A Cliff Edge Evaluation for CANDU-6 Beyond Design Basis Accidents

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Abstract

The condition of nuclear power plant in the event of station black out (SBO) accompanying large-scale natural disaster exceeding design basis accident (DBA) was evaluated. Additional scenarios were added to the evaluation to review capability of the plant to endure different conditions with different actions. The analysis resulted that the key action required from the operator was to ensure the opening of main steam safety valves (MSSVs) in the secondary side and of motor-operated valves for high pressure injection of Emergency Core Cooling System (HPECCS) to mitigate accidents or extend the cliff edge.

1. Introduction

For the purpose of this assessment, "Critical Safe Shutdown Structures, Systems, and Components (SSC)" of CANDU-6 and the plant's capability to respond to the "loss of electrical power and loss of the ultimate heat sink (UHS)" and to " loss of safety functions due to extreme natural disasters" as per the Stress Test Specifications for Nuclear Power Plants in Long-Term Operation were reviewed [1].

Station blackout statuses and loss of ultimate heat sink were assessed with the large-scale natural disaster which exceeds design basis accidents for CANDU-6. In coping with the loss of electrical power and loss of heat sink, the availability of both the dousing tank and MSSVs had to be ensured as they are the key component required to maintain the safety functions. It was found that the availability of gravity-fed make-up water from the dousing tank as a heat sink before the depletion of the steam generator inventory is dependent on the opening of MSSVs in any extreme (cliff-edge) conditions [2].

In addition, seal leakage of primary heat transport pump (hereinafter referred to Seal LOCA) and steam generator tube rupture (SGTR) accidents were evaluated to identify deterministically a cliff edge, the limitation of plant’s capability to react to the combined accidents, such as SBO accompanied by natural disaster. Since the seal of primary heat transport (PHT) pump was confirmed safe for 8 hours after the accident according to Reference 3, a case assuming seal LOCA occurring after 8 hours from the accident and a case assuming seal LOCA and SBO occurring at the same time were analyzed. SG Tubes were evaluated to withstand peak ground acceleration of 0.3g, and could also withstand heat and other factors in the event of high temperature accident [4]. Therefore, the evaluation of SGTR accident with SBO was not necessary, but decided to check for any required responsive actions from the safety reinforcement point of view.

2. Initial Conditions and Analysis Method

The thermal-hydraulic responses of the primary and secondary heat transport systems are simulated using version MOD-3.5d, Revision 2 of the Canadian Algorithm for THEermalhydraulic Network Analysis (CATHENA) code [5]. Behaviors of a typical CANDU 6 NPP against each scenario were evaluated by CATHENA code, one with an assumption that appropriate actions, such as HPECC injection, taken by station operators and the other, without any actions.

The CANDU-6 core configuration comprises 380 channels with each channel in one of two loops. Each loop has 190 channels with two core passes and each core pass is simulated through seven groups considering height and power of the channels. In each core pass, channel groups 1 to 4 locate in the inner core with high-power channels, and channel groups 5 to 7 in the outer core with low-power channels as shown in Figure 1. The CATHENA model (Figure 2) includes a detailed representation of the PHTS and the pressure and inventory control network with liquid relief valves (LRVs) and degasser condenser relief valves (DCRVs).

The primary heat transport system (PHTS) coolant exits the channel via an outlet feeder pipe attached to the outlet end fitting. The initial conditions of the coolants are approximately 11 MPa(a) and 263 °C for the inlet side and slightly above 10 MPa(a) and 310 °C for the outlet side at 100%FP. When 0.3g earthquake accompanying SBO and loss of EPS combined with loss of UHS is assumed, the two possible water sources for the steam generators are dousing tank and EWS reservoir. Further assumptions considered are listed in Table 1.

Table 1. Initial conditions of plant

Reactor component	System assumption
Reactor/Turbine Primary Heat Transport Pumps Main Feed Water Pump	Tripped at 0 second
Auxiliary Feed Water Pump	Not available
Pressurizer Heaters	Operations off
Liquid Relive Valves(LRV)	Fail open
Pressurizer Steam Bleed Valves	Fail close
Main Steam Safety Valve(MSSV)	Acts passive
Degasser Condenser Relive Valve(DCRV)	Acts passive
PHTS Feed/Bleed Valves	Close
Pressurizer Isolation Valves	Fail locked open (No isolation)
Emergency Power Supply(EPS)	Not available
Emergency Water Supply(EWS)	Not available

Concurrently, observation of critical safety parameters and power supply for recovery is to be made by installing seismically qualified battery with capacity of 4 hours and 30 minutes in secondary control area (SCA) for CANDU-6. Also, it is assumed that power can be supplied within 3 hours by a small mobile generator (MG) which can power the required systems and components through the bus for accident mitigation strategy assumption. To supply power to motor operated isolation valves for high pressure emergency core cooling system (HPECCS) to guarantee high pressure safety injection, facilities are being improved to have power supplied by seismically qualified battery in SCA.

3. ANALYSIS AND RESULTS

3.1 SBO + Seal Leakage after 8 hours

PHT pump seal leakage is expected to occur 8 hours later after losing all heat sinks for Wolsong-1 nuclear power plant [3]. In the case of seal leakage of PHT pumps occurring additionally to the situation assumed in Table 2, the start of a cliff edge is assumed when the fuel sheath temperature exceeds 800°C. In this scenario, the seal leakage area introduced at 28,800 second is $7.3\text{x}10^{-4}\text{m}^2$/pump at maximum. At the time of 28,800 seconds, the discharged flow rate from seal leakage is total 139kg/s for $7.3\text{x}10^{-4}\text{m}^2$/pump.

The accident mitigation strategy shown in Table 3 is followed for the first 8 hours. For the analysis of SBO with no operator action after seal LOCA, as shown by the solid black lines in Figures 3 and 4, the failure of fuel sheath temperature is expected around 39,940 seconds under the SBO. For the other analysis, HPECC injection is initiated manually around 10.5 hours (37,800 s) after SBO to prevent the fuel sheath temperature from exceeding 800°C, as shown by the dotted red lines. The water level of HPECC tank needs to be monitored during this stage. The time limit for the use of HPECC safety injection depends on leakage amount from PHT seal.

Table 2. Cliff edge results for earthquake + SBO + Seal Leakage (max area 7.3×10^{-4} m^2/pump)

Event	Times(seconds)
Reactor Trip (sec)	0
Fuel cladding failure (sec)*	39,940
Pressure tube failure (sec)*	40,216
*with no operator actions after Seal LOCA	

Table 3. Sequence of operator action for SBO + Seal Leakage

Event Sequence	Time (sec)	Remarks
Occurred SBO and tripped reactor	0	• Operator moves to SCA • Diagnosis the events by using seismically qualified batteries to be installed at the SCA • Check the critical safety parameters
Crash cooldown (open	~3600	• Dispatch operator to open the isolation valves

MSSVs)		from EWS or Dousing Tank to SG • Open MSSV remotely from SCA or manually in the fields (2ea/SG)
Start to refill by gravity	~5,126	• Confirm the levels of SGs and Dousing • Capacity of dousing tank (500 ton) • SG pressure being below 345kPa(g)
Connect small MG	~11,677	• Install small MG
Occurrence of Seal LOCA after SBO	28,800	• Assumed seal leakage after 8 hours after SBO
Manual ECC High Pressure Safety Injection	37,800	• High Pressure Injection Tank (200 ton) • Observe ECC TK Water Level • Open HPECC motor valve (MV)

3.2 SBO + SGTR

Where earthquake, SBO, and SGTR occur at the same time, it is assumed that the start of cliff edge is when the fuel cladding temperature exceeds 800°C. As shown in Table 4, up to 3 ruptured tubes can be managed by an operator taking appropriate actions within 1 hour from reactor shutdown (3,850s is taken until fuel gets damage when 3 tubes rupture are occurred). However, if more than 4 tubes are ruptured, time taken for the fuel to be damaged is expected within 2,700s.

Table 4. Cliff edge results for earthquake + SBO + SGTR

Event	Number of SGTR		
	10	**4**	**3**
Reactor Trip (sec)	0	0	0
Fuel cladding failure (sec)	1,100	2,700	3,850
Initial discharge flow Rate (kg/s)	95.44	37.84	28.73

For cases where less than 4 SG tubes get ruptured with earthquake and SBO, the shown steps in Table 5 are required for accident mitigation strategy (initial leakage flow rate: 28.73kg/s). As soon as the reactor trips, the operator must check the followings using the battery from SCA within 30 minutes after the shutdown; state of blackout, coolant pressure, containment building pressure, and steam generator water level differences. For the next 30 minutes, several additional actions are required to mitigate the accident.

First, ECC MV is opened manually by SCA battery to prevent the fuel sheath temperature from exceeding 800°C. Next, MSSVs are opened either by remote or manual control. At around 3,700s after reactor shutdown, high pressure safety injection starts and as this step progresses, the water level of ECC tank is observed.

The dousing tank starts to refill the SG 3,900s after shutdown, and the isolation valves connected from dousing tank or EWS pond to SGs are checked to confirm that they opened. The capacity of dousing tank water is 500 tons and the level of both dousing tank and SG is monitored. At around 11,677s HP safety injection dries out and at this point, motorized valves for HP injection are closed and HP tank level is observed. The water levels of SG and dousing tank and pressure of SG are kept observed. By 4.5 days after shutdown, all of the water from dousing tank and emergency feedwater tank (3,400 tons) is depleted.

In the case of performing accident mitigation strategy and injecting HPECC to PHTS as well as providing continuous feedwater to SG, decay heat is removed by MSSV. After activating the small MG, the operator opens MSSV within 3,600s and performs crash cooling, which results in high pressure coolant injection into the affected loop and refills SG. By these actions, the pressure of the primary heat transport system falls as shown in Figure 5 and the integrity of fuel cladding is maintained, as shown by the dotted red lines in Figure 6. Also for the unaffected loop where SGTR did not occur, the coolant of SG secondary side is provided from the dousing tank when the pressure of SG drops after opening MSSV. Figure 5 shows the downward trend of PHT system pressure during transient. As to conclude, fuel gets cooled so the integrity of fuel cladding is maintained as shown in Figure 6.

Table 5. Sequence of operator action for Earthquake + SBO + SGTR

Event Sequence	Time (sec)	Remarks
SBO Occurs + SGTR and tripped reactor	0 ~1,800	• Operator moves SCA • Diagnosis the events by using seismically qualified batteries to be installed at the SCA • Check the critical safety parameters(CSP)
Perform crash cooldown (open MSSVs)	~3,600	• Open HPECC MVs Manually • Open MSSV remotely from SCA
Confirm the injection of HPECC	~3,734	• Monitor ECC Tank levels
Start to refill SG from dousing Tank	~3,914	• Confirm valve status(3461-PV7, PV-41) to Open • Monitor SG and dousing tank levels
Connect small MG	~10,800	• Install small MG
Depleted HP Tanks	~11,677	• Close HPECC MVs
Depleted Dousing Tank and EWS water	+ 4.5 days	• Confirm the levels of SGs and Dousing • Dousing tank (500 ton) • EWS pond (3,400 ton)
Makeup SGs from water purification plant	+ 1.5 days	• Reservoir water (1,667 ton)

4. Discussion

For the SBO, crash cooling should be preceded by opening MSSV within 80 minutes. If the opening of MSSVs is credited, there is no cliff edge as the temperature of the fuel clad remains below 200°C and the pressure of PHTS around 1MPa(a), respectively.
When seal LOCA is assumed to occur 8 hours after SBO, core cooling can be managed and the accident can be mitigated with HPECC operation manually by operator, if opening MSSVs is credited. For this accident, no cliff edge is resulted as the pressure of PHTS and the temperature of fuel clad were around 1MPa(a) and below 200°C, respectively.

In the case of SBO occurring with SGTR, fuel integrity can be preserved under certain conditions. If there are less than 3 ruptured tubes and the initial flow rate is below 28.7kg/s, operator's actions can be available before fuel cladding failure, preserving fuel integrity and minimizing radiation emissions from the containment building. Once additional water can be supplied to EWS pond from seismically qualified water purification plant (reservoir) before EWS pond gets depleted, long-term core cooling operation is available for another 36 hours.

5. Conclusion

The cliff edge was analyzed for the limitation of response for CANDU-6 under the selected scenario cases. In this study, fuel sheath temperature exceeding 800°C was regarded as a cliff edge because it would be a start of fuel damage. For all cases, the provision of a small MG at each unit was an essential task. By also considering inaccessible situation to manually open MSSV and not being able to monitor the situation of the power plant due to fire or an earthquake, a seismically qualified battery is being prepared to be installed at SCA. Until the battery is installed, methods to manually trace and manage data of the power plant are being prepared to be made into a procedure manual.
Once the safety enhancements mentioned above are ready a multi-unit failure accident at a CANDU-6 site would be manageable, which helps mitigate large-scale natural disasters exceeding design basis accidents.

6. References

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[4] H.S. Lim et. al, "Steam Generator Tube Integrity Analysis of a Total Loss of All Heat Sinks Accident for Wolsong NPP Unit 1", NET Volume 46, 2014
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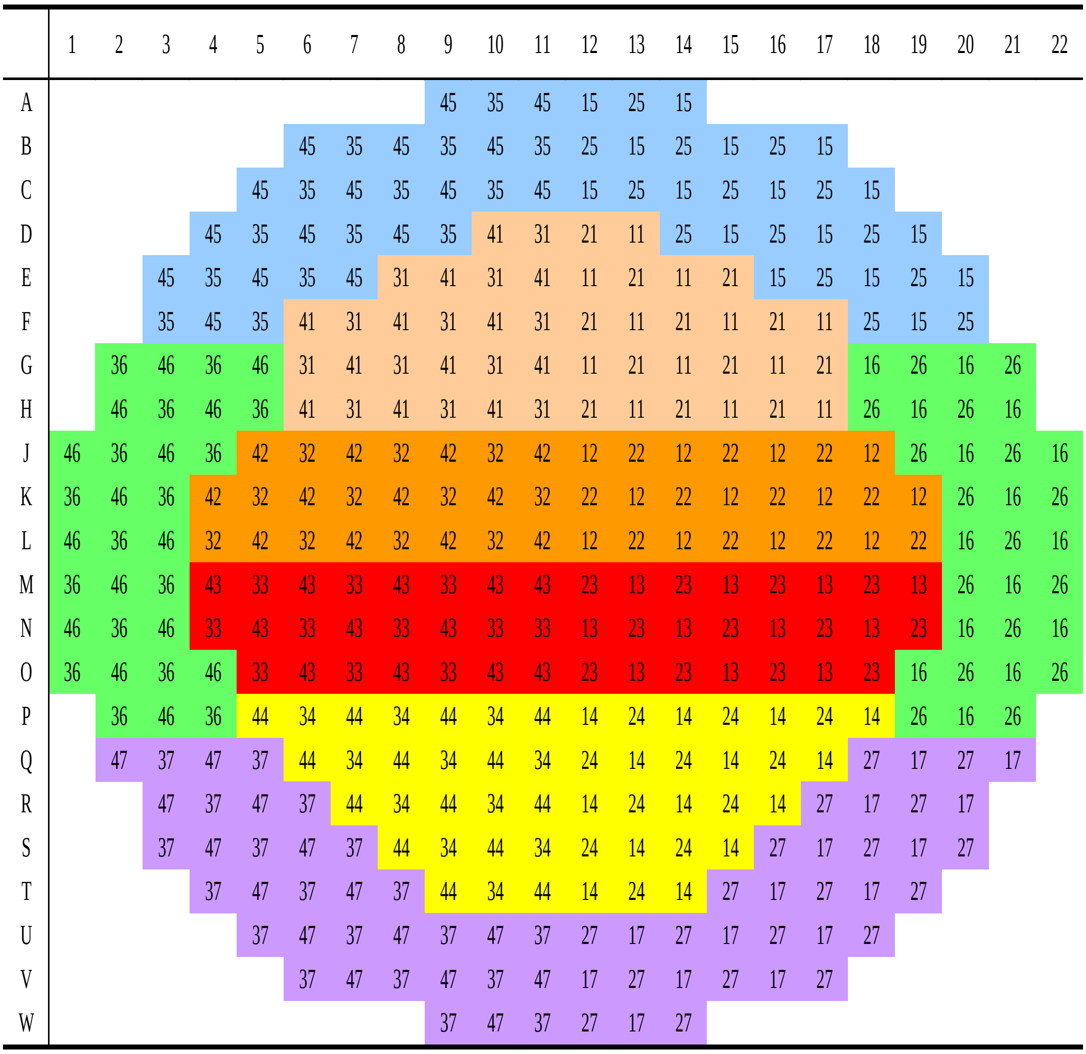

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									45	35	45	15	25	15								
B						45	35	45	35	45	35	25	15	25	15	25	15					
C					45	35	45	35	45	35	45	15	25	15	25	15	25	15				
D				45	35	45	35	45	35	41	31	21	11	25	15	25	15	25	15			
E			45	35	45	35	45	31	41	31	41	11	21	11	21	15	25	15	25	15		
F			35	45	35	41	31	41	31	41	31	21	11	21	11	21	11	25	15	25		
G		36	46	36	46	31	41	31	41	31	41	11	21	11	21	11	21	16	26	16	26	
H		46	36	46	36	41	31	41	31	41	31	21	11	21	11	21	11	26	16	26	16	
J	46	36	46	36	42	32	42	32	42	32	42	12	22	12	22	12	22	12	26	16	26	16
K	36	46	36	42	32	42	32	42	32	42	32	22	12	22	12	22	12	22	12	26	16	26
L	46	36	46	32	42	32	42	32	42	32	42	12	22	12	22	12	22	12	22	16	26	16
M	36	46	36	43	33	43	33	43	33	43	43	23	13	23	13	23	13	23	13	26	16	26
N	46	36	46	33	43	33	43	33	43	33	33	13	23	13	23	13	23	13	23	16	26	16
O	36	46	36	46	33	43	33	43	33	43	43	23	13	23	13	23	13	23	16	26	16	26
P		36	46	36	44	34	44	34	44	34	44	14	24	14	24	14	24	14	26	16	26	
Q		47	37	47	37	44	34	44	34	44	34	24	14	24	14	24	14	27	17	27	17	
R			47	37	47	37	44	34	44	34	44	14	24	14	24	14	27	17	27	17		
S			37	47	37	47	37	44	34	44	34	24	14	24	14	27	17	27	17	27		
T				37	47	37	47	37	44	34	44	14	24	14	27	17	27	17	27			
U					37	47	37	47	37	47	37	27	17	27	17	27	17	27				
V						37	47	37	47	37	47	17	27	17	27	17	27					
W									37	47	37	27	17	27								

Figure 1. CATHENA 7 Groups with each core pass

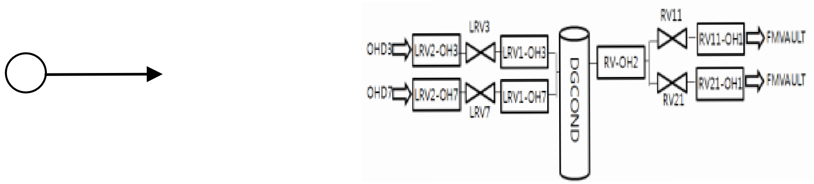

Figure 2. CATHENA Model with DCRV

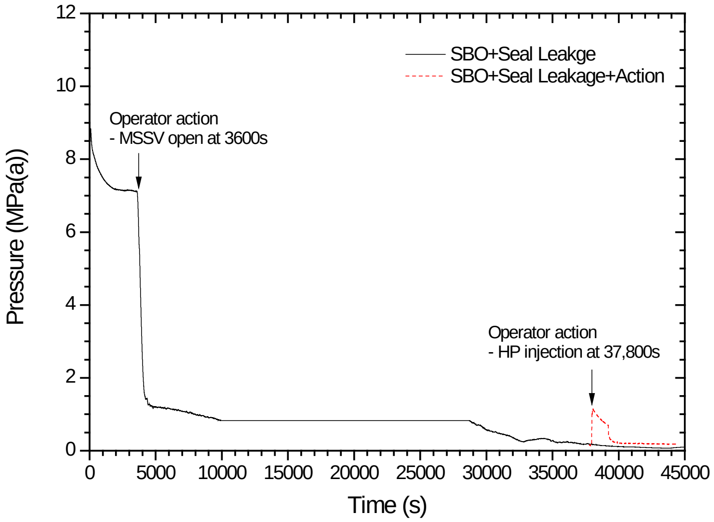

Figure 3. PHTS pressure behavior under the SBO + Seal LOCA

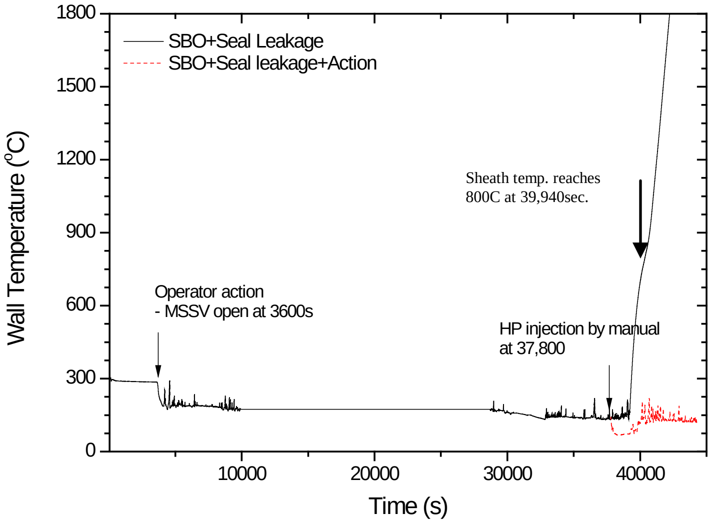

Figure 4. Fuel Sheath Temperature Behavior under the SBO + Seal LOCA

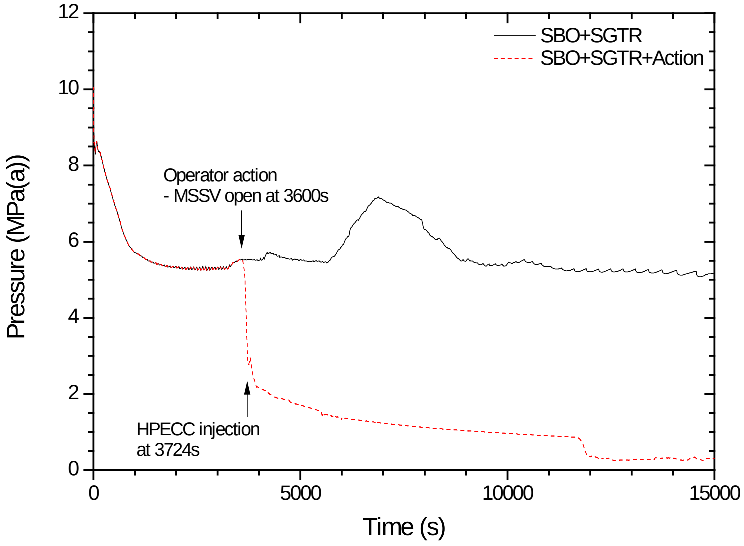

Figure 5. PHTS Pressure Behavior under the SBO+SGTR

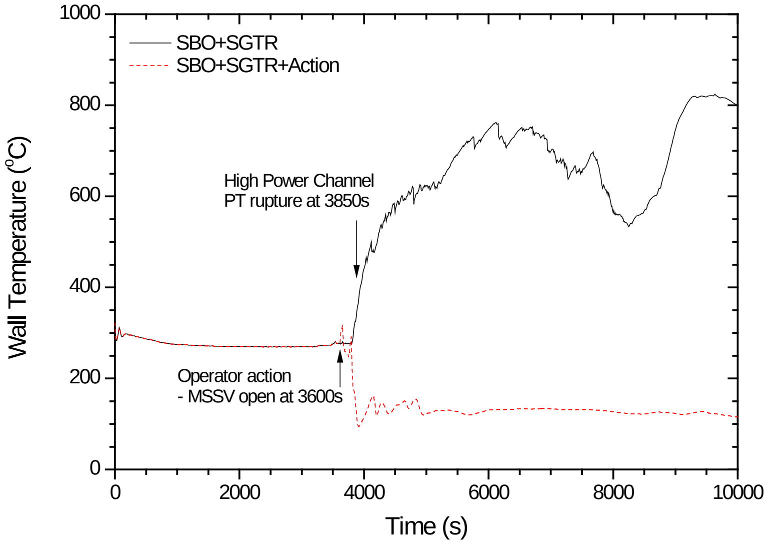

Figure 6. Fuel Sheath Temperature Behavior under the SBO+SGTR