657	608.26	4.435e6
20100658	663.82	4.502e6
20100659	774.93	4.637e6
20100660	1330.5	5.376e6

. *-----end of input-----*