Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, 2003

A Safety Analysis of the End Shield Cooling System Failure Accident for Wolsong1 NPP loaded with CANFLEX-NU fuel

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ABSTRACT

This analysis is done for an assessment of end shield cooling system failures in Wolsong 1 Nuclear Power Plant (NPP) loaded with CANFLEX-NU Fuel. Shield cooling system failures analyzed include loss of inventory from the system, loss of service water to the heat exchangers, and loss of flow. This analysis focuses on the effectiveness of manual trip to terminate the event prior to heatup which could cause unacceptable calandria assembly deformation. For a loss of shield cooling flow, there are 3 alarms within 60 seconds. No boiling of the shield coolant is predicted before 30 minutes, assuming no prior operator action. For a loss of service water to the heat exchangers, there are also 3 alarms within 1 minute, with additional alarms occurring later. No boiling is predicted before four hours, assuming no prior operator action and temperature differentials between the inner and outer tubesheets remain low. Therefore, the manual trip is effective since there is sufficient time (at least 15 minutes) and clear indications (at least 3 alarms within the first 60 seconds) for the operator to recognize a problem and to initiate shutdown and cooldown of the reactor. Significant deformations in the calandria/end shield assembly would not occur. Thus, the integrity of the fuel channels or the operation of the shutdown systems is not jeopardized. For a 100% guillotine break in the pipe at the bottom of the shield tank, results show that there are at least 6 alarms within 20 s, so the operator will have an unambiguous indication of the event. At about 15 minutes, the temperature differential between the inner and outer tubesheet is 35°C. This may cause minor deformation of the assembly, but is within acceptable limits. Therefore, for failures in the shield cooling system, there is sufficient time and clear indications for the operator to safely terminate the event before any calandria deformation could jeopardized fuel channel integrity or shutdown system operation.

1. Introduction

The shield cooling system removes heat which accumulates in the calandria vault and end shields due to nuclear radiation from the reactor core and heat transfer from the fuel channels, heat transport system feeders, and moderator. (See Figure 1 for a schematic representation of the shield cooling system for Wolsong-1). The other main function of this system is to maintain the calandria vault and end shields full of water to provide biological shielding against radiation during normal operation and shutdown conditions. This report describes the safety results on the failures in the shield cooling system. Cases that are assessed include loss of inventory from the system, loss of service water to the shield cooling system, and loss of shield cooling flow. Analysis is carried out to demonstrate that the operator has sufficient time to terminate the event prior to heatup which could cause unacceptable calandria assembly deformation. This work had been done for Wolsong 234 NPP in 1995. There is no difference in analysis methodology and system assumption except alarm set point (Table 1)[1] for application to the Wolsong 1 reactor loaded with CANFLEX-NU fuel.

2. Event Description

2.1 LOSS OF SHIELD COOLING (LOSS OF SERVICE WATER TO HEAT EXCHANGERS)

Loss of shield cooling is characterized by inadequate flow (or loss) of service water to the shield cooling heat exchangers. Because the shield cooling circulation is maintained and there is large mass of shield coolant this condition produces a relatively slow transient.

2.2 LOSS OF SHIELD COOLING FLOW (LOSS OF CIRCULATION)

Loss of flow in the shield cooling system could result from pump operation failure or a pipe break upstream of check valves on the end shield supply headers. The event sequence is similar to the loss of shield cooling case. However, because of the loss of circulation of the large mass of shield coolant, this condition produces a faster heat up transient. The end shields heat up much faster than the bulk of the coolant in the calandria vault.

2.3 LOSS OF SHIELD COOLANT INVENTORY

Losses of shield coolant inventory have different effects on the end shield assembly depending on the location of the break. The fastest loss of shield inventory transient results from pipe failure which causes draining of one or both end shield(s).

The system does not contain enough radioactivity in the coolant to require analysis of doses to the public.

3. Analysis Models and Methodology

Thermohydraulic analysis of the shield cooling system predicts the shield cooling transient behaviour and provides output parameters such as calandria vault and end shield coolant temperatures, levels, pressures, and void fractions and the metal temperature of various end shield components. The results are used to show that there is no excessive temperature differences between the calandria (inner) and end fitting (outer) tubesheets (Figure 2) that could result in overstressing the calandria assembly [2].

3.1 PHYSICS ANALYSIS

The shield cooling system heat load such as:

a. Heat from calandria shell and tubesheet,
b. Heat from end shields,
c. Heat from thermal shield structures,

d. Outside calandria/end shields, and
e. Heat from fuel channels

during full power operation was obtained from Reference 3 and used as input to the thermohydraulic calculations. The total system heat load was assumed to be to 7.5 MW.

3.2 THERMOHYDRAULIC ANALYSIS

The thermohydraulic analysis was performed using the CATHENA computer code [4, 5].

3.2.1 CATHENA Model

The shield cooling system was simulated by a number of pipe components. The model of the shield cooling system includes:

a. One of the two 100 percent circulating pumps, since during normal operation, only one pump is operating and the other is on standby.
b. Two 50 percent heat exchangers are modeled as one 100 percent heat exchanger.
c. The ion exchanger.
d. The expansion (head) tank is modeled as a boundary condition node.
e. Two delay tanks are modeled as one pipe component.
f. Two end shields are modeled as one pipe component and the overpressure protection modeled as a boundary condition node. The end shield node is subdivided into 22 segments, each containing one row of lattice tubes.
g. The calandria vault is modeled as one pipe component which is subdivided into 6 segments.
h. The calandria vault cover gas is modeled as a boundary condition node.

The CATHENA nodalization diagram of the end shield cooling system is shown in Figure 3. The CATHENA model also includes 4 wall (solid) models of the end shield assembly:

a. Carbon steel balls in the end shields,
b. Lattice tubes,
c. Calandria (inner) tubesheet, and
d. End fitting (outer) tubesheet.

These wall models provide the piping heat and metal temperature calculations.

3.3 Methodology and Assumptions for Loss of Flow Analysis

For the loss of flow event, the 100 percent circulating pump was tripped (i.e. failed) and the standby pump was assumed unavailable. The pump trip was modeled by reducing the pump speed linearly from 1800 RPM to zero in 10 seconds.

3.4 Methodology and Assumptions for Loss of Heat Sink Analysis

For the loss of heat sink event, a loss of service water to the shield cooling heat exchangers was assumed by reducing the heat exchanger shell side flow linearly to zero in one second.

3.5 Methodology and Assumptions for Loss of Inventory Analysis

For the loss of inventory event, both 100 percent guillotine and non-guillotine pipe breaks at the bottom of the end shield were simulated. For a 100 percent guillotine break, the cross-sectional area (i.e. 0.073 m^2) of the pipe assumed to fail was used for each of the two break discharges. The break area for a 100 percent non-guillotine break is equal to twice the pipe cross-sectional area (i.e. 0.146 m^2). Smaller breaks were also analyzed. They are expressed as a percentage of the break area of 0.146 m^2.

3.6 MANUAL TRIP

For cases where a manual trip is credited, the timing of the trip is 15 minutes after a clear and unambiguous indication of the event. For shield cooling system failures, the relevant alarms and setpoints are given in Table 1.

4. Analysis Results

The postulated failures analyzed include a loss of end shield coolant flow, a loss of heat sink, and a loss of inventory. The initial conditions predicted by the CATHENA steady state analysis are given in Table 2.

4.1 RESULTS FOR LOSS OF FLOW

As a result from pump failure, a loss of flow occurs. The transients presented for this case assume no operator intervention (i.e. unterminated). Immediately following the loss of flow, the pump discharge low pressure alarm is annunciated at 0.003 s. The operator may try to restore cooling or shut down the reactor after 15 minutes of this clear and unambiguous signal. However, it is conservatively not credited in the analysis.

Due to the decrease in pump discharge pressure and increase in the pump suction pressure, the head tank (connecting to the pump suction) level rises and the calandria vault water level drops. The head tank high level alarm and the calandria vault low level alarm are annunciated at 2 s and 52 s, respectively. The end shield coolant bulk temperature initially increases at a rate of about 0.02°C/s. The calandria vault coolant temperature increases at a much slower rate because of its large water inventory. The end shield fluid temperature and the calandria vault fluid temperature transients are given in Figure 4. A series of end shield outlet/inlet high and calandria vault outlet high temperature alarms continue to be triggered, giving the operator many indications of the occurrence of the accident. Figure 4 shows that the end shield coolant does not boil until about 5500 s (the point at which the fluid temperature and the gas temperature are the same) . The temperature difference between the tubesheets and temperatures of lattice tubes and carbon steel balls of the end shield assembly remain low (Figure 5). Even if the shield coolant boils, it will be some time before the thermal load in the end shield structure causes any concern with respect to the deformations in the calandria/end shield assembly.

The results of this analysis clearly indicate that the manual trip is effective since there is sufficient time (at least 90 minutes) and clear indications (at least 3 alarms within the first 60 seconds) for the operator to recognize a problem and to initiate shutdown and cooldown of the reactor. Significant deformations in the calandria/end shield assembly would not occur. Thus, the integrity of the fuel channels or the operation of the shutdown systems is not jeopardized.

4.2 RESULTS FOR LOSS OF HEAT SINK

Due to a loss of service water to the shield cooling heat exchangers, a loss of heat sink occurs. Again, the transients presented for this case assume no operator intervention. Following a loss of heat sink, the end shield coolant bulk temperature and the calandria vault coolant temperature increase. The end shield fluid temperature and the calandria vault fluid temperature transients are given in Figure 6. As shown in this figure the heat up is very slow because shield cooling circulation is maintained, and because of the large mass of shield coolant.

The head tank low level alarm is annunciated at 17 s. The calandria vault inlet high temperature alarm and the end shield inlet high temperature alarm are annunciated at 43 s and 48 s, respectively. Operator action to shut down the reactor may be credited 15 minutes after these signals. If operator action is not credited (as presented for this case), the end shield coolant bulk temperature and the calandria vault coolant temperature continue to rise slowly with consequential liquid swell. The end shield outlet high temperature alarm, the calandria outlet high temperature alarm and the calandria vault high level alarm are triggered at 3389 s, 3451 s, and 6272 s, respectively.

As shown in Figure 6 if no operator action is credited, the end shield coolant does not boil until about 15000 s (4.2 h). The operator has at least 4 hours, after the second high temperature alarm, to shut down the reactor before boiling of the coolant occurs. Thus, manual trip is effective for this event. Significant deformations in the calandria/end shield assembly would not occur. The integrity of the fuel channels or the operation of the shutdown systems is not jeopardized.

4.3 RESULTS FOR LOSS OF INVENTORY

The results presented in this section assume a 100 percent guillotine break in a pipe near the bottom of the end shield. (This break location results in the fastest drainage rate.) The transients presented for this case assume no operator intervention.

Figure 7 gives the flow discharge transient. The initial discharges are 467 kg/s (from the break closer to the vault) and 341 kg/s (from the break closer to the end shield). Immediately following a loss of flow (i.e. within 10 s), there are five clear alarm signals. Both the pump discharge low pressure alarm and the end shield low level alarm are annunciated at 0.04 s. These are followed by the end shield low level alarm at 0.5 s and the head tank low level alarm at 1.5 s , and the end shield outlet high temperature alarm at 2.7 s and the and end shield inlet high temperature alarm at 5.7 s.

The heatup transients for the inner and outer tubesheets, lattice tubes, and the steel balls in the calandria/end shield assembly are given in Figure 8. End shields continue to heat up until operator action at about 15 minutes. There are at least 6 alarms within 20 s, so the operator will have an unambiguous indication of the event. At about 15 minutes, the temperature differential between the inner and outer tubesheet is about 35°C (Figure 8). This may cause minor deformation of the assembly, but is within acceptable limits, such that fuel channel integrity or the operation of the shutdown systems is not jeopardized. [1]

5. Conclusions

For a loss of shield cooling flow, there are 3 alarms within 60 seconds. No boiling of the shield coolant is predicted before 30 minutes, assuming no prior operator action. Therefore, the manual trip is effective since there is sufficient time (at least 15 minutes) and clear indications (at least 3 alarms within the first 60 seconds) for the operator to recognize a problem and to initiate shutdown and cooldown of the reactor. Significant deformations in the calandria/end shield assembly would not occur. Thus, the integrity of the fuel channels or the operation of the shutdown systems is not jeopardized.

For a loss of service water to the heat exchangers, there are also 3 alarms within 1 minute, with additional alarms occurring later. No boiling is predicted before four hours, assuming no prior operator action and temperature differentials between the inner and outer tubesheets remain low. Again, the manual trip is effective for this event, as there is ample time and indications for the operator to initiate a trip and cooldown of the reactor without any significant deformation of the calandria/end shield assembly.

For a 100% guillotine break in the pipe at the bottom of the shield tank, results show that there are at least 6 alarms within 20 s, so the operator will have an unambiguous indication of the event. At about 15 minutes, the temperature differential between the inner and outer tubesheet is 35°C. This may cause minor deformation of the assembly, but is within acceptable limits. Fuel channel integrity or operation of the shutdown systems is not jeopardized. Smaller breaks would result in similar behavior, with a longer time before operator response is required.

Therefore, for failures in the shield cooling system, there is sufficient time and clear indications for the operator to safely terminate the event before any calandria deformation could jeopardized fuel channel integrity or shutdown system operation.

6. References

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Table 1
Alarm Setpoints for End Shield Cooling System Failure Analysis

VARIABLE	ALARM CONDITION	DESCRIPTION
Level	4.913 m* (Elevation 114.94 m) 5.213 m* (Elevation 115.24 m)	Head Tank Level Low Head Tank Level High
Level	+ 0.150 m** - 0.150 m**	Calandria Vault Water Level High Calandria Vault Water Level Low
Level	110.13 m	End Shield Level Low
Temperature	60.6 °C 49.4 °C	End Shield Inlet Temperature High End Shield Inlet Temperature Low
Temperature	71.0 °C	End Shield Outlet Temperature High
Temperature	54.0 °C 43.0 °C	Calandria Vault Inlet Temperature High Calandria Vault Inlet Temperature Low
Temperature	60.0 °C	Calandria Vault Outlet Temperature High
Pressure	11.72 kPa(g) 8.96 kPa(g)	Calandria Vault Cover Gas Pressure High Calandria Vault Cover Gas Pressure Low
Pressure	483 kPa(g)	Pump Discharge Pressure Low
Differential Pressure	68.9 kPa(d)	Ion Exchanger Pressure Drop High

* Level measurements are with respect to a reference point at an elevation of 110.027 m.

** Measured with respect to the normal operating level of 115.17 m.

Table 2
End Shield Cooling System Initial Conditions

PARAMETER	NOMINAL VALUES
End Shield Cooling System Heat Load	7.5 MW
Calandria Vault Inlet Temperature	49 °C
Calandria Vault Outlet Temperature	54 °C
End Shield Inlet Temperature	60 °C
End Shield Outlet Temperature	66 °C
Calandria Vault Average Temperature	51.8 °C
End Shield Average Temperature	62.9 °C
Pump Discharge	304.64 kg/s
End Shield Inlet Flow	92.4 kg/s

Table 3
Maximum Temperature Differences

Transient Case	Maximum Tubesheet Temperature Difference (Inner-Outer °C)	Maximum Wall Temperature Difference (Top-Bottom °C)
Loss of Flow	15	40
Loss of Heat Sink	15	15
Loss of Inventory	35	15

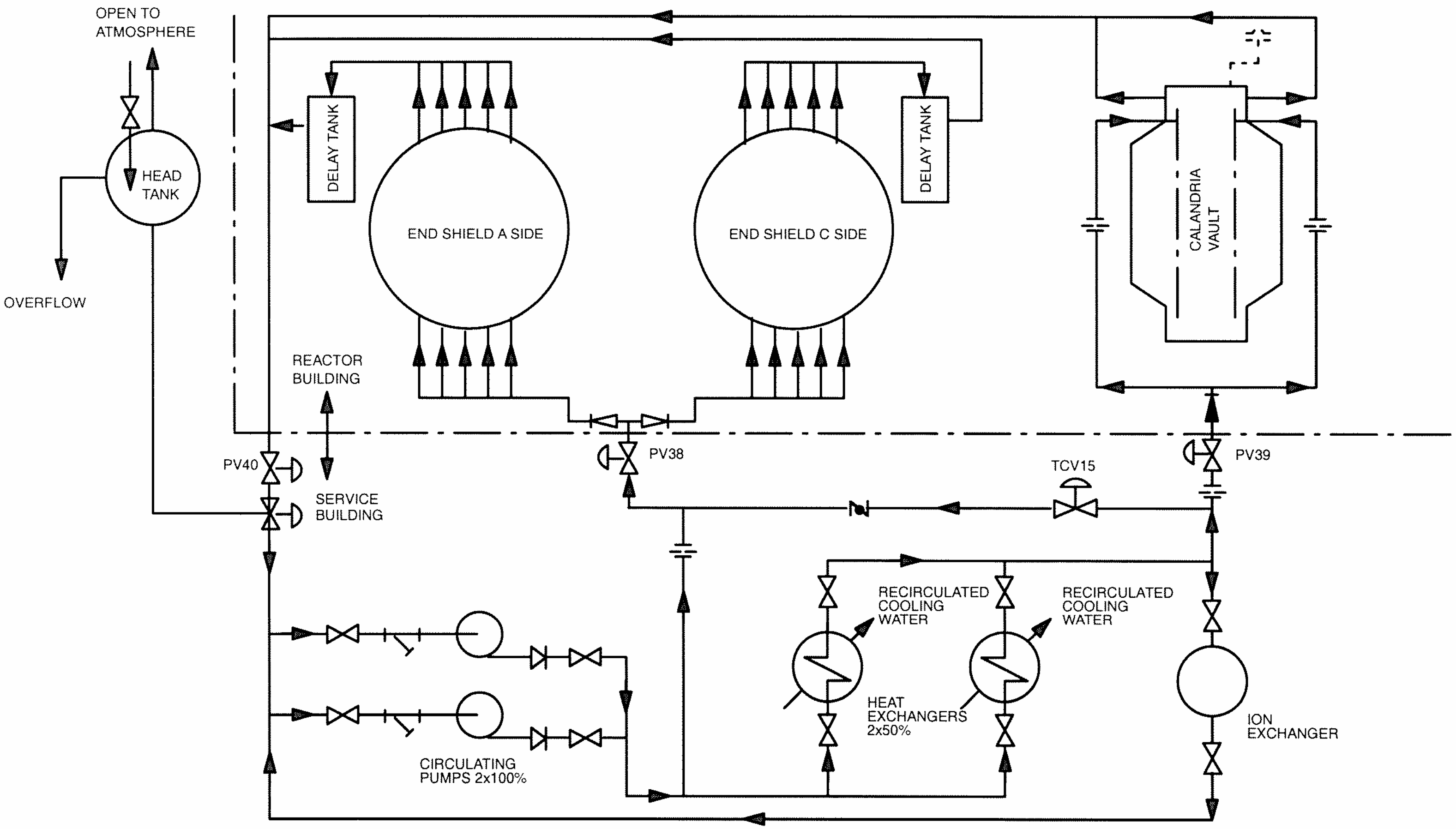


Figure 1 Shield Cooling System

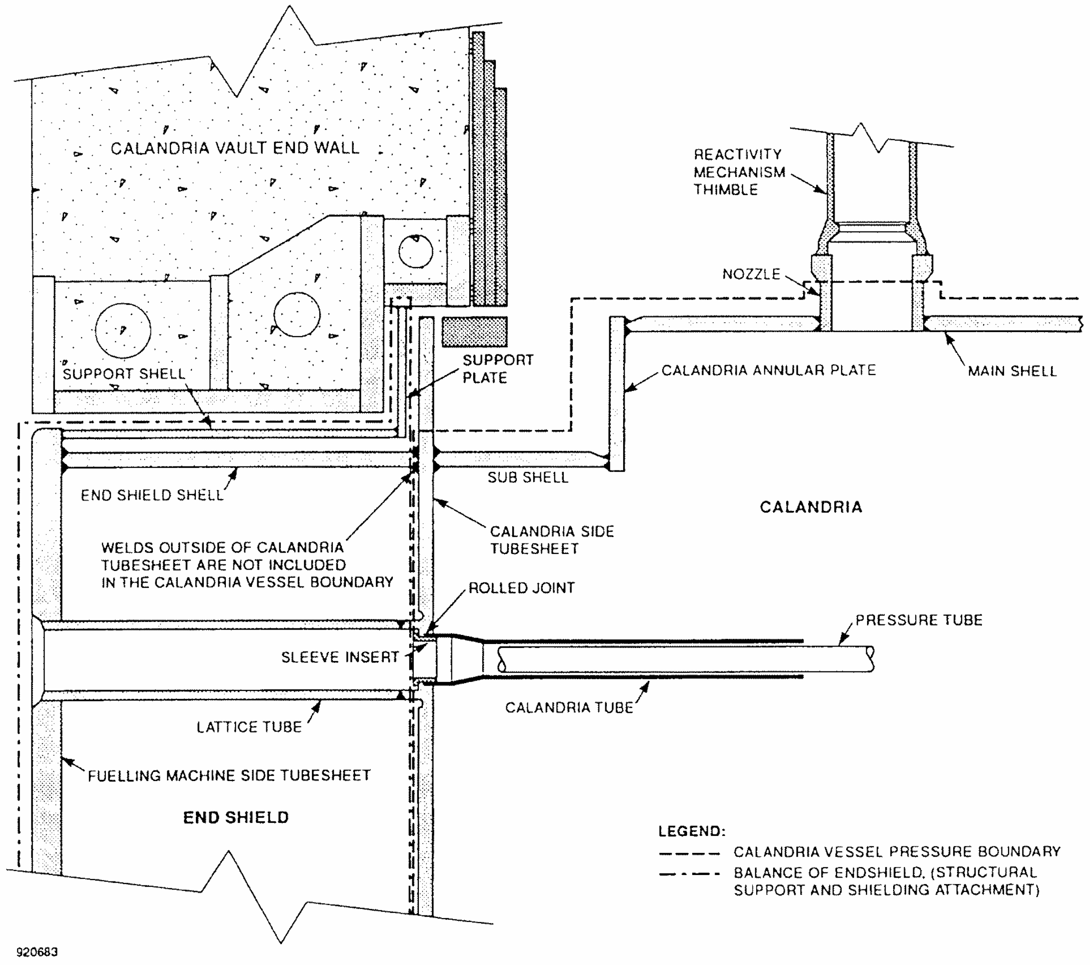
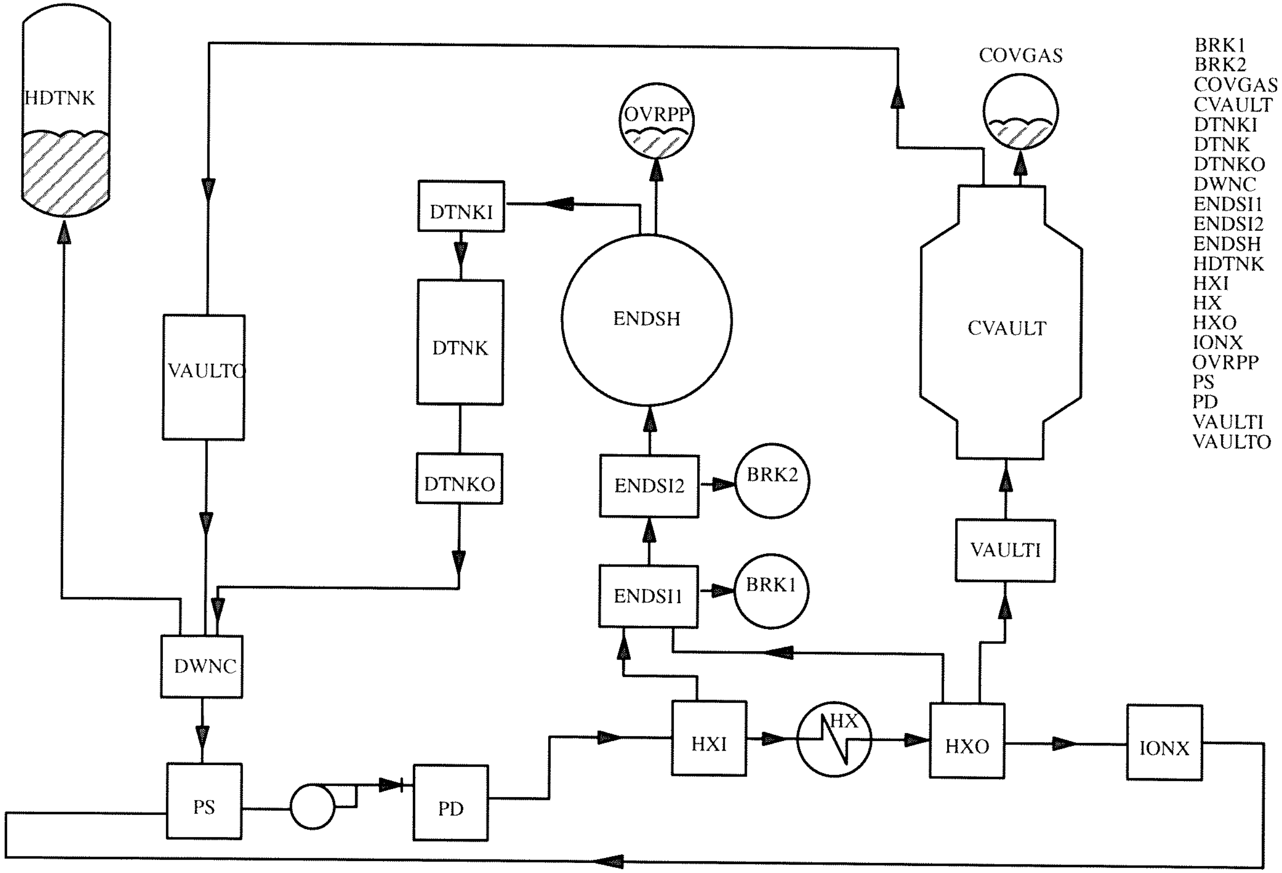


Figure 2 End Shield (Schematic)



BRK1	break location 1
BRK2	break location 2
COVGAS	calandria vault cover gas
CVAULT	calandria vault
DTNKI	delay tank inlet
DTNK	delay tank
DTNKO	delay tank outlet
DWNC	junction
ENDSI1	end shield inlet 1
ENDSI2	end shield inlet 2
ENDSH	end shield
HDTNK	head tank
HXI	heat exchanger inlet
HX	heat exchanger
HXO	heat exchanger outlet
IONX	ion exchanger
OVRPP	overpressure protection
PS	pump suction
PD	pump discharge
VAULTI	vault inlet
VAULTO	vault outlet

Figure 3 Nodalization of CATHENA End Shield Cooling System Model

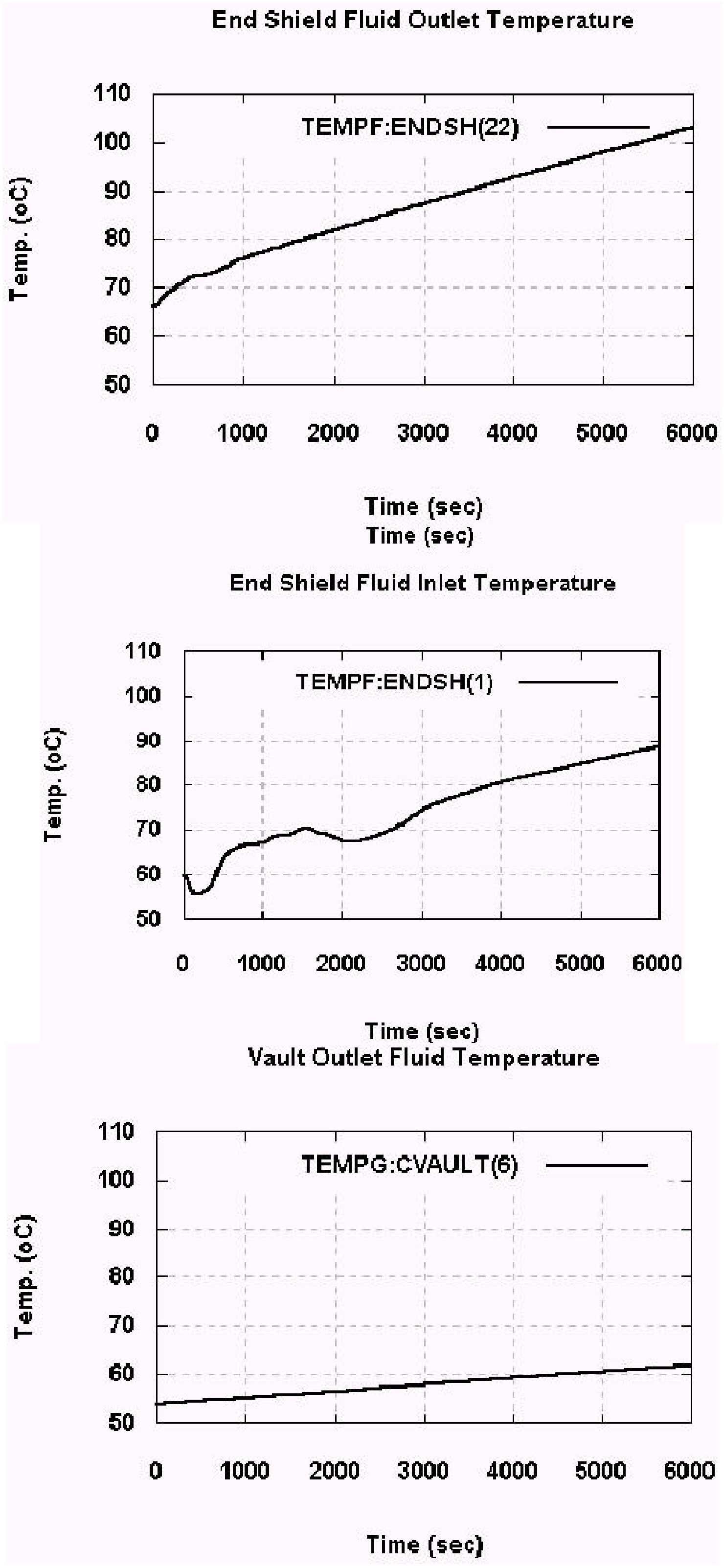


Figure 4 End Shield and Calandria Vault Fluid Temperature Transients for a Loss of Flow

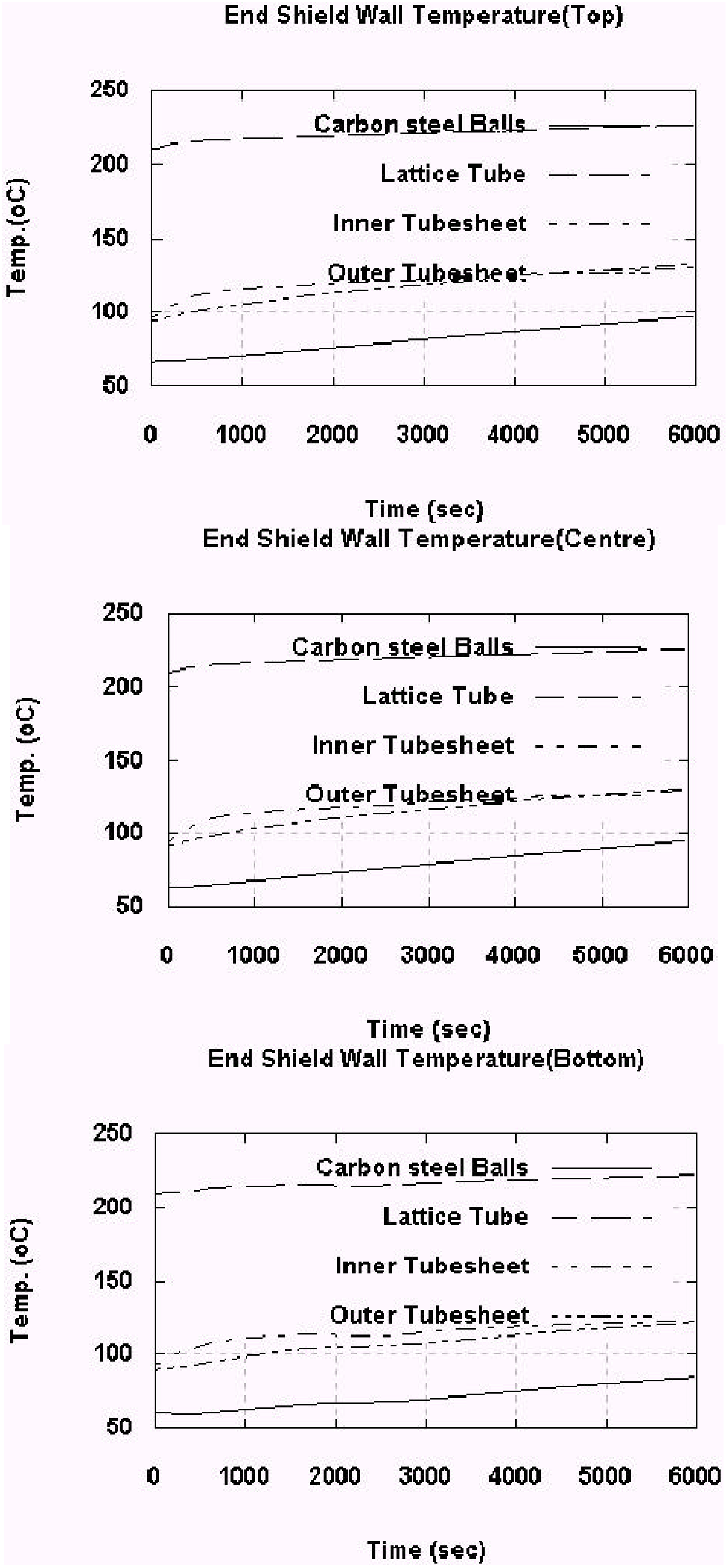


Figure 5 End Shield Wall (Metal) Temperature Transients for a Loss of Flow

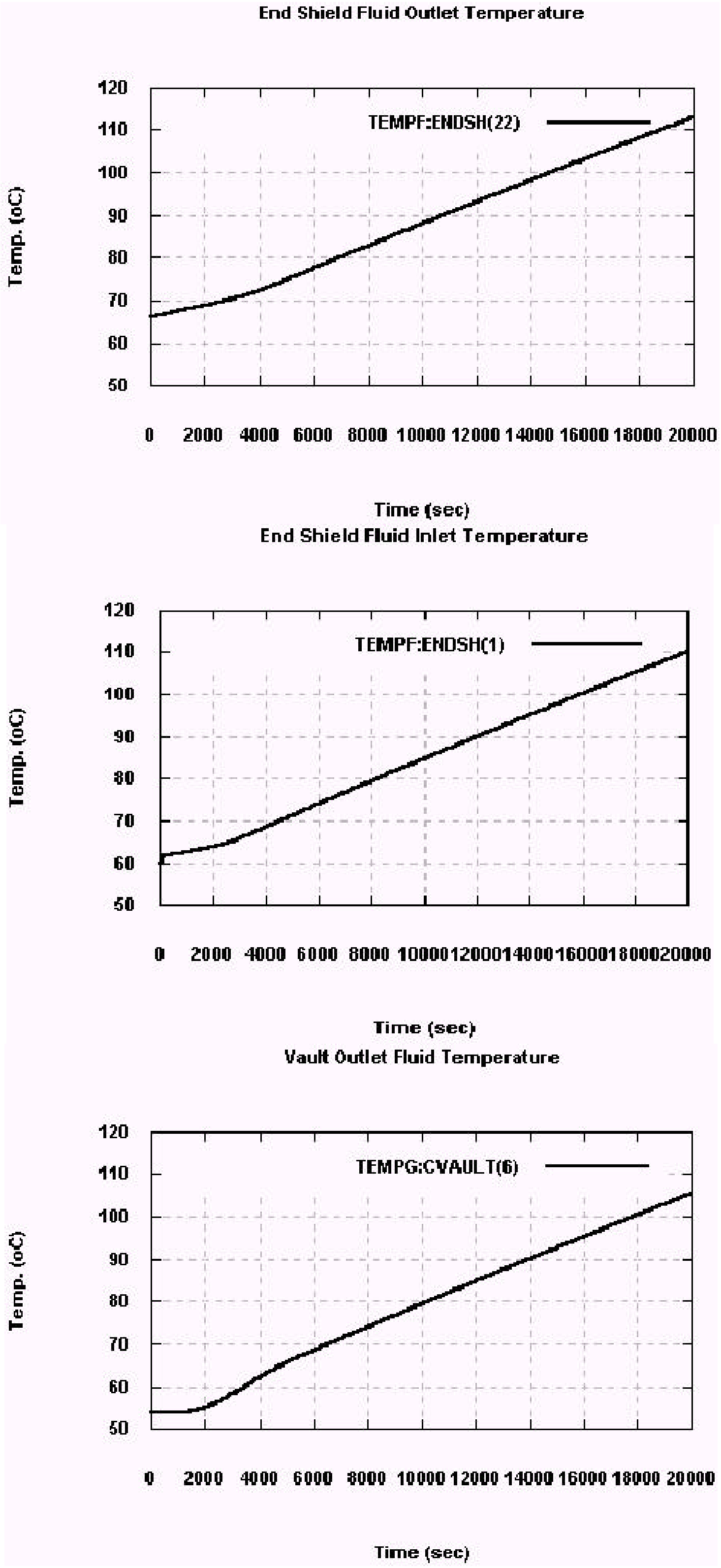


Figure 6 End Shield and Calandria Vault Fluid Temperature Transients for a Loss of Heat Sink

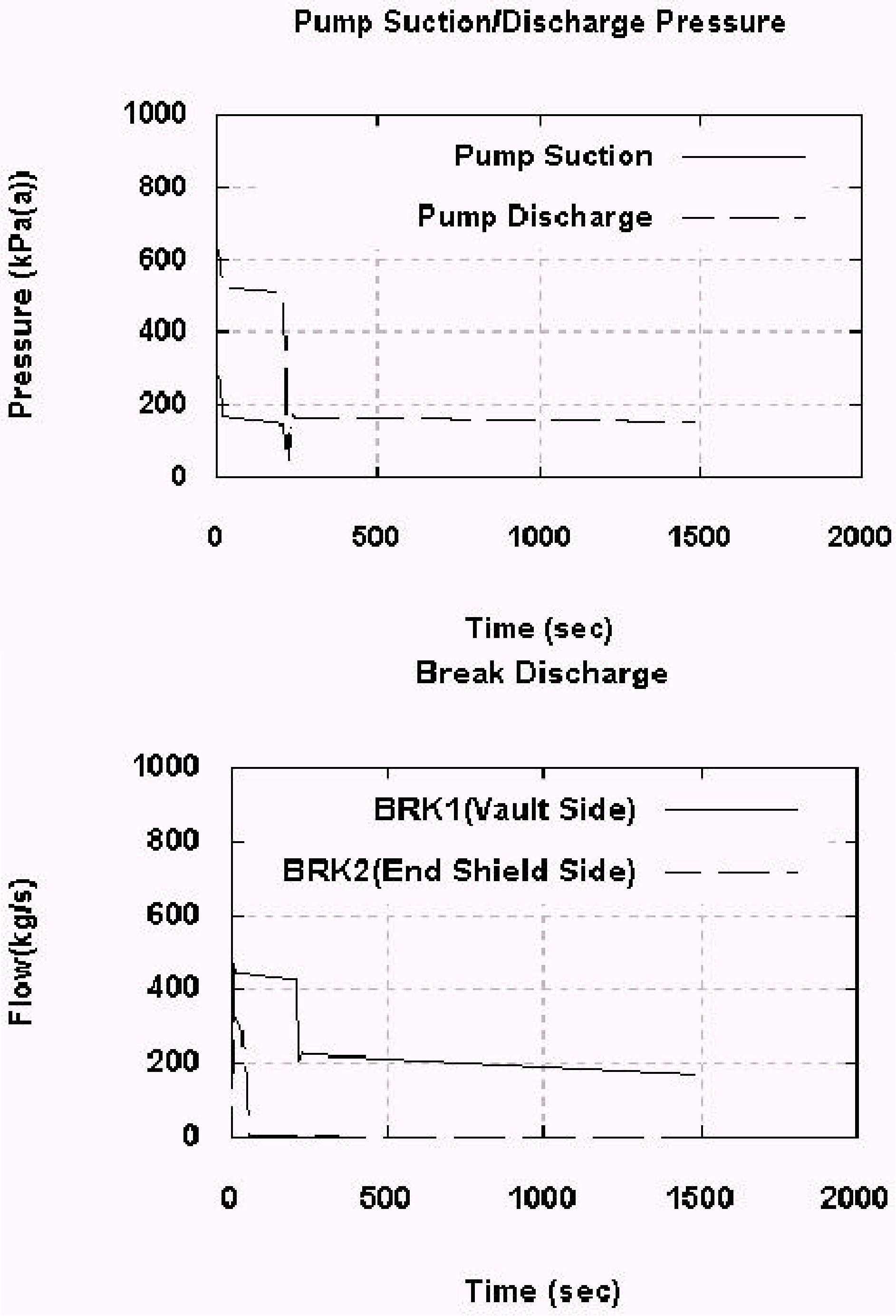


Figure 7 Pump Suction/Discharge Pressure and Break Discharge Transients for a 100% Guillotine Break

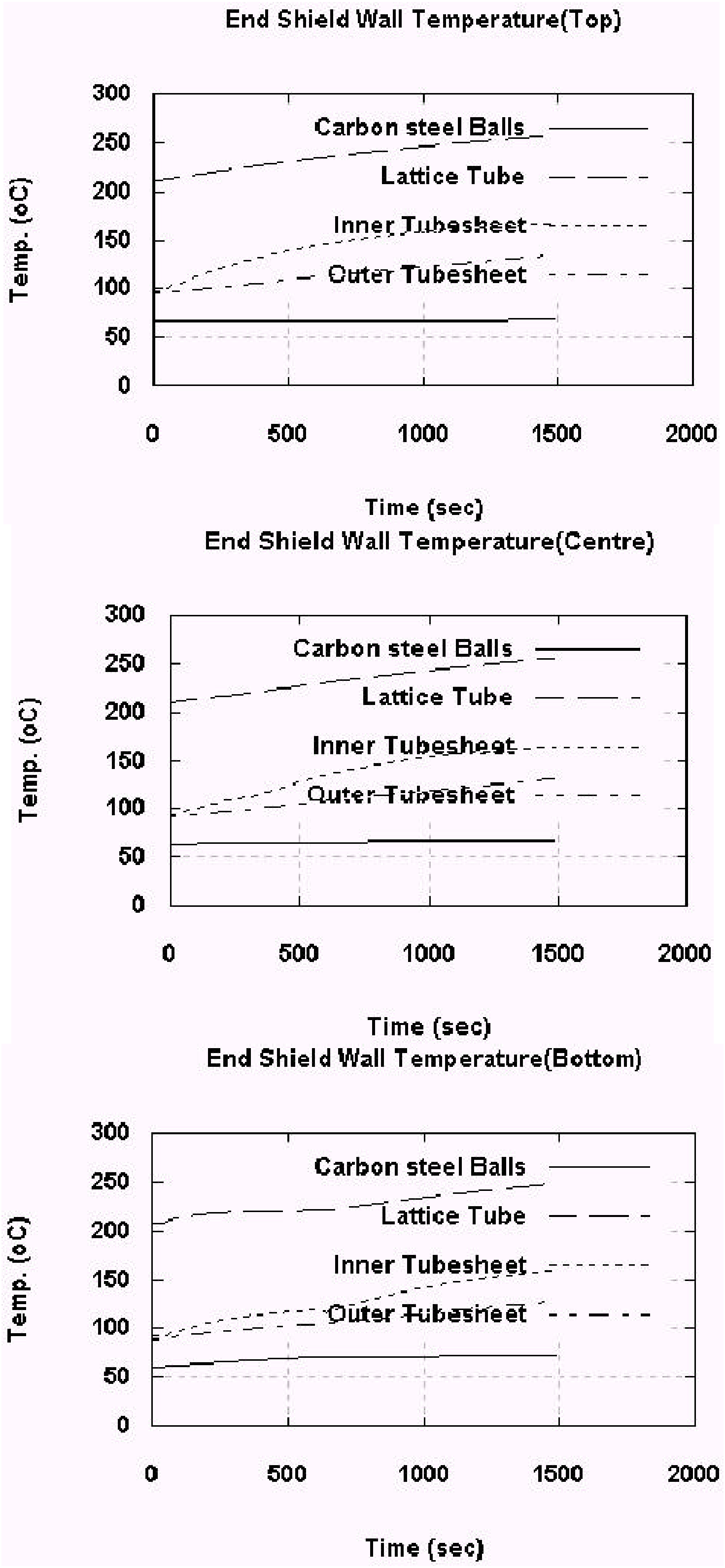


Figure 8 End Shield Wall (Metal) Temperature Transients for a 100% Guillotine Break