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Validation of EOPs/FRGs Procedures Using LOHS Scenario

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ABSTRACT

Validation of EOPs (Emergency Operating Procedures) and FRGs (Function Restoration Guidelines) can be achieved either through plant full scope simulator or on desk top exercises. The desk top exercise is conducted when for the given scenario plant full scope simulator is not suitable. In either verification cases predefined scenario should be evaluated and possible branching foreseen. The scenario presented is LOHS, with bleed and feed procedure initiated. Best estimate light water reactor transient analysis code RELAP5/mod3.3 was used in calculation. Standardized detailed plant model was used. Operator actions were modelled from beginning of the scenario to its termination.

1 INTRODUCTION

The Emergency Operating Procedures validation objective is to ensure that operators can manage emergency conditions using the EOPs. The methods of validation:

(a) The simulator method is a validation method by which control room operators perform control functions on simulator equipment according to a scenario and for an observer/reviewer.

(b) The table top validation is method by which personnel explain and/or discuss procedure action steps in response to a scenario and for an observer/reviewer.

The validation method that will provide the most meaningful and thorough scrutiny for the EOP set is the simulator method. However, the table top methods will have to be used when there is no simulator or if the simulator modelling is incapable of producing a situation that a specific procedure addresses. That alternate validation method must also be performed when actions occur outside the control room. Modelling limitations of the full scope simulator could typically be experienced in a complex thermalhydraulic accident. The EOP developers could validate the accidents that are not covered by the simulator models in table top validation. In all cases the validation should be carried out under conditions that, to the greatest extent possible, simulate conditions during an emergency and include workload and instrument response. Correct application of EOP validation will ensure that the EOPs are usable and correct. Usability encompasses two concepts, level of detail and ease of understanding. The level of detail must be sufficient but not excessive. There should be a balance between providing all possible information and the minimum information needed. The plant specific writer's guide should address the desired level of detail. During validation, the user and observer judge whether the level of detail is sufficient.

When developing validation scenarios the goal is to exercise as many procedures and transitions as possible. It is not expected that every conceivable scenario will be covered.

2 EMERGENCY OPERATING PROCEDURE - CONCEPT [1], [2], [3]

The Emergency Operating Procedures (EOP) provide a network of predefined and prioritized symptom based response strategies that guide the operator in management of emergency transients. Event related recovery and function related restoration strategies are combined to guide diagnosis and plant recovery to the optimal end state while ensuring explicit diagnosis and restoration of the plant safety state independent of event sequence.

The approach to the development of the Emergency Operating Procedures (EOPs) depends on the plant design configuration from a standpoint of the plant response to emergency transients. For example, the maximum shutoff pressure of the safety injection system strongly influences plant response to the postulated accident conditions. Based on this fact, the plant can be considered as low pressure (LP) or high pressure (HP) type. The HP type approach is applicable to the plants that are designed with a safety injection system shutoff pressure greater than the reactor coolant system pressurizer power operated relief valve (PORV) pressure setpoint. High pressure plants utilize the charging pumps as safety injection pumps. The LP version is applicable to plants that are designed with a safety injection system shutoff pressure less than the reactor coolant system pressurizer power operated relief valve (PORV) pressure setpoint. Low pressure plants do not utilize the charging pumps as safety injection pumps. Transient presented in the paper will show response of HP plant.

In general, two types of EOPs are known: Optimal Recovery (Event Oriented) and Critical Safety Function Restoration Concept (Symptom Oriented).

The concept of Optimal Recovery is based on the premise that radiation release and equipment damage can both be minimized through associating the symptoms of an emergency transient with a predefined plant condition and implementing an associated predefined event related recovery strategy to achieve an optimal plant end state. Recovery implies changing the plant state to the optimal end state.

The concept of Critical Safety Function Restoration (symptom related recovery strategies) is based on the premise that radiation release to the environment can be minimized if the barriers to radiation release are protected. Restoration implies returning the plant state to a safe state in which the Critical Safety Functions are satisfied. Hence, a fundamental goal of nuclear safety is the prevention of uncontrolled releases of radioactive materials from nuclear power plants. In order to accomplish this goal the concept of "defence in depth" [4], which translates into providing multiple barriers to the release of the radioactive material, was adopted at the start of the commercial development of nuclear energy as a cornerstone of nuclear safety. As long as the fuel matrix/cladding, reactor coolant system pressure boundary and containment barriers are intact in a nuclear power plant, that plant poses no threat to the health and safety of the general public.

The whole EOPs should provide emergency response strategies that utilize both emergency operations concepts. The Optimal Recovery concept is utilized as the primary emergency operations concept. The associated symptom based recovery strategies are structured to implicitly maintain the Critical Safety Functions. In this way the event related recovery strategies provide guidance to obtain the optimal plant end state while maintaining the Critical Safety Functions.

3 LOSS OF HEAT SINK [5]

A loss of secondary heat sink can occur as a result of several different initiating events. Possibilities are a loss of main feedwater during power operation, a loss of offsite power, or any other scenario for which main feedwater is isolated or lost when the steam generators provide the main heat removal path. For these initiating transients a failure of the auxiliary feedwater (AFW) system to inject or a loss of AFW early in the cooldown, before RHR (Residual Heat Removal) System operation can be established, could lead to a loss of secondary heat sink.

A loss of all feedwater transient is characterized by a depletion of secondary inventory and eventual degradation of secondary heat transfer capability. As secondary heat transfer capability degrades, a loss of secondary heat sink results and core decay heat generation will increase RCS (Reactor Coolant System) temperature and pressure until the pressurizer PORVs or safety valves (SVs) open to relieve the increasing RCS pressure. At this point the opening and closing of the PORVs or safety valves will result in a loss of RCS inventory similar in nature to a Small Break Loss of Coolant Accident (SBLOCA). If operator action is not taken, the pressurizer PORVs or SVs will continue to cycle open and closed at the valve setpoint pressure removing RCS inventory and a limited amount of core decay heat until eventually enough inventory will be lost to result in core uncovery.

3.1 "Bleed and feed" vs. "feed and bleed" technique [6], [7]

Bleed and feed is the process of manually initiating high pressure safety injection and manually opening the pressurizer PORVs to depressurize the RCS to allow the injection of sufficient water which will provide decay heat removal and core cooling. Feed and bleed is the process of manually initiating HPSI (High Pressure Safety Injection - SI charging) and permitting the automatic cycling of the PORVs at their set pressure to vent RCS inventory and provide decay heat removal and core cooling. This process then takes place at RCS pressures at and above the PORV setpoint pressure. The Feed and bleed process is only possible in HP type plants.

Bleed and feed is established by first starting all HPSI and/or HHSI (High Head Safety Injection) pumps and verifying their delivery and, then, manually opening and holding open all PORVs. Feed and bleed is established by starting all HPSI. The injection from the HPSI pumps and the RCS heatup will force an intermittent release of RCS inventory by the pressurizer PORVs. Thus, during the feed and bleed process the pressurizer PORVs are forced to open (automatically) and close repeatedly, relieving excess RCS inventory as a result of HPSI and RCS heatup.

The recommended alternate heat removal method is bleed and feed. Adequate PORV reliability is required to be demonstrated to support the use of feed and bleed since the PORV will open and close continuously over a long period of time. If feed and bleed were initiated when the symptoms of loss of heat sink were observed, the option to later revert to bleed and feed would be lost, since in feed and bleed the SI flow rate is low enough such that the system would begin to boil after a short period of time. Once boiling began, depressurization of the RCS using PORVs without having core uncovery would be highly unlikely. Core uncovery would be necessary to reduce the steam generation rate to a rate that permitted RCS depressurization using pressurizer PORVs. Thus, the use of feed and bleed precludes the use of bleed and feed without core uncovery and possible core damage. Therefore, based on the above arguments, feed and bleed is not recommended to provide an alternative heat removal method during a loss of secondary heat sink condition.

4 DESCRIPTION OF MODEL [8]

Model has been developed to a high level of detail and includes detailed discretization of all important components of the plant primary and secondary side (Reactor Pressure Vessel – RPV and Stem Generators - SG) and the models of the Emergency Core Cooling System - ECCS, Main Feedwater - MFW and Auxiliary Feedwater - AFW and simplified model of charging and letdown system. The ECCS consist of HPSI (High Pressure Safety Injection - SI charging), HHSI (High Head Safety Injection), ACC (Accumulators) and LPSI (Low Pressure Safety Injection - RHR system). Protection and control system has been developed according to the plant available documentation. The model has been developed with necessary fidelity of geometrical and operating parameters. Verified and recommended RELAP5 modelling techniques are used in preparation of RELAP5 input deck.[9] Steady state calculation was verified against real plant data and was found satisfactory. [8] Nodalization has been qualified on steady state and transient level. [10], [11] The overview of SI system is presented in Table 1.

Table 1 Overview of the Plant SI injection system

System	Shut off Pressure [MPa]	Maximum Delivery Capacity Pressure [MPa]
HPSI	20.00	8.24
HHSI	10.50	5.00
ACC	5.00	-
LPSI	1.39	1.05

5 TRANSIENT DESCRIPTION

The plant presented is high pressure (employees charging pumps as safety injection pumps), two loop PWR. Power to primary volume ratio is approximately two times smaller than what is usual. This results in smaller amount decay heat needed to be transferred to SGs, and longer time for SGs to lose their function as a heat sink. Because of that the operator have longer available time before initiating bleed and feed process.

5.1 Main Transient Conditions

From the beginning of transient there is following equipment status:

- MFW (Main Feed Water) and AFW (Auxiliary Feed Water)
- Steam Dump is not Available
- SGs' PORVs and SVs are available
- MSL (Main Steam Line) isolation occurs on the start of transient
- 1/2 ECCS operational - (one HPSI, two HHSI and one LPSI pump)

5.2 Results

Transient starts from full power operation (1000 MWt) and loss of MFW. At the same time both steam lines (SL) are isolated on spurious signal. Overview of sequence of events is given in Table 2.

Table 2 Time Sequence of Events

Event	Time
MFW isolation	0.05 s (on start of LOHS)
SL isolation	0.05 s (on start of LOHS)
Reactor trip (RX)	17.96s (lo-1 SG2 level (SG2 NR (Narrow Range) <setpoint) and steam/FW2 mismatch SG2 setpoint)
Turbine trip	18.46s (on RX trip)
Reactor Coolant Pump (RCP) trip	900s (manual operator trip at Step 4 of FR-H.1)
SI signal	3315.40s (manual - FR-H.1 procedure Caution 1 Step 3 SG2 WR (Wide Range) < setpoint)
Letdown isolated	3315.40s (automatic on SI actuation)
Containment isolation	3315.40s (automatic on SI actuation)
Pressurizer (PRZ) PORVs open	3700s (manual operator opening at Step 16 of FR-H.1)
AFW started	7300s (restoration - minimal to both SG)

Main events and operator actions are shown at Figure 1. The operators actions are based on parameters presented from Figure 2 to Figure 19. The containment response is not modelled. Until implementation of bleed and feed technique it is unlikely that there are conditions for adverse containment setpoints. Afterwards it is possible that the containment parameters will dictate change to adverse containment setpoints. This does not change the overall behaviour of the transient, only time window to achieve required setpoints. Because of that, through transient normal containment setpoints will be used.

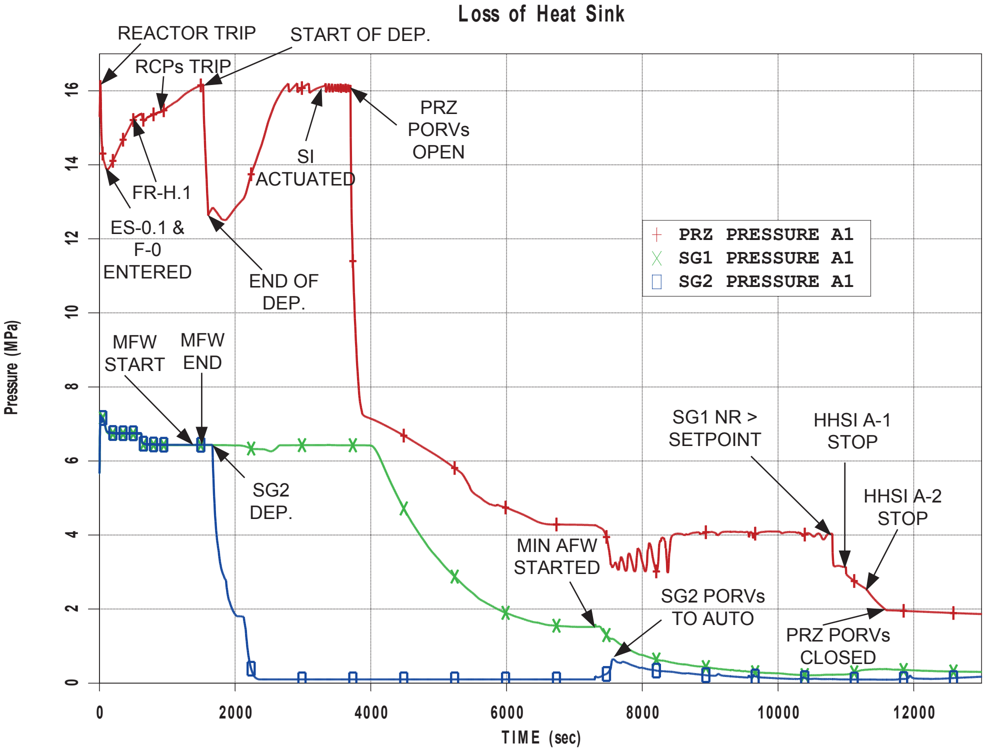

Figure 1: RCS and SGs Pressure

The transient progression is as follows. Procedure E-0 (Reactor Trip or Safety Injection) is entered as response to RX trip (Figure 2). The SGs' NR level is lost at t=80s (Figure 4), but operator missed it. Transition from E-0 to ES-0.1 is made as SI was not actuated and according to readings is not needed at t=100s (Figure 1 and Figure 3). According to rules of usage, F-0 procedure (Critical Safety Function Status Tree - CSFT) is implemented. From F-0 procedure normal containment setpoints are used. From Figure 6 to Figure 8 operator verifies steps at ES-0.1 and F-0 CSFT priorities. At t=500s RED path in F-0 on Heat Sink status tree is recognised (Figure 4 and Figure 9).

This tree represents the third highest priority Critical Safety Function, and as such, is always entered directly after the Subcriticality and Core Cooling tree. The most serious challenge to the Heat Sink Critical Safety Function is an indication of loss of secondary heat sink. A loss of secondary heat sink occurs if decay heat removal is needed through the SGs and all feed flow capability is lost. Feed flow must be re-established or an alternative heat removal mode (e.g., bleed and feed) must be established to prevent core uncovery and eventually an inadequate core cooling condition. Since this is an extreme challenge to the fuel clad/matrix barrier to radioactivity release, immediate operator action is required and a RED priority is warranted. The loss of secondary heat sink condition is the only RED priority included on Heat Sink status tree.

Transfer from ES-0.1 to FR-H.1 Response to Loss of Secondary Heat Sink is made at t=500s (Figure 4 and Figure 9). The guideline FR-H.1 provides guidance to address an extreme challenge (i.e., RED priority) to the Heat Sink Critical Safety Function that results if total feed flow is below a minimum value and level is below the narrow range in all SGs at any time. An early indication that secondary heat transfer capability may be challenged is that AFW flow is not available to any steam generator. Following a RX trip and/or SI, main feedwater isolation is automatically initiated. In this transient MFW is not available and is the initiator of the transient. Auxiliary feedwater flow to the steam generators must be automatically or manually initiated in order to maintain adequate secondary inventory for decay heat removal. Consequently, a failure of the AFW system results in a challenge to the Heat Sink Critical Safety Function. The operator is directed to implement guideline FR-H.1. The objective is to maintain RCS heat removal capability by establishing feed flow to an SG or through establishing RCS bleed and feed heat removal. It is entered at the first indication that secondary heat removal capability may be challenged. This permits maximum time for operator action to restore feedwater flow to at least one steam generator before secondary inventory is depleted and secondary heat removal capability is lost. Once secondary heat removal capability is lost, RCS bleed and feed must be established to minimize core uncovery and prevent an inadequate core cooling condition.

After failure to establish AFW flow to SGs from control room, local operator is dispatched to restore it. The operator then manually trips RCPs (t=900s, Figure 6). Operation of reactor coolant pumps will affect the dryout time of the steam generators due to RCPs heat addition and, therefore, will affect the time at which operator action to initiate bleed and feed must occur. By tripping the RCPs, the effectiveness of the remaining water inventory in the SGs is extended, which extends the time at which the operator action to initiate bleed and feed must occur. This extension of time is additional time for the operator to restore feedwater flow to the SGs.

The next step is for operator to try to start MFW pumps. The MFW is the next source of high pressure water readily available to the operator to re-establish the secondary heat sink. Prior to restoring MFW flow to the SGs, the operator verifies condensate system operation to ensure a source of water to the MFW pumps. Then the MFW isolation valve status is checked. If feedwater isolation has occurred, various actions may be required, depending upon the plant specific logic for FW isolation, to reset SI and FW isolation signals and reopen the FW isolation valves. If either the condensate system cannot be placed in service or no FW isolation valves can be opened, the operator is directed to check the status of the secondary heat sink. If the condensate system is operational and FW isolation valves are open, then MFW is established by the operator. If MFW cannot be established, the operator is directed to attempt to establish condensate flow. In transient reinitiation of MFW is partly successful as the MFW delivers some flow to SG1 for two minutes (from t=1380-1500s, Figure 9). This has no visible effect as seen on Figure 5.

As MFW injection was not successful operator is trying to establish feed flow from the condensate system. For injection from the condensate system to be successful it is required to depressurize SG (low pump head of system). This in turn requires primary depressurization (t=1530s using PRZ PORV) to less than P.06 (so that SI signal can be blocked at t=1660s, Figure 1 and Figure 10). This action is done because of SG depressurization which can lead to fast primary depressurization and automatic SI signal could be reached on either primary or secondary low pressure. In this way SI actuation is prevented and can not hamper or delay recovery. For secondary depressurization SG2 is chosen as some flow from MFW reached SG1. The SG2 is depressurized to below setpoint of condensate booster pump head pressure using SG2 PORV (t=1670-2200s, Figure 1, Figure 10 and Figure 14). Further SG2 depressurization is continued to achieve maximum condensate system flow (SG PORV is left in open position). Time of 15 minutes is left for operator to try to establish flow from the condensate system. The condensate flow was not established, and the operator checks for SGs NR level at t=3100s which is below range. Afterwards operator is checking SGs WR for setpoint which determines actuation of bleed and feed (Figure 5). At that time the setpoint is not reached in both SGs, and operator is instructed to go to first step of FR-H.1 (t=3160s).

At t=3315s setpoint for bleed and feed is reached (Figure 5), and transition to initiating step is made. This step initiates manual SI actuation (Figure 11 and Figure 12). After SI delivery verification of both PRZ PORVs opening is made at t=3700s (Figure 10 and Figure 13). Verification of bleed path is performed (Figure 11 and Figure 12). While proceeding with FR-H.1 the operator is instructed to perform steps in E-0. These steps are performed because it is possible to make a transition to FR-H.1 without having performed the verification of automatic SI actions in E-0. This step specifically instructs the operator to perform that verification. Performing steps in E-0 does not initiate any additional operator action in this transient except verifying plant status. Through bleed and feed implementation RWST level is monitored for need to switch to containment sump (Figure 18).

The operator reach step loop in FR-H.1 where he is trying to establish secondary heat sink and checking for SG WR indication. This loop is maintained, and at t=7300s the minimum AFW for heat removal becomes available (Figure 9). Five minutes after, SG2 PORV is closed (Figure 1, Figure 10 and Figure 14). The operator remains in the step loop monitoring secondary heat sink. The SG1 NR criteria for end of LOHS is reached at t=10 480s (Figure 4).

Following restoration of secondary heat sink in SG1 (later SG2), the operator is instructed to verify core cooling and reduce SI flow. After SI reduction (only HPSI remains - SI charging, Figure 15, Figure 16, Figure 17, Figure 1, Figure 11 and Figure 19) operator is instructed to close PRZ PORVs one by one and to place them in auto position (Figure 1 and Figure 10). During this process primary pressure is closely monitored as PRZ is water solid (Figure 13) and any sharp change in primary pressure could have devastating effects on RCS. In this transient it is assumed that PRZ PORVs will close even after long water discharge. If this would not be the case, the transient would propagate in SBLOCA. The verification of bleed and feed termination is done (Figure 12). Operator establishes normal letdown and charging (Figure 11). The charging and letdown flow is tuned to drain PRZ in normal operating range. The transient ends at t~12000s.

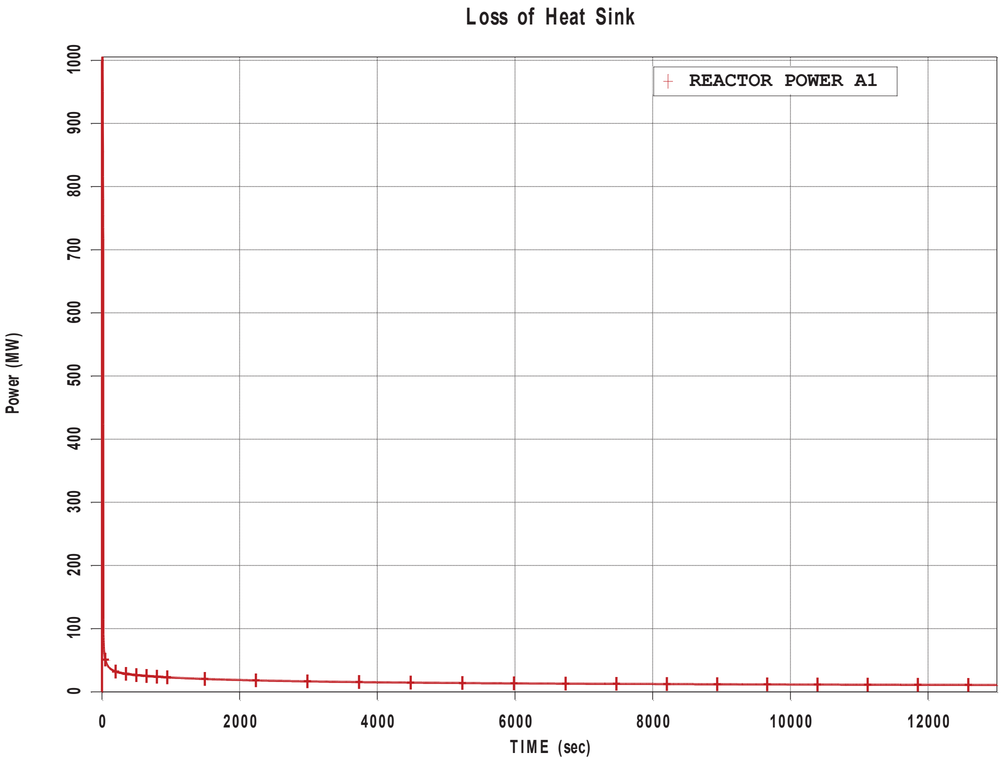

Figure 2: Reactor Power

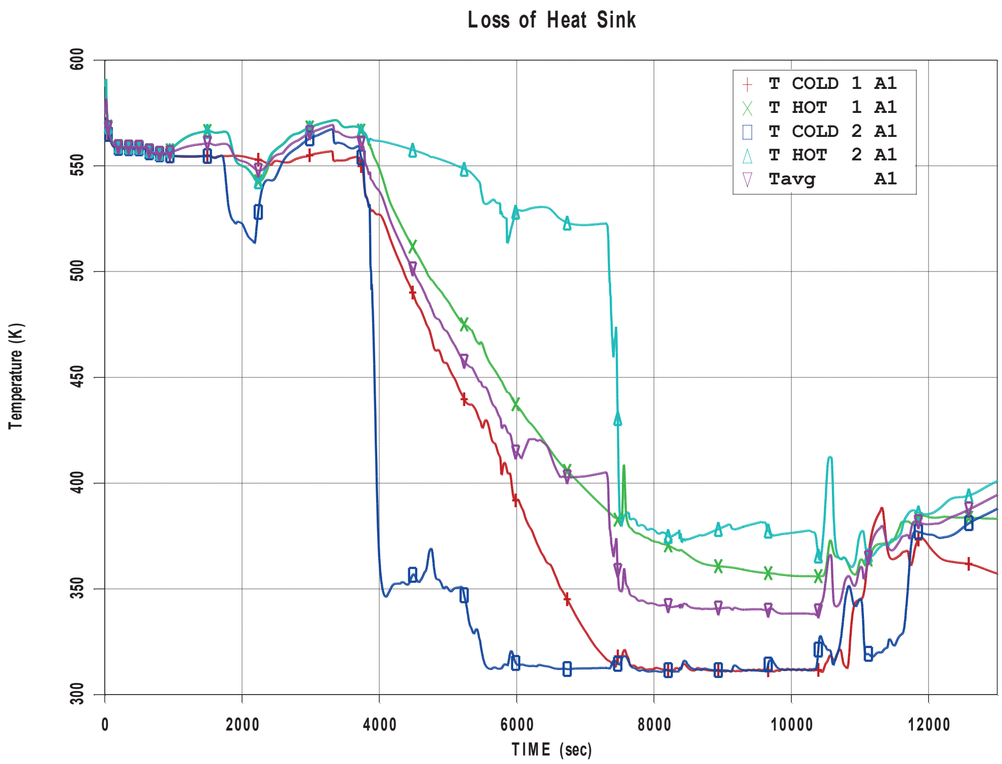

Figure 3: Temperatures Cold Leg, Hot Leg, Tavg

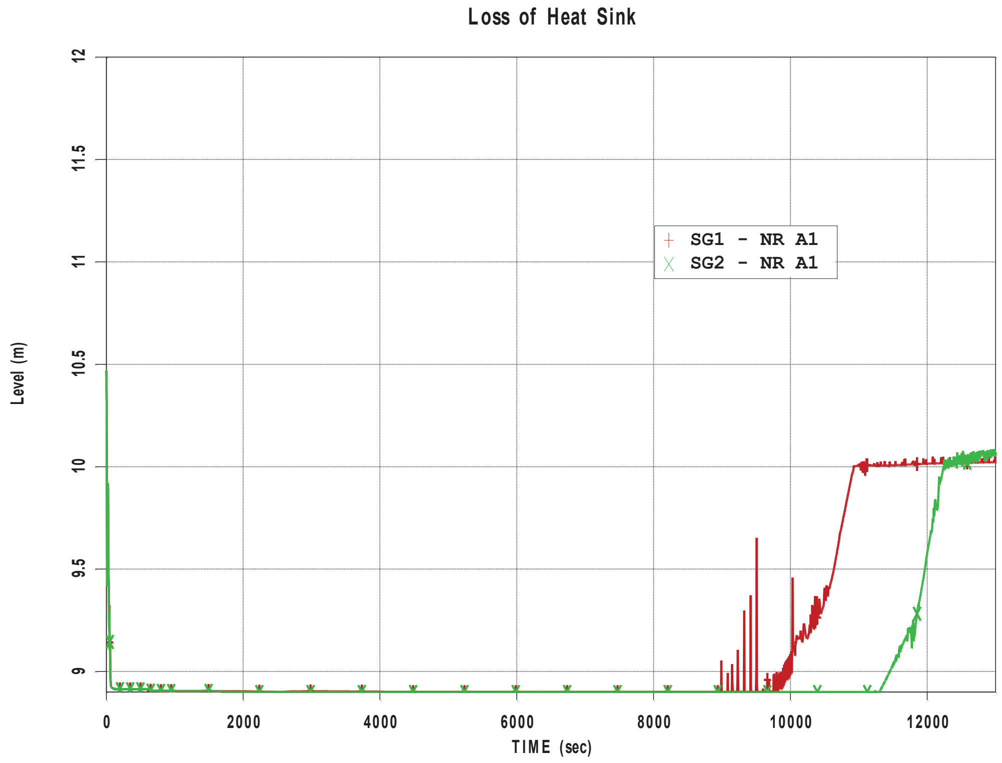

Figure 4: SGs Level - Narrow Range

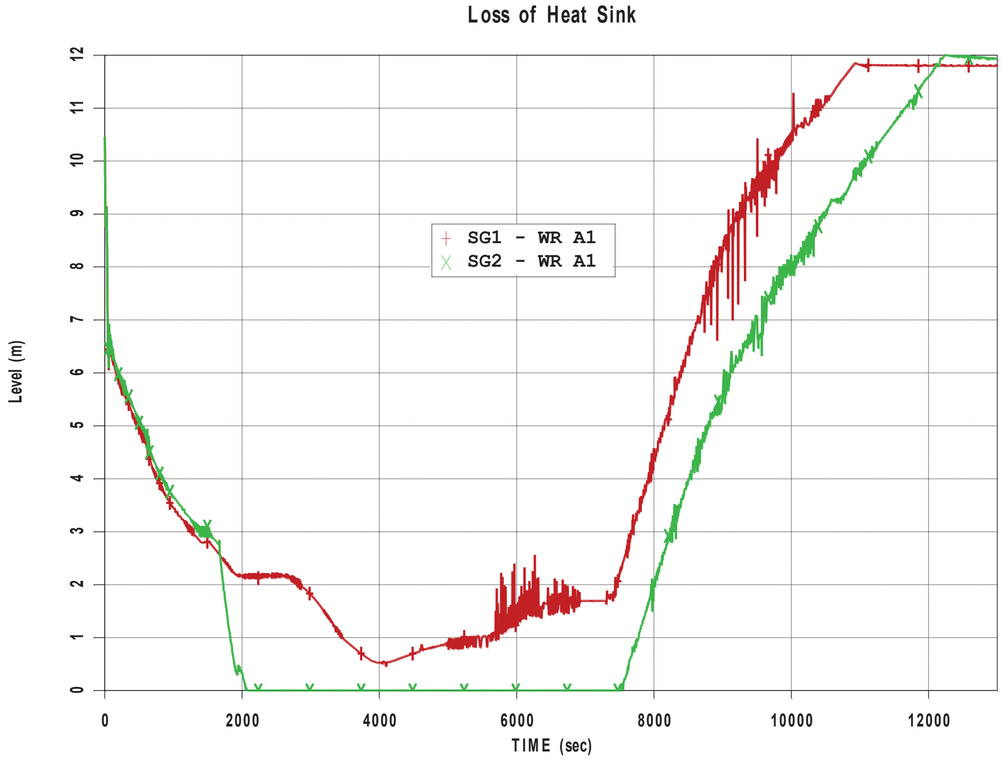

Figure 5: SGs Level - Wide Range

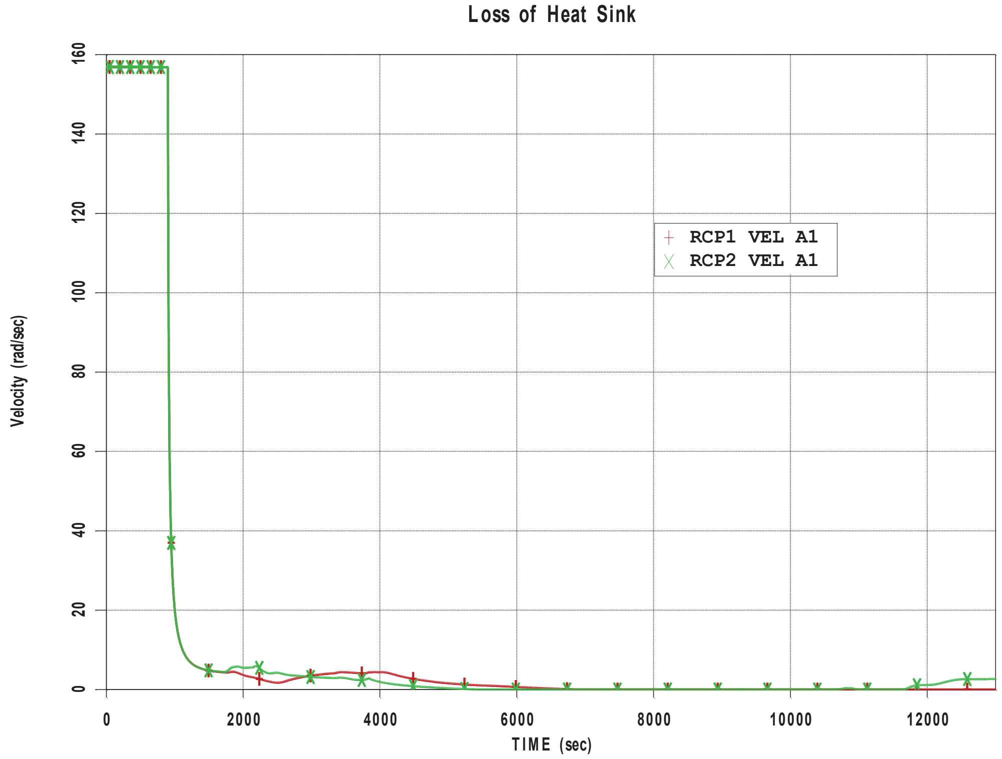

Figure 6: RCPs Velocity

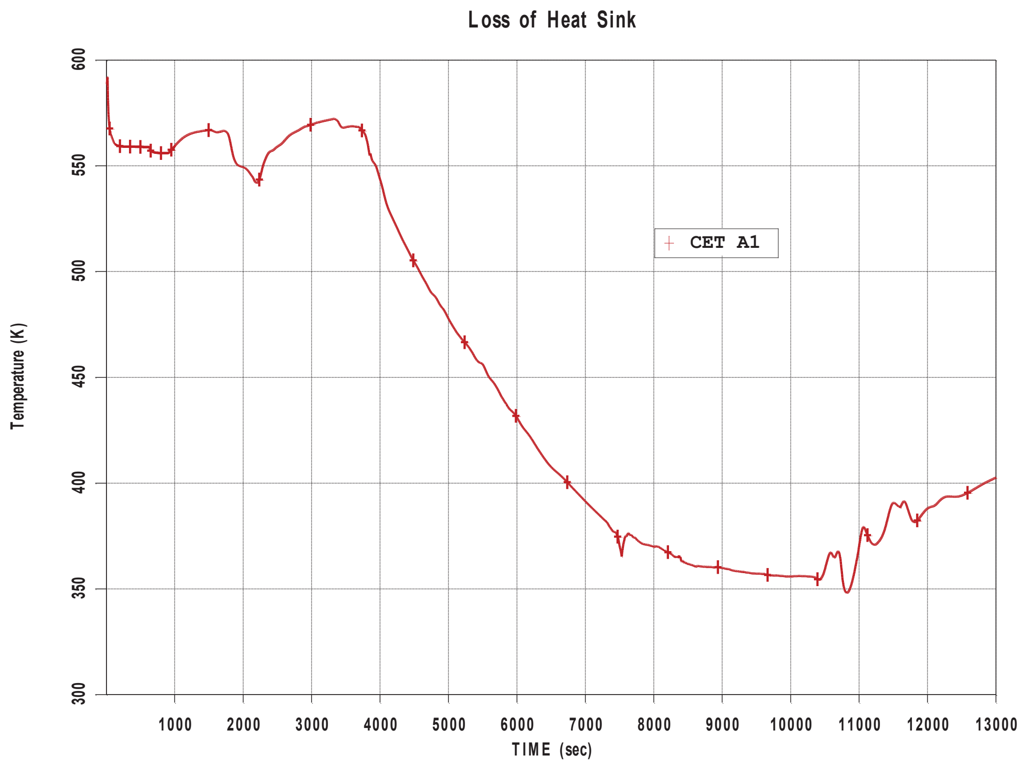

Figure 7: Core Exit Thermocouples (CET) Temperature

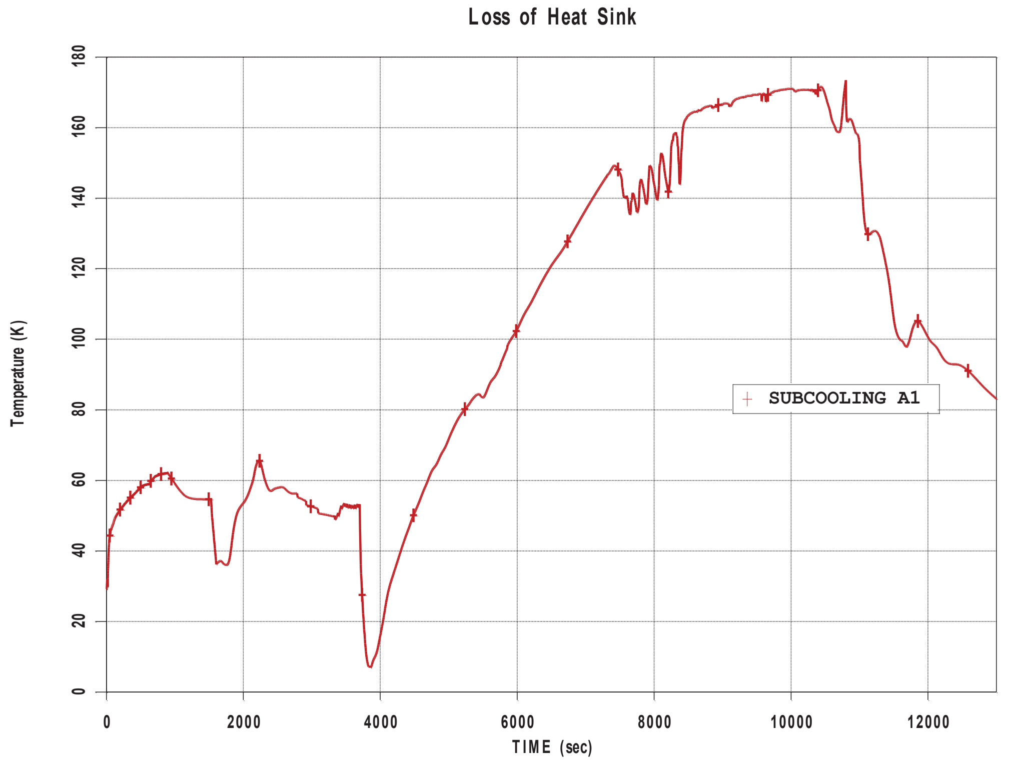

Figure 8: Subcooling

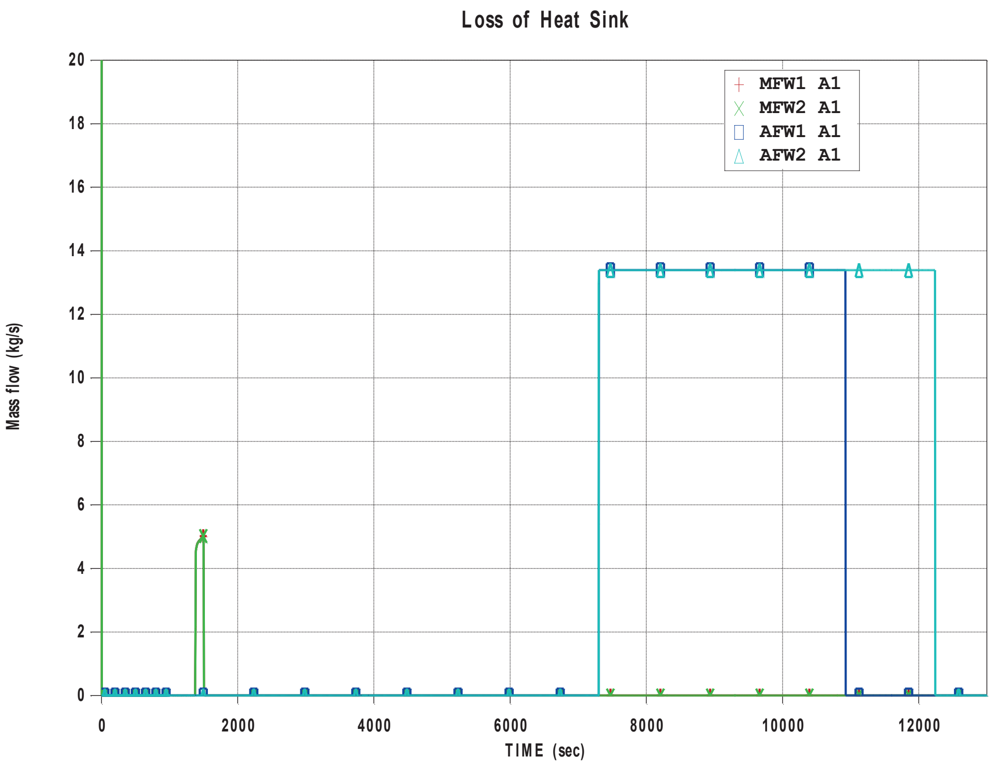

Figure 9: MFW and AFW Flow

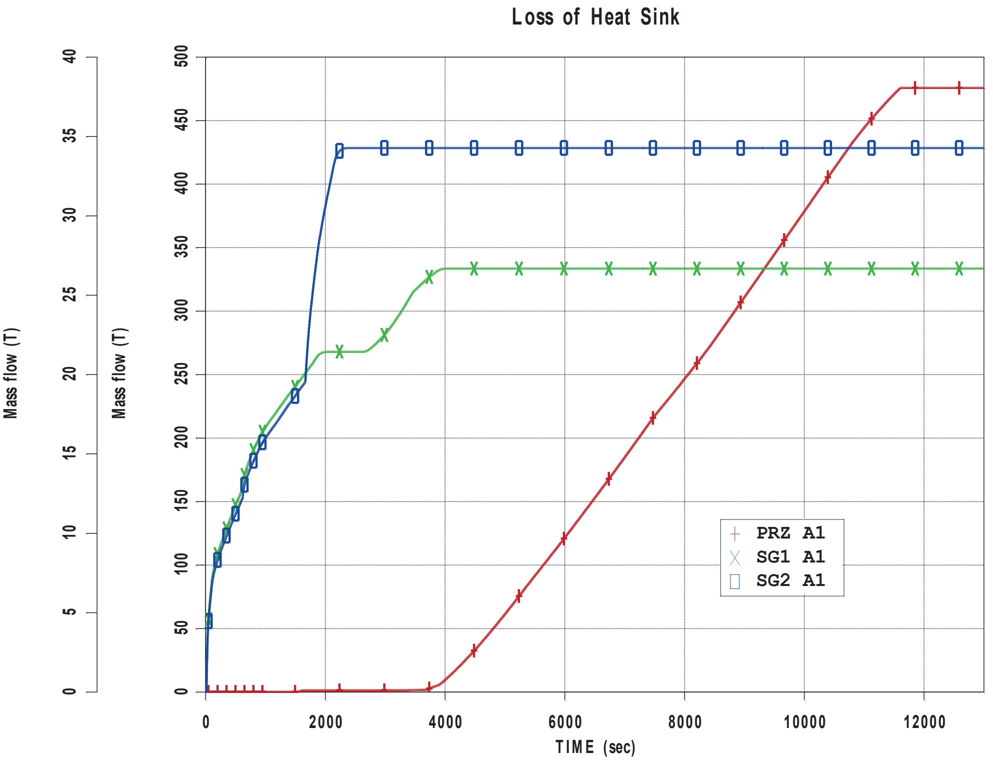

Figure 10: PRZ and SGs Valves Integral

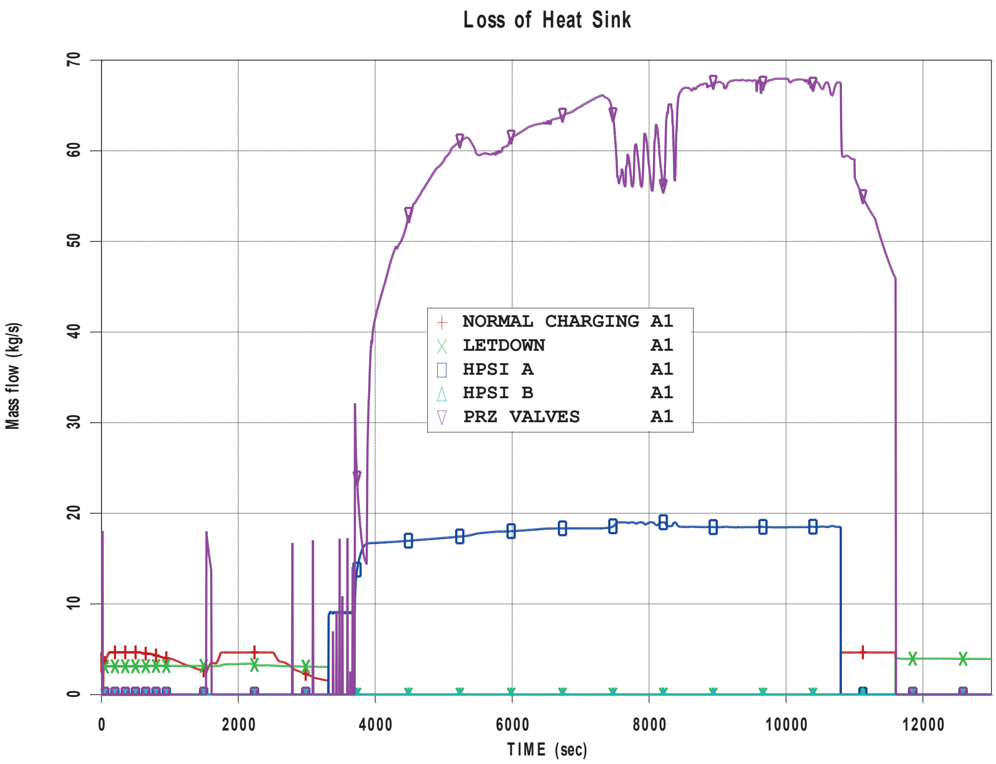

Figure 11: PRZ PORVs, Charging, Letdown and HPSI Mass Flow

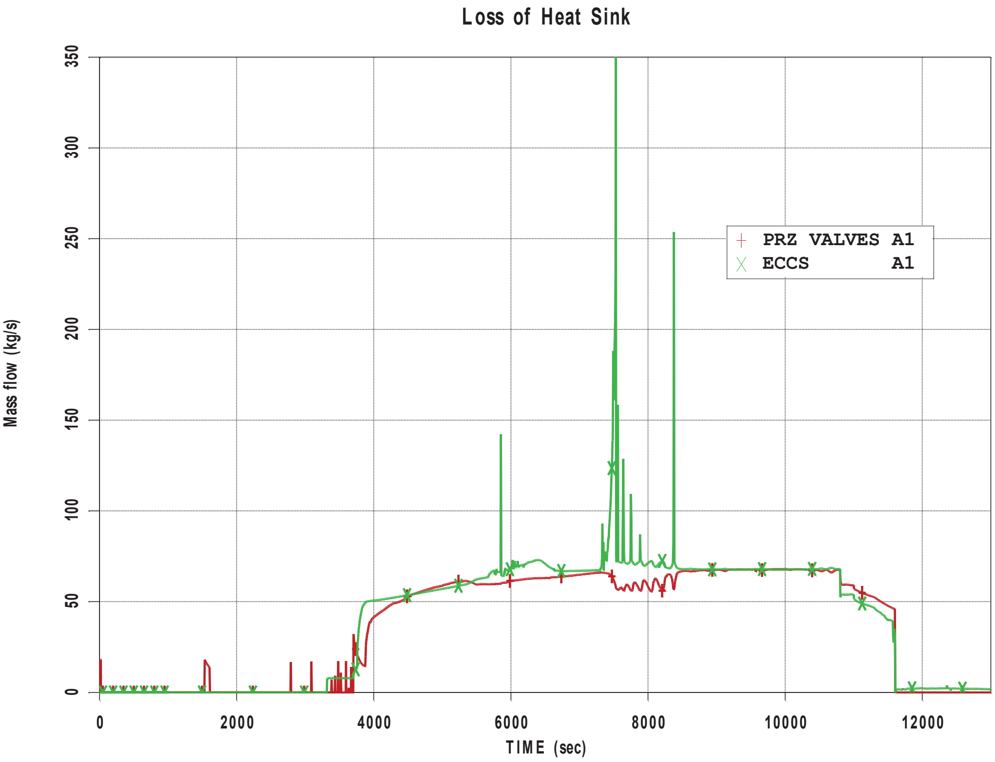

Figure 12: PRZ PORVs and ECCS Flow

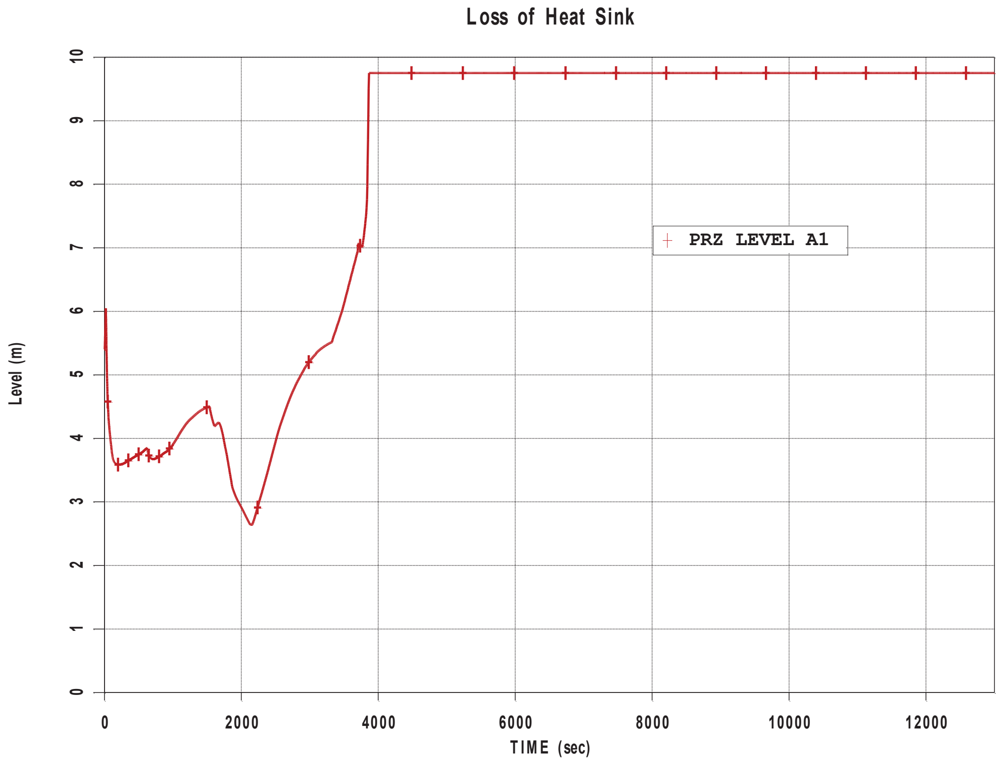

Figure 13: Pressurizer Level

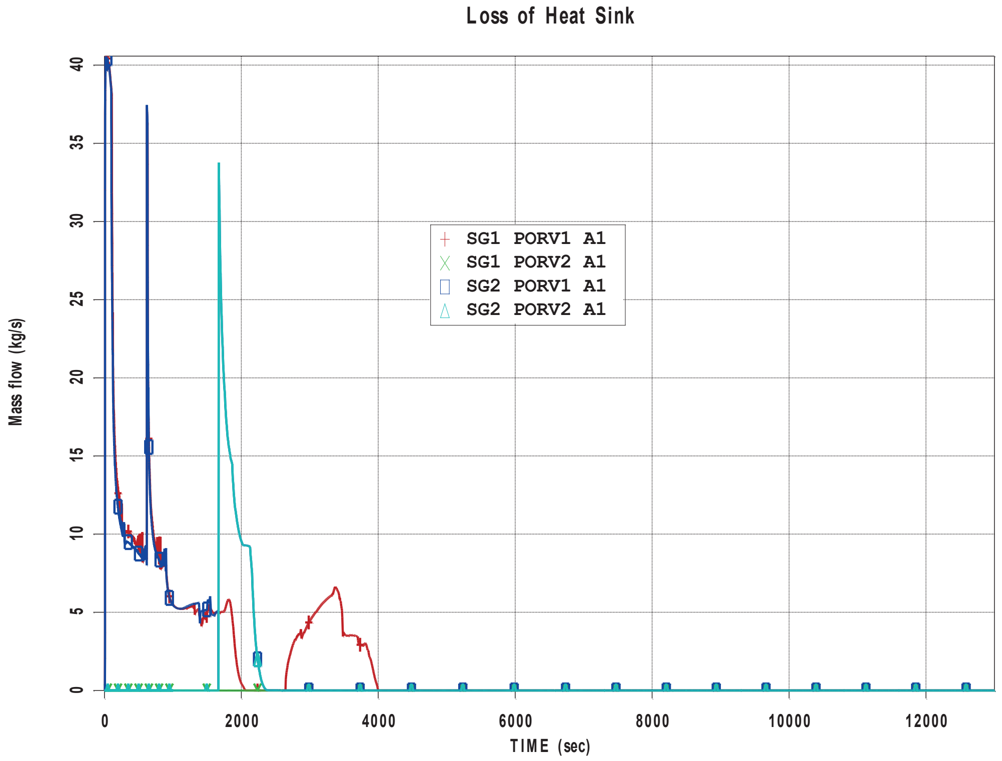

Figure 14: SGs PORVs Mass Flow

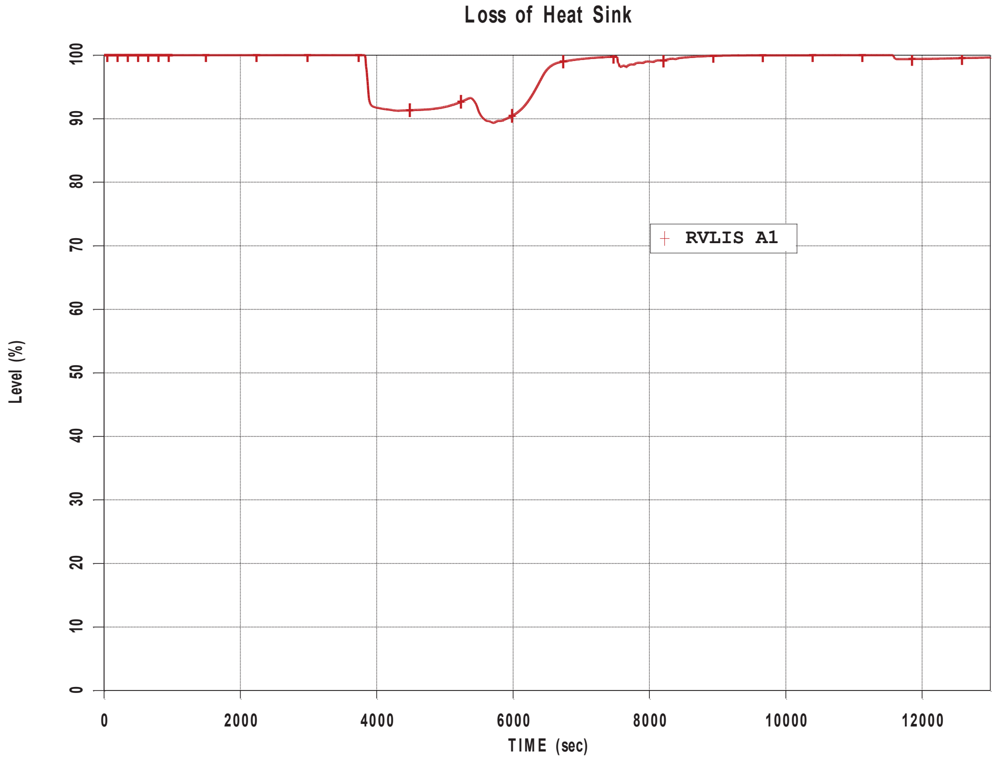

Figure 15: RVLIS Level

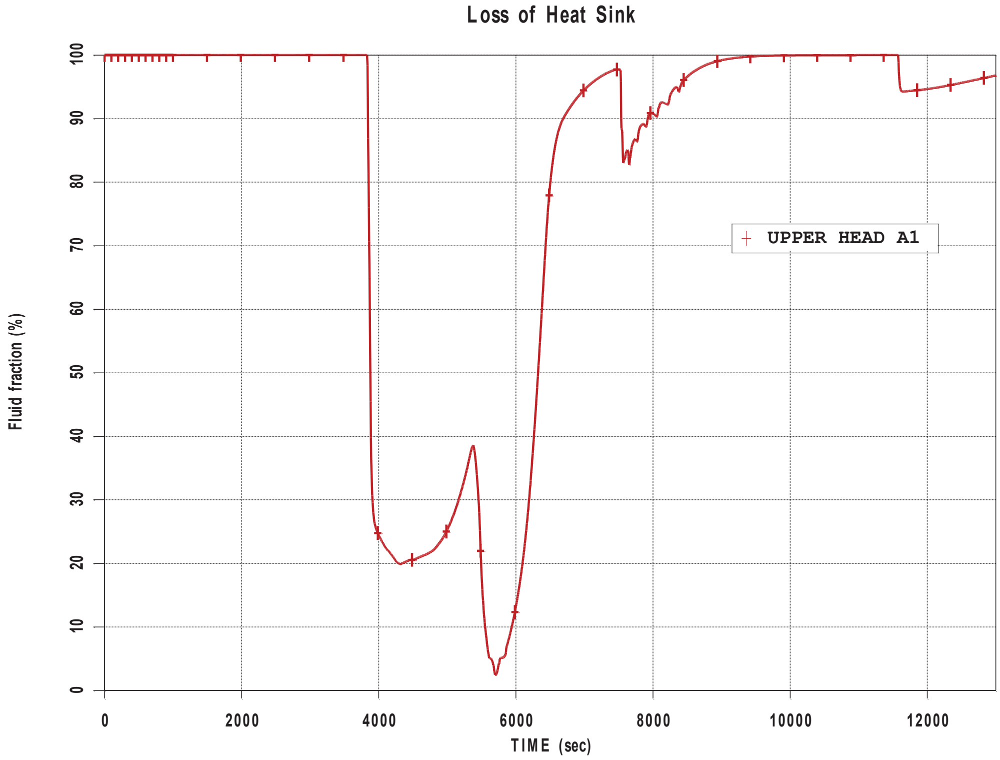

Figure 16: Upper Head Liquid Fraction

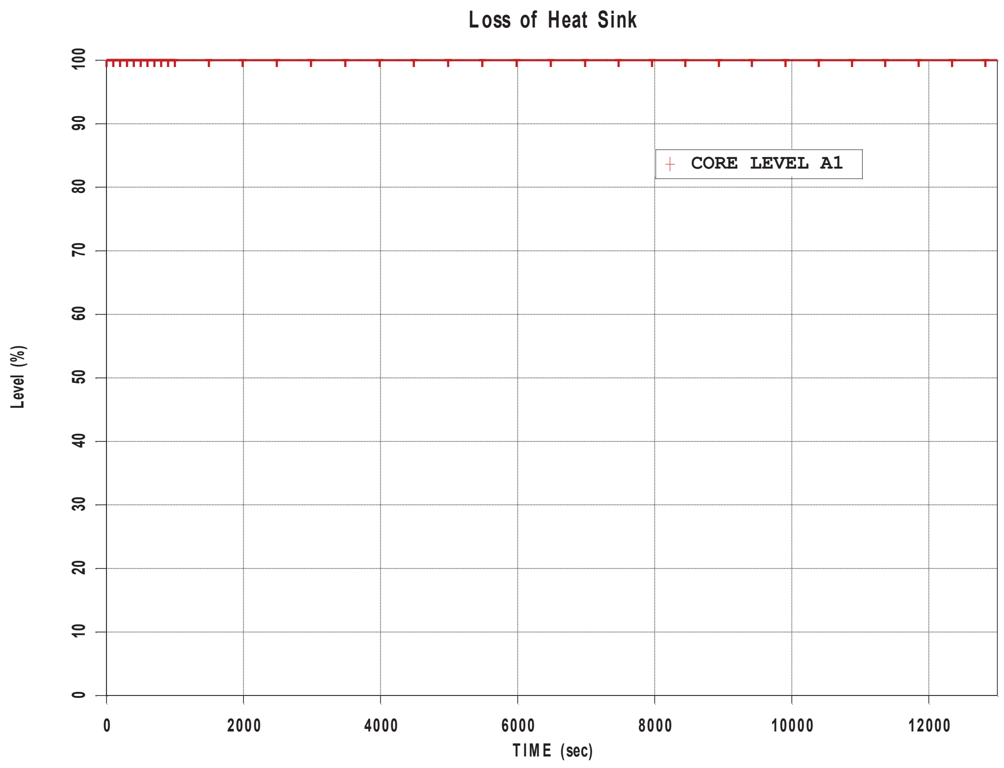

Figure 17: Core Level

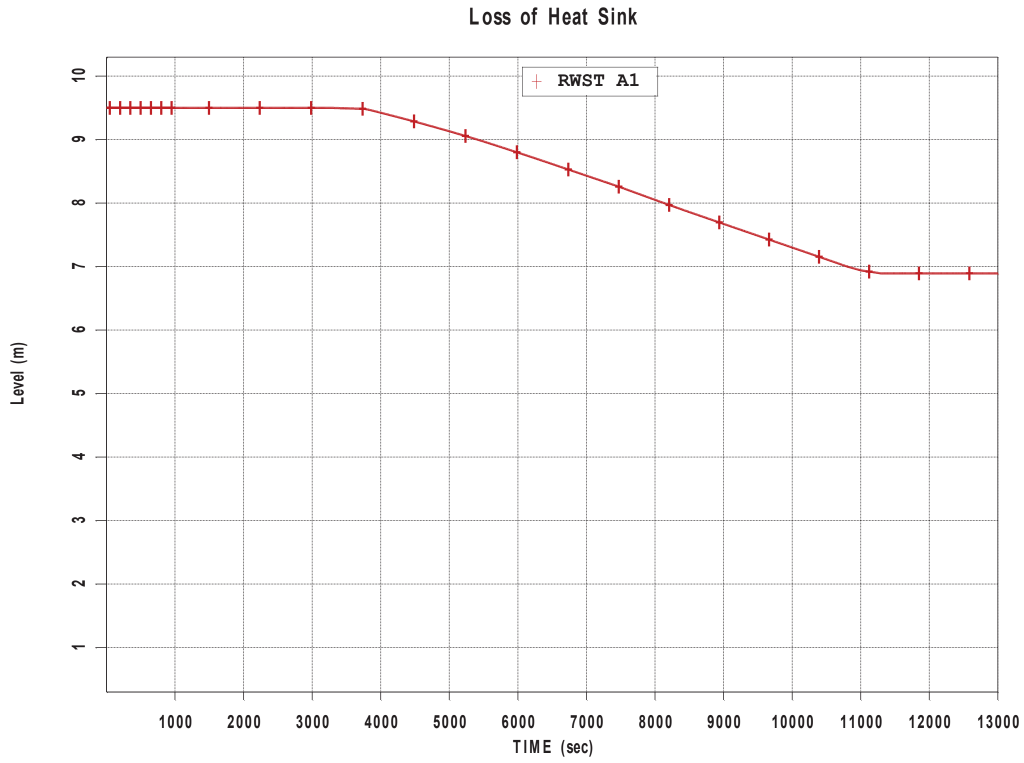

Figure 18: RWST Level

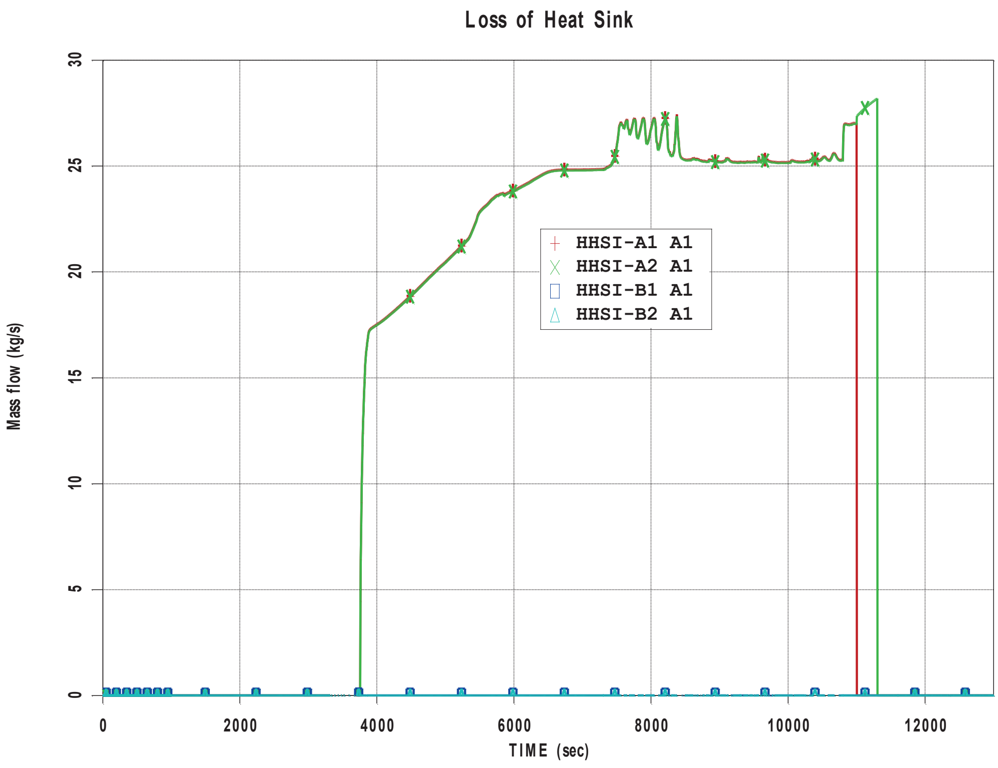

Figure 19: HHSI Pumps Mass Flow

6 CONCLUSION

The paper presents alternative possibility of EOPs and FRGs validation through desk top exercise. The desk top evaluation is conducted when plant full scope simulator is not suitable for given transient or does not have sufficient capabilities to realistically model plant response.

Validation scenario presented was LOHS, with bleed and feed technique initiated. Transient was computed using RELAP5 model which was suitable for the purpose. As presented, modelling of operator actions were done from the start of transient to its termination.

Procedures that were mostly covered are E-0, F-0 and FR-H.1, while ES-0.1 was just barely verified. While performing validation it cannot be expected to pass through every possible scenario and step of procedures. The aim is to focus on procedures intention, its background and the reasoning for operator actions as well as to cover as many steps as possible.

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