Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, 2004

A Trip Coverage Analysis of Total Loss of Class IV Power for Wolsong 1 with CANFLEX-NU Fuel

Kwang Ho Lee, Hoon Choi

Korea Electric Power Research Institute
103-16 Munji, Yusung
Daejon, Korea 305-380

Abstract

This analysis is intended to show that there is adequate reactor trip coverage (i.e., two parameters for each shutdown system) to prevent fuel and fuel channel failure and excessive Primary Heat Transport (PHT) system overpressure for a total loss of class IV power event for Wolsong 1 with CANFLEX-NU fuel. The analysis was performed using the CATHENA circuit model and slave channel model for channel O6. The effect of the reactor regulating system operational or frozen was assessed to show that adequate trip coverage is available for equilibrium CANFLEX-NU fuel and fouled steam generators. For a total loss of class IV power to all PHT pumps at all different initial power levels, there are at least two effective trip parameters for both SDS1 and SDS2. The peak reactor outlet header pressure was within the limit for ASME level B (SDS1) and C (SDS2) transients and fuel failure was precluded for all cases. At 2% initial power and lower, a trip is not required, when the reactor regulating system is operational. Therefore, adequate trip coverage is demonstrated for all cases.

1. Introduction

The analysis of a total loss of class IV power is one portion of the trip coverage assessment required for both shutdown systems. This assessment is intended to show that there is adequate trip coverage (i.e., two parameters for each shutdown system) to prevent fuel and fuel channel failure and excessive PHT system overpressure for this event with CANFLEX-NU fuel in Wolsong-1. The analysis was performed with the CATHENA thermal hydraulic computer code. In this analysis, an equilibrium fuel and fouled steam generator condition was considered. High neutron power trip, high heat transport system pressure trip, low gross coolant flow and low core header to header pressure drop trips were considered for both shutdown systems in this analysis. The CATHENA code was also used (modelling a single high powered channel) to assess the onset of dryout and to calculate fuel, sheath and pressure tube temperatures.

2. Acceptance Criteria

This trip coverage assessment is intended to show that there is adequate trip coverage (i.e., two parameters for each shutdown system) for each event considered. The acceptance criteria against which the analysis results will be judged are the Canadian Nuclear Safety Commission (CNSC) public dose guidelines [1 and 4]. For a total loss of class IV power, this can be demonstrated if the primary circuit remains intact, thus prohibiting release of radioactive material to containment. The requirements for the shutdown systems are given in the CNSC documents R-10, R-77, and R-8 [1 to 3]. In general, two effective trips are required for each shutdown system with exceptions allowed for reasons of impracticality or detrimental to safety [R-8]. In the case of overpressure, if high heat transport system pressure is the first trip, it is the only trip required [R-77].

2.1 Overpressure Limits

The criteria from R-77 are used to demonstrate adequate protection. R-77 requires that certain ASME service limits are met depending on event frequency and whether the first or second shutdown system is assumed to act. A total loss of class IV power is considered to be of moderate frequency (i.e., > 10^{-2}/year). According to Regulatory Guide R-77 [2] the service limit for SDS1 high pressure trip would be level B ("upset") crediting the liquid relief valves (LRVs) and for SDS2 the service limit would be level C ("emergency") with and without crediting the LRVs. For upset condition, peak pressure must not exceed 110 percent of design pressure (i.e., 11.9 MPa(a)). For any emergency condition, the allowable primary stress limit is 120% of the allowable stress or 100% of the yield strength, whichever is greater. However, a conservative target of 120% of design pressure (13.0 MPa(a)) is used to ensure that these limits are met.

2.2 Channel Integrity

R-8 and R-77 require that the fuel channels should not fail. For the channel to fail, the calandria tube must fail. However, for these scenarios, where the coolant pressure remains high, pressure tube failure may result in calandria tube failure. No credit is taken for any margin between the two. The fuel channels should not fail due to internal overheating. If the pressure tube temperature remains below 600°C, pressure tube failure will not occur and no strain calculations are required. This is inferred from experimental work given in References 5 to 7. Thus, pressure tube temperatures below 600°C will ensure no fuel channel failures due to overheating.

2.3 Fuel Integrity

R-8 and R-10 require that the shutdown systems prevent systematic fuel failures. No fuel analysis is required if sheath dryout or flow stratification does not occur in the channel. If dryout or flow stratification does occur, but fuel sheath temperatures remain below 800°C, then fuel failures are precluded and the criteria are still met.

3. Event Sequence

This is a qualitative description of the expected event sequence. The expected event sequence following a total loss of class IV power is:

- All PHT pumps run down.
- The turbine trips due to a loss of condenser vacuum.
- The primary coolant flow decreases due to the rundown of the pumps. The flow-power mismatch raises the primary coolant temperature and pressure, which initiates the opening of the PHT liquid relief valves.
- The steam generator feedwater pumps run down to cause a temporary loss of make-up to the steam generators.
- The reduced flow causes void in the core which produces a small positive reactivity feedback.
- The increase in the reactor power is terminated by the regulating and/or the shutdown systems (i.e., stepback or trip).
- The condenser circulating water pumps and hence the steam condenser become unavailable. This prevents the condenser steam discharge valves from opening. The MSSVs can open to control pressure.
- D_2O feed to the PHT system become unavailable as the respective pumps are operated on class IV power.
- The pressurizer heaters become unavailable since they are operated on class IV power. PHT pressure and inventory control mode is switched automatically to “solid” mode.

4. Analysis Methodology and Assumptions

4.1 Analysis Methodology

The trip coverage analysis was performed using the CATHENA circuit model [8 and 9]. A two loop representation of the heat transport system is utilized. This is a representation where the two loops are modelled separately. A detailed CATHENA single channel model was also used to assess fuel, sheath, and pressure tube temperatures in a high-powered single channel [10]. For cases where dryout is expected to occur, a CATHENA high powered channel model (O6) has been simulated to assess the fuel behavior in more detail [10 to 12]. The timing of the PHT low flow trip utilizes the CATHENA instrumented channel model (channel B10) which has been documented in Reference 10. The CATHENA circuit calculations were used to provide the boundary conditions for this channel simulation. All CATHENA control system data and key parameters are documented in Reference 9 and the CATHENA process system model is also described in detail in Reference 8.

4.2 System Assumptions

For the loss of class IV power, all primary heat transport pumps in both PHT loops are tripped at the beginning of the transient. Trip coverage is assessed for the reactor regulating system operating, as well as frozen. A fouled steam generator and equilibrium core condition was assumed.

- The liquid relief valves (LRVs) are credited for SDS1 analysis. SDS2 analysis is performed with and without crediting operation of the LRVs. When LRVs are credited for overpressurization transients for SDS1, the first 2 to open are assumed unavailable. For overpressure protection analysis, the most severe overpressurization is obtained when the LRVs are not credited for SDS2. For dryout, crediting the LRVs results in the most severe case because of increased voiding. Therefore, all LRVs are credited for dryout calculations for SDS2 and none are credited for SDS2 overpressure transients.
- Pressurizer steam bleed is not credited in this analysis.
- The feed and bleed systems are modelled but are not credited in this analysis. The feed and bleed valves are failed closed at the beginning of the transient for a conservative estimation of peak pressures.
- The main steam system is modelled. Atmospheric steam discharge valves (ASDVs) are modelled but not credited. Eight out of 16 main steam safety valves (MSSVs) are conservatively assumed to open for this overpressure transient. A turbine trip is assumed to occur simultaneously with the loss of class IV power. The condenser steam discharge valves (CSDVs) are also closed as a consequence of the loss of condenser vacuum following the loss of power since this leads to a more rapid increase in steam generator pressure, and hence results in a more conservative evaluation of trip coverage.
- The feedwater system is modelled. However, the feedwater pumps are tripped on the loss of class IV power, hence steam generator level control is unavailable in the short term for trip coverage analysis. The auxiliary feedwater pump is not available in the time frame of this analysis, but would be available for the long term.

In addition, the analysis is done for fouled steam generators (end of reactor life) which results in a ROH quality of 4.5 percent at 103 percent full power steady state. An equilibrium fuel is considered and presented in Reference 9.

5. Analysis Results

Analysis was performed for fouled steam generators with equilibrium CANFLEX-NU fuel in Wolsong-1. A range of initial power levels was considered. The initial conditions of the heat transport system for various power levels are given in Table 2.

5.1 Total Loss of Class IV Power from 103% Full Power

The event sequence for 103%FP with RRS frozen case is shown in Table 3. The loss of class IV power causes the PHT pumps to begin to rundown. The pressure and temperature in the core increase as the flow through the core decreases. Some pressure relief is available through the cushioning effect of the pressurizer. The reactor trips when a trip setpoint is reached. Following that, the pressure reaches the peak value, then, it decreases quickly.

At 103% FP, the first trip is SDS1 high pressure (immediate trip), which occurs at 3.27 seconds. The second trip is high neutron power on both SDS1 and SDS2 at 3.37 seconds, which results in a peak ROH pressure of 11.6 MPa(a). The transient results are shown in Figure 1. Therefore, both high neutron power and high pressure trips are effective in limiting the peak pressures to within the required limit of 11.9 MPa(a) for SDS1. The fourth trip is SDS1 low flow. It is predicted to occur at 3.62 seconds, based on a simulation of channel B10. The peak pressure is greater than 11.8 MPa, the allowable limit for SDS1. The SDS2 high pressure trip would occur at 4.98 seconds, with a peak ROH pressure of 12.9 MPa(a). The transient results are shown in Figure 2. Therefore, both the high power and SDS2 high pressure trips are effective in limiting peak ROH pressures to within 120% of design pressure (13.0 MPa(a)), the conservative target used in this analysis. The low core pressure drop trip occurs later, at 5.6 seconds, but is not effective at this power. Dryout was predicted to occur, in channel O6, at 3.2 seconds. Therefore, there are five trips (three on SDS1 and two on SDS2) effective in precluding fuel failure.

5.2 Total Loss of Class IV Power from Lower Initial Powers

For an initial power of 90% FP, the first two trips are SDS1 high pressure (immediate) at 3.15 seconds, followed by SDS1 low flow at 3.46 seconds. Peak ROH pressures are 11.5 MPa(a) or less. The SDS2 high pressure trip occur at 5.24 seconds, and limits peak ROH pressure to 12.8 MPa(a). The SDS1 and SDS2 high power trip occurs at 9.85 seconds. This results in a peak ROH pressure over 13.0 MPa(a). These trips are not effective for both overpressure and fuel failure criterion, since dryout is predicted to occur at 4.0 seconds, with a peak sheath temperature over 800°C. Figure 3 shows the transient results for the simulation of channel O6 for this case.

Similar results are obtained for an initial power of 80% FP. The low flow and high pressure trips are effective on SDS1 and the high pressure and low core pressure drop trips are effective on SDS2. Again, the high power trip occurs later and, not effective in limiting peak pressure to within the required limits and in precluding fuel failure.

At 50% initial power, the low flow, low core pressure drop and high pressure (SDS1 immediate and SDS2) trips are all effective in limiting peak pressure to within the required limits. There is no pre-trip dryout for all these trips, and the peak sheath temperatures are 768°C or less. Similar results were obtained for initial powers of 20% and 10% FP.

5.3 Effect of RRS on Total Loss of Class IV Power

Because of the speed of the transient, the operation of the reactor regulating system has very little effect on the results, at higher initial powers. The effect is only noticeable at very low initial powers (10% FP and less). For these initial powers, if the reactor regulating system is not available, trips occur on high pressure, low flow and low core pressure drop. If the reactor regulating system is available and functioning normally, trips are not required and peak pressures remain below the required limits, and fuel dryout is precluded. These results are discussed in more detail in the following section.

5.4 Analysis from Very Low Initial Powers and Thermosyphoning Analysis

For an initial power of 10% FP, with RRS frozen, the SDS1 low flow and SDS2 low core pressure drop trips occur within about 10 seconds. The PHT high pressure trip occurs later, when sufficient power has been added to the coolant to reach the onset of quality and the system pressurizes. This occurs at about 89 seconds. Before that time, the PHT pressure remains below the SDS1 trip setpoint, due to the operation of the liquid relief valves. If the LRVs were not available, the SDS1 and SDS2 high pressure trips would occur earlier. A log rate trip on both SDS1 and SDS2 is also predicted as a result of the onset of voiding, but those trips were not credited in this analysis. There is a small amount of pre-trip dryout, but sheath temperatures remain well below the 800°C limit and fuel failures are not predicted.

For an initial power of 10% FP, with the RRS operating to maintain reactor power, the PHT pressures remain well below 110% of design pressure, and adequate fuel cooling is maintained by thermosyphoning. The transient results are shown in Figure 4 with SDS2 high pressure trip. Figure 5 shows the results of analysis from 2% FP with no reactor trip credited. Figure 6 shows the results of the long term analysis for a loss of class IV power from 103% FP, with a trip on SDS2 high pressure. The fuel remains well cooled throughout the transient.

6. Conclusions

For RRS assumed to be frozen, the SDS1 and SDS2 high power trips are effective at very high power in limiting peak pressures to within the required limits. They are effective down to 90% FP in preventing fuel failures. The PHT high pressure trips on both SDS1 and SDS2 are effective throughout the entire power range in preventing both excessive overpressurization and in preventing fuel failures. The SDS1 low flow trip is also effective over the entire power range in both preventing overpressure limits and precluding fuel failures. The SDS2 low core pressure drop trip is effective for overpressure for initial powers of 80% and lower. It is effective up to 90% initial power in preventing fuel failures. Both the SDS1 low flow and the SDS2 core pressure drop trips are initially conditioned out at very low powers. However, because RRS is frozen, power eventually begins to rise, and the trips are automatically conditioned back in, and are effective at that point.

For the case of RRS assumed to be operating, at 2% initial power and lower, a trip is not required, since peak pressures remain below the required limits and fuel dryout is not predicted, since thermosyphoning is adequate to ensure fuel cooling. Above 2% power, the trip coverage is almost the same as the RRS frozen case.

Consequently, for reactor power levels where a trip is required to prevent heat transport system overpressurization or to maintain fuel and fuel channel integrity against overheating, there are at least two effective trip parameters. Therefore, adequate trip coverage is demonstrated.

Acknowledgement

This work has been carried out under the research and development program of the Korean Minisrty of Science and Technology.

References

1. CNSC Regulatory Document R-10, "The Use of Two Shutdown Systems in Reactors", 1977 January 11.
2. CNSC Regulatory Document R-77, "Overpressure Protection Requirements for Primary Heat Transport Systems in CANDU Power Reactors Fitted with Two Shutdown Systems", 1987 October 20.
3. CNSC Consultative Document R-8, "Requirements for Shutdown Systems for Nuclear Power Plants", 1991 February 21.
4. CNSC Consultative Document C-6, "Requirements for the Safety Analysis of CANDU Nuclear Power Plants", 1980 June.
5. H.E. Rosinger, R.S.W. Shewfelt, M.G. Wright, "An Examination of the Anisotropic Characteristics of CANDU Pressure Tubes at 773-1173 K", Atomic Energy of Canada Limited Report, WNRE-385, 1980 June.
6. R.S.W. Shewfelt, et al, "A High Temperature Creep Model For Zr-2.5 Wt% Nb Pressure Tubes", Atomic Energy of Canada Limited Report, AECL-8156, 1983 November.
7. R.S.W. Shewfelt, D.P. Godin, L.W. Lyall, "Verification of a High Temperature Transverse Creep Model for Zr-2.5 Wt% Nb Pressure Tubes", Atomic Energy of Canada Limited Report, AECL-7813, 1984 January.
8. M.Y. Ohn, "CATHENA Above Header Model", W1-CANFLEX-AR-010, Rev.0, 2001 January.
9. M.Y. Ohn, "CATHENA Trip Coverage Analysis Model", W1-CANFLEX -AR-002, Rev. 0, March 1994.
10. B.J. Moon, "CATHENA Fuel Channel", W1-CANFLEX -AR-009, Rev. 0, July 2001.
11. B.N. Hanna, Editor, "CATHENA Input Reference", AECL-WL Report: THB-CD-012, Rev. 2.0, 1991 October.
12. J.P. Mallory, Editor, "CATHENA GENHTP Input Reference", AECL-WL Report: THB-CD-013, Rev. 2.0, 1991 October.

Table 1
SDS1 and SDS2 Trip Setpoints for a Total Loss of Class IV Power

Trip Parameter	Design Setpoint	Analysis Setpoint	Delay Time (S)	Time Constant (S)
High Neutron Power	124% full power (detector setpoint; equivalent to ~100% bulk power)	117% full power (bulk power)	0.15	0.01
Low Gross Coolant Flow (SDS1)	80% nominal in instrumented channels	70% nominal	0.182	0.3
High Heat Transport System Pressure (SDS1) immediate trip	10.55 MPa(a)	10.65 MPa(a)	0.182	0.3
High Heat Transport System Pressure (SDS1) delayed trip	10.34 MPa(a) + 3sec. time delay (>70% FP)	10.44 MPa(a) + 3sec. time delay (>70% FP)	0.182	0.3
High Heat Transport System Pressure (SDS2)	11.72 MPa(a)	11.82 MPa(a)	0.183	0.3
Low Core Differential Pressure (SDS2) immediate trip	620 kPa(d)	520 kPa(d)	0.184	0.3

Table 2
Initial Conditions at Various Power Levels

Initial Power	**(% FP)**	**103**	**75**	**50**
Fuel Type		Equilibrium	Equilibrium	Equilibrium
Total Thermal Power-to-Coolant	(MW)	2112	1536	1024
RIH Pressure	(MPa(a))	11.35	11.32	11.32
ROH Pressure	(MPa(a))	9.99	9.99	9.99
RIH Enthalpy	(kJ/kg)	1133	1126	1116
RIH Temperature	(°C)	268	265	263
ROH Temperature	(°C)	311	303	290
ROH Quality	(%)	4.5	0.0	0.0
Mass Flow Rate per Pass	(kg/s)	1918	1972	1985
Steam Generator Condition		fouled	fouled	fouled
Steam Flow to Turbine	(kg/s)	1077	774	509
Steam Generator Power	(MW)	2124	1552	1040
Steam Generator Pressure	(MPa(a))	4.7	4.7	4.7

Table 3
Sequence of Events for a Total Loss of Class IV Power (103% FP, RRS Frozen)

Time (sec.)	Event and System Response	Remarks
0.0	PHT pumps begin to rundown	PHT flow decreases, PHT temperature and pressure increase
	Feedwater pumps begin to rundown (over 3 sec.)	feedwater flow decreases
	Steam flow to turbine ramped down	steam flow reduces
	loss of service water to steam condenser	CSDVs unavailable
	zone control failed; MCAs frozen	RRS frozen and power increases
	loss of feed pumps to PHT system	no feed into PHT
	pressurizer heaters failed off	partial loss of pressure control
3.3	SDS1 PHT high pressure trip	if first SDS1 & SDS2 trips are not credited power is reduced and PHT pressure peaks and then begins to reduce
3.4	SDS1 high neutron power trip SDS2 high neutron power trip	if previous trips ignored
3.6	SDS1 low flow trip (channel B10) reached	if previous trips ignored
4.1	LRVs open (when credited)	if previous trips ignored
5.0	SDS2 PHT high pressure trip	if previous trips ignored
		shutdown system action terminates the power increase and reduces PHT pressure

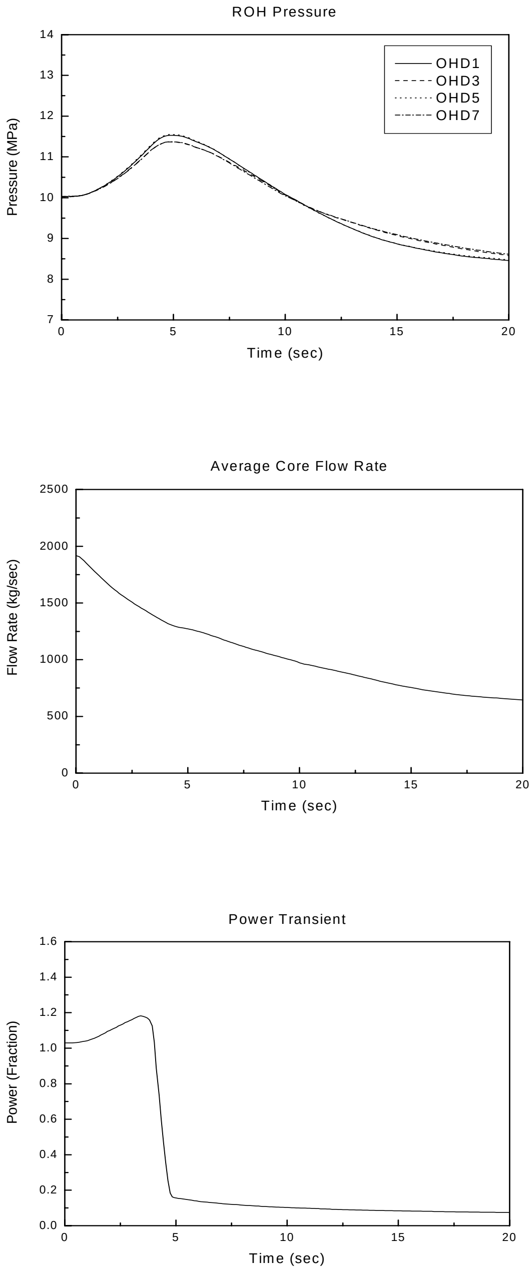

Figure 1. Total Loss of Class IV Power (RRS Frozen) 103% FP, 2 LRVs, SDS1 High Pressure Trip

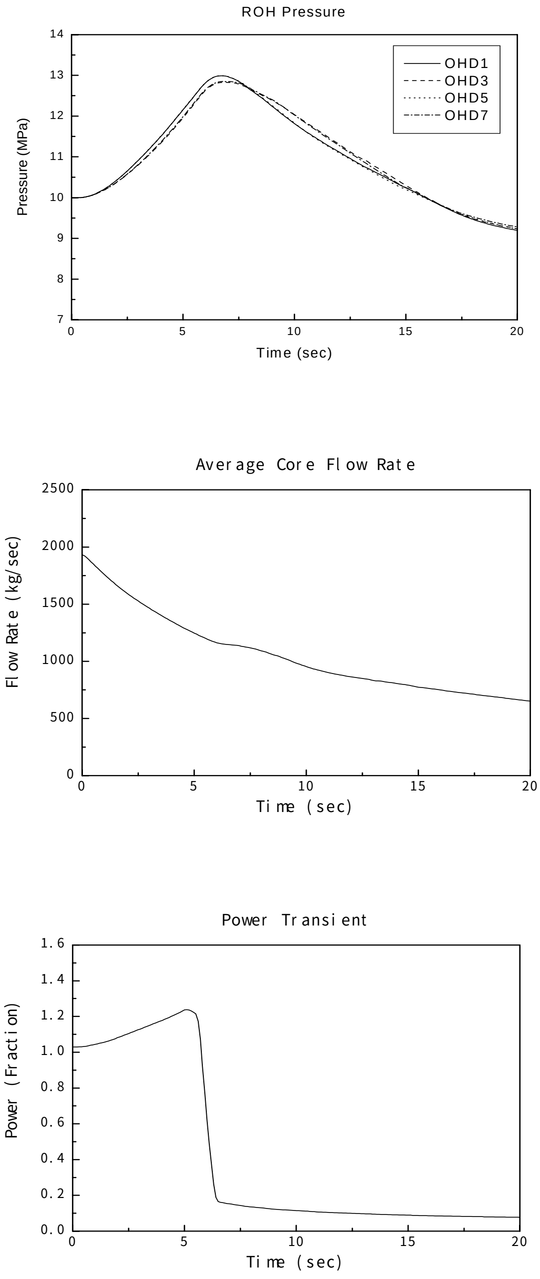

Figure 2. Total Loss of Class IV Power (RRS Frozen) 103% FP, No LRV, SDS2 High Pressure Trip

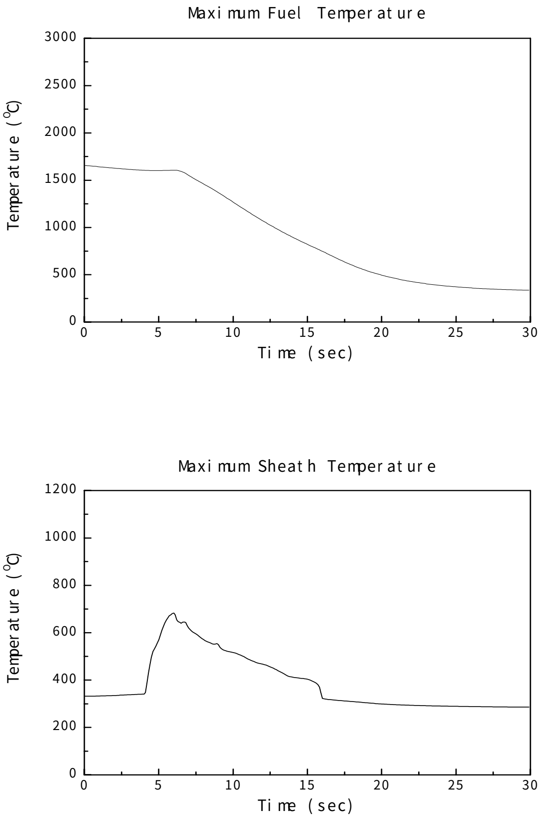

Figure 3. Total Loss of Class IV Power (RRS Frozen, Channel O6) 90% FP, 4 LRVs, SDS2 High Pressure Trip

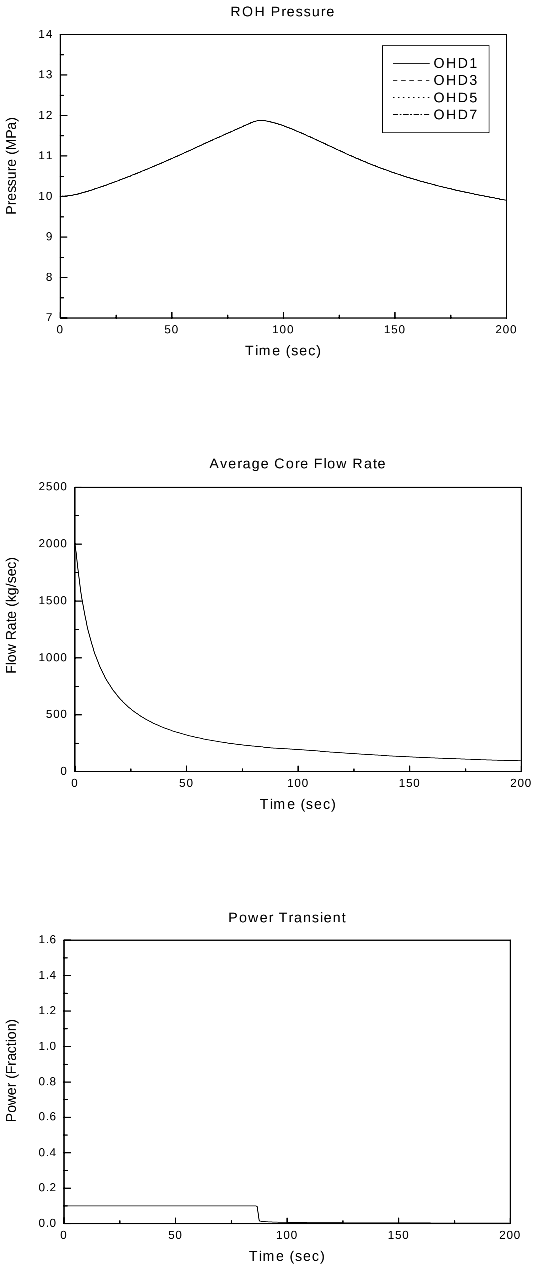

Figure 4. Total Loss of Class IV Power (RRS Operating) 10% FP, No LRV, SDS2 High Pressure Trip

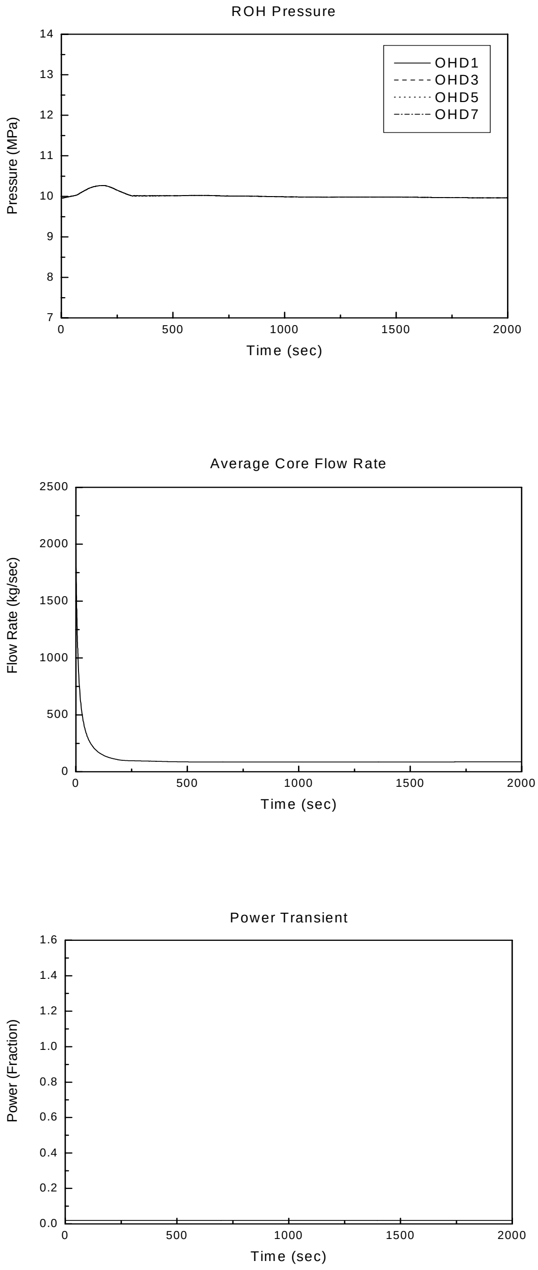

Figure 5. Total Loss of Class IV Power (RRS Operating) 2% FP, 2 LRVs, No Trip

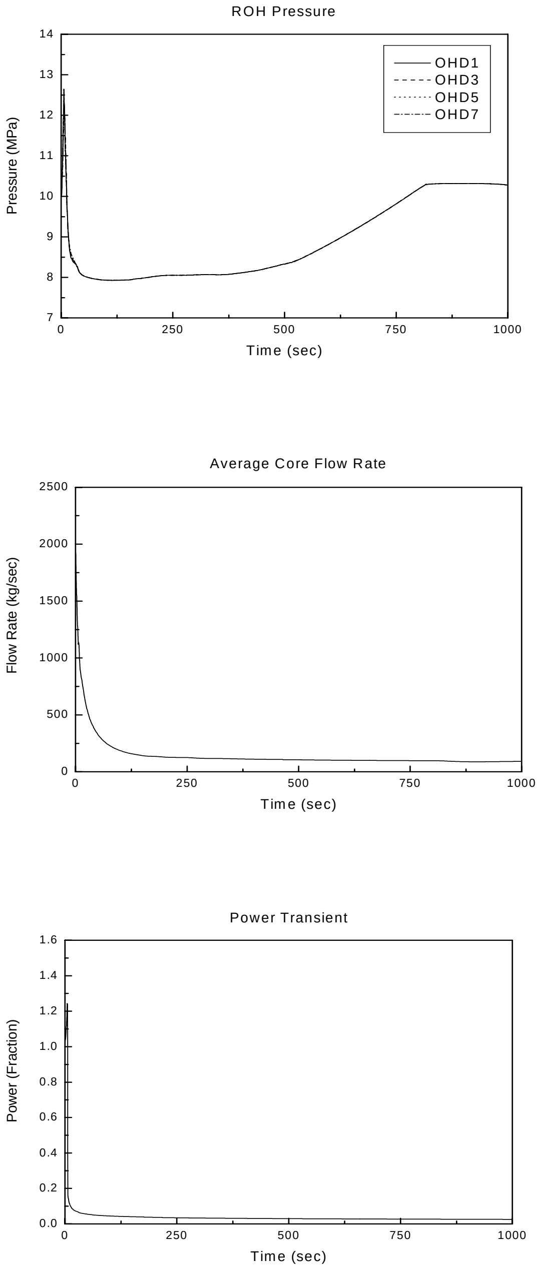

Figure 6. Total Loss of Class IV Power (RRS Operating) 103% FP, No LRV, SDS2 High Pressure Trip, Long Term Thermosyphoning