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Total Loss of Feed Water for VVER 1000

Pavlin Groudev, Malinka Pavlova
Institute For Nuclear Research And Nuclear Energy, Sofia 1784, Bulgaria

ABSTRACT

This paper discusses the results of the thermal-hydraulic investigations of the Total Loss of Feed Water (TLFW). RELAP5/MOD3.2. computer code has been used to simulate TLFW of VVER-1000 Nuclear Power Plant (NPP). The model provides a significant analytical capability for the specialists working in the field of NPP safety. This paper provides a discussion of various RELAP5 parameters calculated for the TLFW scenario. The purpose of the scenario is to predict the behavior of NPP and to help correctly define the operator action for validation and verification of Emergency Operating Instructions (EOIs).

EOI analyses are designed to provide the response of monitored plant parameters to identify symptoms available to the operators, timing of loss of critical safety functions and timing of operator actions to avoid loss of critical safety functions or core damage. The principal acceptance criteria for EOIs are averting the onset of core damage.

Two scenarios for TLFW are presented in the report:

- Base case – Total loss of feed water without operator actions. In Base case is investigated plant response to the event.
- TLFW with operator actions. In this analysis are involved additional failures of plant equipment.

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1. Introduction

The response of the VVER 1000/V320 nuclear steam supply system to the Total Loss of Feed Water (TLFW) initiating event have been analyzed to identify the behavior of important VVER process variables.

In the event of total loss of feed water at the plant the operator can see rapid decreasing of the Steam Generators water levels; loss of natural circulation in primary circuit; increasing of core exit temperature up to 400 ^{o}C and reaching saturated temperature at the Pressurizer safety relief setpoint. These points have been accepted as limiting times for the operator actions in the second scenario. In the report is presented an investigation of plant response to different combinations of component availability in which the operator can be effective in averting core melt.

Failing the pressurizer safety valves opened will maximize energy removal and is therefore not bounding to a Feed and Bleed strategy in which the operator has recourse only to the YR line. For VVER 1000 the issue is not inventory - it is RCS total energy storage/removal.

The following acceptance criteria is used to analyze Total loss of feed water for VVER–1000/V320: Fuel cladding temperature– not more than 1200 ^{o}C.

As a boundary condition for all cases it is assumed that SG water level is minimal - 170 cm because core heat removal and heat sink are the most challenged Critical Safety Functions (CSFs) for TLFW. In this way the steam generator heat sink capability is maximum reduced.

2. Event Description

A loss of normal feed water (from pump failures and trips or valve malfunctions) results in a reduction of capability of secondary system to remove the heat generated in the reactor core. If an alternative supply of feedwater was not supplied to the plant, core residual heat following SG dryout would heat the primary system water to the point where water relief from the pressurizer would occur, resulting in a substantial loss of water from the Reactor Coolant System.

Total disappearance of feed water caused by closing of valves (normal feed water and auxiliary feed water) of NPP station causes closing of turbine stop valves which causes opening of BRU-Ks.

Various aspects of total loss of feed water events are discussed as appropriate in succeeding subsections. In this report are presented two scenarios.

As a base case for TLFW is a case with minimum available resources that should not result in core melt. For this case was also assumed that the flow rate of Emergency Feed

Water pump is realistic, but its temperature is equal to the temperature of Auxiliary Feed Water pumps.

Should a total loss of feed water accur at SG water level 170 cm, there are a couple of events which will follow this event: switching off all Main Coolant Pumps (MCPs) due to SG water level; actuation of the Reactor Protection System (RPS) after 0,4+1,2s due to “Three of Four MCPs switched off” and after this signal all control rods drop in 4s to the bottom of the core; turbine stop valves close.

The number of secondary side Relief and Safety valves is 12 (and also four turbine bypass valves – BRU-Ks). In both TLFW analyses BRU-Ks are available .A bounding case for the secondary side valves is to fail closed, because the BRU-Ks and SVs will not remove energy from the Reactor Coolant System (RCS) when they are closed. But, it is not realistic to assume that almost all secondary side SVs are failed closed. To fail closed some more of the rest secondary side valves will not challenge heat sink due to capability of the other valves to remove successfully energy from RCS.

The pressure in primary circuit will increase and reach set point of opening the first Pressurizer Safety valve after SG heat removal is lost. The Safety valve will try to support the pressure in primary circuit opening at 185 kgf/cm^2 and closing at 176 kgf/cm^2 . Cycles repeatedly, even under single phase liquid conditions will increase probability of failure of this valve. For all calculations it was assumed that the Pressurizer Safety valve will not fail opened when the Pressurizer is filled up. The Pressurizer SV will continue to cycle as a bounding condition.

3. Base Case for “Total loss of feed water”

In Base case is investigated plant response to the event “Total loss of feed water” and here are not included operator actions.

Scenario

I. Initial status.
   - I.1. Power 100 %.
   - I.2. Assumption: Safety system # 3 is under repair and Safety system #2 failed to start.
   - I.3. Operator do not interact during the accident.
   - I.4. Steam Generator water level is assumed to be 1.7 m.

II. Both Feed Water Pumps failed to work (initiation of TLW) and do not start to work Auxiliary pumps.

III. In accordance with point II Turbine Stop Valves (TSVs) close.

IV. In accordance with point III BRU-Ks start to open and support pressure in the Main Steam Header (MSH) equal to pressure that has been in MSH 1 sec. before to close TSVs.

V. Switching off all MCPs in accordance with water level loss in SGs (1.7 m)

VI. When water level drop in SGs is 1 000 mm from the nominal water level of 2.4 m, the TX 10 SO4 line (Emergency Feed Water Line) will open and when water level drop is 1100 mm the Emergency Feed Water Pump TX 10 D01 will start to inject.
When water level drop in SGs is 1300 mm the EFW line will close with delay of 21 s.
T_{TX} = 30 ^{0}C. As bounding condition was assumed T_{TX} = 164 ^{0}C - This is a temperature of Auxiliary feed water.

VII. Reactor SCRAM actuates according to signal “ Switch off 3 from 4 MCP” (by low level in SGs) with delay 1.2 sec.

VIII. Actuation of Automatic Step by Step Load according to the saturated temperature $\Delta t_S < 10\ ^0C$ duplicates the Reactor SCRAM and it switches off the letdown/makeup lines.

Results

The calculated sequence of events for the Base Case of TLFW is presented below.

Table 1.

Event	Time, s
Feed water pumps are tripped	0.0
Turbine Stop Valve closed	0.0
MCPs are tripped	0.0
BRU-Ks #1, #2, #3 and #4 start to open	1.0
REACTOR SCRAM	1.6
The make up system reaches max flow rate	19.8
Emergency feed water pump(TX10DO1) starts to inject water to SGs- total flow rate 150 m^3 /hour	36.0
Minimum Pressurizer Water Level - 6.4 m	103.0
Pressurizer SV opens	560.0
Stabilization of primary circuit pressure	≈3000.0

The most important parameter behavior is shown in Figure 1. through 6. The calculation was performed up to 15000 s into the transient time.

Should a total loss of feed water appear, Turbine is isolated. All four MCPs are tripped due to low level in SG. Actuation of RPS (Reactor SCRAM) after 0,4+1,2s due to “3 of 4 MCPs switched off” and after this signal all control rods drop in 4s to the bottom of the reactor core. In the first five seconds from the event, the pressure in primary circuit increases and reaches 167.2 kgf/cm^2 at the core exit point due to losing of cooling. The BRU-Ks start to open (due to closing of turbine stop valves). After first few seconds the pressure in primary side drops mostly due to Reactor SCRAM and due to cooling of primary circuit by secondary side (opening of the BRU-Ks - see Table 1. of events). Approximately after 70 sec. the primary pressure begins to increase due to residual heat, which continues to 560 sec. and reaches 185.0 kgf/cm^2 (see Figure 1.). After opening and closing of Pressurizer SV three times at 176 kgf/cm^2 , pressure in primary circuit starts do drop due to cooldown by SGs. Primary side pressure did not reach a set point of starting ASSL .

Comparison of pressure in primary and secondary side is shown in Figure 1.

During the whole transient time there is a natural circulation. It is presented in Figure 6.

During the whole transient there is a sufficient margin (it is always more than 60 deg.) to the boiling temperature (see Figure 2.)

After reaching Steam Generator water level equal to 1.3 m. (see Figure 3.) Emergency Feed Water Pump (EFWP) starts to inject into SGs #1, #2, #3 and #4. The limit of maximum EFW flow rate for each SG is 37.5 m^3 /hr (the total flow rate is 150 m^3 /hr). The Steam Generator water levels are supported to be 2.3 m. At the beginning of transient BRU-Ks start to work, after some time their flow rates decrease and they start to support 60 kgf/cm^2.

Figure 4. presents the behavior of Pressurizer water level. During the first 100 sec the fast decreasing of Pressurizer water level comes mainly from SCRAM, when the

pressure drops rapidly. The reason for increasing of Pressurizer water level after the first 100 sec comes from the Make-up system and from the three times of opening of Pressurizer SV - after 560 sec. (see figure 1.).

The Pressurizer SV opens only three times due to starting of the EFW pump and it cools down the primary coolant system through SGs.

The work of EFWP with water temperature equal to the temperature of Auxiliary feed water bounds the work of EFW and the work of Auxiliary pumps.

The Base Case calculation shows that with minimum resources and without operator actions the reactor core does not melt. Figure 5. shows the fuel cladding temperature during the whole transient time.

Figure 6. shows that during the whole transient there is sufficient flow rate in primary loops, which successfully cools down the reactor core.

4. Total loss of feed warer with operator action.

In this analysis are involved additional failures of plant equipment. It was assumed failure of Emergency feed water pumps and all HPPs. Due to this in the second analyses is performed Feed and Bleed with TK pumps (Starting of Make-up pumps to cooldown and opening of YR line). TK pumps are available at pressure above TQx3 pumps head, but have less flow rate. TQx4 pumps have low capacity and are not appropriate for cooling down the RCS.

In this case it is accepted that only TK pumps are available after reaching saturated temperature (at the Pressurizer safety relief setpoint) in primary side. The operator starts TK pumps after reaching this set point.

Starting primary decompression by YR system when primary side saturation margin becomes 15^o-20^o C is a reasonable and prudent operator intervention point, but it's not bounding. By set point "saturation margin 10^oC" all containment isolation valves are closed and make up system is not available. The restoration of the TK system needs additional time. Due to all above, it was accepted that after reaching primary saturated temperature at Pressurizer safety relief setpoint the operator starts TK pumps. This action will bound all earlier TK pump actuation cases. The pumps start to inject water in primary circuit immediately, but with flow rate of 80 m^3 /hr and the temperature of the injected water is equal to the temperature of HPP.

In this analysis have been involved and operator action – Feed & Bleed (F&B) using TK pumps.

Scenario:

I. Initial status.
   - I.1. Power 100 %.
   - I.2. Steam Generator water level is assumed to be 1.70 m.

II. Both Feed Water Pumps failed to work (initiation of TLW) and do not start to work Auxiliary pumps RL 51, 52.

III. In accordance with point II Turbine Stop Valves (TSVs) close.

IV. In accordance with point III BRU-Ks start to open and support pressure in Main Steam Header (MSH) equal to pressure that has been in MSH 1 sec. before closing of TSVs.

V. Switching off all MCPs in accordance with water level loss in SGs (1.7 m).
VI. Reactor SCRAM actuates according to signal " Switch off 3 from 4 MCPs" (by low level in SGs) with delay of 1.2 sec.
VII. The operator starts to borate the primary side with TK pump - with 40 g/l and $60 m^3$/hr.
VIII. Actuation of Automatic Step by Step Load according to the saturated temperature $\Delta t_S < 10\ ^0C$ duplicates the Reactor SCRAM and it switches off the letdown/makeup lines.
IX. The operator opens YR line and starts to cooldown the reactor core with TK pumps after reaching saturated temperature (at the Pressurizer safety relief setpoint) in primary side.

The calculated sequence of events for the operator actions for TLFW and cooldown using TK pumps is presented below.

Table 2.

Event	Time, s
TLFW	0.0
Turbine Stop Valves closed	0.0
MCPs are tripped	0.0
BRU-Ks #1, #2, #3 and #4 start to open	1.0
REACTOR SCRAM	1.6
The make up flow rate reaches max. flow rate	19.8
The operator starts the Make up pump to inject borated water with 40 g/l and 60 m^3 /hr.	180.0
The SV of Pressurizer starts to cycle	670.0
Reaching of a safety boron concentration	2460.0
Dryout of SGs	5100.0
Actuation of ASSL. The Make up/let down systems stop to inject.	6410.0
Saturation margin 0^o C	7100.0
The operator opens YR line	7100.0
The operator starts cooling down using TK pumps	7100.0
Loss of natural circulation	7850.0
Accumulators start to inject	9190.0

The most important parameters behavior is shown from Figure 7. through 12. The calculation was performed up to 15000 sec. into the transient time. Figure 7. presents the primary side pressure behavior.

Decreasing of primary side pressure between 5 sec. and 70 sec. comes due to Reactor SCRAM and work of BRU-Ks. Approximately after 70 sec. the primary pressure begins to increase due to residual heat, which continues to 670 sec. and reaches 185.0 kgf/cm^2 (see Figure 7.). After this set point the pressure in primary circuit starts to cycle between the opening and closing set points of 185 kgf/cm^2 and 176 kgf/cm^2. Decreasing of primary side pressure between 2900.0 sec. and 4600.0 sec. comes due to BRU-Ks work, decreasing of core residual heat and mainly due to work of make up / let down system (see Figure 11.). The operator starts the Make up pump to inject borated water with 40 g/l and 60 m^3 /hr at 180 sec. After reaching of a safety boron concentration the Make up pump continues to work following the automatic controllers and the injection of water depends on the primary side pressure and on the Pressurizer water level. During the time when Pressurizer water level is over 11.0 m the Make up pump is not injecting water in primary circuit. It leads to less heat removing from RCS, which is bounding.

Approximately after 4600.0 sec. the primary pressure begins to increase again due to residual heat, which continues to 5400.0 sec. and reaches 185.0 kgf/cm^2 (see Figure 7.). After this set point the pressure in primary circuit starts again to cycle between the opening and closing set points of 185 kgf/cm^2 and 176 kgf/cm^2. Decreasing of primary side pressure after 7100 sec. comes due to opening of Pressurizer YR line by operator. In this case the operator starts primary decompression by YR system when primary side temperature becomes saturated at the Pressurizer safety relief setpoint.

As the coolant is saturated, decreasing of pressure leads to flashing in the Pressurizer, which delays the RCS depressurization.

Margin to the boiling temperature is presented in Figure 8. Steam Generator water levels are shown in Figure 9.

The fuel cladding temperature is shown in Figure 12. During the whole transient time except time between 6530.0 sec. and 7170.0 sec. the fuel cladding temperature is less than 350 ^{0}C. In this calculation there is no problem with the core cooling. The maximum fuel cladding temperature of 357.0 ^{o}C is reached at 7100.0 sec.

5. Conclusions:

The main conclusions for both TLFW analyses are:

1. The two investigated analyses show successful core cooling and management of this transient.
2. Both calculations demonstrate sufficient safety margin in relation to “Total loss of feed water” event.
3. To mitigate the severity of TLFW, it is necessary to restore Auxiliary or Emergency Feed water or if it is impossible, to minimize RCS inventory loss within a period of time and to restore at least one safety pump so that RCS inventory could be restored.

6. References

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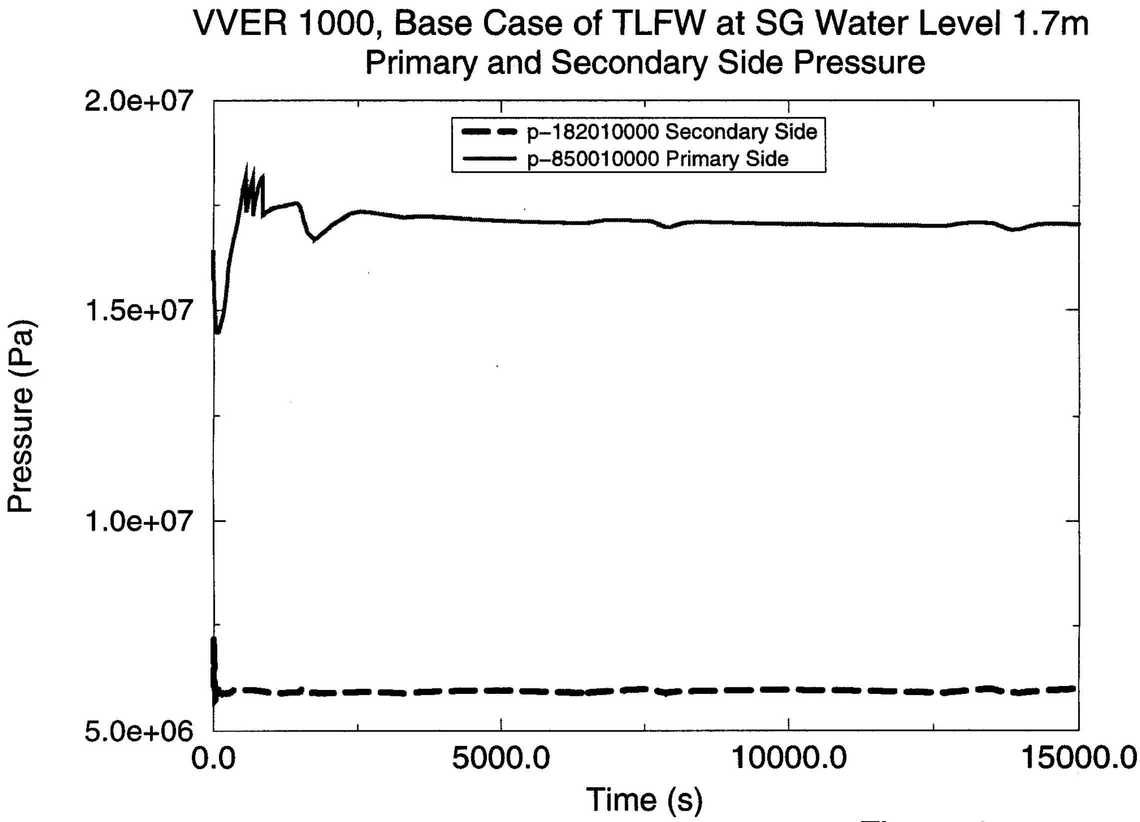

Figure 1.

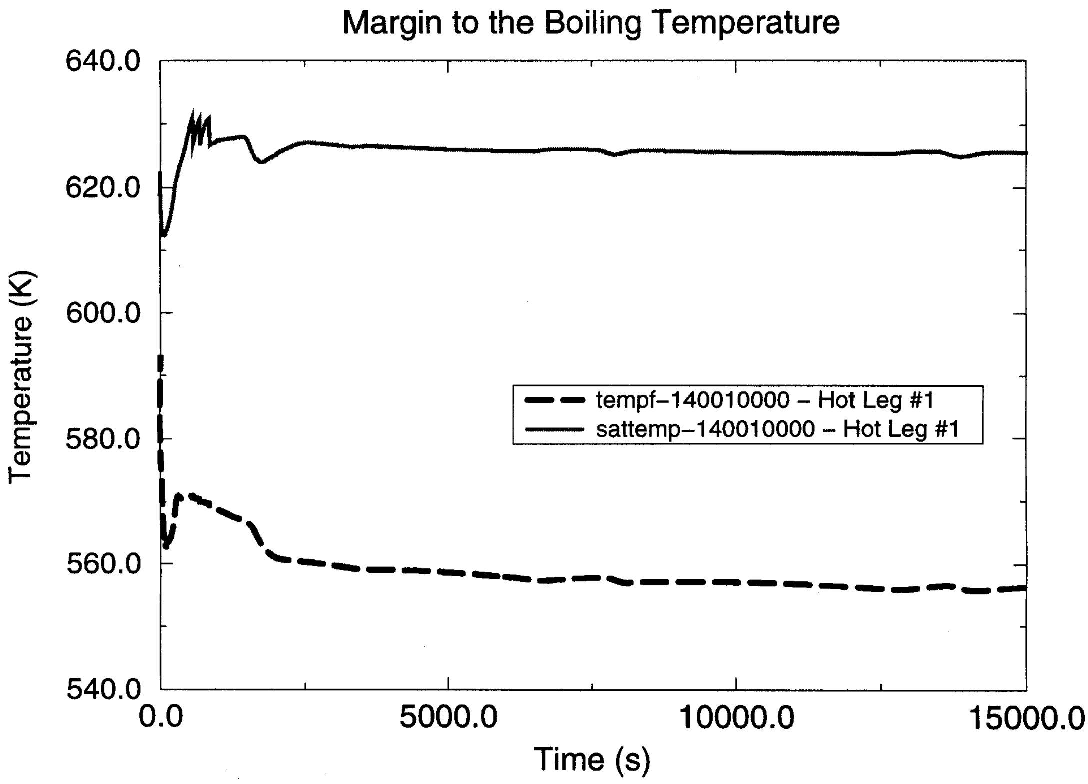

Figure 2.

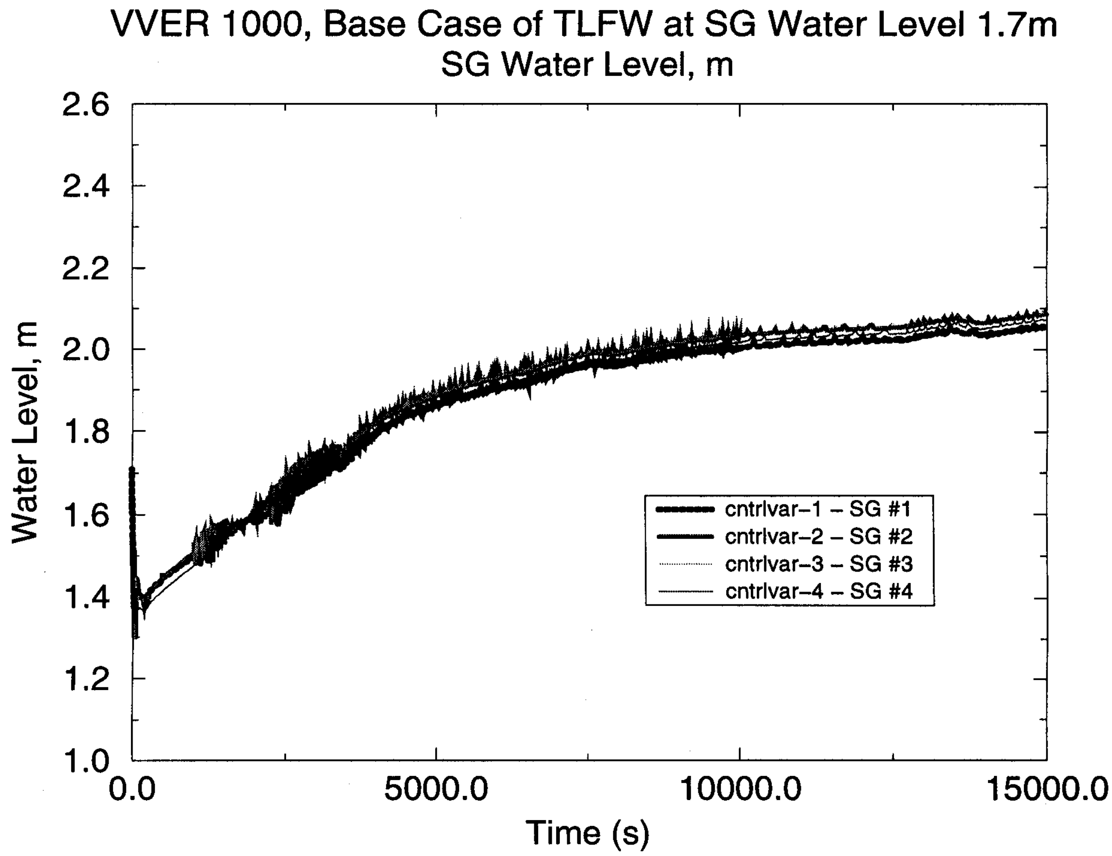

Figure 3.

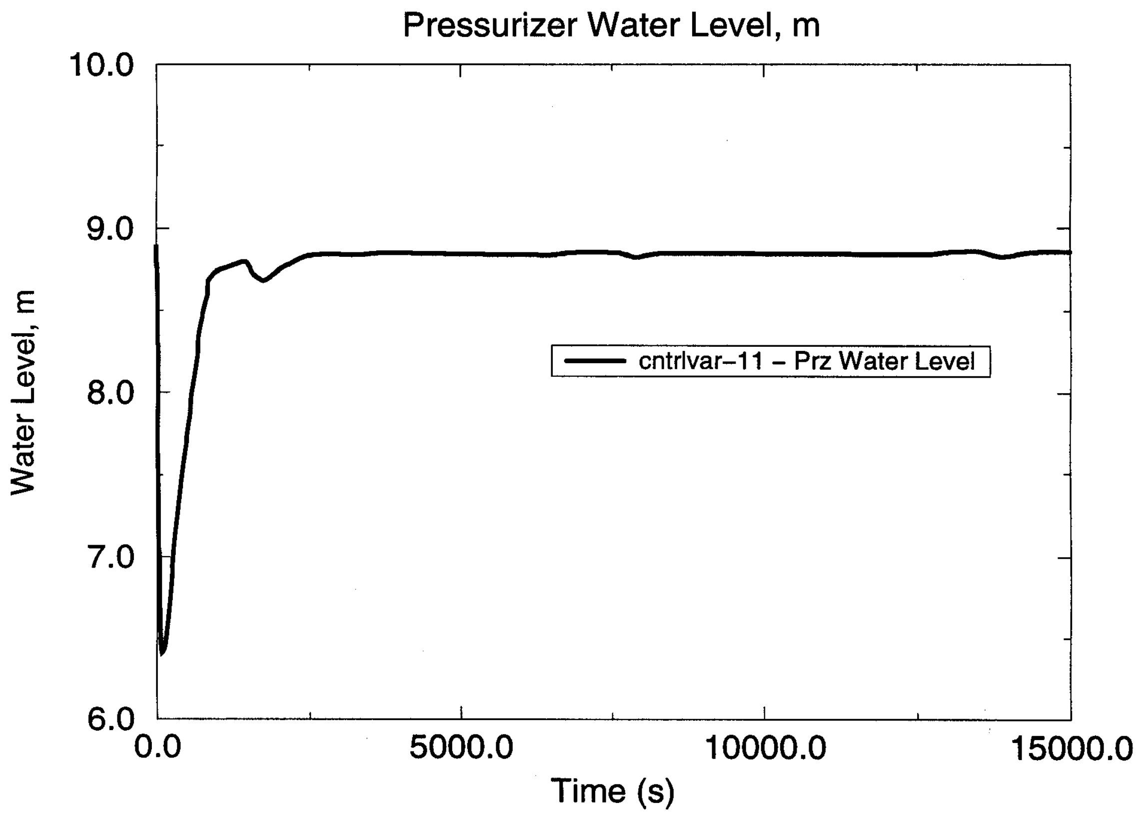

Figure 4.

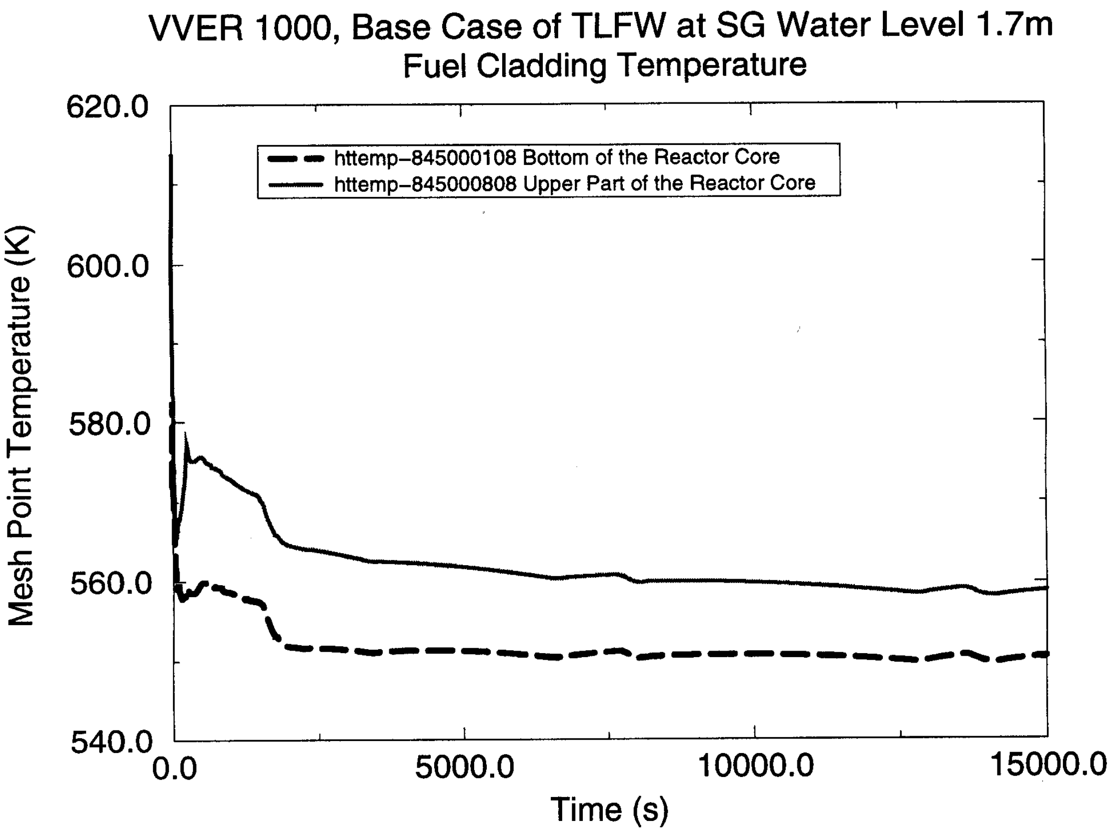

Figure 5.

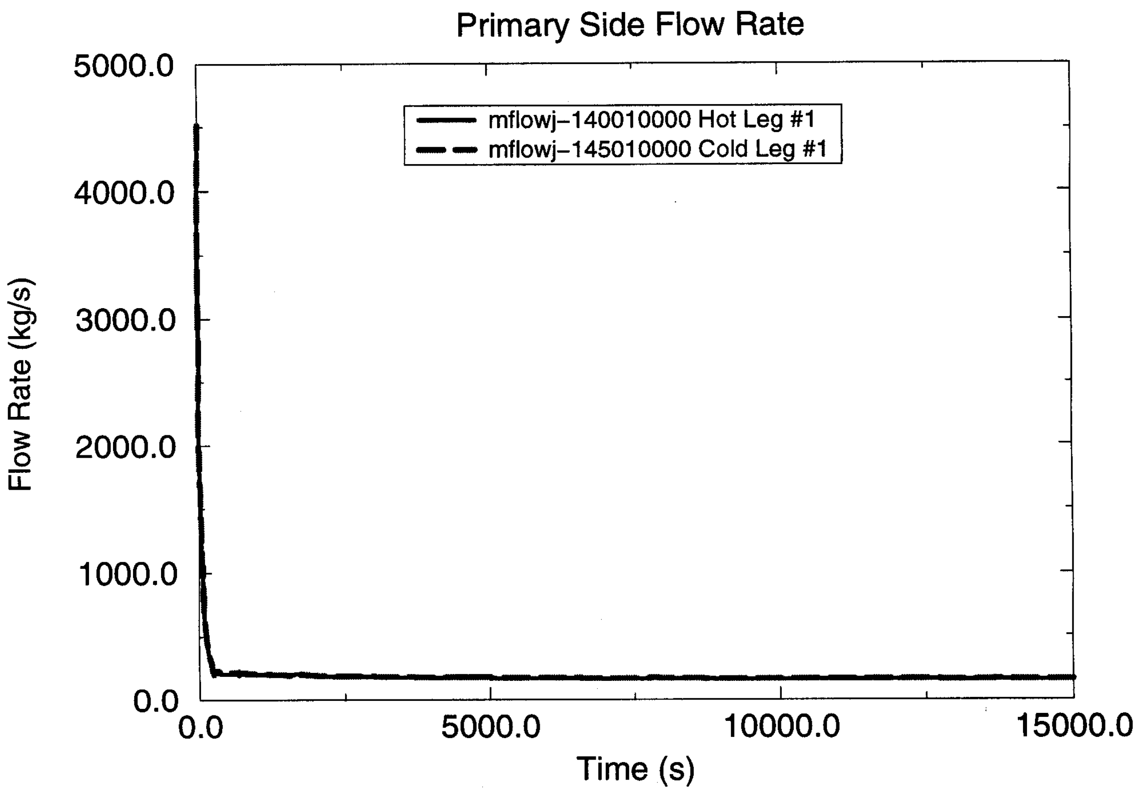

Figure 6.

TLFW at SG Water Level 1.7m, Operator Action – Cooldown by TK Pumps
Primary and Secondary Side Pressure

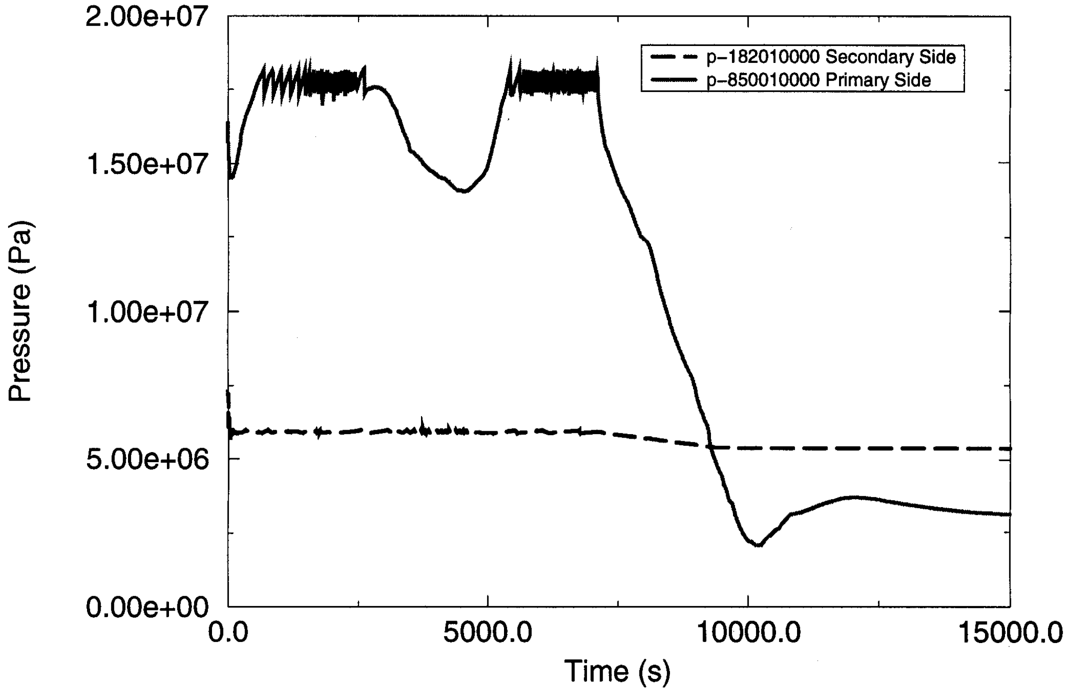

Figure 7.

Margin to the Boiling Temperature

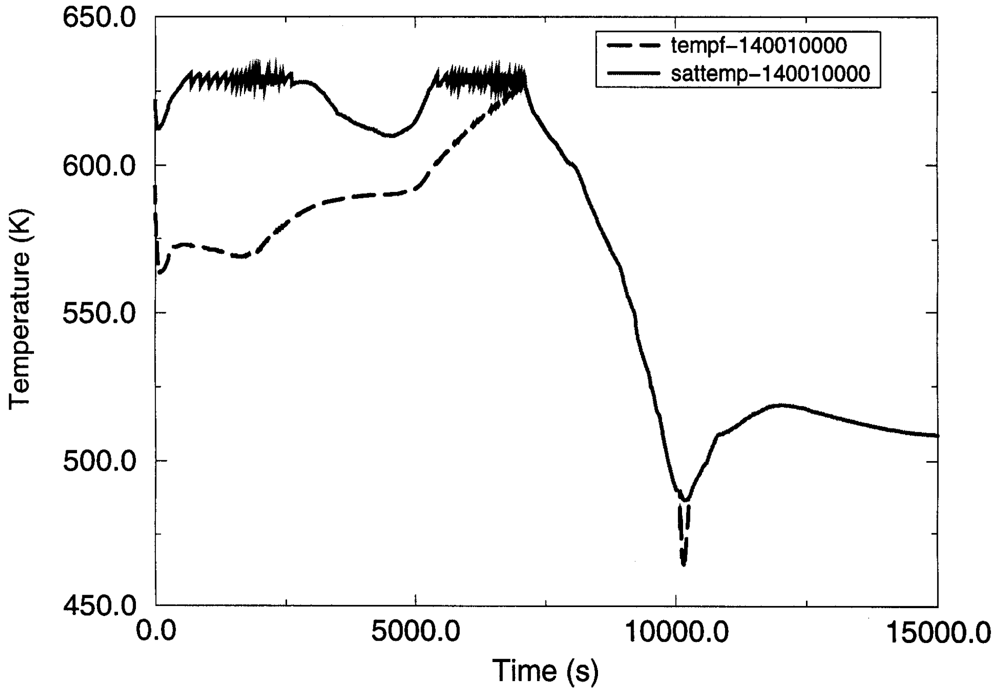

Figure 8.

TLFW at SG Water Level 1.7m, Operator Action–Cooldown by TK Pumps

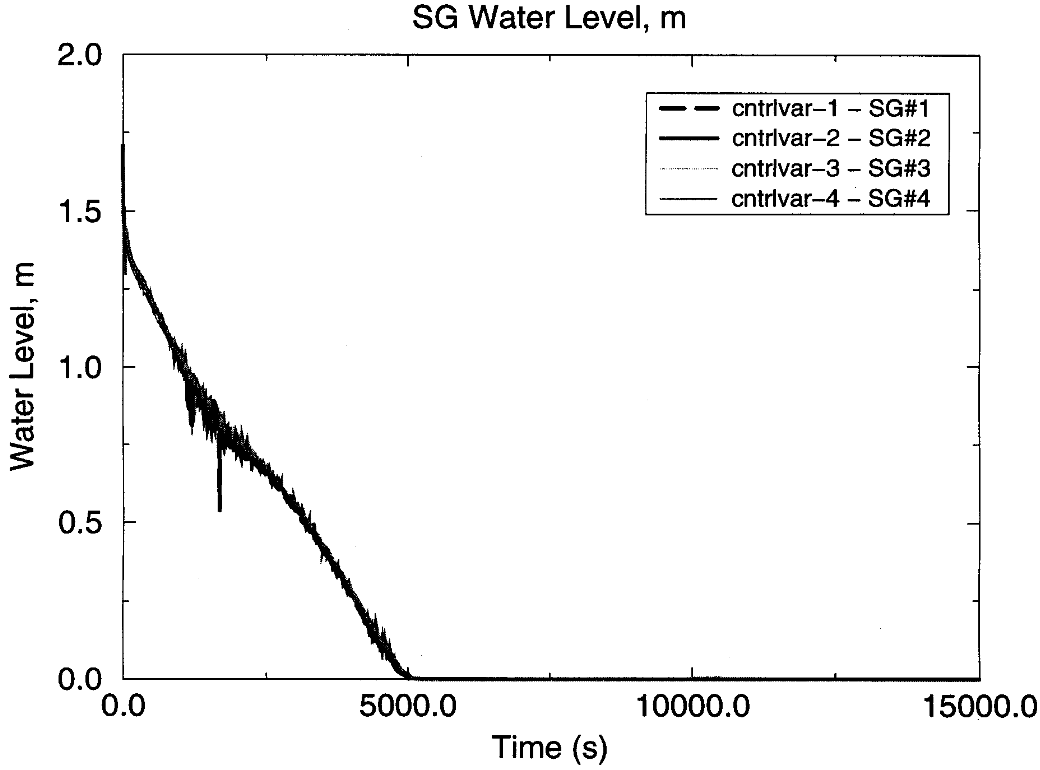

Figure 9.

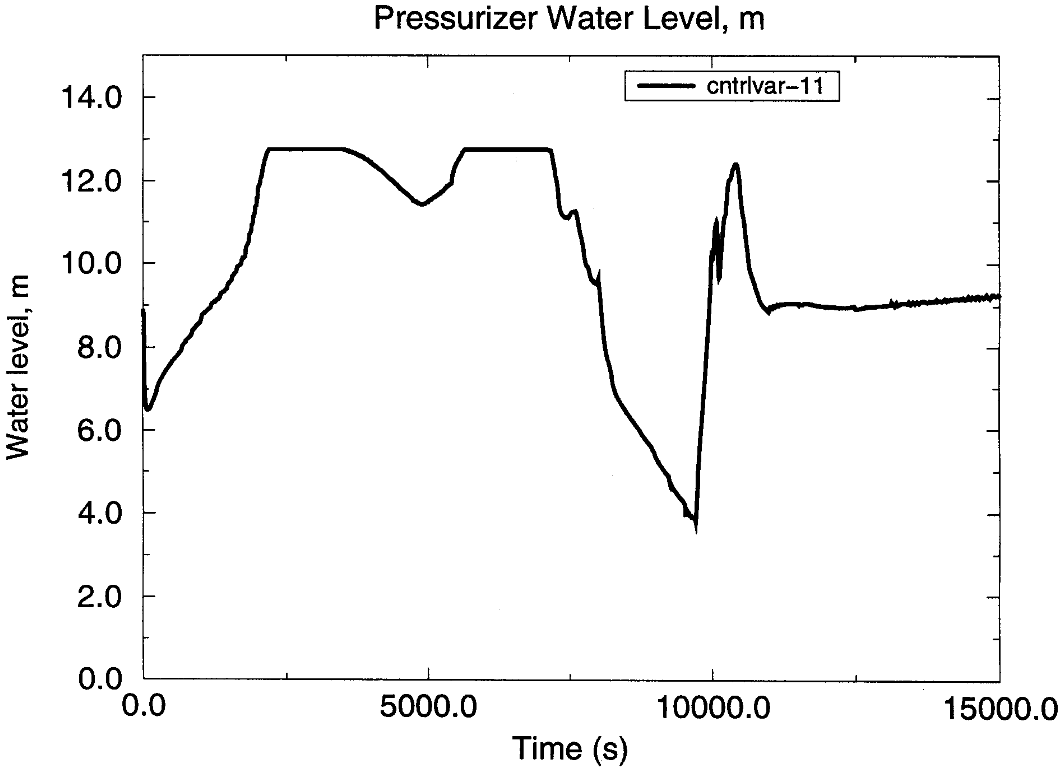

Figure 10.

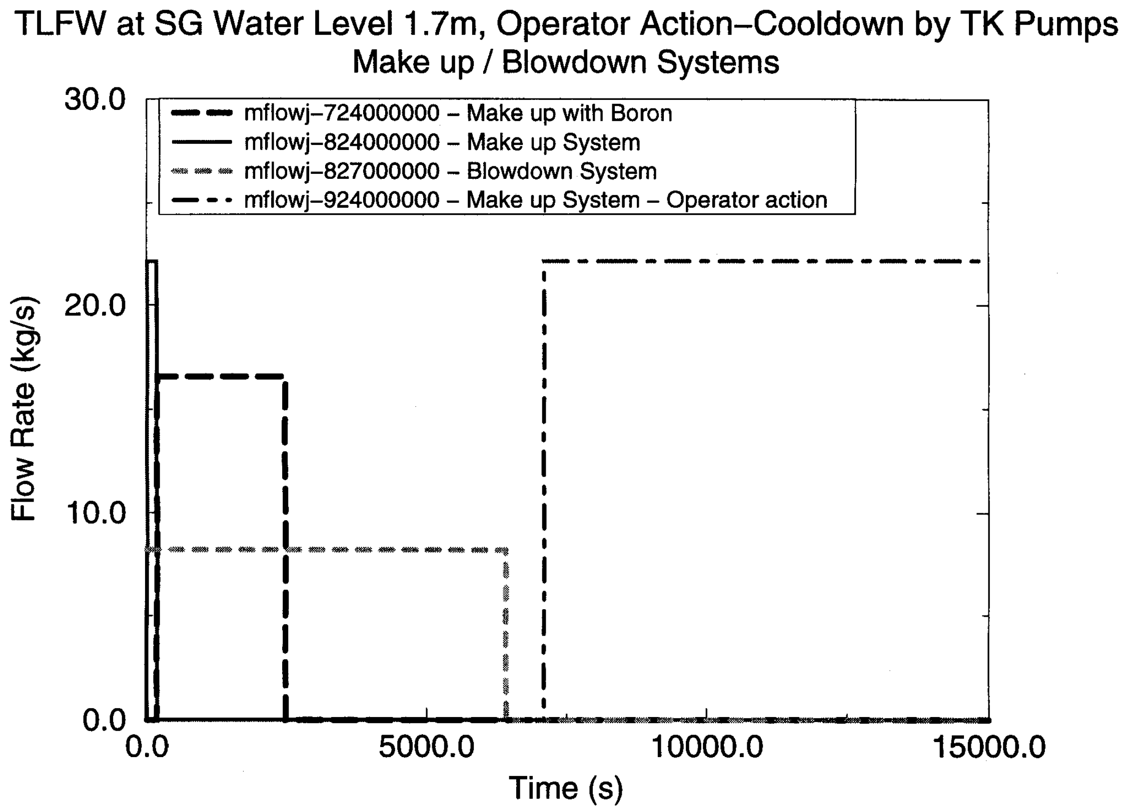

Figure 11.

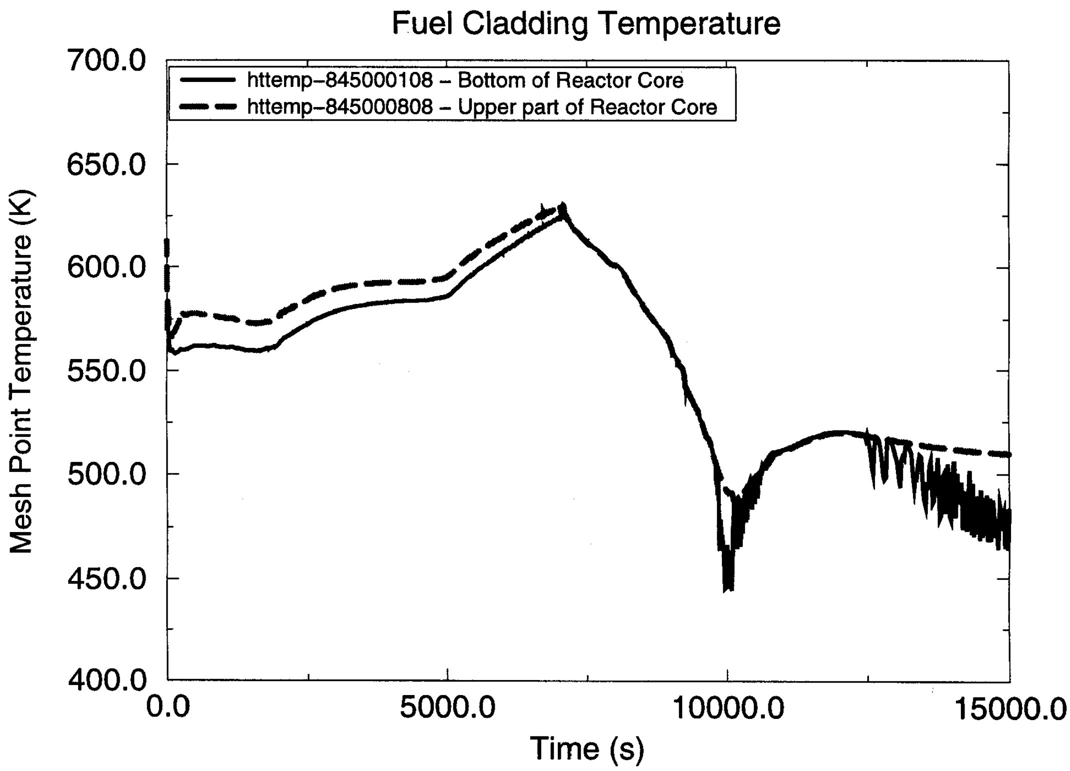

Figure 12.