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Thermal hydraulic Safety Analysis of End Fitting Failure with Failure of ECCS for Wolsong NPP Unit 1 Loaded with CANFLEX-NU

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Abstract

This study was done as a part of the safety analysis for full CANFLEX-NU loaded core in Wolsong NPP unit 1. End Fitting Failure with the loss of emergency core cooling system(ECCS) was analyzed in the view of reactor thermal hydraulic trend and fuel channel integrity. Loop isolation failure has no impact on fuel channel integrity and thermal hydraulic behaviors are similar to those with loop isolation available. For ECC injection failure, PHTS inventory and pressure decrease, and the fuel channel integrity may be damaged due to the loss of fuel channel cooling. For the ECC injection failure with the loss of steam generator crash cooldown(SGCC), most behavior are similar to the case with SGCC available, except that PHTS depressurization rate is slower than for only the ECC injection failure.

Introduction

Failure of a fuel channel end fitting (EFF) in PHWR could lead to the rejection of fuel bundle from one channel into a fuelling machine vault. Any Fuel bundles ejected in this manner are likely to be damaged by impact, so that a prompt release of fission products to containment would be expected. The behavior of EFF with Emergency Core Cooling System(ECCS) available is similar to small LOCA with ECCS available and the fuel and fuel channel integrity is assured. So this study concentrates on the cases with ECCS failure. The failures which can occur in the ECCS is the loss of ECC injection, the loss of loop isolation, the loss of steam generator crash cooldown(SGCC) and the loss of ECC injection with the simultaneous loss of SGCC. Among them, the cases which include SGCC failure were not analyzed for Wolsong NPP Unit 234(W234) because W234 has dual SGCC systems. But Wolsong NPP Unit 1(W1) is possible to loss SGCC, so those cases need to be analyzed for that failure. This study covers only the thermal hydraulic behavior of reactor and fuel channel integrity for the ECCS failures.

Event Sequence

A complete severance of the end fitting occurs in one of the fuel channels. Under extremely severe conditions, all fuel bundles are ejected from channel through the severed end fitting by the high pressure coolant. This is accompanied by the discharge of the coolant from the primary heat transport system(PHTS). The fuel bundles become damaged as they land in the fuelling machine vault. Some fuel elements separated from the end plates and could break into pieces. The primary coolant discharge through the break creates a highly turbulent condition in the vault atmosphere. Fission products from the damaged fuel are released into the vault atmosphere depending on the amount of initial damage to the fuel, the degree of fuel heat up and the rate of UO_2 oxidation. And the pressure and inventory control system for PHTS responds to maintain nominal conditions. For break discharges above the capacity of this system, the PHTS has a net inventory loss and depressurizes. Prior to loop isolation on low PHTS pressure, the pressurizer, heavy water feed system, and the intact loop make up some of the lost inventory in the broken loop. The PHTS depressurization causes voids in the core which produce a positive reactivity feedback. The reactor regulating system (RRS) acts to keep the reactor power constant until reactor trip occurs. The reactor trips on one of the process trip signals, by one of the two independent shutdown systems. The turbine runs back following reactor trip. The main feedwater system continues to feed the steam generators from the condenser. If ECCS is available, the loop isolation valves close after the low header pressure setpoint is reached. And once these valves are closed, the PHT loops are isolated from other loop and the pressurizer, the purification system, and the heavy water feed and bleed system. And automatic ECC injection and steam generator crash cooldown(SGCC) occur on a low header pressure signal, conditioned by high containment pressure. First, in the case of failure of ECC injection, the broken loop inventory and pressure continues to decrease without coolant makeup. So flow decreases and heat removal from the fuel channel decreases. So fuel and pressure tube heat up and may deform. But cooling of the intact loop is similar to the case with ECC injection available, except there is no makeup from ECC as the loop cools down. But with forced circulation or thermosyphoning, fuel cooling of intact loop is adequate. Second, for the failure of both of ECC injection and SGCC, the behaviors of PHTS are similar to the above first case except the slow depressurization of PHTS. Third, if the SGCC does not occur, ECC can not be injected due to no depressurization of PHTS to the ECC gas pressure. So the behavior is very similar to the first case. Forth, the behavior of the failure of loop isolation is similar to the case of ECCS available except that the intact loop depressurize with broken loop as inventory continues to discharge from the intact loop. Both loops remain cooled by forced circulation or thermosyphoning and heat removal by steam generator and ECC injection.

Analysis Assumption

1) Primary Heat Transport System; All PHT pumps will continue to run until the pump trip is initiated by the operator when the trip condition as W234 is met, which is for conservatism . D_2O feed and bleed system and pressurizer is assumed to function according to normal pressure and inventory control logic

2) Secondary Heat Transport System; Normal steam generator level control system(SGLC) and normal steam generator pressure control (SGPC) is assumed to operating. 8 out of 16 MSSVs are credited for SGCC. Turbine is tripped by complete turbine unloading or high steam generator level.

3) Reactor Regulating System; Maintains reactor power constant prior to trip, but setback and stepback are not credited.

4) Reactor Shutdown System; Two shutdown systems are available but only one acting at one time is assumed. The trip time is taken to be the second process trip (third trip if higher reactor building pressure is included) of the later of the two SDSs.

5) Emergency Core Cooling System; The availabilty of emergency core cooling injection and loop isolation and SGCC are dependant on the analysis cases.

Acceptance criteria

It must be demonstrated that each of the two independent shutdown systems will arrest the reactivity and power excursion, and will maintain the reactor in a shutdown state. And the fuel and fuel channel integrity must be assured. For assurance, the temperature of fuel sheath and pressure tube must be below 800℃ and 600℃ respectively. But in the dual failure cases(Class 5 event) such as this study, the high temperature of fuel sheath above 800℃ is allowed.

System Modelling

Thermal hydraulic analysis consists of circuit and single channel calculations. The circuit calculation determines the system responses to a break, thus giving the transient values of the important process variables such as break discharges and enthalpy for containment analysis, core refilling time, coolant flow, inventory and pressure. The header conditions obtained from the circuit calculation are used as the boundary conditions for single channel thermal hydraulic calculations.

CANDU Thermal hydraulic computer code CATHENA are used for circuit and single channel simulations.

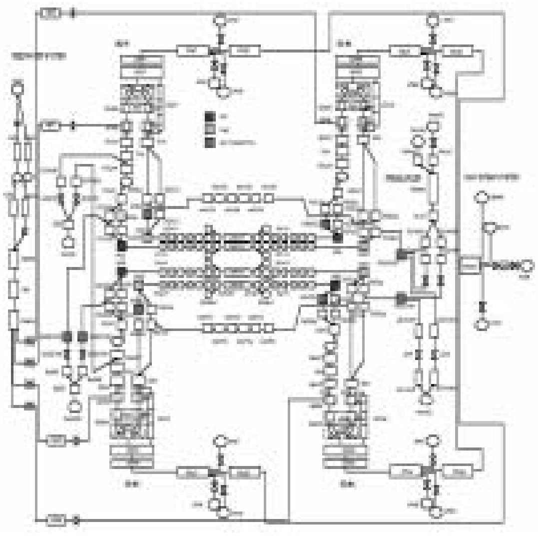

Figure 1 CATHENA nodalization of primary and secondary heat transport system of W1

Circuit Model

The primary heat transport system consists of inlet header, outlet header, fuel channels, PHT pumps, steam generator primary side, pressurizer and D_2O feed and bleed system. The secondary heat transport system consists of steam generator secondary side, feedwater system and main steam systems. The emergency core cooling system consists of high pressure ECC injection, medium pressure ECC injection and low pressure ECC injection and steam generator crash cooldown(SGCC) and loop isolation. The nodalizations of the primary heat transport system, secondary heat transport systems are given in Figure 1. In the average channel circuit model, core passes 1, 2 and 3 are represented by an average channel. Core pass 4 is represented by an average channel (94 averaged) in parallel with a single channel (the broken channel). And the initial conditions for average channel circuit model is as table 1.

Table 1 Initial Conditions for Average Channel Circuit Model (103% power)

(Channel O6_mod in Parallel with the Average Channel in Core Pass 4)

	pass 1	pass 2	pass 3	Pass 4(4-1)	Pass4(4-2)
				averaged from 94 channels	Channel O6_mod
RIH Pressure (MPa)(a)	11.4	11.4	11.4	11.4	
RIH Temperature (°C)	268	268	268	268	
ROH Pressure (MPa)(a)	10.0	10.0	10.0	10.0	
ROH Temperature (°C)	311	311	310	310	
ROH Flow Quality (%)	4.4	4.6	4.7	4.5	
Pump Suction Pressure (MPa)(a)	9.58	9.58	9.58	9.58	
PHT Pump ΔP (MPa)	1.80	1.80	1.80	1.80	
Core flow (kg/s)	1921	1918	1919	1892	23.0
Fuel Power per pass (MW)	526.0	526.0	526.0	518.7	7.3
Pumping Power (MW)	16				
Heat to 2nd Side per SG (MW)	529	532	533	532	
Pressurizer Level (m)	12.48				
Steam Drum Pressure (MPa)(a)	4.70	4.70	4.70	4.70	
Steam Drum Temperature (°C)	260	260	260	260	
Total Steam Flow	1077				
Total Feedwater Flow (kg/s)	987				
Feedwater Temperature (°C)	186	186	186	186	
SG Recirculation Ratio	5.46:1	5.46:1	5.46:1	5.46:1	

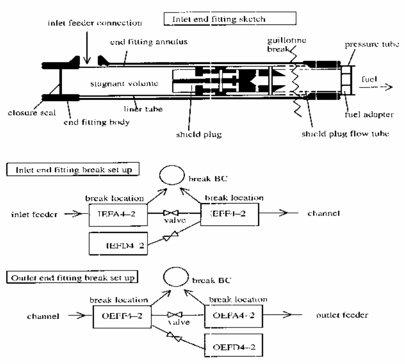

Figure 2 Scheme of Fuel Channel End Fitting and Nodalization for EFF

Two break locations are considered as the Figure 2. One at the inlet end fitting and the other at the outlet end fitting. The break is assumed to be a guillotine break between the end fitting annulus and flow tube. Since the discharge from the dead space is small and short, only the discharges from the annulus and flow tube are modeled. Containment back pressure is assumed to be constant at atmospheric pressure.

Single Channel Model

Two single channels (O6_mod and B10) are modeled. Each model includes the inlet feeder, inlet end fitting, fuel channel, outlet end fitting and outlet feeder. The inlet and outlet header are boundary conditions taken from the circuit result. The required header boundary conditions are pressure, vapour enthalpy, liquid enthalpy, void fraction and flow regime indicator. Channel O6_mod has the same geometry as O6 but the channel power and the bundle power of the two center bundles have been modified to the licensing limits of 7.3 MW and 935kW respectively. Channel B10 is a low power, high elevation, flow–instrumented channel.

Analysis Scope

Full circuit analyses at 103% full power with three different broken channels were performed. The three broken channels were A9, O6_mod and W10. With each broken channel, two break locations (inlet and outlet EFF) were simulated to identify the worst break location for containment analysis. The worst location for a high power channel (O6_mod) is where the break discharge is the highest. For the low power channel (A9 and W10), the worst location is where the break discharge is the lowest such that the high reactor building pressure signal (for reactor trip and containment isolation) and/or dousing may not come in. The thermal hydraulic analysis is performed assuming the reactor is tripped on the second process trip (third trip if high reactor building pressure signal comes in prior to this).

The results between the two break locations are compared. The break discharge data are input to the containment analysis. The header conditions are used as boundary conditions for intact single channel simulations to demonstrate the fuel and fuel channel integrity.

Analysis Results

The thermal hydraulic behaviors of PHTS for all each ECCS failure cases before LOCA signal occurs are same to those for ECCS available, which is shown in the figure 3, 5, 6 and table 2. Among three break locations, O6_mod channel(highest power channel) has the largest initial discharge mass of 109.7kg/s and the inlet end fitting failure has larger discharge than the outlet one due to the header pressure difference. The two trip signals needed for reactor trip are low PHTS pressure and low pressurizer level in sequence for the channel of O6_mod, and for two other channels, the sequence are inverse, which is assumed to be due to the difference in discharged mass quantity.

When the loop isolation is unavailable, the events and sequences are similar to the ECCS available case except the loss of loop isolation as figure 3 and table 2. Since there is continuous coolant makeup from the intact loop and pressurizer, for the small discharge cases such as channel A9 and W10, the depressurization of the PHTS is slower than with loop isolation available as shown figure 6. Therefore the time for ECC injection is delayed a little. ECC coolant is injected into the intact loop and pressurizer as well as the broken loop, so ECC tank and dousing tank is depleted earlier and low pressure ECC from containment sump is injected earlier. And slave channel(O6_mod) analysis shows that the fuel and fuel channel integrity maintains enough.

When the ECC injection is failed, there is no coolant makeup, and the inventory and the pressure for both primary and secondary side continue to decrease, and in addition, SGCC makes the depressurization more rapid as in figure 6. Stratification occurs in the reactor header due to low two-phase flow and high void. Eventually the fuel channel heat up occurs at different time for each break channel as in figure 7. The late heat up is needed to be analyzed further. This analysis is out of scope in this study. For the intact loop, after loop isolation, the coolant inventory remains constant. Without ECC injection, the intact loop is cooled by forced circulation until HT pump trip. Following HT pump trip, the fuel channel is cooled by the two phase thermosyphoning. The fuel and fuel channel integrity is assured because long term cooling of intact loop is maintained by steam generators.

When the steam generator crash cooldown unavailability is added to the failure of ECC injection, the depressurization of the PHTS is delayed as in figure 3 and the stratification occurs earlier. Other behavior such as HTS inventory and pressure decreasing and fuel channel heat up are similar to the case of ECC injection failure with SGCC available

Finally, the loss of loop isolation do not harm the fuel channel integrity, but if loss of ECC injection occurs, the fuel channel integrity can be damaged.

Further study

When the ECC injection fails, regardless of SGCC availability, the fuel channel integrity can be damaged. So the analysis for late heat up is needed. This study will be carried using another code, CHANII. And the cooling capacity of moderator must be analyzed for the contacting of pressure tube and calandria tube.

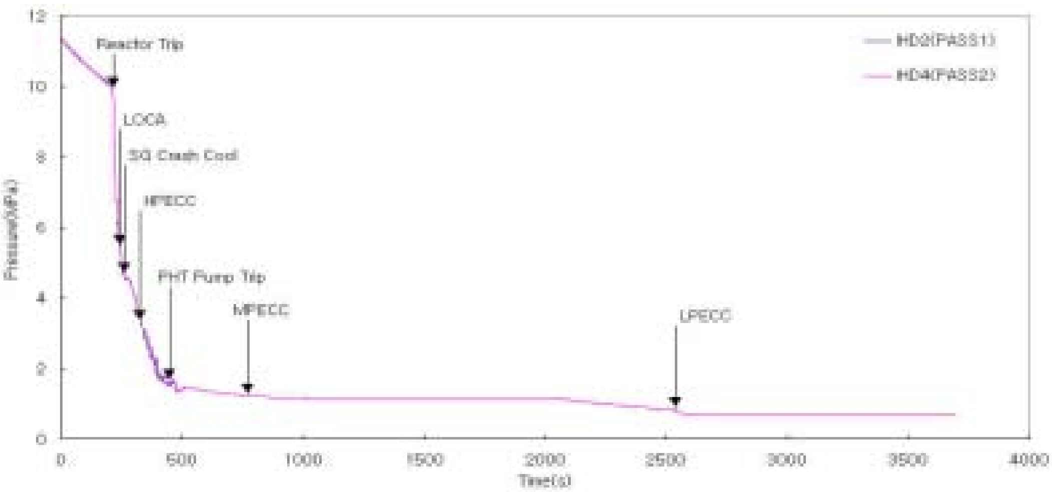

Figure 3 Inlet Header Pressure for Inlet EFF at Channel O6_mod
with Loss of Loop isolation

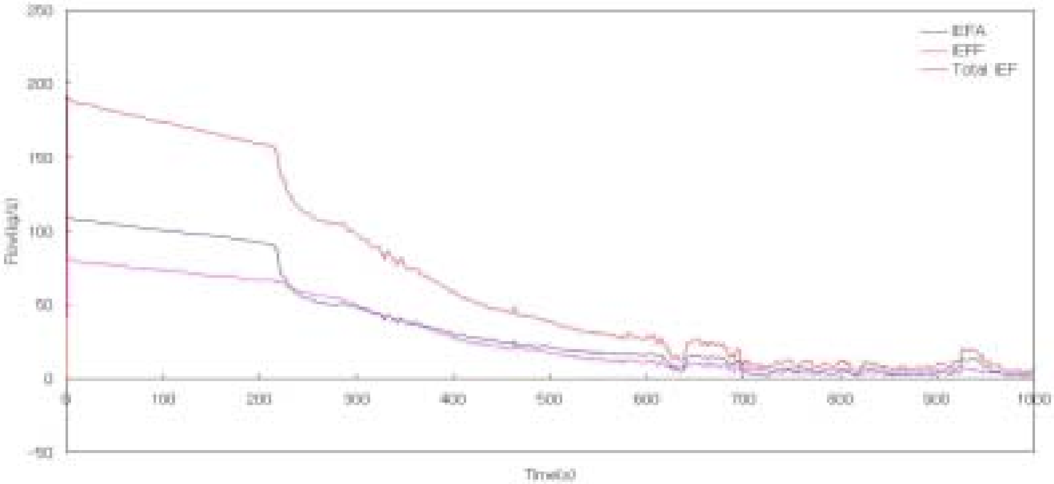

Figure 4 Break Discharge for Inlet EFF at Channel O6_mod
with Loss of ECC Injection with Loss of Loop Isolation

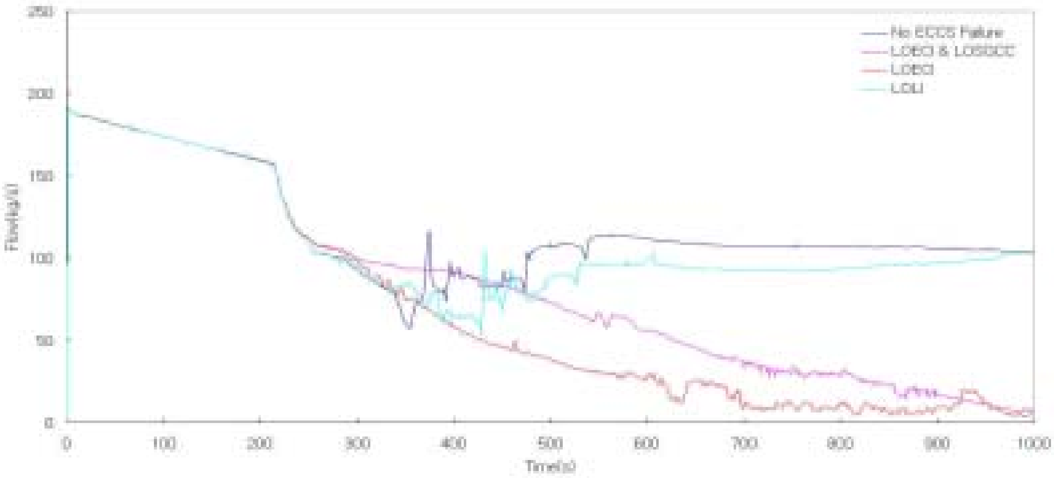

Figure 5 Break Discharge for Inlet EFF at Channel O6_mod for each failure cases

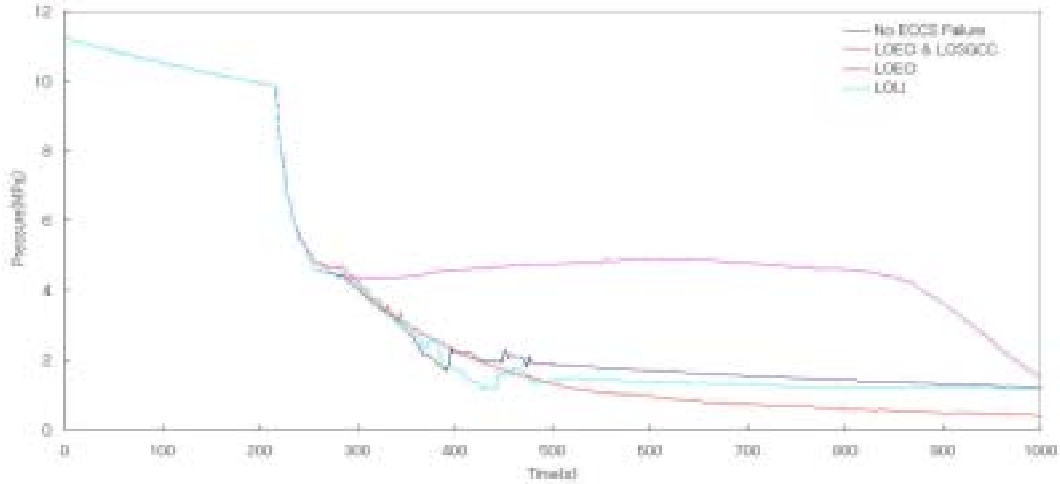

Figure 6 IHD Pressure for Inlet EFF at Channel O6_mod for each failure cases

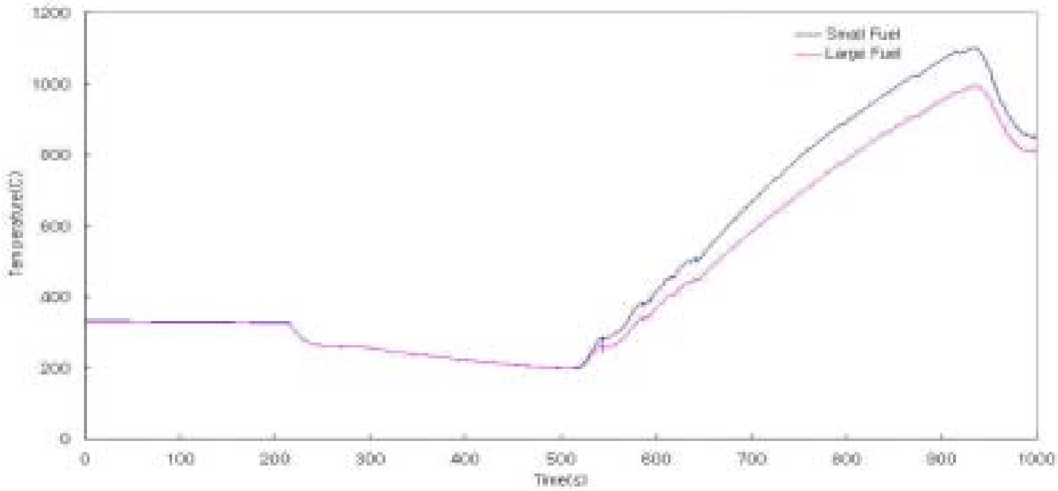

Figure 7 Fuel Sheath Temperatures for Inlet EFF at Channel O6_mod
with loss of ECC injection

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Table 2 Event Sequences of Each Failure Cases

Broken Channel		**A9 Inlet**				**O6_mod Inlet**				**W10 Inlet**			
Cases of ECCS Failure		No Failure	LOECI &CC	LOECI	LOLI	No Failure	LOECI &CC	LOECI	LOLI	No Failure	LOECI &CC	LOECI	LOLI
Initial	**annulus side, EFA (0.005545m^2)**	38.3	38.3	38.3	38.3	109.7	109.7	109.7	109.7	45.6	45.6	45.6	45.6
Break	**flow tube side, EFF (0.006829m^2)**	73.9	73.9	73.9	73.9	82.4	82.4	82.4	82.4	46.9	46.9	46.9	46.9
Discharge (kg/s)	**Total**	112.2	112.2	112.2	112.2	192.1	192.1	192.1	192.1	92.5	92.5	92.5	92.5
First process	**Low ROH pressure**					182.1	182.1	182.1	182.1				
Trip (s)	**Low pressurizer level**	350.4	350.4	350.4	350.4					423.0	423.0	423.0	423.0
Second process	**Low ROH pressure**	372.0	372.0	372.0	372.0					495.0	495.0	495.0	495.0
trip (s)	**Low pressurizer level**					214.4	214.4	214.4	214.4				
LOCA signal (conditioned by high reactor building pressure signal) (s)		407.7	407.7	407.7	407.7	246.5	246.5	246.5	246.5	530	530	530	530
Loop isolation initiation (s)		407.7	407.7	407.7	*	246.5	246.5	246.5	*	530	530	530	*
Turbine governor valve fully closed (s)		409.4	409.4	409.4	409.4	250.8	250.8	250.8	250.8	533	533	533	533
Loop isolation completed (s)		427.7	427.7	427.7	*	266.5	266.5	266.5	*	550	550	550	*
SG crash cooldown initiation (s)		437.7	*	437.7	437.7	276.5	*	276.5	276.5	560	*	560	560
HP ECI initiation (first rupture disk opens) (s)		493.4	*	*	495.4	335.1	*	*	332.7	616	*	*	619
PHT pump trip (s)		628.3	1670.9	661.07	630.6	469.7	1069.4	484.39	467.6	749	2009.4	767.18	753.5
MPECI begins (s)		1792.0	*	*	1369.0	997.0	*	*	784.0	1954	*	*	1668.0
HP ECI stop (s)		2134.0	*	*	1685.0	1354.0	*	*	1240.0	2175	*	*	1974.0
MP stop and HP restart		5634.0	*	*	5111.0	3089.5	*	*	2066.0	5836	*	*	5343.0
HP stop and LP begin		6641.0	*	*	6155.0	3601.0	*	*	2559.0	6960	*	*	6388
broken loop pass 3 & 4 average fuel channel refill (s)		542.	*	*	549.0	381	*	*	444.0	670	*	*	663.0
intact loop pass 1 & 2 average fuel channel refill (s)		575.0	*	*	558.0	424	*	*	443.0	681	*	*	676.0
Pass 4 broken single channel refill (s)		2054.0	*	*	1785.0	1011	*	*		2532	*	*	2364.0