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Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models-Duane Arnold

Chapters 1 to 8

Appendices A to C

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ABSTRACT

This report extends the work documented in NUREG-2187, “Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Byron Unit 1,” issued January 2016, to the Duane Arnold Energy Center. Its purpose is to produce an additional set of best estimate thermal-hydraulic calculations that can confirm or enhance specific success criteria for system performance and operator timing found in the agency’s probabilistic risk assessment tools. Along with enhancing the technical basis for the agency’s independent standardized plant analysis risk (SPAR) models, these calculations are expected to be a useful reference to model end users for specific regulatory applications.

This report first describes major assumptions used in this study. It then discusses the major plant characteristics for the Duane Arnold Energy Center, in addition to the MELCOR model used to represent the plant. Finally, the report presents the results of MELCOR calculations for selected initiators and compares these results to SPAR success criteria, the licensee’s success criteria, or other generic studies.

The study results provide additional timing information for several probabilistic risk assessment sequences, confirm many of the existing SPAR modeling assumptions, and give a technical basis for a few specific SPAR modeling changes, including the following potential changes:

- Degraded high-pressure injection and relief valve Criteria (non-anticipated transient without scram): A single control rod drive pump injecting at the postscram increased injection rate is sufficient for reactor pressure vessel (RPV) water inventory makeup. Additionally, two control rod drive pumps injecting at the postscram injection rateprovide enough makeup to the RPV to facilitate a cooldown of the RPV to cold shutdown conditions. This increased injection is currently not queried in the SPAR models but could be added.

- Mitigating strategies usage: If diverse and flexible coping strategies (FLEX) are not available, success of long-term cooling for these scenarios is only possible with both anticipatory venting and condensate storage tank (CST) availability. Currently, CST availability is not queried in the SPAR models. This could be added for scenarios for which no alternate injection is available. For loss-of-offsite-power scenarios, FLEX injection led to success in all scenarios that gave FLEX credit. Given the ability of FLEX to prevent core damage, this confirms that the SPAR models should have FLEX equipment added.

- Emergency core cooling system injection following containment failure or venting: Depending upon the size of containment failure, wetwell and drywell pressure will fall, potentially to the point of allowing high-pressure injection restart following its loss. This action could be added to the SPAR models.

- Safe and stable end-state considerations: If the CST is unavailable, the long-term availability of high-pressure injection is questionable at best. CST should be queried when high-pressure injection systems are the source of long-term makeup. Additionally, increased postscram control rod drive hydraulic system injection is adequate for makeup. This increased injection is a candidate for inclusion in the SPAR model. Depressurizing when reaching the heat capacity limit curve is important, since the rate of

seal leakage, as well as the rate of injection, is pressure dependent. This depressurization is a candidate for consideration in the SPAR models.

FOREWORD

The U.S. Nuclear Regulatory Commission (NRC) uses its standardized plant analysis risk (SPAR) models to support many risk-informed initiatives. A number of processes ensure the fidelity and realism of these models, including cross-comparison with industry models, review and use by a wide range of technical experts, and confirmatory analysis. This report—prepared by the staff of the Office of Nuclear Regulatory Research, in consultation with the staff of the Office of Nuclear Reactor Regulation; experts from Energy Research, Inc. and Idaho National Laboratory; and the agency's senior reactor analysts—represents a major confirmatory analysis activity.

Probabilistic risk assessment (PRA) models for nuclear power plants rely on underlying modeling assumptions known as success criteria and sequence timing assumptions. These criteria and assumptions determine what combination of system and componentavailabilities will lead to postulated core damage, as well as the timeframes during which components must operate or operators must take particular actions. This report investigates certain thermal-hydraulic aspects of a particular SPAR model (which is generally representative of other models within the same class of plant design), with the goal of further strengthening the technical basis for decisionmaking that relies on the SPAR models. This report augments the existing collection of contemporary Level 1 PRA success criteria analyses and, as such, supports (1) maintaining and enhancing the SPAR models that the NRC develops, (2) supporting the NRC's risk analysts when addressing specific issues in the accident sequence precursor program and the significance determination process, and (3) informing other ongoing and planned initiatives. This analysis employs the MELCOR computer code and uses a plant model developed for this project.

The analyses summarized in this report provide the basis for confirming or changing success criteria in the SPAR model for the Duane Arnold Energy Center. Based on further evaluation, these results could apply to similar plants, while future analyses could apply to other design classes, as occurred in the past (see NUREG-2187, "Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Byron Unit 1," issued January 2016). The staff expects to continue its focus on confirming success criteria and other aspects of PRA modeling using its state-of-the-art tools (e.g., the MELCOR computer code) as it develops and improves its risk tools.

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ACKNOWLEDGMENTS

This report is the result of the efforts of many members of the U.S. Nuclear Regulatory Commission staff and the staff of its contractors, Energy Research, Inc., and Idaho National Laboratory. Furthermore, the report benefited greatly from the contributions of senior risk analysts and other selected agency staff members in specific areas of the project. The authors would especially like to recognize the support from Mahesh Chawla, James Corson, Ron Harrington, Tarek Zaki, and Joseph Staudenmeier. The authors also appreciate the assistance provided by the licensee's staff at the Duane Arnold Energy Center.

ABBREVIATIONS AND ACRONYMS

ac	alternating current
ADAMS	Agencywide Documents Access and Management System
ADS	automatic depressurization system
AIP	alternate injection procedure (EOP)
ANS	American Nuclear Society
AOP	abnormal operating procedure
ASP	accident sequence precursor
ATWS	anticipated transient without scram
BWR	boiling-water reactor
C	Celsius
CD	core damage
CDF	core damage frequency
CDS	condensate system
CFR	*Code of Federal Regulations*
CRDHS	control rod drive hydraulic system
CST	condensate storage tank
DAEC	Duane Arnold Energy Center
dc	direct current
ECCS	emergency core cooling system
ED	emergency depressurization
EDG	emergency diesel generator
ELAP	extended loss of ac power
EOP	emergency operating procedure
ESF	engineered safety feature
ESFAS	engineered safety features actuation system
F	Fahrenheit
FLEX	diverse and flexible coping strategies
FSG	FLEX support guideline
HCL	heat capacity limit
HCV	hardened containment vent
HCVS	hardened containment vent system
HPCI	high-pressure coolant injection
HPI	high-pressure injection
IORV	inadvertent open relief valve
IPE	individual plant examination
ISG	interim staff guidance
LCO	limiting condition for operation
LOCA	loss-of-coolant accident
LOCHS	loss of condenser heat sink

LODCA	loss of vital dc bus A
LODCB	loss of vital dc bus B
LOIAS	loss of instrument air system
LOMFW	loss of main feedwater
LOOP	loss of offsite power
LOOPGR	loss of offsite power grid related
LOOPPPC	loss of offsite power plant centered
LOOPWR	loss of offsite power weather related
LORWS	loss of river water system
LPCI	low-pressure coolant injection
LPCS	low-pressure core spray
LPI	low-pressure injection
MAAP	modular accident analysis program
MFW	main feedwater
MLOCA	medium loss-of-coolant accident
MSIV	main steam isolation valve
MSL	main steamline
NCV	noncited violation
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NRC	U.S. Nuclear Regulatory Commission
PB	Peach Bottom
PCPL	primary containment pressure limit
PCS	power conversion system
PCT	peak clad temperature
PID	proportional-integral-derivative
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
RPS	reactor protection system
RPV	reactor pressure vessel
RWCU	reactor water cleanup
SAMP	severe accident management procedure
SBO	station blackout
SC	success criterion/criteria
SDP	significance determination process
SEP	site emergency plan
SFP	spent fuel pool
SLC	standby liquid control
SLOCA	small loss-of-coolant accident

SNL	Sandia National Laboratories
SP	suppression pool
SPAR	standardized plant analysis risk
SRV	safety/relief valve
TAF	top of active fuel
TRANS	transient
UFSAR	updated final safety analysis report
UHS	ultimate heat sink
WW	wetwell

1 BACKGROUND

1.1 Confirmatory Success CriteriaProject

The success criteria for system performance and operator timing in the U.S. Nuclear Regulatory Commission's (NRC's) standardized plant analysis risk (SPAR) models are largely based on historical analysis, such as that in NUREG/CR-1150, "Severe Accident Risks: An Assessment for Five Nuclear Power Plants—Final Summary Report" (NRC, 1990), and NUREG/CR-4550, "Analysis of Core Damage Frequency from Internal Events Methodology Guidelines" (NRC 1987). Licensees have used a variety of methods to determine success criteria, including conservative design-basis analyses and more realistic best estimate methods. Consequently, in some situations, plants that should behave similarly from an accident sequence standpoint have different success criteria for specific scenarios. In addition, concerns periodically arise when reviewing licensee sequence timing and success criteria analyses in the course of performing event or condition risk assessments that could be better resolved with an updated set of thermal-hydraulic success criteria calculations. For these reasons, this report investigates particular success criteria and sequence timing issues of interest for the boiling-water reactor (BWR)/4 Mark 1, using the Duane Arnold Energy Center's (DAEC's) model. This report continues work previously documented for other plant type and scenario pairings in NUREG-1953, "Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Surry and Peach Bottom," issued September 2011 (NRC, 2011a); NUREG/CR-7177, "Compendium of Analyses to Investigate Select Level 1 Probabilistic Risk Assessment End-State Definition and Success Criteria Modeling Issues," issued May 2014 (NRC, 2014a); and NUREG-2187, "Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Byron Unit 1," issued January 2016 (NRC, 2016a).

As noted, this analysis uses the DAEC model. The staff chose this plant because, although it has a lower power, it is reasonably representative of the BWR/4 Mark 1. Specifically, DAEC is generally similar to the following other plants:

- Browns Ferry Units 1, 2, and 3
- Brunswick Units 1 and 2
- Cooper
- Dresden Units 2 and 3
- Hatch Units 1 and 2
- Fermi Unit 2
- Hope Creek Unit 1
- FitzPatrick
- Monticello
- Nine Mile Point Unit 1
- Oyster Creek
- Peach Bottom (PB) Units 2 and 3
- Pilgrim
- Quad Cities Units 1 and 2
- Vermont Yankee

However, all of these plants have design, operational, and licensing differences that should be considered before applying the results of this study to them.

1.2 Hazard, Mode, and Radiological SourceScope

As of model version 8.50, the DAEC SPAR model includes Level 1 at-power internal events, internal flooding, internal fire, tornado, and seismic initiators. These are all considered potentially within the scope of this project, although actual modeling may vary. Conversely, other hazards, Level 2 and Level 3 probabilistic risk assessments (PRAs), and the spent fuel pool (SFP) are all outside the project scope.

1.3 Issues To BeInvestigated

This report is not intended to comprehensively confirm all success criteria within the chosen plant's SPAR model but rather to focus on particular success criteria and sequence timing issues of interest to the significance determination process (SDP) and the accident sequence precursor (ASP) program, namely, those that have either been central to past analyses or that are expected to be central in upcoming analyses. It is often the case that modeling assumptions important to particular event or condition assessments are not also important in the baseline PRA, so it should be understood that examination of an issue here does not necessarily mean that it is a risk-significant issue in the overall plant risk. However, the types of assumptions that are made when determining plant success criteria can have a significant impact on the calculated risk profile and, therefore, on the outcome of the agency's risk-informed activities, such as SDP and ASP insights (i.e., green versus white findings).

From a spectrum of possible issues to be investigated, and in consultation with the NRC's risk analysts, researchers selected four issues (or categories of issues), as follows:

- degraded high-pressure injection (HPI) and relief valve criterion fornon-anticipated transient without scram (ATWS)scenarios
- mitigating strategies (namely diverse and flexible coping strategies (FLEX)) usagein loss of alternating current (ac) power and otherscenarios
- emergency core cooling system (ECCS) injection following containment failure or venting
- safe and stable end-stateconsiderations

Each of these issues is the topic of a specific section of this report. Each section starts by describing the basic issue or set of issues, lays out the calculations performed to investigate the issue(s), provides the results of those simulations, and draws conclusions with respect to PRA modeling.

The details of the scenarios to be considered appear later, but an example of a real-world situation that might benefit from the investigations in this report is the failure of the automatic condensate storage tank (CST) switchover for high-pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC). During 2015, a relay at DAEC necessary to perform this function was in a degraded state, leading to a very low safety significance noncited violation (NCV) (NCV 05000331/2015004-02), as documented in the associated NRC integrated inspection report (NRC, 2015a). The dominant (yet still small) contributor to the risk assessment was a small loss-of-coolant accident (LOCA), followed by failure of all HPI sources and the failure to depressurize and use low-pressure sources. There are fundamental mission time considerations embedded in this and most risk assessments. For instance, if a more restrictive end-state definition were used (in lieu of the notional 24-hour determination currently used in the SPAR model), would other initiators (namely, transients) now experience core damage for this same set of events? If so, and if the increase in core damage frequency (CDF) were large enough to warrant consideration of recovery in the risk assessment, would use of the FLEX equipment (assuming there was an operational basis[1] for its deployment) have provided a viable alternative success path from the perspective of sequence timing and success criteria?

1.4 Plant Selection

Based on input from the NRC's risk analysts, the authors determined that the BWR Mark I would be the best subject design class to pursue, in light of the relative importance of issues to be investigated and the vintage and breadth of contemporary confirmatory analyses. The authors surveyed the suite of operating BWR Mark I plants, weighing characteristics such as thermal power level; SPAR internal events station blackout (SBO) contribution; SPAR model scope, design, and operational considerations (e.g., similarity of cross-tying capabilities, number of trains of emergency power); and the utility's engagement in risk-informed activities. Ultimately, the authors determined that DAEC provided the best mix of these characteristics, despite having the lowest power level of all operating BWR/4 Mark I plants. Table 1-1 Major Plant Characteristics for DAEC shows the major plant characteristics for DAEC.

Table 1-1 Major plant characteristics for DAEC

Characteristic	Value
Owner/operator	NextEra
Design type	General Electric BWR/4 Mark I
Power level	1,912 megawatts thermal (MW(t))
HPI and makeup systems	RCIC HPCI Control rod drive hydraulic system (CRDHS) Reactor water cleanup (RWCU) system (not an injection system)
Safety and safety/relief valves (SRVs)	Eight total valves—two per steamline,[2] encompassing: - two Dresser Maxiflow spring-loaded safety valves, one each on steamlines B and C - six Target Rock SRVs, four with automatic depressurization system (ADS) function and two with low-low setpoint function
Low-pressure injection (LPI) systems	Core spray Low-pressure coolant injection (LPCI) mode of reactor heat removal (RHR)
Containment systems	Suppression pool cooling (SPC) mode of RHR Containment spray mode of RHR Hardened containment vent system (HCVS)

1 What represents an operational basis for deployment will depend, in part, on application-specific guidance that the NRC is developing.

2 Figure 5.1-1, Sheet 1, in the final safety analysis report (FSAR) shows these valves, discussed in FSAR Section 5.2.2.4 (DAEC, 2005).

Table 1-1 Major plant characteristics for DAEC (continued)

Characteristic	Value
	Other wetwell (WW) and drywell venting paths
Volumes in cubic meters (m^3): • Drywell free volume • Suppression pool water volume • CSTs water inventory	• ~3,680 m^3 [130,000 cubic feet^3(ft^3)] • ~1,670 to 1,740 m^3 (440,000 to 460,000 gallons) • ~1,514 m^3 (400,000 gallons) (both tanks combined)*
Licensed method for compliance with Title 10 of the *Code of Federal Regulations* (10 CFR) 50.63, "Loss of All Alternating Current Power" (the SBO rule)	4-hour coping time, based on NUREG-1776, Appendix B (NRC, 2003) The initial actions are the same for 10 CFR 50.63 and FLEX, based on the licensee's integrated plan in response to EA-12-049 (NRC, 2012a).

* The value cited here is from page 6.3-8 of the UFSAR. DAEC actually has two CSTs that are always interconnected. The technical specification limit on CST inventory is significantly lower that this value and relates to CS suction requirements (level ≥3.4 meters [11 feet] in one tank or ≥2.1 meters [7 feet] in both tanks).

Safety valves discharge directly to the drywell and have no restrictions. The SRVs discharge into the suppression pool through a discharge pipe on each valve. The SRVs are nitrogen operated. The solenoids controlling the nitrogen supply are powered from the 120-volt (V) instrument ac bus. On loss of power from one bus, the load can be manually transferred to the alternate essential bus. On the receipt of a containment isolation signal, the nitrogen supply isolation valves close, and the basic valve logic does not permit reopening until the isolation signal is cleared. Isolation override circuitry and separate control switches for the isolation valves defeat the isolation logic and provide safety-grade power to the isolation valves to allow opening. The two non-ADS SRVs include a low-low setpoint function that modifies the automatic opening and closing relief set points following any SRV opening at its normal steam pilot setpoint to mitigate the induced high-frequency loads on the containment and thrust loads on the SRV discharge lines (see UFSAR Sections 5.4.13.2 and 7.6.5).

More information about DAEC's design and operation appears throughout the remainder of the report and, in particular, in Section 2.3.5 The environmental report associated with license renewal (DAEC, 2008a) contains a dated (circa 2008) synopsis of the DAEC PRA development history and the current (at that time) estimated risk profile (e.g., dominant initiators, Fussel-Vesely importance measures).

2 MAJOR ASSUMPTIONS AND PEER REVIEW DESCRIPTION

2.1 Major Assumptions

Assumptions made during the conduct of this study are documented throughout this report. For example, assumptions related to particular calculations are discussed in the section where those calculations are documented. Table 2-1 collects major assumptions into one table.

Table 2-1 Major assumptions in the MELCOR calculations

Category	Assumption	Comments
General	A **core damage** surrogate of peak nodal temperature equal to 1,204 degrees Celsius (degrees C) (2,200 degrees Fahrenheit [degrees F]) is used.	This selection has been previously justified for this type of MELCOR analysis (see Section 2 of NUREG-2187 [NRC, 2016a]).
	Wetwell water is well mixed within each azimuthal node.	The wetwell model is not set up to capture thermal stratification. However, the SRV outlet is low in the wetwell, so thermal stratification is not expected to be significant in the scenarios modeled in this report because of mixing induced by SRV operation.
	Power conversion [steam] system (PCS) is not modeled in detail.	The turbine and condenser are not modeled in detail. They are simply modeled as a heat/energy sink for steam passing through the steamlines.
	Unless otherwise stated, a loss of feedwater also results in an eventual loss of the PCS for pressure control.	A train of feedwater/condensate is needed for the condenser to be available long term, since the condenser tubes will eventually be covered and steam condensation would not be effective.[1]
	The CRDHS injection rate is not increased by default after a scram.	The CRDHS pump is able to inject at an increased rate but the postscram increase is commonly discounted in analyses. A “nominal” injection rate is assumed by default of a single CRDHS pump operating at the prescram rate of 9.61 m^3/hour (hr) (42.3 gallons per minute (gpm)).
	LPCI and CRDHS operated in “batch mode.”	Code-automatic modeling assumes these pumps are turned off at Level 8 and on at Level 2. This logic is regarded as modeling operator action, which is desirable to assume and credit for numerical convenience. Only enhanced CRDHS rates are given this control.

[1] Unless otherwise stated, the PCS is not immediately made unavailable upon a loss of main feedwater (LOMFW). Instead, turbine bypass valves modulate closed until the main steam isolation valves (MSIVs) shut on low main steamline pressure. This MSIV closure signal was found to be not plant-actual (at DAEC, this signal is only active when the turbine is running), but the behavior it elicits; namely, the eventual loss of the condenser’s ability to condense steam, is thought to be. However, there is some uncertainty as to when the PCS would be lost, and the convention for the licensee’s PRA is to assume it is immediately unavailable. Throughout this document, a number of sensitivity calculations include a loss of the PCS occurring simultaneously with the loss of feedwater.

Table 2-1 Major assumptions in the MELCOR calculations (continued)

Category	Assumption	Comments
	The 18-inch drywell and wetwell vents are assumed to fail directly into the reactor building.	It is assumed that venting through the old drywell or wetwell vents opens a flowpath directly to the reactor building because of a ductwork failure. The old vents are unhardened and could therefore leak or rupture when demanded.
	The net positive suction head (NPSH) available to RCIC/HPCI is approximated using dynamic wetwell conditions postsimulation.	The NPSH available for RCIC is approximated using the equation $NPSH = \frac{P_{WW}}{g\rho} - (h_{WW} - h_{RCIC}) - h_{loss} - \frac{P_V}{g\rho}$ where the loss term is derived using conditions given in the UFSAR (NPSH is 7.86 meters (25.8 feet) when wetwell water temperature is 76.7 degrees C (170 degrees F), the wetwell water level is 3.083 meters (10.116 feet), and it is at atmospheric pressure). For HPCI, the same loss term is used with a plant-actual for h_{HPCI}.
Core modeling	Axial power profile is derived from information provided by NextEra on a per-assembly basis for middle of cycle.	
	Bypass flow is assumed to be 15%.	This refers to the flow that does not transit the core inside the fuel assembly channel boxes.
	The core nodalization consists of 10 axial levels, 5 radial divisions.	This is standard MELCOR modeling practice (see for example NUREG/CR-7110 [NRC, 2013b]). Given the large amount of effort required to change the nodalization, this was not investigated in a sensitivity analysis.
ECCS operation	Setpoint for RCIC/HPCI turbine trip on low reactor pressure vessel (RPV) pressure is reduced to 0.52 megapascal (MPa) (75 pounds per square inch, gauge (psig)).	In earlier versions of the MELCOR deck, there was a low primary side pressure trip setpoint of 1.03 MPa (150 pounds per square inch, differential (psid)) between the wetwell and RPV steamlines (taken from UFSAR Table 15.0-6, p. 124/141). This was changed in later versions of the deck, since it did not appear to agree with what is in the emergency operating procedures (EOPs) (they state that RCIC is available down to RPV pressure of 1.03 MPa [150 psig]). In addition, the RCIC system description gives an RPV pressure of 0.52 MPa (75.0 psig) as the trip setpoint for the RCIC turbine. Even though a differential pressure setpoint is more realistic, the RCIC system description and the PB precedent were followed with a trip setpoint of 0.52 MPa (75.0 psig).
	Injection of the ECCS pumps is operated in "batch mode" with an expanded upper bound.	The pump is either throttled full open or is secured as RPV water level reaches a lower and upper level setpoint (by default, Level 2 and Level 8, respectively). Unless otherwise stated, the upper bound is expanded per EOP-1 recommendation to be just below the steamlines.
	RCIC/HPCI pumps trip on high steamline level.	The flooded main steamline trip occurs when the water level rises to approach the bottom of the horizontal run of the main steamline piping. This piping layout is not plant specific to DAEC. This trip is meant to capture the uncertainty associated with turbine operation with high water content in the steamlines.

2.2 Description of the DAEC MELCOR Model

The DAEC model used for this analysis is based on the as-built, as-operated plant, as understood from information compiled from discussions with plant operation and engineering staff, site visits, and a review of plant documentation and operating procedures. Where information about DAEC was unavailable, the model uses applicable data from a PB MELCOR model.[2] All calculations used MELCOR 2.2.9541. The MELCOR input deck used for the calculations described in this report was under active development throughout the project. This was to correct code errors, improve logic, and better reflect the as-operated plant. APPENDIX A to this report describes the code version used for each of the calculations performed for this report. In general, all of the calculations described in Chapters 3–6 used Revision 7, with minor changes made as needed.

The following tables (Tables 2-2 through Table 2-6) present a high-level capturing of the structures, systems, components, and operator action surrogates that are represented in the DAEC MELCOR model developed for this project. Understand that MELCOR simulates the thermal-hydraulic and post-core-damage behavior of the plant, in terms of the major structures, systems, components, and actions that affect this response. The MELCOR model is somewhat like the software used to support nuclear power plant simulator functionality, except that, in the case of typical MELCOR models, there is more capability in modeling the response after fuel heatup and less capability with respect to modeling support systems, normal operation, and the human-machine interface. Throughout these tables, the term "relevant" refers to things that are "known" to the MELCOR model (and thus relevant) such as RPV water level, versus things that are not "known" to the MELCOR model (and thus are not relevant), such as high filter/demineralizer differential pressure.

Table 2-2 Structures included in the DAEC MELCOR model

Structures	Comments
Drywell	Includes drywell walls and floor, pedestal, pedestal doorway, CRDHS removal hatch, CRDHS hydraulic pipe openings, primary vacuum breakers, main vents, normal leakage path, liner/flange failure path, and old vents.
Suppression pool	Includes a pool of water, hardened vent, vacuum breakers, inlet for RCIC/HPCI/SRVs, RCIC/HPCI/RHR suction.
Reactor building	Includes all levels, all major rooms, the main equipment hatch, the rail bay door, blowout panels, normal leakage, and overpressure failure (does not include the capability to analyze refueling configurations or steamline breaks).
SFP	Only modeled as a tank of water with the ability to specify a volumetric heat generation rate for instances where SFP cooling would be failed (thus allowing a simplistic model of the steam generation rate for an extended loss of pool cooling occurring in conjunction with a reactor accident).

[2] NUREG/CR-7110, "State-of-the-Art Reactor Consequence Analyses Project," Volume 3, "Peach Bottom Integrated Analysis," Revision 1, issued May 2013, used the same model.

Table 2-3 Systems included in the DAEC MELCOR model

Systems	Comments
Nuclear steam supply system	Includes RPV, recirculation loops, jet pumps, core (excluding neutronics modeling), dryers/separators
Main steam	Simplified—includes main steam isolation valves (MSIVs), flow restrictors, turbine bypass valves, abstraction of the turbines, main condenser including the hotwell, and the condensate system[3]
RCIC	Includes emergency makeup function by modeling steam extraction and suppression pool discharge, injection from CST or suppression pool and associated depletion of water source, pump curve, control functions to mimic manual and automatic modes of operation, relevant automatic initiation logic, relevant automatic isolation logic, relevant turbine trip logic, relevant pump throttling logic, and relevant additional trip logic
HPIC	Includes emergency makeup function by modeling steam extraction and suppression pool discharge, injection from CST or suppression pool and associated depletion of water source along automatic switchover, pump curve, control functions to mimic manual and automatic modes of operation, relevant automatic initiation logic, relevant automatic isolation logic, relevant turbine trip logic, relevant pump throttling logic, and relevant additional trip logic
CRDHS	Includes pump curve and injection sources for each train; also includes option for increased postscram injection rate from one or two pumps
RWCU	To include normal operation suction from the bottom head and recirculation loops, return to the feedwater lines, basic differential pressure and temperature of system, relevant isolation signals, and relevant trip signals
Containment spray mode of RHR	Includes pump curve and injection sources for each train
LPCI mode of RHR	Includes pump curve and injection sources for each train and the ability to model the loop select logic for RHR injection
Shutdown cooling mode of RHR	N/A, not used
Suppression pool cooling mode of RHR	Simplified—each RHR train includes one heat exchanger, which removes heat from the water at a calculated rate
ADS	See “SRVs” in Table 2-4
Wetwell sprays	Includes pump curve and injection sources for each train of RHR
Drywell venting	Includes the old, nonhardened 18-inch vent to the reactor building.
Wetwell venting	Includes both the old, nonhardened wetwell 18-inch vent and the hardened wetwell vent path being used for Order EA-13-109 compliance[4] (the hardened vent to the environment)
Reactor protection system (RPS)	Most but not all reactor trip signals (i.e., signals generated by unmodeled aspects such as neutronics) are modeled.
Engineered safety features (ESFs)	All relevant ESF actuation system (ESFAS) logic is modeled.

[3] Note that NRC training material provides a convenient pressure drop estimate of 55 psig between the RPV steam dome and the turbine control valves (NRC, 2002).

[4] Based on (NextEra, 2014b), this vent is designed to remove 191.2 megawatts (MW) at a wetwell pressure of 0.37 MPa (53 psig), via a 25.4-centimeter (10-inch)-diameter pipe.

Table 2-4 Other components included in the DAEC MELCOR model

Components	Comments
SRVs	Valves modeled individually or in banks to cover the four relevant functions described in Section 5.4.13.2 of the DAEC UFSAR
Main steamline (MSL) flow restrictors	N/A
MSIVs	Includes an assumption on default closure time of 4 seconds, reflecting typical design considerations (long enough for RPS to trip the reactor to minimize a power/pressure transient but short enough to minimize inventory loss)
FLEX pump injection	Includes pump curve, injection, and level control logic
CST	Simplified—a tank of water that automatically refills until reactor trip to mimic the condenser and feedwater systems that control CST level during normal operation
Reactor building vent damper	Includes the ability for user to open the reactor building vent damper located at the top of the reactor building

Table 2-5 Operator action surrogates included in the DAEC MELCOR model

Operator Actions	Comments
Heat capacity thermal limit depressurization	Includes logic to automatically mimic manual operator actions to "walk down" the heat capacity limit (HCL) curve[5]
Controlled 55.6 degrees C/hr (100 degrees F/hr) depressurization	Includes logic to automatically mimic manual operator actions to depressurize at a cooldown rate of 55.6 degrees C/hr (100 degrees F/hr)
Drywell and wetwell venting	Includes logic to mimic operator action to vent the drywell and wetwell and maintain a user-defined target pressure band
RCIC throttling	Includes logic to throttle RCIC injection rate to maintain a desired level band
RCIC/HPCI expanded level control	Includes logic for RCIC batch injection using an expanded level band that assumes operator action to secure the pump just before level reaches the steamlines.

Table 2-6 Default MELCOR modeling values

Modeling Area	Parameter	Value[1]
Reactor coolant system (RCS)		
	Operating pressure	7.172 MPa (1,040 psig)
	Vessel free volume	297.92 m^3 (10,521 ft^3)
	Level 8 (Hi Level)	14.059 meters (211 inches above TAF[2])
	Normal water level	13.652 meters (191 inches above TAF[2])
	Level 2 (LoLo Level)	11.735 meters (119.5 inches above TAF[2])
	Top of active fuel (TAF)	8.914 meters (29.25 feet)
Balance of plant		
	Initial CST water volume	1,185.6 m^3 (313,200 gal)
		9.61 m^3/hr (42.3 gpm)

1 All elevations are relative to the bottom of theRPV.

2 The TAF referenced here is a pre-uprate level of 28.74 feet (8.761 meters).

[5] The calculations below use the summary HCL curve in EOP-2; however, the alternate HCL curves were provided.

Table 2-6 Default MELCOR modeling values (continued)

Modeling Area	Parameter	Value[1]
	RHR heat exchanger water temperature	29.4 degrees C (85 degrees F)
ECCS/ESF		
	Lowest SRV relief setpoint	7.65 MPa (1,110 psid)
	ADS activation	10.325 meters (33.87 feet) (Level 1)
	Default RCIC level on/off	11.735 meters/13.957 meters (38.50 feet/45.79 feet)
	Default HPCI level on/off	11.735 meters/13.907 meters (38.50 feet/45.63 feet)
	RCIC trip setpoints:	
	- Flooded MSL	Water in line rises above 2.3 meters (7.5 feet)
	- Loss of ac/dc power	
	- Low MSL pressure	1.001 MPa (145.2 psid)
	- High turbine exhaust pressure	0.345 MPa (50 psig) in the wetwell
	- Low wetwell water level	Disabled
	- High wetwell water temperature	121 degrees C (250 degrees F)
	HPCI trip setpoints:	
	- Flooded MSL	Water in line rises above 2.3 meters (7.5 feet)
	- Loss of ac/dc power	
	- Low MSL pressure	1.036 MPa (150.3 psid)
	- High turbine exhaust pressure	0.965 MPa (140 psig) in the wetwell
	- Low wetwell water level	Disabled
	- High wetwell water temperature	121 degrees C (250 degrees F)
	HPCI suction swap-over to torus on high wetwell water level	-12.910 meters (42.356 feet)
	RCIC injection rate	90.8 m^3/hr (400 gpm)
	HPCI injection rate	681.4 m^3/hr (3,000 gpm)
FLEX		
	FLEX pump injection rate	Follows a provided pump curve
	FLEX pump shutoff head	0.758 MPa (110 psig)
Containment		
	Initial drywell temperature	44.72 degrees C (112.5 degrees F)
	Initial wetwell temperature	30.8 degrees C (87.5 degrees F)
	Initial wetwell level	-13.037 meters (-42.772 feet)
Other operator actions		
	Containment venting setpoints	Primary containment pressure limit (PCPL) requirement: .467 MPa (53 psig)
		Anticipatory for hardened containment vent (HCV): 0.170 MPa (10 psig)
		Anticipatory 18-inch drywell and wetwell vents: 0.205 MPa (15 psig)

[1] All elevations are relative to the bottom of the RPV.

2.3 Shakedown and Benchmarking of the DAEC MELCOR Model

2.3.1 Steady State

Before performing a MELCOR calculation, it is considered modeling best practice to perform a preaccident steady-state calculation to allow the problem to settle down to a steady state that adequately agrees with normal operations. Table 2-7 presents a number of DAEC plant-specific parameters and how MELCOR compares at the end of the 300 seconds steady-state calculation.

Table 2-7 Comparison of MELCOR-predicted steady-state to plant conditions.

Parameter	Plant		MELCOR
	Value	Reference	
Reactor thermal power, MW(t)	1,912	Updated Final Safety Analysis Report (UFSAR) Figure 15.0-3 (DAEC, 2005)	1,912
RPV dome pressure, MPa	7.172	UFSAR Figure 15.0-3 (DAEC, 2005)	7.172
RPV Dome temperature, kelvin (K)	–	–	560.7
Saturation temperature at RPV dome pressure, K	560.7	Steam tables; 7.172 MPa	560.7
Steam flow rate, kilograms per second (kg/s)	1,052.3	UFSAR Figure 15.0-3 (DAEC, 2005)	1,048.6
Feedwater flow rate, kg/s	1,049.7	UFSAR Figure 15.0-3 (DAEC, 2005)	1,047.2
CRDHS flow rate, kg/s	2.646	UFSAR Figure 15.0-3 (DAEC, 2005)	2.64
Heat loss from cleanup/demineralizer, MW(t)	2.7	UFSAR Figure 15.0-3 (DAEC, 2005)	2.7
Feedwater temperature, K	495.0	UFSAR Figure 15.0-3 (DAEC, 2005)	495.1
Downcomer water temperature, K	551.5	UFSAR Figure 15.0-3 (DAEC, 2005)	553.2
Core channel flow rate, kg/s	6,173.9 (for the sum)	UFSAR Figure 15.0-3 (the MELCOR sum is 6,176.4) (DAEC, 2005)	5,261.6
Core bypass channel flow rate, kg/s			914.8
Total recirculation pump flow rate, kg/s	2,670.1 (28,035 gpm) per pump)	UFSAR Table 5.1-1 (DAEC, 2005)	2,660.5
Total flow entrained into jet pumps, kg/s	3,503.8	Previous two items	3,513.2
Pressure drop across the core, bar-d	3.96 (57.4 psid)	UFSAR p. 15.3-56 (DAEC, 2005)	3.96
Downcomer water level (above vessel bottom), meters	13.652	Modular Accident Analysis Program (MAAP) variable ZWNORM	13.652

2.3.2 Comparison to Select Licensing-Basis Analysis

Licensing-basis accident analysis can be helpful for ensuring that PRA-related MELCOR calculations show the expected general trends and thus for identifying errors or important omissions in the modeling. Only qualitative or semiquantitative comparisons are appropriate, in that licensing-basis analysis deliberately employs initial and boundary conditions that attempt to envelope the plant's response and thus deviate from the best estimate plant response.

The shakedown calculations used Revision 5 of the DAEC MELCOR model with MELCOR 2.2.9541. In the process of performing these scenarios, minor modifications and corrections were made to the deck. Revision 6 of the DAEC model incorporated these changes, described below.

2.3.3 Application of the Baseline Small Loss-of-Coolant-Accident Sequence

Section 3 addresses the modeling and analysis of sequences involving use of the small LOCA (SLOCA) equipment in more detail. Here, the SLOCA scenario that is analyzed from the UFSAR is considered as one means of validating the DAEC MELCOR model.

2.3.3.1 Baseline Sequence Narrative

Coincident with the initiation of the break, a complete loss of offsite power (LOOP) is assumed to occur. Reactor coolant begins to exit the vessel rapidly into the drywell at the critical mass flux, and the reactor vessel water level begins to drop, as does the reactor pressure. The reactor is assumed to scram immediately. The emergency diesel generators (EDGs) start on the LOOP condition, and all loads are stripped off the essential ac buses. The nonessential buses are lost, leading to a loss of feedwater and a recirculation pump coastdown.

As the RPV level reaches the various level setpoints, ECCS systems are actuated (the actuation on high drywell pressure is conservatively ignored to delay injection), vessel isolation signals are generated, and LPCI loop select logic actuates to determine which recirculation loop is broken and, depending upon the assumed break size, either successfully selects the nonbroken loop (for larger breaks) or the broken loop (for smaller breaks). If the plant had previously been operating in single loop recirculation mode, loop select logic would trip the running recirculation pump and effect a short-time delay to allow it to coast down before it selects the "broken" recirculation loop. The reactor level continues to drop and uncovers the fuel, which begins to heat up.

Once the EDGs are up to speed, the output breaker closes on the essential ac buses, and the low-pressure ECCS pumps (and other essential loads) are sequenced onto the buses, the pumps start, and their minimum flow bypass valves open 10 minutes into the transient. The ADS actuation logic initiates on the lowering RPV level and ECCS pumps running, the ADS 2-minute time delay expires, and the valves open. Once the reactor pressure decreases to the respective permissive setpoints, the injection valves for core spray and LPCI (based upon the "chosen" loop-by-loop select logic) open and allow injection to begin to the RPV, which occurs 10 minutes into the transient. The injection refills the lower vessel plenum area, the water level inside the core shroud rises, and the fuel stops heating up. Water level is maintained at the top of the jet pumps and long-term recovery mode is entered.

At this point, operators activate the RHR heat exchanger in the operating RHR loop. One RHR pump at 1,090 m^3/hr (4,80 gpm) is realigned so that flow goes through the heat exchanger before returning to the suppression pool. The other RHR pump is shut down. This configuration is maintained throughout the accident. The core spray pump injection to the vessel is maintained at 704.1 m^3/hr (3,100 gpm).

2.3.3.2 Other Licensee Analysis Assumptions of Note

An SLOCA is defined in the UFSAR as one that does not, of itself, depressurize the RCS to allow LPI but requires the use of ADS. The break size of the SLOCA varies from 9.3 cm^2 (0.01 ft^2) to 93 cm^2 (0.1 ft^2) to cover the range of small breaks.

The loss of Division II of 125V direct current (dc) is the limiting single failure for this event. This results in the loss of HPCI, “B” and “D” RHR (LPCI) pumps, and the “B” core spray pump. The remaining two RHR pumps are those that inject to the recirculation loop. The LPCI loop select logic determines which recirculation loop is broken and closes the chosen recirculation line. For breaks less than 465 cm^2 (0.5 ft^2), the selection logic is assumed to fail, and injection is, conservatively, to the broken loop.

2.3.3.3 MELCOR Analysis and Comparison to Licensee Analysis

Table 2-8 includes the general boundary conditions for the LOOP scenarios. The primary difference between the two simulations described here is the break size (9.3 cm^2 [0.01 ft^2] and 65 cm^2 [0.07 ft^2]). Following the licensee approach, in the case of the smaller break, the loop selection logic is assumed to fail and injection is to the broken loop.[6] The UFSAR provides no figures or timing of events for this accident and so a more qualitative comparison is made as to the MELCOR model’s ability to match the utility’s conclusions of a safe and stable state following the accident.

Table 2-8 Boundary conditions for LOOP/SLOCA validation calculation

System	Condition
RCS	100% (full power) Reactor successfully trips on first-in RPS signal or loss of offsite ac. An SLOCA occurs at time zero (break sizes of 9.3 cm^2 [0.01 ft^2] and 65 cm^2 [0.07 ft^2]).
Balance of plant	Offsite power is lost at time zero. Turbine trip occurs upon loss of feedwater or loss of ac. Feedwater and condensate fail at time zero. MSIV closure occurs upon loss of offsite ac.

[6] To achieve this in the current model, the “B” and “D” pumps were used instead of the actually available “A” and “C” pumps. This is a result of the way in which the MELCOR model was constructed with loop select logic in only one line. Since these pumps are identical, it is of little consequence.

Table 2-8 Boundary Conditions for LOOP/SLOCA Validation Calculation (continued)

ECCS/ESF	EDGs start successfully and low-pressure ECCS is sequenced onto the buses.[1] ECCS actuation is on level only. ESF signals successfully perform their functions. HPCI is unavailable. RCIC is unavailable. CRDHS and standby liquid control (SLC) are unavailable upon loss of offsite ac. One train of LPCI/core spray is available (only “A” and “C” LPCI pumps).
Containment	Suppression pool cooling is unavailable. Nominal drywell and wetwell initial conditions are present.
Other operator actions	ADS is actuated on low level.

[1] Technical specifications call for a diesel generator start and load-on in less than 10 seconds.

For the first calculation, a 65-cm^2 (0.07-ft^2) break occurs simultaneously with a LOOP. Upon loss of ac, the reactor scrams and MSIVs close. Feedwater, condensate, and recirculation pumps are also lost. Because of the break in the recirculation line, there is a 300 kg/s loss of coolant from the RCS and the water level in the RCS falls. The level reaches TAF at 165 seconds and bottom-of-active fuel at 290 seconds. The fuel begins to heat up, reaching a peak cladding temperature (PCT) of about 606.7 degrees C (1,224 degrees F).

EDGs are assumed to be available and are therefore up and running 10 seconds after the loss of power. LPCI is then actuated on the low RPV level but is unable to inject because of the still-pressurized RCS. The delay for ADS actuation is satisfied at 224 seconds and brings down the RCS pressure rapidly. RHR—in LPCI mode[7]—begins injecting at 370 seconds (6 minutes) drawing from the wetwell. The RCS is reflooded, and the fuel is cooled, averting cladding oxidation and damage.

Since operator action in throttling the LPCI injection is not considered, the flow rate into the vessel is much greater than that coming out of the break and back into the wetwell. The wetwell water level exceeds the high-level trip setpoint of the RHR pumps at 74 seconds and LPCI injection stops. Water continues out of the break and refills the wetwell until the code-automatic RHR recovery setpoint is reached and LPCI injection resumes until, again, the pumps are tripped on low suction level. This cycle continues until the calculation is terminated at 6,040 seconds (1 hour and 4 minutes). The reactor has reached a safe and stable state at this point and results generally agree with what the UFSAR describes.

For the second simulation, a 9.3 cm^2 (0.01 ft^2) hole is considered for the SLOCA. The results of this calculation are similar to those of the previous calculation with a few minor differences. The smaller hole size causes a slower progression of the accident. By the time ADS actuates at 647 seconds, the Downcomer water level has not yet reached the TAF. LPCI injection begins at 880 seconds (15 minutes) and the peak cladding temperature reaches 435 degreesC

[7] The FSAR refers to the injection of both LPCI and low-pressure core spray (LPCS). However, only a single train of RHR is available, and so only one mode of injection (LPCI or LPCS) is possible. The calculations here have used the LPCI mode of low-pressure ECCS injection, since it has the lower shutoff head (1.36 MPa [197 psid] versus 1.82 MPa [264 psid] for LPCI) and injection is conservatively further delayed. However, this choice should not make much difference for this scenario.

(815 degrees F). Without operator action to throttle the RHR pumps, the same trip/recovery cycle is seen here, and the reactor is in a stable state.

The start of LPI in the two cases above are 6 and 15 minutes, which agrees with the 10 minutes given in the UFSAR.

2.3.4 Application of the Baseline FLEX Sequence

Section 4 addresses the modeling and analysis of sequences involving use of the FLEX equipment in more detail. Here, a baseline FLEX-usage scenario is considered as one means of validating the DAEC MELCOR model.

2.3.4.1 Baseline Sequence Narrative

This section will focus on the notional timeline (from NextEra, 2013a) associated with the accident progression and mitigation, as an introduction to the sequence of interest. The sequence is covered in more detail in subsequent sections. All times are referenced to the initiating event (a LOOP), which takes place at time zero.

Following loss of all ac power and normal access to the ultimate heat sink (UHS) at time zero, and a subsequent declaration of an extended loss of ac power (ELAP), the operators will initiate a controlled depressurization of the RCS using SRVs at a rate of 44.4–55.6 degrees C/hr (80–100 degrees F/hr) and maintain a pressure band of 1.03–1.37 MPa (150–200 psig). They then perform load-shedding actions (within 2 hours) to extend the battery life of the safety-related station batteries. During this time, RCIC (or HPCI if RCIC is unavailable) provides core makeup from either the CST or the suppression pool (depending on availability but with preference given to the CST). Before depletion of the batteries (in 4–8 hours), a portable diesel generator will power station battery chargers.[8] During this same time window (and before assumed RCIC failure), the reactor will be manually depressurized[9] further to allow LPI, and a portable diesel-driven pump will be aligned to inject water into the RPV. The source of water for this pump will be the circulating water pit,[10] with makeup from the Cedar River, as needed.

[8] More specifically and based on 2016 communications with plant staff as part of this project, dc load shedding will begin within 1 hour after the loss of all ac power and will be completed within 2 hours of the loss of ac power. This reduced dc load allows the 1D1 battery (e.g., supply to RCIC) to be available for 8 hours and the 1D2 and 1D4 (e.g., supply to HPCI) to be available for 10 hours. Before depletion, FLEX strategies align a portable 480V generator to the normal battery chargers. The normal battery chargers are sized to recharge the batteries concurrent with carrying the full dc load in roughly 4 hours. There was no review of recharge time under FLEX strategies, as the portable generators are assumed available for charging.

[9] Based on (NextEra, 2013a), safety-related pneumatic accumulators would accomplished this, in combination with either (1) a portable diesel generator providing dc power through the station battery chargers or (2) a portable battery cart used to directly provide dc power to the valves (per severe accident management procedure (SAMP)-707).

[10] If external flooding prevents the laying of temporary hoses for this purpose, the main turbine condenser system hotwell will be used (NextEra, 2015a).

During the period of 8 to 16 hours,[11] the containment will be vented using a hardened vent (and anticipatory venting may occur before that), operated from either the main control room or a remote operating station in the 1A3 switchgear room, to prevent containment failure. APPENDIX B includes more detail about these venting actions. Table 2-1 (in NextEra, 2013a) provides the manual actions required to operate the HCVS. This is also the general time window when charging capacity will be established for batteries in portable communications equipment and refueling of portable equipment will be initiated.

In the longer term (notionally 24–72 hours), equipment will be brought in from the National SAFER [Strategic Alliance for FLEX Emergency Response] Response Center to restore power to a 4,160V essential bus and to restore access to water from the Cedar River. Containment venting during this period would use an onsite portable diesel generator to power the needed 480V bus and compressed gas bottles would provide motive valve power.

Attachments 5 and 6 of (NextEra, 2013a) include a full list of systems credited and instruments needed for core cooling.

2.3.4.2 Other Licensee Analysis Assumptions of Note

Other assumptions of note in the licensee analysis include the following:

- Recirculation pump seal leakage under SBO conditions is 4.1 m^3/hr (18 gpm) per pump at rated pressure (NRC, 2014b and NextEra, 2016).

- FLEX Support Guideline FLEX-AB-100 indicates that the timeline for switchover from RCIC to FLEX injection could be much later if the suction source were not from the suppression pool. While the CST is the preferred source of RCIC/HPCI injection, it is not seismically qualified. Hence, analyses and timelines appear to assume injection from the wetwell.

2.3.4.3 MELCOR Analysis and Comparison to Licensee Analysis

The FLEX validation calculation follows the boundary conditions outlined in Table 1. There are two separate MELCOR calculations that differ in the switchover from RCIC to FLEX injection at 4 and 8 hours, referred to as Case 1 and Case 2, respectively, to cover the range of switchover times described in (NextEra, 2013a).

[11] Based on EA-12-049 Integrated Plan, it is stated that venting may start as early as 3.3 hours (estimated time for containment pressure to reach 0.069 MPa [10 psig]) but no later than 7 hours (associated with a containment pressure of 0.37 MPa (53 psig)), and periodically thereafter. Whereas the EA-12-049 Integrated Plan describes venting as occurring in 8–16 hours, it was clarified with plant staff in September 2016 that the apparent conflict has to do with the availability of details about the HCVS design when the FLEX Integrated Plan was developed, as well as occasional reference to industry-generic information. With the final design, 3.3 hours is the time that anticipatory venting would be expected, if trying to maintain a pressure of 0.069 MPa (10 psig). Meanwhile, if no anticipatory venting were performed, then the primary containment pressure limit of 0.37 MPa (53 psig) would nominally be reached at 13 hours.

Table 2-9 Boundary conditions for the FLEX validation

System	Condition
RCS	100% (full power). Reactor successfully trips on first-in RPS signal or loss of offsite ac. Nominal[1] recirculation pump seal leakage.
Balance of plant	Offsite power is lost at time zero. EDGs fail. DC power is available indefinitely by recharging from portable diesel(s). Turbine trip occurs upon loss of feedwater or loss of ac. Feedwater and condensate fail at time zero. MSIV closure occurs upon loss of offsite ac.
ECCS/ESF	ESF signals successfully perform their functions. CST is unavailable. HPCI is unavailable. RCIC is available. CRDHS and SLC are unavailable upon loss of ac power. LPCI/core spray are unavailable upon loss of ac power.
Containment	Suppression pool cooling is unavailable. Nominal drywell and wetwell initial conditions are present.
Other operator actions	Actions related to RPV depressurization—after 30 minutes, the RCS is depressurized by the SRVs at a rate of 55.6 degrees C/hr (100 degrees F/hr). Actions related to containment venting: operators vent containment via the hardened vent to maintain a pressure band of 7–10 psig per site emergency plan (SEP) 301.3 to maintain RCIC. A pressure band of 45–53 psig is used upon loss of RCIC.[2] Actions to align alternate injection via a FLEX pump: before loss of RCIC (assumed at 4 and 8 hours), operators depressurize the RCS to allow for LPI.[3]

[1] In this context, this means 4.1 m^3/hr (18 gpm)/pump at the lowest SRV pressure setpoint (loss-of-ac scenarios).
[2] SEP 301.3 directs operators to maintain a pressure of 5 to 10 psig in an ELAP to maintain RCIC/HPCI injection. It also states that, if the purpose is instead containment integrity, a 45 to 53 psig band is directed. Hence, upon loss of RCIC, it is assumed that operators would switch to this higher pressure band, since the FLEX pump is the injection source.
[3] The depressurization logic used here is that built for a "walkdown" of the Graph 4 curve in the EOPs.

Up until 4 hours, the two MELCOR calculations are identical. Upon a LOOP, all ac-dependent pumps (e.g., condensate, feedwater, recirculation, RHR) are unavailable. Because of the assumed 4.1 m^3/hr (18 gpm) per pump recirculation pump seal leakage, the water level in the RCS begins to fall, reaching Level 2 at 7 minutes. Thirty seconds later, the delay for RCIC initiation is satisfied, and it begins to inject into the RPV from the wetwell (HPCI and CST are assumed unavailable). Injection continues until the pump is tripped upon reaching Level 8. RCIC automatically restarts when the RCS level reaches Level 2. Until the initiation of RPV depressurization at 30 minutes, the RPV pressure cycles on the SRVs.

Abnormal Operating Procedure (AOP) 301.1 directs operators to begin a controlled cooldown of the reactor at a rate of 44.4–55.6 degrees C/hr (80–100 degrees F/hr) within 30 minutes of the accident with a target pressure of 1.03–1.38 MPa (150–200 psig). This pressure band is meant to extend the life of the RCIC.

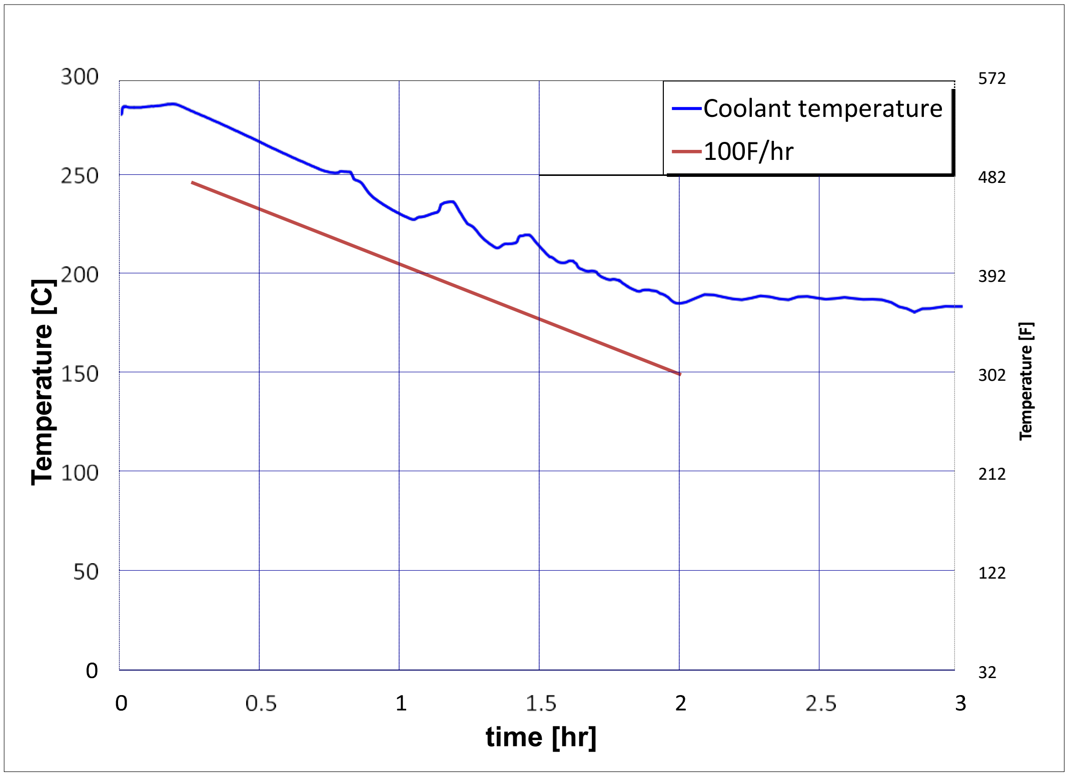

Figure 2-1 Recirculation line coolant temperature during controlled depressurization of the RCS

Before RCIC failure (on high wetwell temperature if injecting from the wetwell; or on CST depletion or high backpressure if injecting from the CST), operators will align the FLEX pump and depressurize the RPV. This is expected to occur 4–8 hours into the accident. At 4 hours, MELCOR results show the wetwell temperature at around 105 degrees C (221 degrees F). For Case 1, at 4 hours, the following events occur simultaneously: RCIC is tripped, a controlled depressurization begins according to Graph 4 of EOP-2, and the FLEX pump is started. The FLEX pump is unable to inject until RPV pressure falls below 0.758 MPa (110 psig), which occurs 9 minutes later. The same three events occur in Case 2 at 8 hours.

SAMP-708 directs operators to throttle FLEX pump injection to “maintain RPV level.” It is not indicated whether the level would be held at a constant value or modulated between, for example, Level 8 and Level 2, as is the case with RCIC/HPCI injection. Originally, logic for throttling the FLEX pump with a proportional-integral-derivative (PID) controller was used to maintain “Normal” RPV level. However, preliminary calculations revealed that the overshooting that is typical of a PID controller led to overfilling the RCS and spilling water out of the SRVs into the drywell. Hence, the injection is now dictated by a trip/reset of the pump at 485/303.5 centimeters (191/119.5 inches) (“Normal” and “Lo” levels). This tight band attempts to follow the assumption that the FLEX pump valves would be throttled to maintain a relatively constant level. This tight band is supported MAAP calculations were run with similar logic for the B.5.b pump (thought by the staff to be the same as the FLEX pump).

In an ELAP scenario, AOP 301.1 directs operators to use the hardened vent in accordance with SEP 301.3 to maintain a drywell pressure of 0.03–0.07 (5–10 psig) (a pressure band of 0.05-0.07 MPa (7–10 psig) is maintained code-automatically[12]), with the intention of extending RCIC/HPCI injection from the wetwell. If the venting purpose is instead containment integrity, SEP 301.3 requires a 0.31- to 0.37-MPa (45- to 53-psig) pressure band. Hence, upon loss of RCIC, it is assumed that operators would switch to this higher pressure band since FLEX is the injection source. For Case 1, the pressure does not reach 0.07 MPa (10 psig) before the switchover to the FLEX pump at 4 hours, and the first demand for venting is at 14.4 hours when the pressure reaches 0.37 MPa (53 psig). This is consistent with the timeline in (NextEra, 2013a) for opening the hardened vent at 8–16 hours. Figure 2-4 shows the five venting cycles. In Case 2, drywell pressure reaches 0.07 MPa (10 psig) at 5.7 hours and the hardened vent opens. When the valves open, the wetwell and drywell pressure decrease initially. However, once the wetwell has become saturated, the pressure begins to rise with the rising wetwell temperature. Pressure never falls back below the 0.05 MPa (7 psig) closing setpoint, and it is not until injection is switched to the FLEX pump at 8 hours that the hardened vent is closed because of the increased target pressure.

The bulk wetwell water in Case 2 reaches 121 degrees C (250 degrees F) right around 8 hours. However, the water temperature in one of the three wetwell nodes reaches 121 degrees C (250 degrees F) around 7.4 hours. This is in line with FLEX-AB-100, which assumes wetwell temperature will reach this temperature at 7.5 hours if RCIC suction is on the wetwell.

It is worthwhile to compare these results with similar calculations from the utility. The utility provided no calculations that directly relate to the FLEX actions. However, a 2011 report by DAEC gives an assessment of SBO coping capability under various specified assumptions. The DAEC MAAP calculation has similar boundary conditions to the first of the staff's calculations (Case 1). In the MAAP simulation, RCIC injects from the wetwell until 3.7 hours, when the wetwell temperature reaches 93.3 degrees C (200 degrees F), at which point the RPV is depressurized to allow injection from the B.5.b pump (thought by the staff to be the same as the FLEX pump). Figure 2-2 through Figure 2-6 graphically display the results from the staff's MELCOR calculation.

A primary difference in the boundary conditions of the MAAP and MELCOR calculations lies in the depressurization of the RCS. In the case of MAAP, operators depressurize to 3.45 MPa (500 psig) at 15 minutes, 2.07 MPa (300 psig) at 30 minutes, and 1.38 MPa (200 psig) at 2.5 hours. This contrasts with the more rapid 55.6 degrees C/hr (100 degrees F/hr) depressurization in MELCOR. This difference does not appear to have a measurable impact on RCIC injection.

In the drywell, there is a slightly faster pressurization in the staff's calculation than in the licensee's, caused by the higher water temperature in the staff's results. The cause of this difference is likely multifaceted but, in general, there is good agreement on the wetwell conditions.

There was also agreement between the injection rates of the alternative injection from the B.5.b and FLEX pumps. It is not clear what the injection criteria for DAEC were, but the overall flow rate is similar to that calculated by MELCOR.

[12] The AOPs/SAMPs call for a 0.03–0.07 MPa (5–10 psig) pressure range but also direct operators to limit offsite releases. It is thought that a range of 0.05–0.07 MPa (7–10 psig) fulfills both these requirements.

Calculations end at 24 hours with the plant in a stable, shutdown state. No attempt is made to model the long-term (phase 3) FLEX strategies in which offsite equipment is brought in from the Regional Response Center.

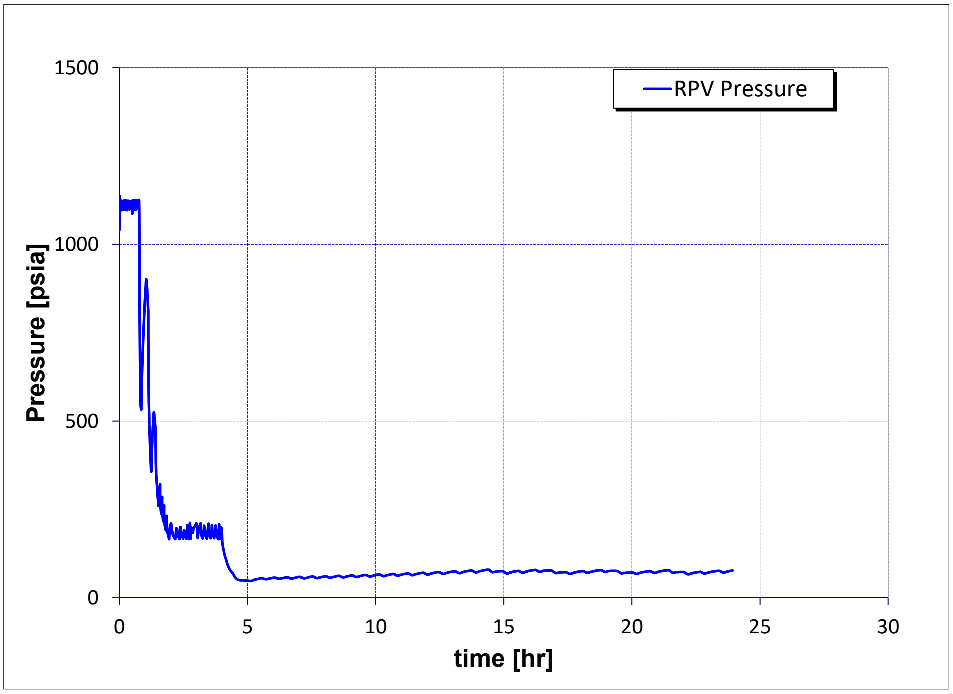

Figure 2-2 RPV pressure (Case 1)

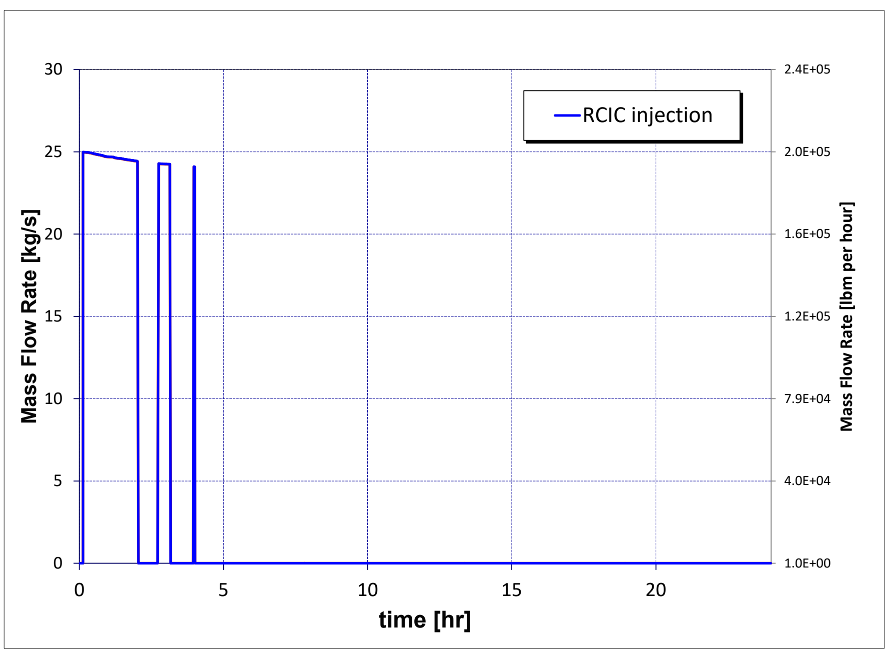

Figure 2-3 RCIC flow (Case 1)

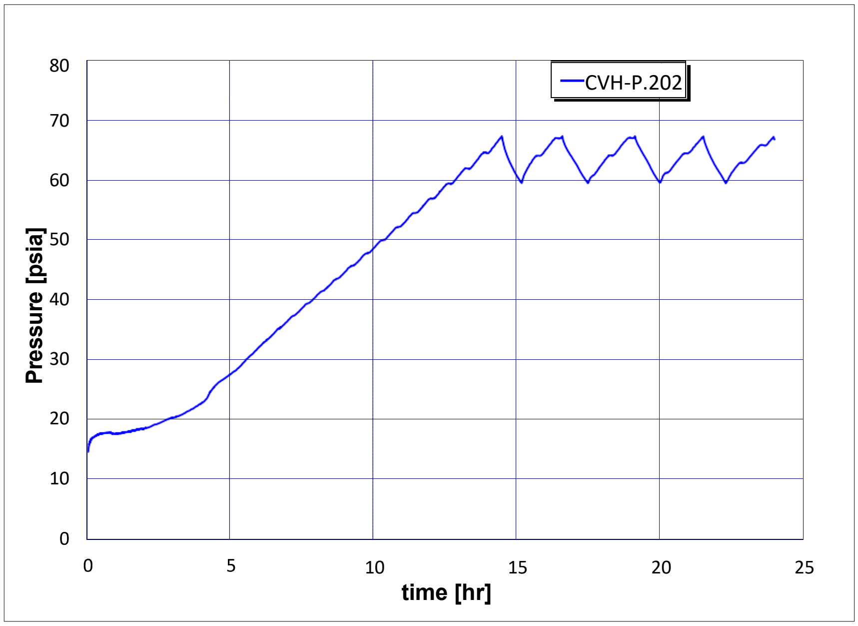

Figure 2-4 Drywell pressure (Case 1)

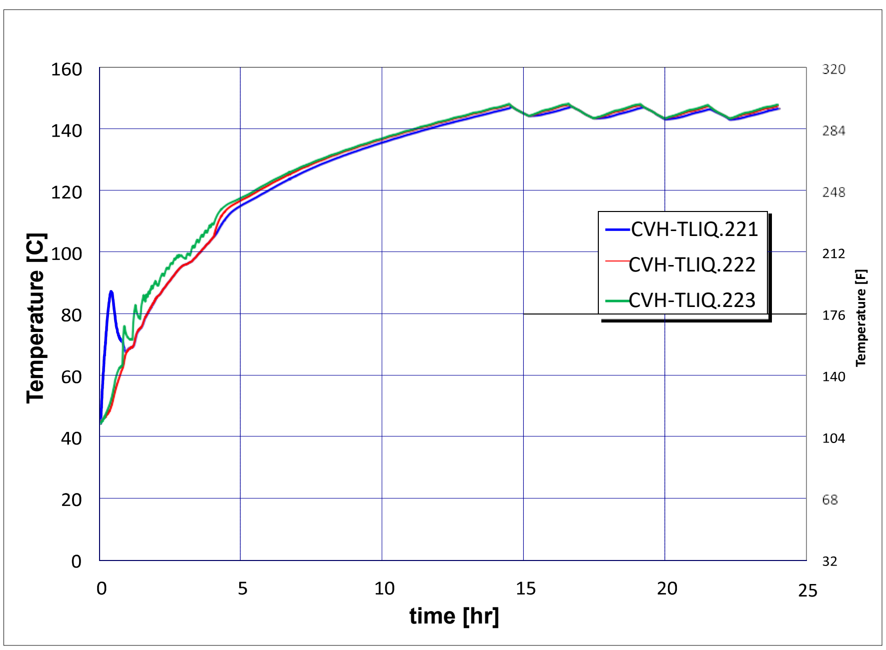

Figure 2-5 Wetwell water temperature (Case 1)

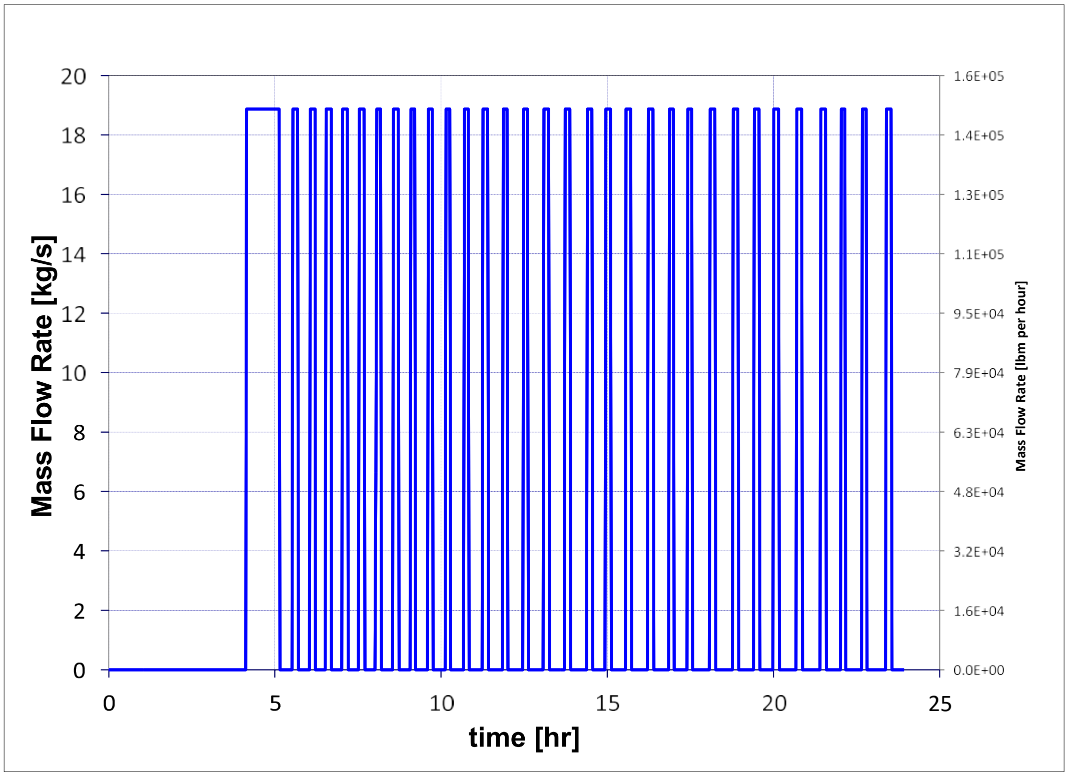

Figure 2-6 FLEX pump flow (Case 1)

2.3.5 Application of a Baseline Station BlackoutSequence

Sections 4 and 5 of this document address the modeling and analysis of sequences involving SBO in more detail. This section considers a baseline SBO coping scenario as one means of validating the DAEC MELCOR model.

2.3.5.1 Baseline Sequence Narrative

This section will focus on the notional timeline from the extended SBO MAAP analysis associated with the accident progression and mitigation, as an introduction to the sequence of interest. Subsequent sections cover the sequence in more detail. All times are referenced to the initiating event (SBO), which takes place at time zero.

Following loss of all ac power and normal access to the UHS at time zero, but in the absence of a declaration of ELAP and subsequent FLEX invocation, RCIC provides core makeup from the CST. The operators manually depressurize the reactor in accordance with AOP 301.1. Initially, full RPV emergency depressurization (ED) is assumed not to occur because of the caution in AOP 301.1 to maintain RPV pressure above 200 psi. The B.5.b pump is aligned for LPI and dc power is extended by use of the technical support center diesel generator. At 16.3 hours, the RCIC turbine trips on high backpressure. Shortly thereafter, at 17.8 hours, the containment is vented upon reaching 53 psig, which allows the B.5.b pump to continue injecting into the RPV. TAF is reached at 18.8 hours and RPV ED (using four SRVs) occurs at 19.1 hours. Core damage is not reached by the end of the simulation at 24 hours.

2.3.5.2 MELCOR Analysis and Comparison to LicenseeAnalysis

The SBO accident scenario follows the conditions listed in Table 2-10, which is extracted from the MAAP scenario. There, the partial controlled depressurizations are to occur at 0.25, 0.50, and 2.50 hours. The opening of the SRV is to be controlled such that system pressure falls to and then remains at 500, 300, and 200 psig at the respective times. According to the PB input deck (Sandia National Laboratories [SNL], 2014b), the RCIC turbine trips at a wetwell pressure of 42 psig.

Table 2-10 Boundary Conditions for the SBO Validation

System	Condition
RCS	100% (full power). Reactor successfully trips on loss of offsite ac. Nominal[1] recirculation pump seal leakage.
Balance of plant	All ac and dc power is lost at time zero. Turbine trip occurs upon loss of ac. Feedwater and condensate fail at time zero. MSIV closure occurs upon loss of offsite ac.
ECCS/ESF	ESF signals successfully perform their functions. HPCI is unavailable. RCIC is available; its electrical requirements are satisfied indefinitely. CRDHS and SLC are unavailable. LPCI/core spray are unavailable.
Containment	Suppression pool cooling is unavailable. Nominal drywell and wetwell initial conditions are present.
Other operator actions	Actions related to RPV depressurization: partial controlled depressurizations occur at prescribed times; rapid depressurization occurs at vessel water level -64 centimeters (-25 inches). Actions related to containment venting: operators will depressurize containment using the hardened vent if the pressure exceeds 0.37 MPa (53 psig). Actions to align alternate injection via a low-pressure pump: operatorswill align the pump, assumed to be able to inject as soon as depressurization actions appropriately lower the vessel pressure.

Table 2-11 compares the timings of important events, as predicted by the utility's and staff's calculations. Figure 2-7 through Figure 2-10 graphically display the results for the MELCOR simulation.

The MELCOR calculations give similar results, but there is a timing difference from the MAAP calculations. Figure 2-7 shows the temperature of the wetwell water according to the present calculation. When RCIC is not injecting, the SRV being used for the controlled depressurization discharges into CV221, which models one sixth of the wetwell. The water temperature of CV221 accordingly cycles with RCIC activity and shows a sizable periodic increase over the temperature of the water of CV222, which models one-half of the wetwell. The containment pressure also cycles markedly with RCIC activity (Figure 2-8) in a way that the utility's calculation does not reflect. These observations suggest that, in the present calculation, the nodalization of the wetwell, set up to include less than perfect homogenization of the wetwell water, contributes to the overall more rapid containment pressurization in the present calculation. Of course, there are probably more mundane reasons for the difference, including different volumes or water inventories for the wetwell in the MELCOR versus the utility's models that cannot be ruled out without more details of the utility's model. In any case, the timing differences between the two calculations appear to be caused by the faster wetwell pressurization in the present calculation. This faster pressurization leads to RCIC carrying out one less duty in the present calculation. This also leads to further differences in time for the events that follow. More particular comments refer to the other figures, as follows.

Figure 2-9, showing water level in the vessel, is qualitatively similar to the MAAP calculation but includes a possible discrepancy of the elevation difference between the set points at which RCIC is turned on and off (between LoLo and Hi Levels, or roughly 2 meters for the MELCOR calculation versus roughly 10 unknown units for the utility's calculation). In the present calculation, after the FLEX pump first begins to inject, the water level initially rises very high in the vessel in a way that the utility's calculation does not reflect.

Neither calculation predicts cladding temperatures approaching core damage, but the utility's calculation shows a pronounced peak in the cladding temperature around the time of the rapid depressurization that the MELCOR calculation does not predict. This appears to be caused by a drop in water level that is at or below the 2/3 core height, resulting in a higher heatup than that of the MELCOR calculations where the water level remains above this threshold.

Figure 2-10 Indicates that the FLEX pump included in the MELCOR calculation has roughly twice the flow rate of the B.5.b pump that the utility's calculation includes. Since the B.5.b pump is shown briefly to become deadheaded, the FLEX pump may also be a pump of higher head, but this possibility was not investigated quantitatively. No attempt was made to adjust the FLEX pump injection rate in the MELCOR model to more nearly resemble the B.5.b pump rate of the utility's MAAP model since the FLEX pump as represented in the MELCOR model is known to be consistent with the actual pump at the plant.

The MELCOR model appears to credit greater initial CST water inventory than does the utility's model (which may be assuming the technical specification minimum inventory). The difference is inconsequential in these calculations because neither calculation predicts CST depletion.

Table 2-11 Timing of important events for SBO validation

Event	Time (in hours except as noted)		Remarks
	Utility	NRC	
Initiation of transient	0.0	0.0	Trip of all electrical pumps, MSIV closure, start of recirculation pump leakage at nominal rate of 4.1 m^3/hr (18 gpm) per pump.
Beginning of RCIC injection, suction from the CST	-	0.13	NRC: 30 seconds after Downcomer water level attains Level 2. Utility: Start time indistinguishable in the figure since the start time is so close to 0.
Controlled depressurization	0.25	0.25	With one SRV; target pressure 500 psig.
Controlled depressurization	0.50	0.50	With one SRV; target pressure 300 psig.
Controlled depressurization	2.50	2.50	With one SRV; target pressure 200 psig.
End of RCIC injection	~15.0	12.43	

Table 2-11 Timing of important events for SBO validation (continued)

Event	Time (in hours except as noted)		Remarks
	Utility	NRC	
RCIC turbine trip on high backpressure	16.3	13.87	Trip caused by high wetwell pressure of 42 psig. For the NRC, this trip occurs while RCIC is idle.
Beginning of first period of containment venting	17.8	15.80	Caused by high wetwell pressure of 53 psig.
Water level falls below TAF	18.8	16.01	
End of first period of containment venting	~18	16.06	The vent is reclosed around 45 psig, too high to reenable the RCIC turbine.
Rapid depressurization	19.1	16.33	Four SRVs are held open; initiated when Downcomer water level attains -64 centimeters (-25 inches).
Beginning of second period of containment venting	~19.0	16.36	NRC: open at 0.37 MPa (53 psig).
Beginning of LPI	~18.7	16.39	Utility: B.5.b pump. NRC: FLEX pump.
Water level rises above TAF	~19	16.61	NRC: last of several times at which level rises above TAF.
End of second period of containment venting	~19	16.72	NRC: close at 0.34 MPa (48.7 psig) instead of 0.31 MPa (45 psig) (restart error associated with the double back from 17.81 hours). No more demands for venting as of 24 hours.
NRC only: close all SRVs	–	17.22	NRC: for solution of numerical problems.[13]
NRC only: reopen two SRVs	–	18.39	NRC: for solution of numerical problems.[14]
End of calculation	24.0	24.0	

[13] Numerical difficulties in the code required a restart at 16.72 hours to alter the time steps of the calculation. As a result, the hardened vent was inadvertently closed at 16.72 hours because of a reinitialization of the trip function. This error was not noticed for some time, and when it was noticed, it was left uncorrected since it does not significantly change the results. (The vent closed at 0.34 MPa (48.7 psig) instead of 0.31 MPa (45 psig). Had the pressure ever reattained the opening setpoint, the vent would have opened, and subsequently reclosed, correctly.)

[14] The time-steps change proved ineffective in fixing the calculational issue; therefore, at 17.22 hours, all the SRVs were closed. This intervention allowed the code to pass the problematic time, and, over the time that it was enforced, induced so small a repressurization of the vessel that the FLEX pump was not affected. Two SRVs were reopened at 18.39 hours, and in that configuration, the problem ran uneventfully to its planned end time at 24 hours.

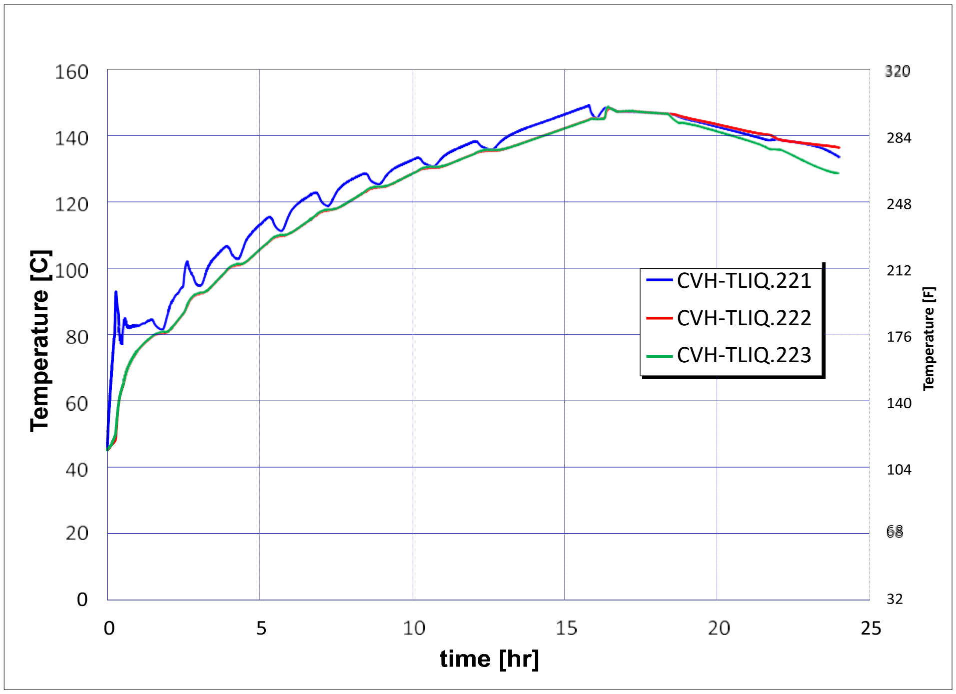

Figure 2-7 Wetwell water temperature (NRC)

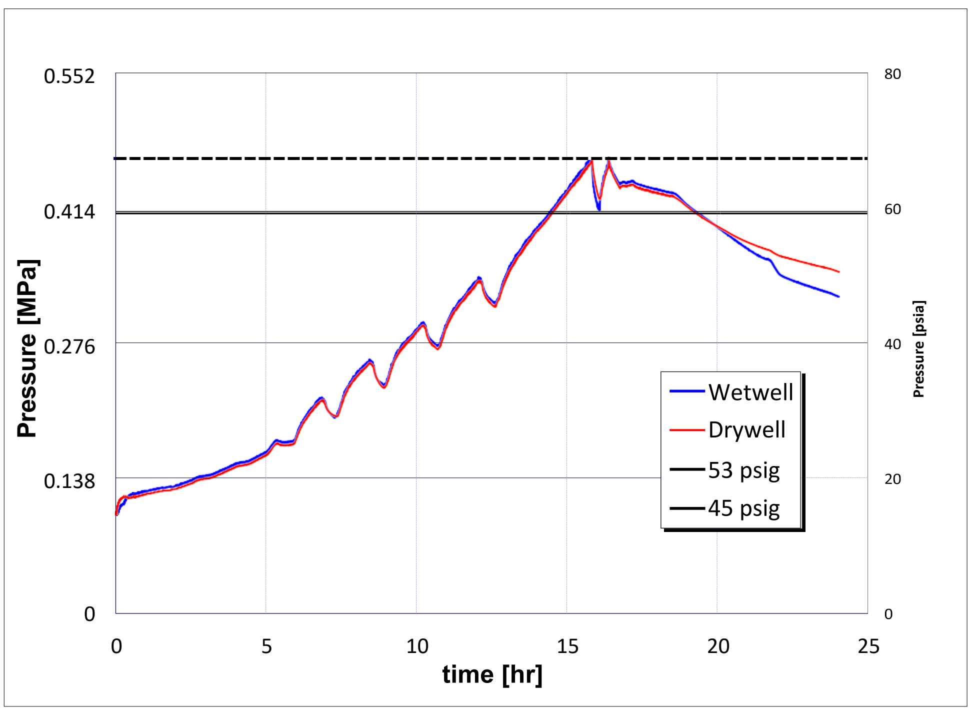

Figure 2-8 Containment pressure (NRC)

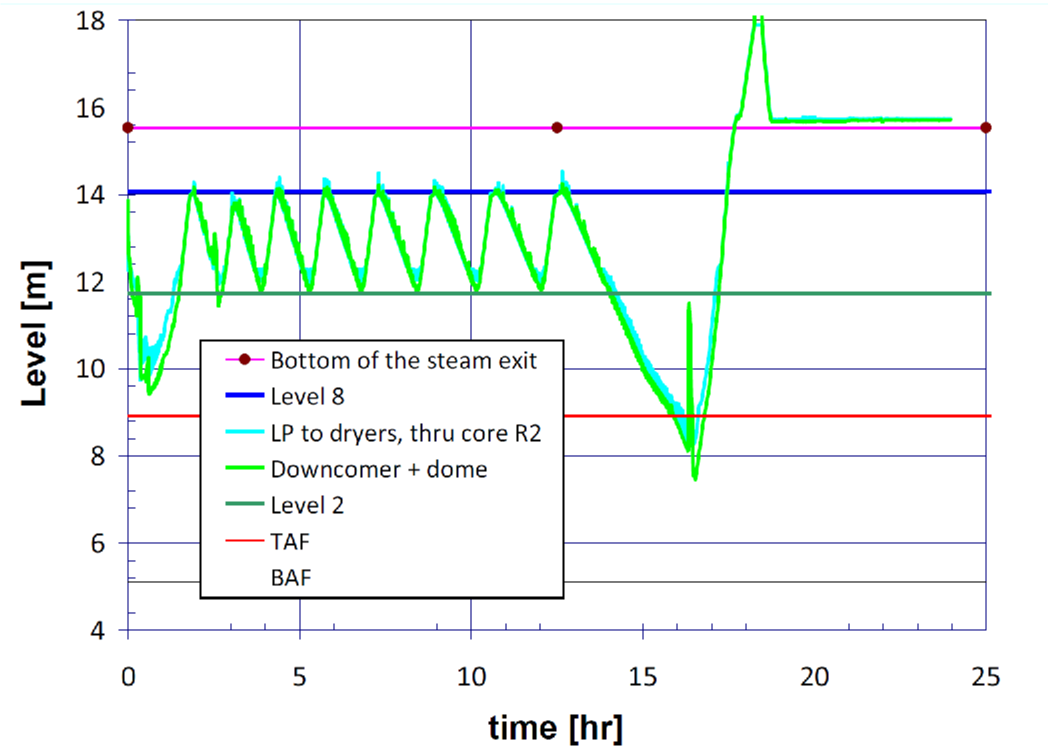

Figure 2-9 Vessel water levels (NRC)

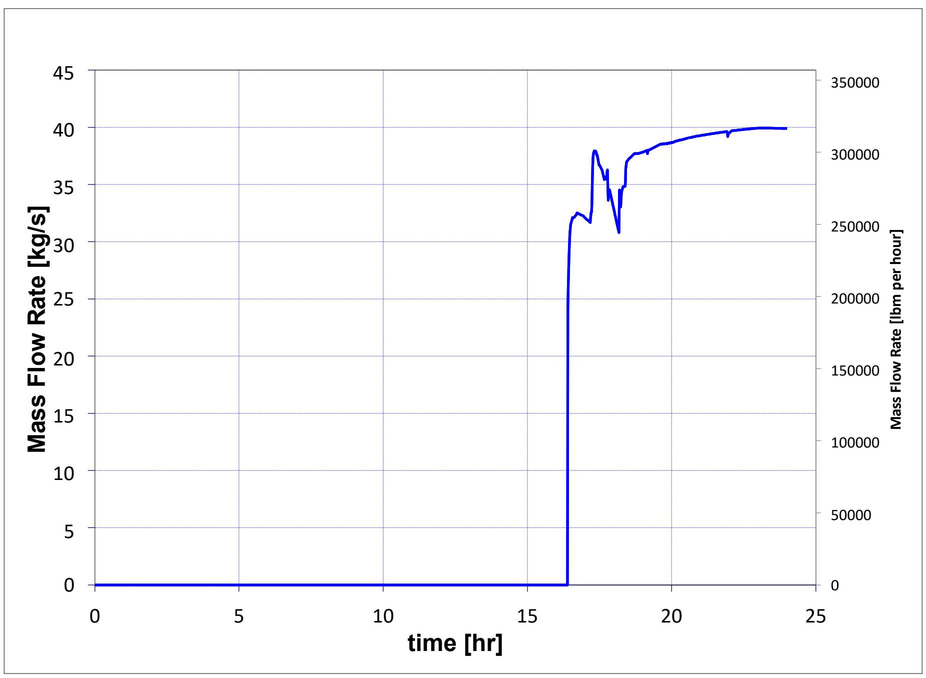

Figure 2-10 FLEX pump flow (NRC)

2.3.6 Updated Shakedown Based upon Latest Deck Revision

The MELCOR input deck used for the calculations described in this report was under active development throughout the project. A number of modifications were made to correct input errors, improve the performance of system logic, or reflect feedback received from internal and external stakeholders on plant design and operations (see Appendix A). The version of the deck that was used for the aforementioned shakedown and benchmark calculations was Revision 5 (with minor alterations that were rolled into Revision 6), while the version used for the calculations in the subsequent sections of this report was Revision 7. Most of the modifications made between these revisions were such that the changes to the benchmarks should be minimal. However, a recalculation of the “FLEX Case 1” benchmark scenario from Section 2.4.4 using Revision 7a of the deck is provided here. The discussion below centers on the primary differences between the original and updated calculation and the changes to the model that influenced them.

There were two rather significant changes made to the wetwell models going from the Revision 5 to the Revision 7 MELCOR decks. First, the wetwell Downcomer was split from a single control volume to three separate volumes. The modification was motivated by unrealistic flow behavior between the wetwell volumes. This change led to more efficient mixing between the three wetwell volumes.[15] The second modification affecting the wetwell was the initial wetwell water temperature. A unit conversion error caused the Revision 5 initial water temperature to be 317.5K versus the intended 304.0K. As a result, the wetwell water temperature reaches a peak value of 148 degrees at 18 hours with the corrected value versus 14 hours in the original calculation.

Also contributing to the difference in pressure and temperature in the wetwell and drywell is the subtle difference in RPV pressure. The pressure is maintained at 50 psid (per EOP-1 direction) above the wetwell pressure rather than at 50 psig. This leads to less heat transfer to the wetwell and a slower pressurization.

The flow rate of the FLEX pump was also altered going from Revision 5 to Revision 7a, with a vendor-provided pump curve offering more pressure-dependent injection rate information. A tighter level band also led to more rapid cycling of the pump.

[15] This new nodalization was validated against test data from the Monticello BWR, as seen in (NRC, 1984).

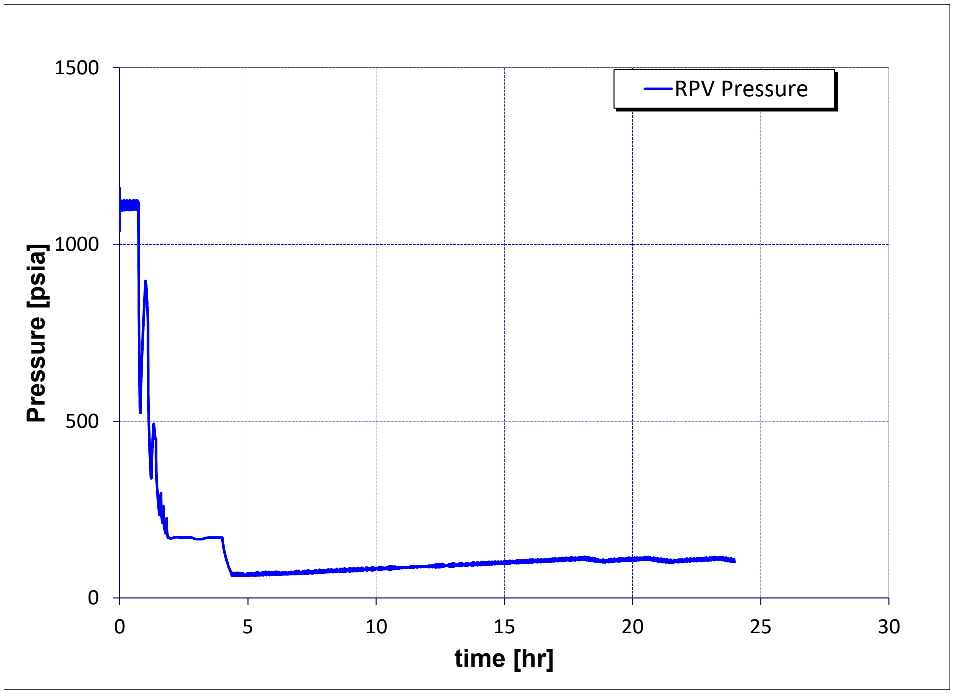

Figure 2-11 RPV pressure (Case 1, updated)

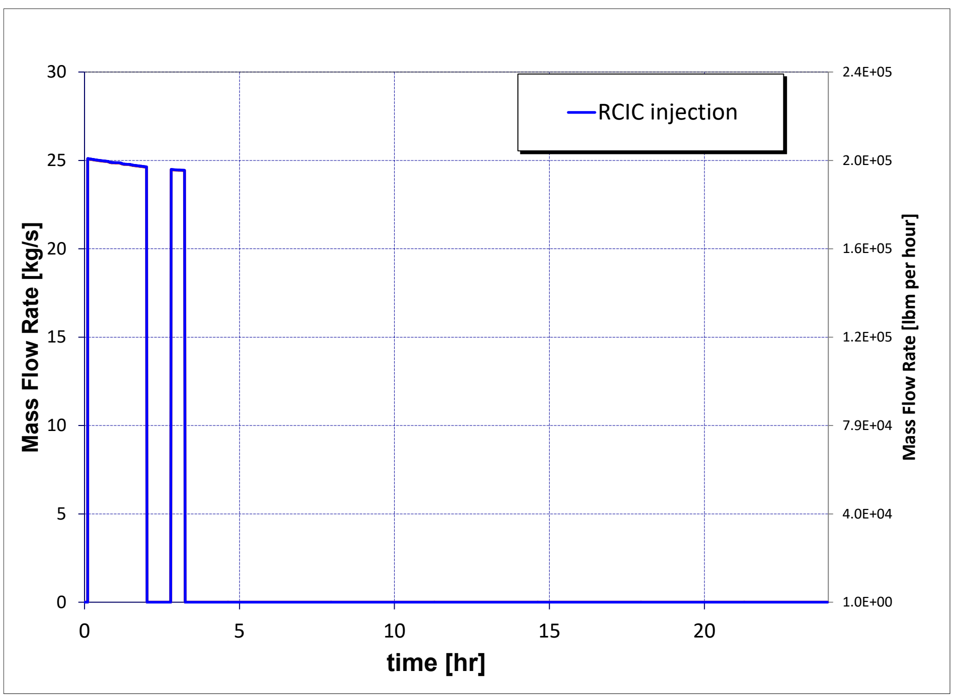

Figure 2-12 RCIC flow (Case 1, updated)

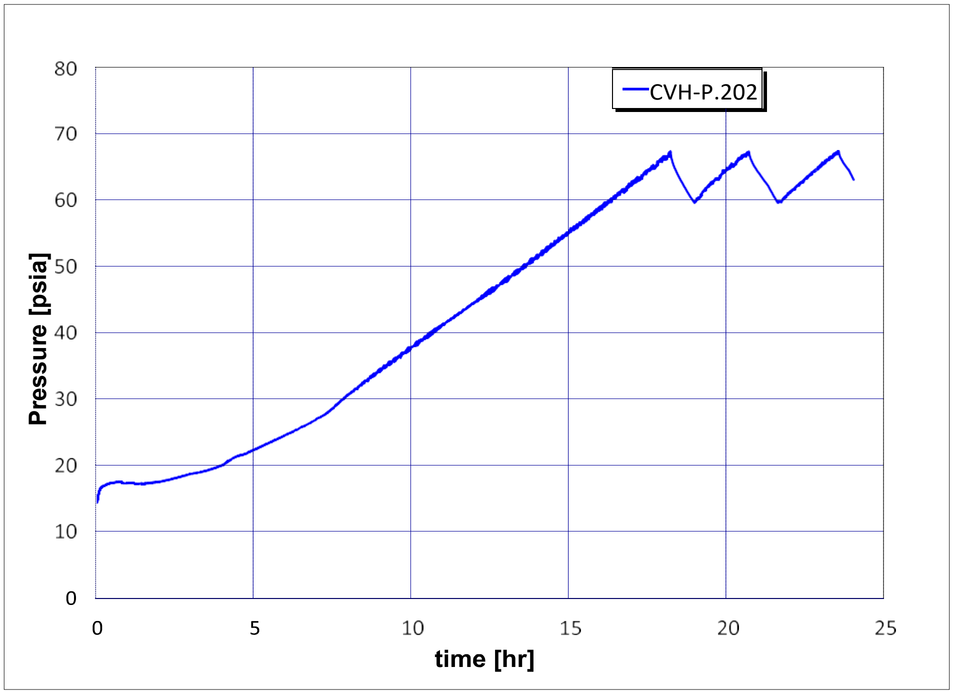

Figure 2-13 Drywell pressure (Case 1, updated)

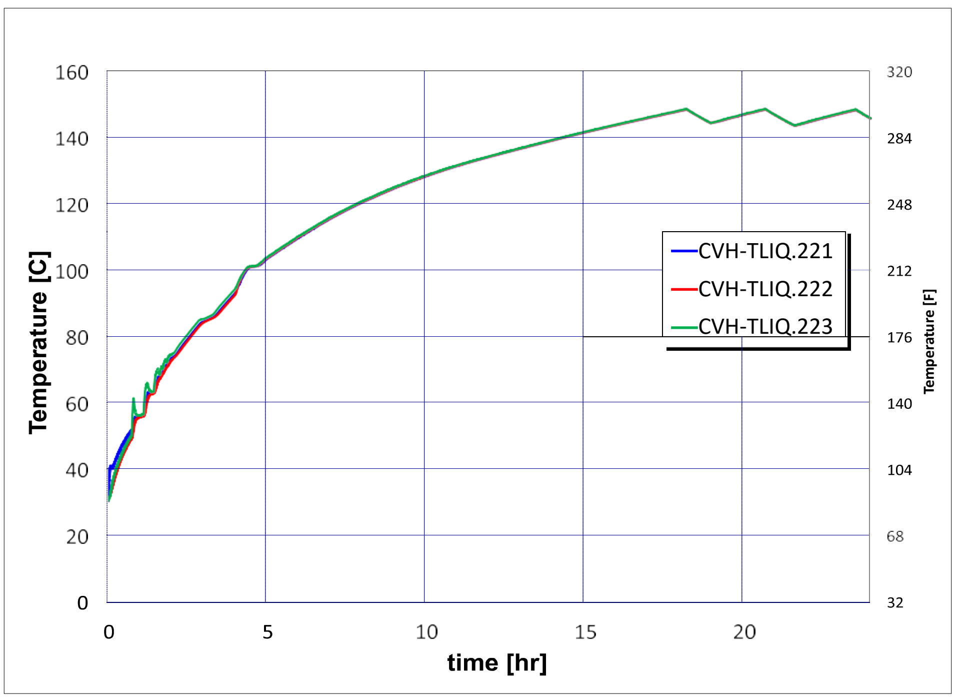

Figure 2-14 Wetwell water temperature (Case 1, updated)

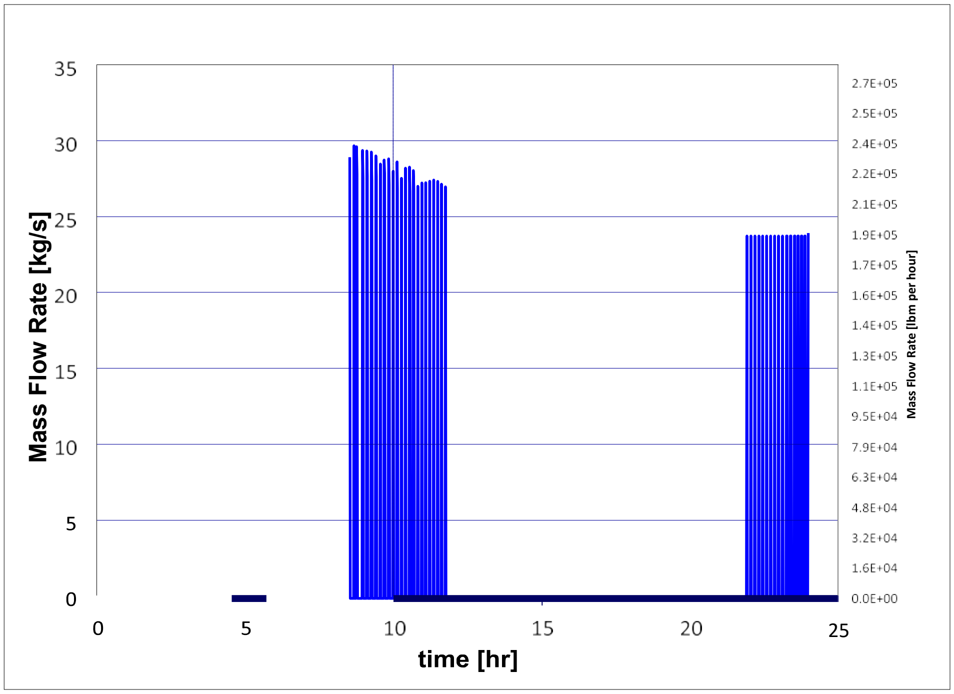

Figure 2-15 FLEX pump flow (Case 1, updated)

3 SUCCESS CRITERIA FOR SITUATIONSWITH DEGRADED HIGH-PRESSURE INJECTION AND RELIEF VALVECRITERIA FOR NON-ANTICIPATED TRANSIENT WITHOUTSCRAM

3.1 Issue Description

Following certain initiating events, coincident with degraded HPI capabilities (i.e., loss of RCIC and HPCI), operators will use alternate HPI capabilities to maintain the RPV level (e.g., CRDHS, SLC). If there is insufficient capability to maintain the RPV level above a specified level band[1] or insufficient blowdown capacity in the suppression pool, and an LPI system is available, operators will manually initiate the automatic depressurization system (the automatic function having been inhibited very early in the EOPs for a non-ATWS condition). This initiation will open up multiple SRVs to depressurize the RPV and allow for LPI. This function applies to both ATWS and non-ATWS sequences, but the focus in this section is on the non-ATWS applications. Conversely, if sufficient alternate HPI capability and suppression pool capacity are available, operators will proceed with a normal cooldown and depressurization to achieve low-pressure conditions. The rate of cooldown will depend on the adequacy of injection to maintain the level but will not exceed 55.6 degrees C/hr (100 degrees F/hr). In the intermediate case, where HPI is sufficient for maintaining the level but insufficient for supporting a plant cooldown, operators will try to maintain RPV pressure within a 200-psig band and may close the MSIVs as a means of buying additional time for restoration of HPCI or RCIC.[2] Note that some natural plant cooldown and depressurization may occur during this period. The above situations are covered by the EOPs (most notably EOP-1), along with alternate injection procedures ([AIPs] 406 and 407[3]).

For the relevant PRA sequences, assumptions are made regarding what high-pressure capabilities are needed to maintain the level, when operator action is required, and how many ADS valves must open to reach conditions where LPI sources (e.g., low-pressure CS) in conjunction with any available HPI sources (e.g., CRDHS) can provide adequate inventory control and decay heat removal before core damage. The relevant success criteria in many PRA models originated from design-basis analyses, and in the case of many models, have been refined over time to remove conservatism. However, there are a number of related modeling assumptions (e.g., water level representation used for the operator cue for manual actuation) and scenario definition characteristics (e.g., amount of credit for CRDHS), that, when combined with the accepted variability in computational modeling and user effect, can result in different analyses predicting different requirements for substantively similar designs or conditions.

[1] In these circumstances, operators are not permitted to initiate ADS before reaching +0.38 meter (+15 inches) RPV level and must initiate ADS before reaching -64 centimeters (-25 inches) RPV level. If the RPV is still at high pressure and there is no expectation for recovery of additional HPI capability, then initiation is more likely to happen early. Conversely, if the system is nearing the low-pressure shutoff head and level is dropping slowly, then late action is more likely.

[2] On keeping the MSIVs open (to dump decay heat out of containment) versus closing them (to limit inventory loss), if HPI is lost and the RPV level is dropping, then an EOP-1 contingency will dictate efforts to maintain the level, including closure of the MSIVs if warranted. This action is implicit, as one means to stabilize pressure—at DAEC, this means of stabilizing pressure is trained on but not explicitly called out in the EOPs. Note that if the crew loses control of the RPV level (low), then there is an automatic MSIV closure at +1.6 meters (+64 inches).

[3] The site provided these additional procedures following the November 2016 site visit.

For this reason, the sequence timing and success criteria assumptions for ADS relief valve criteria for non-ATWS sequences periodically become important aspects of an event or condition assessment.[4]

To investigate this issue, the approach will be to quantitatively address the variability around a point estimate that would arise from reasonable alterations to the boundary conditions and underlying modeling for this particular scenario. Factors of interest in this regard (based on previous SDP-related examinations) include items that would have both a positive and negative influence on core heatup:

- number of SRVs participating in the depressurization or degraded performance of one or more valves (e.g., caused by vibration-induced valve stem/piston damage or degradation of the N_2 accumulator in cases with loss of instrument air), noting that 4 of 6 SRVs at DAEC have ADS functionality

- SRV discharge path characteristics that affect flow rate and depressurization

- HPI failure to run, as opposed to failure to start

- credit for CRDHS flow before and after depressurization, including the following:

  - normal post trip flow
  - enhanced flow using one train
  - enhanced flow using two trains

- credit for additional alternate injection from standby liquid control

- source and achieved flow of LPI (e.g., delivered CS flow +/- 10 percent)

- manual actions taken before ADS to stabilize RPV pressure/level (e.g., manual closure of MSIVs) or to pursue a normal plant cooldown, or both

- automatic, as opposed to manual, initiation of ADS (i.e., failure to inhibit automatic actuation)

- timing of manual actuation (e.g., near the top of the allowable level band versus near the bottom)

- decay heat formulation in the MELCOR model (e.g., +/- 10 percent)

- recirculation pump seal leakage

Manual reactor depressurization using the SRVs appears in the following SPAR v8.50 main event trees:

- inadvertent open relief valve (IORV)
- loss of condenser heat sink (LOCHS)

[4] Examples of events that led to this situation include the 2015 inspection and enforcement activities for Dresden (NRC, 2015c) and Oyster Creek (NRC, 2015e).

- loss of vital dc bus A (LODCA)
- loss of vital dc bus B (LODCB)
- loss of instrument air system (LOIAS)
- loss of main feedwater (LOMFW)
- loss of offsite power (LOOP)
- loss of river water system (LORWS)
- medium loss-of-coolant accident (MLOCA)
- SLOCA
- general plant transients (TRANS)

Manual reactor depressurization using the SRVs also appears in some transfer event trees. From model quantification, the following sequences are most affected by less reliable operator-enacted depressurization or multiple ADS SRVs being unavailable:

- LOMFW-62
- LOOPxx-35
- LOIAS-71
- TRANS-52-35

All of these sequences are variations on a theme, wherein the reactor is successfully shut down, 4,160V ac power is available, SRVs successfully reseat (if demanded), HPI fails, manual reactor depressurization fails, and core damage ensues. (The transient initiator involves a consequential or coincidental LOOP.) CRDHS is not considered as an alternate adequate source of injection alone, given the failure of RCIC/HPCI, as it is in the general TRANS (without LOOP) analogous sequence.

From this, and from the inspection of the various event trees, three sequences are selected for further consideration here. The first (TRANS-30) is selected as a non-LOCA case with success of HPI. The second (TRANS-49) is selected as a variation of the sequences that were found to be important above but with consideration of CRDHS. The third (SLOCA-25) is selected as a LOCA case.

3.2 Transient Sequence

3.2.1 Calculation Matrix Development

Table 3-1 describes the PRA sequence that is the focus of this section.

Table 3-1 PRA sequences of interest for depressurization—TRANS

PRA Seq.	Event	Description
TRANS-30	Initiator	General plant transient occurs (e.g., unexpected reactor trip).
	/RPS	Reactor is successfully shut down.
	/OEP	Offsite power is available.
	/SRV	SRVs successfully reclose (if demanded).
	PCS	Power conversion system fails (e.g., operator fails to maintain feedwater injection).
	MFW	Main feedwater fails (e.g., operator fails to maintain feedwater injection).
	HPI	High-pressure injection fails (meaning RCIC and HPCI are both unavailable).

Table 3-1 PRA sequences of interest for depressurization—TRANS (continued)

PRA Seq.	Event	Description
	/DEP	Manual depressurization of the reactor occurs (e.g., two of six SRVs opened by operator).
	CDS	Condensate system fails (e.g., operator fails to maintain condensate injection).
	/LPI	LPI succeeds (namely one train of LPCI or one train of core spray succeeds).
	/SPC	Suppression pool cooling late succeeds (namely, at least one train of RHR provides suppression pool cooling).
	OK	Core damage is averted.
TRANS-49	Initiator	General plant transient occurs (e.g., unexpected reactor trip).
	/RPS	Reactor is successfully shut down.
	/OEP	Offsite power is available.
	/SRV	SRVs successfully reclose (if demanded).
	PCS	Power conversion system fails (e.g., operator fails to maintain feedwater injection).
	MFW	Main feedwater fails (e.g., operator fails to maintain feedwater injection).
	HPI	High-pressure injection fails (meaning RCIC and HPCI are both unavailable).
	DEP	Manual depressurization of the reactor fails (e.g., five of six SRVs fail to open).
	CRD	CRDHS fails to provide makeup (meaning that either train fails).
	CD	Core damage

Table 3-2 provides the calculation matrix for the subsequent MELCOR calculations, while Table 3-8 provides the calculation boundary and initial conditions. A discussion of the key modeling assumptions made for these calculations follows.

Table 3-2 Calculation matrix—HPI and SRV criteria for non-ATWS—TRANS

Case #	Sequence	CRDHS	Manual actions to stabilize level/pressure (MSIV closure)	Method of RPV depressurization	Timing of ADS initiation	No. of SRVs during ADS
1.	Based around TRANS-30	Nominal[1]	Manual (6 minutes)	N/A	+38 centimeters (+15 inches)	1
2.						2
3.					-64 centimeters (-25 inches)	1
4.						2
5.			Automatic (16 minutes on low level)		+38 centimeters (+15 inches)	1
6.						2
7.					-64 centimeters (-25 inches)	1
8.						2
9.		1-train, maximized[2]	Early manual closure (10 minutes)	Follow the HCL curve	N/A	N/A
10.				ED		

Table 3-2 Calculation matrix—HPI and SRV criteria for non-ATWS—TRANS (continued)

Case #	Sequence	CRDHS	Manual actions to stabilize level/pressure (MSIV closure)	Method of RPV depressurization	Timing of ADS initiation	No. of SRVs during ADS
11.			Early manual closure (20 minutes)	Follow the HCL curve		
12.				ED		
13.			Automatic (none)	Follow the HCL curve		
14.		2-trains, maximized[3]	Early manual closure (10 minutes)	N/A		
15.			Early manual closure (20 minutes)			
16.			Automatic (none)			
17.	Based around TRANS-49	1-train, maximized	Early manual closure	N/A	N/A	N/A
18.			Automatic (none)			
19.		2-train, maximized	Early manual closure			
20.			Automatic (none)			

[1] With this HPI capacity, level will drop too quickly to prompt timely actions with regard to pursuing a normal plant cooldown.

[2] With this HPI capacity, level is maintained but is not sufficient to facilitate a normal plant cooldown. ED is required, however, when the wetwell water temperature rises and RPV pressure reaches the "action is required" region of the HCL curve (Graph 4 in the EOPs).

[3] With this HPI capacity, level is maintained and is sufficient to facilitate a normal plant cooldown at a rate of 44.4–55.6 degrees C/hr (80–100 degrees F/hr). Hence, ED is never required.

Table 3-3 Initial and boundary conditions—HPI and SRV criteria for non-ATWS—TRANS

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 3-2.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on first-in RPS signal. No recirculation pump seal leakage. Number of SRVs available—see Table 3-2.
Balance of plant	Offsite power remains available. Support systems are available unless specified otherwise. Turbine trip occurs at the time of reactor trip. Feedwater and condensate fail at the time of turbine trip. MSIV closure—see Table 3-2. Condenser is assumed available to explore MSIV closure time; in subsequent chapters, the condenser is not available.

Table 3-3 Initial and boundary conditions—HPI and SRV criteria for non-ATWS—TRANS (continued)

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 3-2.	
System	**Condition**
ECCS/ESF	ESF signals successfully perform their functions. HPCI and RCIC are unavailable. CRDHS—see Table 3-2. SLC—available, but not used. LPCI/core spray—one train of LPCI is available for RPV injection.
Containment	Suppression pool cooling—one train is available. Nominal drywell and wetwell initial conditions (see Table 2-6).
Other operator actions	LPCS may need to be disabled per EOP-1, if other low-pressure systems are available. Actions to stabilize level/pressure—see Table 3-2. Timing of manual ADS initiation—see Table 3-2.

The initiating event in each of these cases is an unanticipated reactor trip. The preferred sources of HPI, RCIC, and HPCI are unavailable, and only a single train of RHR is available by sequence definition.

Since the usual sources of HPI are unavailable, operators employ alternate means of injection, in this case CRDHS pumps. AIP 407 directs operators to start both pumps if available and raise the output to maximum. While the CRDHS pump is able to inject at an increased rate, the postscram increase is commonly discounted in analyses. The series of scenarios described in Table 3-2 shows the number of pumps available and the overall rate of injection. A "nominal" injection rate assumes a single CRDHS pump is operating at the prescram rate of 11.54 m^3/hr (42.3 gpm). The maximized injection rate depends on the number of pumps operating and the RPV pressure (high pressure: 40.2 m^3/hr (177 gpm) with one pump or 68.1 m^3/hr (300 gpm) with two pumps; low pressure: 51.1 m^3/hr (225 gpm) with one pump or 79.5 m^3/hr (350 gpm) with two pumps).

As mentioned in the opening paragraphs of this section, operator action to depressurize the reactor will depend on the amount of HPI available and its sufficiency to support the inventory loss expected during the depressurization. In the cases within this section, the three levels of CRDHS injection (nominal injection, single train maximized, and two trains maximized) fell within the three situations described in the opening paragraph (insufficient HPI, enough injection to maintain level, and enough injection to support a reactor cooldown, respectively).

Given a nominal injection rate, the injection is insufficient to maintain the RPV level and thelevel falls rather quickly. MSIVs close on low RPV level, and operators take action to depressurize the RPV by ADS after level reaches +38 centimeters (+15 inches) and before it reaches -64 centimeters (-25 inches), with the two ends of the spectrum explored in the calculationmatrix. The number of ADS valves available is also explored here with either one or two of the four total ADS valves available for emergency relief.

When a single train of CRDHS is injecting at the maximum rate, the makeup is sufficient to maintain level but may not be enough to facilitate a normal reactor cooldown. MSIVs remain open unless operators manually close them to limit inventory losses. Operators try to maintain RPV pressure within a 200 psig band. When the "action is required" region of the HCL curve (Graph 4 in the EOPs) is reached, operators are required to depressurize. There is some uncertainty whether operators would perform a rapid ED at this point or slowly modulate valves to stay below the HCL curve and "follow" it down. A slow depressurization is performed here with a rapid depressurization explored in a sensitivity calculation.

With two trains of CRDHS injection available at the maximum rate, there is plenty of HPI to support a normal cooldown of the reactor to achieve low-pressure conditions and allow for LPI; in this case, LPCI. The rate of cooldown will depend on the adequacy of injection to maintain level but will not exceed 55.6 degrees C/hr (100 degrees F/hr). It is assumed in these calculations that the depressurization begins at 30 minutes at a rate of 44.4 degrees C/hr (80 degrees F/hr). This choice in timing is somewhat arbitrary but was deemed reasonable, since it would take time for operators to assess the sufficiency of injection and initiate a cooldown. The rate of depressurization is the lower bound of the suggested rate in the EOPs and is thought reasonable, since it seems unlikely that operators would depressurize the reactor at the maximum recommended rate when only alternate injection sources are available. Regardless, the calculation is not particularly sensitive to these variables.

In the calculations with increased CRDHS injection, the assumption is that the CRDHS injects in "batch mode" with the pump (or pumps) secured when RPV level reaches Level 8 and restarted when level falls to Level 2. While this is the automatic mode of injection for HPCI and RCIC under normal conditions, there is no indication in the procedures that this is the method used for alternate injection using the CRDHS pumps. It was chosen for the sake of modeling convenience and to ensure that water does not spill over into the steamlines.

Early operator action to manually close the MSIVs to maintain pressure and limit inventory loss is also explored at various times. The condenser is assumed to be available in these scenarios in an effort to explore the impact of early MSIV closure. In reality, a train of feedwater or condensate is necessary for long-term availability of the PCS, since the condenser tubes would eventually be covered with water and rendered ineffective. Therefore, cases with "automatic" or no closure of the MSIVs assumes indefinite availability of the condenser for steam condensation.

3.2.2 MELCOR Simulation Results

The following discussion is based on the results of the TRANS-30 scenarios (Cases 1–16). In addition to this, APPENDIX C APPENDIX D to this report provide figures for selected parameters of interest.

In the cases with nominal CRDHS injection (Cases 1–8), makeup is insufficient to maintain level, and the RPV water level falls quickly. In the cases without manual action to close the MSIVs, they close automatically on low RPV level (+163 centimeters [+64 inches]) at 16 minutes. Inventory is no longer lost through the steamlines to the condenser, but pressure quickly rises and the SRVs begin to cycle, dumping steam to the wetwell. The RPV water level continues to fall and ADS actuates when level reaches the assumed level setpoint of either +38 or -64 centimeters (+15 or -25 inches) with either one or two SRVs available for ADS. RHR is in LPCI mode by default and begins injection once RCS pressure is sufficiently low. Since RHR is needed in LPCI mode, and only one train of RHR is available by scenario definition, no wetwell cooling is available. Operators maintain RPV pressure around 0.34 MPa (50 psig) by modulating the SRVs as needed. Hence, torus water temperature slowly continues to rise. When wetwell pressure reaches the required PCPL of EOP-2 of 53 psig, the hardened vent in the torus is opened and decay heat is expelled through the vent.

None of the scenarios with nominal injection results in core damage. However, in some cases, the core uncovers and experiences some heatup during ADS depressurization. Table 3-4 demonstrates the impact of various factors on the extent of this heatup. The factor with the greatest impact is the number of valves available. A single valve is able to depressurize the reactor and allow for LPI; however, the depressurization takes several minutes, during which time LPCI is deadheaded. During this time, the core uncovers and begins to heat up. As pressure continues to decrease, water in the feedwater lines begins to flow back into the RPV. This water enters the RPV Downcomer, re-covering much of the core and preventing the core from overheating further, even before LPCI is able to inject. Some uncertainty is associated with the timing of water entering the RPV from the feedlines. Table 3-5 includes two sensitivity scenarios with the feedwater line isolated from the RPV at time zero. The scenarios still do not go to core damage, but there is a somewhat greater heatup of the core before LPCI is able to inject. Case 5b reaches 660 degrees C (1,220 degrees F) and Case 7a reaches 703 degrees C (1,297 degrees F).

With a second valve available, the depressurization rate is increased and LPCI injects sooner, precluding any significant heatup of the core. In addition, there is very little heatup of the core when waiting until the water level is at -64 centimeters (-25 inches), and there is no heatup when LPCI is initiated at +38 centimeters (+15 inches).

Table 3-4 Timing of Significant Events and the Maximal Peak Cladding Temperature Reached in the TRANS-30 with nominal CRDHS injection

Case #	**MSIV closure (min)**	**ADS actuation (min)**	**Core uncovery (min)**	**Maximum PCT[1] degrees C** (degrees F)
1.	6.0	38.4	41.7	437 (819)
2.	6.0	38.4	42.2	- [2]
3.	6.0	52.1	45.5	499 (930)
4.	6.0	52.1	45.5	331 (628)
5.	16.3	39.0	42.3	441 (826)
6.	16.3	39.0	42.3	- [2]
7.	16.3	52.8	45.5	504 (939)
8.	16.3	52.8	45.5	336 (637)

[1]Recall that a PCT of 1,204 degrees C (2,200 degrees F) is the core damage surrogate.
[2]The maximum cladding temperature occurred during steady state (i.e., no heatup during the transient).

Manual action to close the MSIVs does not have a significant effect on the scenarios with nominal CRDHS injection. The difference between automatic closure on low water level and the assumed manual action is only 10 minutes. When the MSIVs are closed, RPV pressure quickly rises and the SRVs begin to cycle, so the difference in inventory lost in these 10 minutes is small.

In cases where a single train of CRDHS is able to inject at the maximum capacity (Cases 9–13), the water level initially falls as inventory is lost through the MSIVs and SRVs. However, as the decay heat of the reactor decreases, the injection from the CRDHS is able to offset this loss and recover the RPV level. Since the rate of injection is low, a cooldown of the reactor to low pressure, shutdown conditions is not initiated.

Manual action to close the MSIVs has a greater impact on the scenarios with a single train of increased CRDHS injection. Since the water level does not fall as far, automatic closure of the MSIVs does not occur and without operator action to close the MSIVs, the turbine bypass valves regulate RPV pressure by dumping steam to the condenser. However, with the early closure of the MSIVs at 10 minutes (Case 9), pressure quickly rises and reaches the SRV relief setpoint and begins relieving into the suppression pool (either by cycling on the lowest pressure SRV or by operators opening a valve to keep pressure below this setpoint), which reduces inventory, although not quite as much as the 20-minute case. The difference in RPV level between the 10-minute case and the 20-minute case (Cases 9 and 11) is only 11 centimeters (4.5 inches) at their lowest points. Another impact of early manual MSIV closure is the amount of decay heat that goes to the suppression pool rather than out the steamlines. This impacts the time needed to reach the “action is required” region of the HCL curve. If operators perform an ED (as in Cases 10 and 12), the loss in inventory is greater if ED occurs earlier in the transient, so early manual closure is less beneficial. If not performing an ED and operators only modulate the SRVs to stay below the HCL curve (as in Cases 9 and 11), then this is not a concern. The HCL curve is reached at 5.2 hours, when MSIVs are closed at 10 minutes versus 6.0 hours when closed at 20 minutes. ED, when the HCL curve is crossed in Cases 10 and 12, results in a level drop of 2.2 and 2.5 meters respectively. However, it is not enough to uncover the core in either case.

In the case with no operator action to close the MSIVs to maintain inventory, steam continues to be dumped to the condenser. Because of this, the wetwell water temperature does not rise and the HCL curve is never reached. Wetwell cooling is also not required and RHR remains dormant throughout the calculation

In those cases where two trains of CRDHS are available (Cases 14–16), there is more than enough makeup to maintain the RPV water level. Because of this, a reactor cooldown can occur. Operators are assumed to start the cooldown at 30 minutes at a rate of 44.4 degrees C/hr (80 degrees F/hr). During this depressurization, CRDHS injects in batch mode through two cycles, injecting cool water from the CST that also aids in the cooldown of the reactor. Depressurization continues until pressure is low enough for LPCI to inject. These calculations assume that operators switch to LPCI when pressure drops below 200 psig. Also, at this time, one CRDHS is secured and the other is reduced to the nominal injection rate per AIP-407.

Early closure of the MSIVs at 10 versus 20 minutes has little measurable impact on these scenarios. There is abundant coolant being injected into the RPV, and the reactor cooldown begins at 30 minutes. However, in the 10-minute case, the SRVs cycle on the relief setpoint for several minutes before the initiation of the cooldown, but they do not in the 20-minute case. When MSIVs are left opened, the reactor cooldown is performed using the turbine bypass valves rather than the SRVs. Hence, the cooldown does not result in any significant heatup of the wetwell, the HCL curve is never reached, and wetwell cooling is not needed.

The following discussion is based on the results of the TRANS-49 scenarios (Cases 17–20) as they compare to the TRANS-30 cases.

By sequence definition, depressurization capabilities are not available. In the sequence description, this corresponds to fewer than two ADS valves being available. The TRANS-30 calculations show that a single valve is successful in depressurizing the reactor in this scenario. Hence, for these calculations, the inability for operators to depressurize implies no SRVs are available except in a pressure relief function.

For the cases that have no early closure of the MSIVs (Cases 18 and 20), the simulation progresses the same as in the analogous TRANS-30 cases (Cases 13 and 16). This is because the turbine bypass valves are being used rather than the SRVs to maintain RPV pressure and the inability to depressurize through the ADS system is nonconsequential.

In the case with early closure of the MSIVs and a single train of CRDHS (Case 17), only a single train of CRDHS is available, and it is sufficient to maintain level. The single train of RHR operates in wetwell cooling mode and extends the time to reach the HCL curve. EOP-1 directs operators to modulate the SRV to prevent the RPV from cycling on the SRVs. However, in this case, the ability to manually operate the SRVs is assumed lost and the SRVs cycle at the lowest SRV setpoint. The HCL curve is eventually crossed at 6.1 hours and without SRV operation available, operators would be directed to use alternate means to reduce pressure (Table 7 of EOP-1). Since RCIC and HPCI are unavailable by scenario definition, operators would be directed to use the MSL drains, RWCU (only modeled as a heat sink that ceases at reactor scram), or other steam-driven equipment to reduce the RPV pressure. Since the NRC's current model does not include these other systems, no further action to depressurize is modeled and RPV pressure remains elevated.

The case with early closure of the MSIVs and two trains of CRDHS (Case 19) progresses very similarly to that with a single train of CRDHS. Even though there is sufficient injection to support a cooldown, with MSIVs closed and SRVs unavailable, the pressure remains high, cycling on the lowest setpoint SRV. The HCL curve is crossed at 4.9 hours, and operators would seek alternative means to reduce pressure.

Sensitivity Calculations

In addition to these results, additional sensitivity studies were run to investigate specific issues, documented in Table 3-5.

Table 3-5 Sensitivity study matrix—HPI and SRV criteria for non-ATWS

Case #	Sensitivity	Impact
5a	Increase CRDHS flow rate to mimic alternate flow provided by the SLC system (12.7 m^3/hr [56 gpm] per EOP-1, Table 2A).	Initially, there is little difference between this sensitivity and the base calculation. The additional injection from SLC does little to offset the initial loss of inventory through the steamlines. ADS is actuated at 46.4 minutes when level reaches +38 centimeters (+15 inches). The increased injection has a greater impact in the long term. Until 8 hours, LPCI goes through 3 cycles (versus 4 cycles in the base calculation). After 8 hours, LPCI is no longer called upon to inject. SLC makeup is sufficient to prevent level from reaching L 2 between 8 and 24 hours. This is in contrast to 4 more duty cycles of LPCI that occur in the base calculation.
6a	LPI provided by CS rather than LPCI	There is little difference in the calculation. In the base calculation, it is the timing of LPI that makes a difference in the calculations, not the source of that injection.
6b	Automatic initiation of ADS (i.e., operator fails to inhibit ADS early)	ADS activates 120 seconds after the water level in the vessel Downcomer falls below Level 1. ADS actuates at 16.3 minutes, which is just after MSIV closure. The core briefly uncovers at 19.3 minutes but LPCI injection allows for level recovery. In this case, bypassing

Table 3-5 Sensitivity study matrix—HPI and SRV criteria for non-ATWS (continued)

Case #	Sensitivity	Impact
		automatic ADS actuation and manually actuating it delayed the need for LPCI by about 20 minutes.
6c	Recirculation pump seal leakage of 4.1 m^3/hr (18 gpm) per pump	There is a minimal impact of recirculation pump seal leakage on the results of the transient. ADS actuation and core uncovery both occur 4 minutes sooner; there are some minor timing differences downstream of when LPCI injects.
5b 7a	Feedwater line isolated from the RPV at start of scenario	In the base calculation, the water in the feedwater line enters the RPV Downcomer just as the core begins to heat up and thereby arrests the heatup. In this scenario, a valve is added to the feedwater inlet to isolate the line at the start of the transient. Without this water, the core continues to be uncovered during the long ADS depressurization from a single valve. Core damage does not occur in either case but there is more heatup of the core before LPCI is able to inject.

3.3 Small Loss-of-Coolant Accident Sequence

3.3.1 Calculation Matrix Development

Table 3-6 describes the PRA sequence that is the focus of this section.

Table 3-6 PRA sequences of interest for depressurization—SLOCA

PRA Seq.	Event	Description
SLOCA-25	Initiator	Leakage occurs between 0.5- and 2-inch equivalent diameter (e.g., through-wall crack in recirculation piping).
	/RPS	Reactor is successfully shut down.
	/OEP	Offsite power is available (failure sequence disabled in model).
	/VSC	Failure of vapor suppression (top event is disabled in model)
	PCS	Power conversion system fails (e.g., operator fails to maintain feedwater injection).
	MFW	Main feedwater fails (e.g., operator fails to maintain feedwater injection).
	HPI	High-pressure injection fails (meaning RCIC and HPCI are both unavailable).
	/DEP	Manual depressurization of the reactor occurs (e.g., two of six SRVs opened by operator).
	CDS	Condensate system fails (e.g., operator fails to maintain condensate injection).
	/LPI	Low-pressure injection succeeds (namely one train of LPCI or one train of CS succeeds).
	/SPC	Suppression pool cooling late succeeds (namely, at least one train of RHR provides suppression pool cooling).
	OK	Core damage is averted.

Table 3-7 provides the calculation matrix for the subsequent MELCOR calculations, while Table 3-8 provides the calculation boundary and initial conditions. The following describes the key modeling assumptions made for these calculations.

Table 3-7 Calculation matrix—HPI and SRV criteria for non-ATWS—SLOCA

Case #	Sequence	CRDHS	Timing of ADS initiation	# of SRVs during ADS
21.	Based around SLOCA-25—1-inch equivalent steam (steamline, inside drywell) break	1 train, maximized	N/A	N/A
22.		2 trains, maximized	N/A	N/A
23.	Based around SLOCA-25—1.8-inch equivalent liquid (recirculation loop) break	1 train, maximized	+15	1
24.				2
25.			-25	1
26.				2
27.		2 trains, maximized	+15	1
28.				2
29.			-25	1
30.				2

Table 3-8 Initial and boundary conditions—HPI and SRV criteria for non-ATWS—SLOCA

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 3-7.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on first-in RPS signal. No recirculation pump seal leakage. Number of SRVs available—see Table 3-7.
Balance of plant	Offsite power remains available. Support systems are available unless specified otherwise. Turbine trip occurs at the time of reactor trip. Feedwater and condensate fail at the time of turbine trip. MSIV closure—see Table 3-7.
ECCS/ESF	ESF signals successfully perform their functions. HPCI and RCIC are unavailable. CRDHS—see Table 3-7. SLC—Available, but not used. LPCI/core spray—one train of LPCI is available for RPV injection.
Containment	Suppression pool cooling—one train is available. Nominal drywell and wetwell initial conditions (see Table 2-6) are present.
Other operator actions	LPCS may need to be disabled per EOP-1, if other low-pressure systems are available. Actions to stabilize level/pressure—see Table 3-7. Timing of manual ADS initiation—see Table 3-7.

The initiating event in these scenarios is an SLOCA. The break size and location are varied with either a 1-inch equivalent steamline break or a 1.8-inch equivalent break in the recirculation line.

The steamline break takes place upstream of the MSIVs inside containment. The break size and location are interchanged in sensitivity calculations.

As in the TRANS scenarios, both RCIC and HPCI are unavailable and CRDHS is explored as the alternate source of injection with either one or two trains available for HPI. Operator action to initiate a cooldown of the reactor is contingent upon the sufficiency of CRDHS to provide sufficient makeup to support the cooldown.

For the steamline break cases, the scenarios play out similarly to the TRANS cases with a single train insufficient to support a reactor cooldown while two trains are sufficient. For the cases with a break in the recirculation line, the water level falls too quickly for CRDHS to provide sufficient makeup. MSIVs close on low RPV level, and operators take action to depressurize the RPV using ADS after level reaches +38 centimeters (+15 inches) and before it reaches -64 centimeters (-25 inches), with the two ends of the spectrum explored in the calculation matrix. The number of ADS valves available is also explored here, with either one or two of the five total ADS valves available for emergency relief.

Again, early operator action to manually close the MSIVs to maintain pressure and limit inventory loss is explored. Cases with “automatic” or no closure of the MSIVs assumes indefinite availability of the condenser for steam condensation.

3.3.2 MELCOR Simulation Results

The following discussion is based on the results of the SLOCA-25 scenarios (Cases 21–30). In addition to this, APPENDIX C to this report provides figures for selected parameters of interest.

In the cases with a steamline break (Cases 21 and 22), the break is small enough that pressure and level do not drop significantly. The setpoint for automatic MSIV closure at Level 1 is not reached and MSIVs remain open. Steam is dumped to the condenser through the turbine bypass valves. With a single CRDHS pump available, operators would likely not go to cold shutdown, since the amount of alternate HPI is only just sufficient to maintain RPV water level. The wetwell water temperature heats up because of the steamline break that fills the drywell with steam. As the drywell pressure rises, steam is forced through the Downcomer vents to the wetwell, where it condenses. A single train of RHR is operating in wetwell cooling mode and keeps the wetwell temperature from rising to the point of reaching the HCL curve. Hence, depressurization is never required, and operators maintain RPV pressure in a 1.38-MPa (200-psi) band with some cooling of the RPV occurring from the injection of relatively cool CST water into the vessel by CRDHS.

With two trains of CRDHS, there is sufficient makeup to support a reactor cooldown. It is assumed to begin at 30 minutes at a rate of 44.4 degrees C/hr (80 degrees F/hr). Since the condenser is available, the depressurization uses the turbine bypass valves. Once pressure reaches 200 psig, RHR switches function to LPCI mode and becomes the source of injection. At this point, one of the CRDHS pumps is secured and the other is throttled to inject at a reduced rate (the “nominal” rate) in accordance with AIP-407.

The larger, recirculation line break causes the RPV water level to fall quickly. Unlike the TRANS and steamline break scenarios, CRDHS at the enhanced injection rate is unable to prevent a rapid decrease in water level even with both pumps operating. While none of the scenarios result in core damage, the core uncovers and, in some cases, experiences core heatup during ADS depressurization. Table 3-9 demonstrates the impact of various factors on the extent of this heatup. The factors with the greatest impact are both the number of SRVs available for ADS actuation and the timing of ADS actuation.

In the cases with a single train of CRDHS available, the MSIVs close automatically at 4.8 minutes on the low RPV water level. Pressure rises shortly thereafter, and the RPV begins to cycle on the lowest setpoint SRV. Soon after, operators initiate ADS as the water level continues to fall and reaches either +38 centimeters (+15 inches) or -64 centimeters (-25 inches). If two SRVs are available, there is only modest heatup of the core when operators wait to activate at -64 centimeters (-25 inches) (in Case 26) and no measurable heatup if ADS begins at +38 centimeters (+15 inches) (in Case 24). However, there is a rather significant heatup of the core if there is only a single valve available (Cases 23 and 25).

As in the TRANS scenarios above, as pressure decreases, water in the feedlines drains back into the RPV. However, Table 3-10 includes a sensitivity with the feedline isolated at the start of the transient and it shows little difference. A single valve is able to depressurize the reactor and allow for LPI with no core damage occurring. However, the margin for error is small, and crediting a single SRV for success is not recommended in this case.

Depressurizing the RPV in this case is important not just to speed the LPCI but also to increase CRDHS injection and decrease break leakage. The difference in injection between low and high pressures (40.2 m^3/hr [177 gpm] versus 51.1 m^3/hr [225 gpm]) means that the faster pressure is reduced, the sooner CRDHS can inject at a higher rate. Table 3-10 gives sensitivities with nominal CRDHS injection and two SRVs available. Both scenarios end in success, highlighting the importance of depressurization over injection rate.

Before ADS actuation, there is not a significant difference when two trains of CRDHS are available. The additional injection is still small compared to the loss through the break, and the water level falls quickly. MSIVs actuate on low level at 5.1 minutes. After ADS actuation, heatup of the core is less significant before LPCI, when a single SRV is available.

In those cases, with two SRVs available for ADS, CRDHS injection prevents core damage from occurring during the depressurization. LPCI begins after RPV pressure falls below the assumed deadhead pressure of 197 psid. This injection is able to recover the RPV water level fully, and all calculations thereafter are in a safe and stable state. With a single SRV, the time to depressurize the RPV is extended, and there is more uncertainty as to whether core damage would occur.

A number of cases (Cases 22, 23, 26–30) began to run very slowly caused by numerical issues in the code after RPV depressurization and in the long-term RHR cooling phase (after 8 hours in all cases). Since the reactor is in a safe and stable state in each of these scenarios at this point, no attempt was made to restart these scenarios and they were terminated before 24 hours.

Table 3-9 Timing of significant events and the maximal peak cladding temperature reached in the 1.8-Inch recirculation line SLOCA cases

Case #	**MSIV closure (min)**	**ADS actuation (min)**	**Core uncovery (min)**	**Maximum PCT degrees C (**degrees F)[1]
23.	4.8	8.5	10.2	820 (1,508)

Table 3-9 Timing of significant events and the maximal peak cladding temperature reached in the 1.8-Inch recirculation line SLOCA cases (continued)

24.	4.8	8.5	11.3	-
25.	4.8	10.8	9.9	865 (1,589)
26.	4.8	10.8	9.9	384 (723)
27.	5.1	9.4	11.5	581 (1,078)
28.	5.1	9.4	12.5	-
29.	5.1	12.1	10.8	609 (1,128)
30.	5.1	12.1	10.8	344 (651)

[1]Recall that a PCT of 1,204 degrees C (2,200 degrees F) is the core damage surrogate.
[2]The maximum cladding temperature occurred during steady state (i.e., no heatup during the transient).

Sensitivity Calculations

In addition to these results, additional sensitivity studies were run to investigate specific issues, documented in Table 3-10.

Table 3-10 Sensitivity study matrix—HPI and SRV criteria for non-ATWS

Case #	Sensitivity	Impact
21a	Early closure of the MSIVs (10 minutes)	Operators take early action to close MSIVs at 10 minutes to conserve inventory. SRVs are then used to regulate pressure rather than the turbine bypass valves in the base case. Even with a train of wetwell cooling available, the wetwell water temperature rises to the point that it crosses the HCL curve at 12.0 hours. A single SRV is throttled open to keep RPV pressure below the HCL curve. This has little impact, however, on the RPV level and the overall results of the scenario.
24a 26a	Nominal CRDHS Injection	The CRDHS injection rate is reduced in these scenarios to the "nominal" prescram rate of 9.61 m^3/hr (42.3 gpm). In both cases, the reduced CRDHS injection results in a more rapid drop in level with MSIV closure occurring at 4.5 minutes. ADS actuation begins sooner at 7.4 minutes and 9.7 minutes in Case 24a and 26a, respectively. Because the rate of injection is reduced, there is more uncovery of the core and the core heats up more. Unlike the base case, there is some modest heatup of the core in Case 24a with PCT reaching 373 degrees C (703 degrees F). In the second case, there is also slightly more heatup of the core with PCT reaching 478 degrees C (892 degrees F). In either case, using two SRVs to depressurize, the reactor is still able to expedite LPCI to prevent significant core uncovery.
24b 26b	LPI provided by a single train of core spray rather than LPCI	The LPCS model was modified to operate in batch mode between Levels 2 and 8. There is no indication in the procedures that this is how the pump would actually be operated. The choice was for modeling convenience and so that water would not flood the steamlines. Core spray injects to the region below the vessel shroud dome. Following ADS actuation, LPCS is able to inject sooner, since the shutoff head of LPCS is 264 psid versus 197 psid for LPCI. In the first case, LPCS begins injecting 3 minutes sooner but still after the water level has reached its lowest point and recovered from water in the feedwater line re-entering the vessel. LPI begins sooner but at a slower rate with LPCS rather than LPCI, and level reaches Level 8 at about the same time as the base case. In the second case, LPCS begins injecting at roughly the same time that the core begins to heat up. PCT reaches 378 degrees C

Table 3-10 Sensitivity study matrix—HPI and SRV criteria for non-ATWS (continued)

Case #	Sensitivity	Impact
		(712 degrees F), and the core is completely covered at 16.5 minutes versus at 20.8 minutes in the base case.
24c	Automatic initiation of ADS (i.e., operator fails to inhibit ADS early)	In the base case, pressure briefly rises after MSIV closure and the SRVs cycle before ADS actuation. In this sensitivity, both MSIV closure and ADS actuation occur at 4.8 minutes, and there is no cycling of the SRVs. ADS actuation occurs only 4 minutes sooner than if operators waited for level to fall to +38 centimeters (+15 inches), so there is not a significant difference in the results, apart from minor shifts in timing.
23a 24d	Recirculation pump seal leakage of 4.1 m^3/hr (18 gpm) per pump	In the first case, the seal leakage causes ADS to actuate 0.4 minutes sooner. Because of this, the lowest RPV water level is slightly higher than the base case. The highest PCT attained is 813 degrees C (1,495 degrees F), 7 degrees C (45 degrees F) less than the base case. Because the seal leakage is so much less than the injection rate of LPCI, it has little impact on the rate of level recovery once LPI begins. In the second case, the seal leakage has a minimal effect on the simulation. MSIV closure and ADS actuation start 0.1 minutes sooner and water level falls slightly faster after each LPCI cycle. Again, there is no heatup of the core.
21b 24e	Break size and location of SLOCA exchanged	These sensitivities use a modified version of the deck with the size of the steamline break and recirculation line break interchanged. In the first case, the larger steamline break causes the level to fall faster than in the base case. MSIVs close at 44.0 minutes on low RPV level. After the MSIVs close, the loss of inventory is reduced, and CRDHS is able to recover the water level. The RPV pressure does not remain elevated as in the base case but slowly falls over the course of the simulation. The "action is required" region of the HCL curve is never reached, since a single train of wetwell cooling is available and RPV pressure is kept low from the larger steamline break. In the second case, with a smaller recirculation line break, the RPV water level falls much more slowly, but a single train of CRDHS is still unable to maintain the RPV water level. The MSIVs close at 9.4 minutes on low RPV level and ADS actuates at 23.0 minutes. The core just barely uncovers at 26.7 minutes before it is re-covered by CRDHS injection.
23b	Feedwater line isolated from the RPV at start of scenario	In the base calculation, the water in the feedwater line enters the RPV Downcomer just as the core begins to heat up and thereby arrests the heatup. In this scenario, a valve is added to the feedwater inlet to isolate the line at the start of the transient. There is minimal impact on the scenario from the water not entering or leaving the feedline. As in the base scenario, core damage does not occur, and there is a similar heatup of the core before LPCI is able to inject.

3.4 Conclusions Drawn from MELCOR Results

The staff makes the following observations about the MELCOR results with regard to TRANS-30 and 49:

- CRDHS injection alone operating at the nominal, prescram rate is insufficient in providing makeup to the RPV following an unexpected reactor trip. Another source of HPI (such as RCIC) or LPI with successful ADS operation is necessary for success.

- A single SRV is able to depressurize the RPV and core damage is avoided. However, the uncertainty associated with the volume of water entering and leaving the vessel (i.e., seal leakage, CRDHS injection, feedwater line emptying) at this time makes success of this scenario uncertain.

- The small difference in timing for MSIV closure (6 versus 16 minutes and 10 versus 20 minutes) had little impact on the results. Of greater importance is whether MSIVs are closed at all and whether steam is condensed in the wetwell or condenser. If the condenser is available and MSIVs do not close on low RPV level, the HCL curve will never be reached and ED is not required. Without availability of the condenser, operator action to depressurize the RPV will be necessary to remain below the HCL curve.

- A single CRDHS pump injecting at the postscram increased injection rate is sufficient for RPV water inventory makeup. However, it may not be sufficient to support an RPV cooldown in the first few hours of the transient.

- Two CRDHS pumps injecting at the postscram injection rate provide more than enough makeup to the RPV and can facilitate a cooldown of the RPV to cold shutdown conditions as long as a train of RHR is available.

- Without ADS, operators would have to use alternative means to depressurize the RPV after reaching the HCL curve.

- Operator initiation of ADS at either the +15-inch or -25-inch level has little impact on the success of the scenario.

The staff makes the following observations about the MELCOR results with regard to SLOCA:

- Given an SLOCA in the steamline, pressure and level fall but a single train of CRDHS at the increased postscram rate is able to maintain the RPV level. This is true for both a 1-inch and 1.8-inch equivalent break. With two trains, there is more than enough injection to maintain level and to support a cooldown to cold shutdown conditions.

- For a small, recirculation line LOCA, the loss of inventory is significant enough that even both CRDHS pumps operating at full capacity are insufficient to maintain level. A single train was insufficient even for a smaller 1-inch equivalent break.

- As in the TRANS cases, two SRVs are necessary for ADS success. In addition, operator action to activate ADS at either the +15-inch or -25-inch level has little impact on success.

4 MITIGATING STRATEGIES (FLEX) USAGE IN LOSS-OF-ALTERNATING-CURRENT-POWER SCENARIOS

4.1 Issue Description

Following the severe accidents of March 2011 at the Fukushima Dai-ichi nuclear power plant site in Japan, the NRC issued several new regulatory requirements, including Order EA-12-049. This order required all U.S. nuclear power plants to implement strategies that allow them to cope without their permanent electrical power sources for an indefinite amount of time. The associated strategies must keep the reactor core and spent fuel stored in pools cool, as well as protect the containment. The mitigation strategies use a combination of already installed equipment (e.g., steam-powered pumps), additional portable equipment that is stored on site, and equipment that can be flown in or trucked in from one of two regional response centers.

During the implementation of the above order, the NRC issued interim staff guidance (ISG) in the form of JLD-ISG-12-01, "Compliance with Order EA-13-109, Order Modifying Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation under Severe Accident Conditions," in August 2012 (NRC, 2012a), and Revision 1 of the same in January 2016 (NRC, 2016b). The January 2016 revision states the following, in part:

> The NRC staff considers that the development, implementation, and maintenance of strategies and guidance in conformance with the guidelines provided in NEI 12-06, Revision 2, are an acceptable means of meeting the requirements of Order EA-12-049, subject to the exceptions, additions, and clarifications in the enclosure with this ISG. However, NRC endorsement of NEI 12-06, Revision 2, does not imply NRC endorsement of references listed in NEI 12-06, Revision 2.

Nuclear Energy Institute (NEI)-12-06, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," Revision 2, issued December 2015 (NEI, 2015a), in turn, provides development, implementation, and maintenance guidance for the strategies and equipment, including the FLEX support guidelines (FSGs), which serve as a new set of guidance governing response to declared ELAP events.

These strategies and equipment are designed for use in postulated accidents where an ELAP is declared during the course of responding to an SBO, and so this project will provide confirmatory information with respect to the success criteria and sequence timing assumptions associated with potential licensee use in risk-informed licensing and oversight submittals. However, in some cases licensees have sought credit for these strategies and equipment in non-ELAP scenarios (loss-of-ac-power scenarios more generally, or otherwise). Examples include the following:

- Watts Bar Units 1 and 2—EDG completion time extension based on availability of a FLEX diesel generator (TVA, 2016) and (NRC, 2017)
- Palo Verde Units 1–3
  - credit for FLEX in shutdown risk management (as stated by the Palo Verde licensee during public meetings)

– use of alternate ac FLEX connection box and FLEX diesel-driven steam generator makeup pump for exigent technical specification change (NRC,2016c)

For this reason, this project will develop similar confirmatory information for other scenarios of interest.

For Mark I and II containment designs, the NRC issued separate orders related to venting capabilities; namely, Order EA-12-050 "Order to Modify Licenses with Regard to Reliable Hardened Containment Vents" (NRC, 2012a), and a superseding modification in Order EA-13-109, "Order to Modify Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions" (NRC, 2013a). The extension of venting capabilities covered by Order EA-13-109 is closely coupled with venting strategies used in the response to ELAP events.

Similar to the process described above for the mitigating strategies order, the NRC has issued two ISGs (JLD-ISG-2013-02, "Compliance with Order EA-13-109, Order Modifying Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions," dated November 14, 2013 [NRC, 2013a], and JLD-ISG-2015-01, "Compliance with Phase 2 of Order EA-13-109, Order Modifying Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation under Severe Accident Conditions," issued April 2015 [NRC, 2015b]) for Order EA-13-109 implementation, ultimately endorsing (with exceptions and clarifications) NEI-13-02, "Industry Guidance for Compliance with Order EA-13-109," Revision 1, issued April 2015 (NEI, 2015b).

4.1.1 DAEC Post-Fukushima Actions Related to Mitigating Strategies

In response to NRC Order EA-12-049, DAEC submitted an overall integrated plan on February 28, 2013, and 6-month periodic updates thereafter. DAEC is subject to all five hazards covered by the implementing guidance of this order: seismic; external flooding; storms with high winds; snow, ice, and low temperatures; and high temperatures (NextEra, 2013a). In December 2016, DAEC came into full compliance with this order (NextEra, 2016).

Similarly, in response to NRC Order EA-13-109, DAEC submitted its overall integrated plan on June 25, 2014, and 6-month periodic updates thereafter. The original plan and subsequent updates address a plant modification to provide a new severe-accident-capable hardened wetwell vent (i.e., HCVS). DAEC anticipates coming into final compliance with this order during the next refueling outage (NextEra, 2018).

4.1.2 The Scenario Assumed for Mitigating Strategies Formulation

The purpose of the response to the mitigating strategies order was to develop strategies capable of mitigating a simultaneous loss of ac power and loss of normal access to the UHS resulting from a beyond-design-basis event by providing adequate capability to maintain or restore core cooling, containment, and SFP cooling capabilities (at all units on a site).

The following assumptions apply to the conditions leading up to the event and to the initiator itself (from NextEra, 2013a and NRC, 2014b):

- The plant has been operating at 100 percent for at least 100 days or has just been shut down because of the impending event; SFP heat load assumes the maximum design-basis heat load for the site.

- Reactor and support systems are in normal operational ranges, and all plant equipment is operating normally or is available from the standby state.

- The initiating event is assumed to be a LOOP resulting from an external event, with no prospect for recovery.

- All installed sources of emergency onsite ac power and SBO alternate ac power sources are assumed unavailable and not imminently recoverable.

The following additional assumptions apply after the event occurs:

- Normal access to the UHS is lost, but the water inventory in the UHS remains available and robust piping connecting the UHS to plant systems remains intact. The motive force for river water supply pumps is assumed to be lost with no prospect for recovery.

- Cooling and makeup water inventories contained in systems or structures with designs that are robust with respect to seismic events, floods, and high winds, and associated missiles are available.

- Fuel for FLEX equipment stored in structures with designs that are robust with respect to seismic events, floods and high winds, and associated missiles remains available.

- Permanent plant equipment that is contained in structures with designs that are robust with respect to seismic events, floods, and high winds, and associated missiles is available.

- Other equipment, such as portable ac power sources, portable backup dc power supplies, spare batteries, and equipment for 10 CFR 50.54(hh)(2), may be used, provided it is reasonably protected from the applicable external hazards.

- Elements of the installed electrical distribution system, including inverters and battery chargers, remain available, provided they are protected consistent with the current station design.

- Recovery of damaged plant equipment is excluded.

- No additional events or failures are assumed to occur immediately before or during the event, including security events.

- All boundaries of the SFP are intact (e.g., liner, gates, transfer canals). Although sloshing may occur during a seismic event, the initial loss of SFP inventory does not prevent access to the refueling deck around the pool. The SFP cooling system is intact, including attached piping.

- Offsite personnel start arriving at 6 hours, and the site will be fully staffed by 24 hours after the event.

4.1.3 DAEC Plant Modifications To Comply with the Post-FukushimaOrders

In accordance with (NextEra, 2013a; NextEra, 2014a), plant modifications made specifically to address the mitigating strategies order include the following:

- addition of one portable 480V generator for alternate power connections:
  - to repower 125V dc battery chargers (1D12 and 1D120), 250V dc battery charger ID43, and 480V ac load center IB032[1]
- addition of two 120V ac generators for alternate instrument power connections:
  - to repower 120V ac generator to IY11 and IY21 or connect 120V ac generator to instruments locally
- a diverse injection point for connection of portable pumps to the RPV, using:
  - a 4-inch branch installed on the RHR service water piping at location GBB-004[2]
  - a connection point from the main turbine condenser system hotwell (to be used in flooding events only, as the condenser is not seismically qualified)[3]
- new portable equipment storage locations
- deployment location for portable equipment during floods
- strategies for replenishing fuel supplies for portable equipment

Attachments 2 and 3 of (NextEra, 2013a)[4] include an equipment use matrix for Phases 2 and 3 of the mitigating strategies order.

In accordance with (NextEra, 2014b; NextEra, 2015b), additional plant modifications to address the severe accident capable hardened vent order include the following:

[1] This load center designation was updated in (NextEra, 2014a).

[2] (NextEra, 2013a) states that this involves a 4-inch branch to be installed on the 12-inch GBC-005, RHR service water piping upstream of MO 1942 in the South East Corner Room. (NextEra, 2014a) updates the location but does not specify whether the other characteristics (e.g., relationship to MO 1942) still apply.

[3] (NextEra, 2013a) stated that a buried pipe would be installed to provide circulation pit water from the pump house to the (flood-protected area) turbine building. In (NextEra, 2015a), this approach was replaced by the use of the hotwell.

[4] As indicated in (NextEra, 2014a), Attachment 6 of (NextEra, 2013a) inadvertently omits reactor water level indication.

- A remote operating station for the HCVS is installed in the 1A3[5] essential switchgear room in the turbine building.

- A new wetwell vent path is installed using an existing spare penetration off the wetwell, with new primary containment isolation valves and a new rupture disk. The vent piping is routed in to the south reactor building stairwell, up to the refuel floor, and out the reactor building roof. Attachment A of (NextEra, 2015b) includes a schematic of the ventpath.

- A dedicated uninterruptable power supply and disconnect switches needed to power the HCVS are installed.

- Attachment B of (NextEra, 2015b) lists the process instrumentation for the HCVS.

The only HCVS-related portable equipment identified in (NextEra, 2014b), beyond the portable diesel generator described above under the EA-12-049 modifications, is the compressed gas cylinders for longer term valve motive force.

This series of cases investigates what PRA functions the FLEX equipment and strategies can satisfy and what limitations need to be placed on failure or success of such equipment and strategies. For these cases, there are several key uncertainties to be explored. The bullets highlighted below in bold are the focus of this case.

The following are key uncertainties:

- time of loss of ac power (i.e., EDG failure to run)

- time of battery depletion[6]

- time of ELAP declaration

- time of RCIC loss (if other than upon battery depletion), including possible consideration of the following:

  - efforts to manually operate RCIC without dc power (i.e., “blackrun”)

  - suppression pool conditions:

    - heatup (i.e., NPSH or bearing overtemperature)
    - pressure (i.e., high turbine exhaust pressure)
    - level (i.e., insufficient suction)

  - RCIC turbine flooding from RPV overfill or insufficient steam from RPV underfill

- RCIC delivered flow

[5] (NextEra, 2014b) updated this location from the original integrated plan.

[6] This item encapsulates various issues that are transparent to the MELCOR model, such as the effectiveness of load-shedding efforts, the fluctuation in charge during the battery lifecycle, the extent of the demands on the batteries (e.g., SRV lifts, RCIC operation), and efforts to align a 480V ac generator to extend battery life.

- availability of HPCI
- number of relief valves actuating during depressurization and timing of action (also the subject of Chapter 3)
- recirculation seal leakage
- flow rate achieved by ac-independent injection, and timing of injection—could also consider inadvertent partial diversion of flow (as at Fukushima) or core inlet plugging if dirty water is being used
- timing and nature of containment venting (also the subject of Chapter 5)[7]
- effect of containment venting/failure on late injection (also the subject of Chapter 6)

Although this investigation is anticipatory (focused on PRA uses that have not yet materialized), the existing SPAR model is still used as an anchor point for selecting one SBO sequence with postulated late-use of diverse RPV injection using a FLEX pump and one non-SBO sequence of the same. Section 4.2 describes the SBO sequence, while Section 4.3 describes the non-SBO (LOMFW) sequence.

4.2 Station Blackout Sequence

4.2.1 Calculation Matrix Development

Table 4-1 describes the PRA sequence that is the focus of this section.

Table 4-1 SBO sequence of interest for FLEX-based diverse injection

PRA Sequence	Event	Description
LOOPGR-38-9	Initiator	A grid-related LOOP occurs.
	/RPS	Reactor is successfully shut down.
	EPS	Both divisions of emergency onsite power (diesel generators) fail, resulting in an SBO.
	/SRV	SRVs successfully reclose (if demanded).
	/RPSI	Recirculation pump seals retain their integrity.
	/RCI02	RCIC successfully provides high-pressure RPV makeup before battery depletion.
	EXT	RCIC fails at or near the time of battery depletion (e.g., because of failures related to valve alignment).
	/DEP-B	Manual depressurization of the reactor occurs (e.g., two of six SRVs opened by operator).
	/FWS	AC-independent injection succeeds in providing low-pressure RPV makeup (assumed here to come from the FLEX pump diverse injection capability). *Set to fail in current baseline model.*

[7] Site-specific information related to containment venting can also be found in Technical Support Guidance Appendix C and SEPs 301.1–301.3. The licensee provided most of these with its postsite visit submittal, while it included the SEP 301.1 just before the site visit with the FSG supporting material.

Table 4-1 SBO sequence of interest for FLEX-based diverse injection (continued)

PRA Sequence	Event	Description
	OPR-12H	Offsite power is not recovered within 12 hours.
	DGR-12H	A diesel generator is not recovered within 12 hours—*implying that the FSG-based action to receive and hook up a 4160kV turbine generator from the National SAFER Response Center has not occurred.*
	/CVS-B	Containment venting operations are successful.
	/L01	Injection continues after venting operations.
	OK	Core damage is averted.

Table 4-2 provides the calculation matrix for the subsequent MELCOR calculations, while Table 4-3 provides the calculation boundary and initial conditions. A discussion of the key modeling assumptions made for these calculations follows.

Table 4-2 Calculation matrix— mitigating strategies—SBO

Case #	Time of ac loss	Time of loss of RCIC [1 2 3]	CST availability	Venting actions[4]
1	t = 0	t = 4 hours (FLEX pump provides injection thereafter)	Available	Required
2				Anticipatory
3			Unavailable	Required
4				Anticipatory
5		t = 8 hours (FLEX pump provides injection thereafter)	Available	Required
6				Anticipatory
7			Unavailable	Required
8				Anticipatory
9		Indefinite (no FLEX injection)	Available	Required
10				Anticipatory
11			Unavailable	Required
12				Anticipatory
13	t = 2 hours	t = 4 hours (FLEX pump provides injection thereafter)	Available	Required
14		t = 8 hours (FLEX pump provides injection thereafter)		
15		Indefinite (no FLEX injection)		Anticipatory
16			Unavailable	

[1] Although the SPAR model dictates that RCIC would fail from battery depletion, the FLEX portable diesel generator may be able to provide this battery power. RCIC failure here is assumed to occur, not for one particular reason but rather based on a myriad of potential failure modes, such as high exhaust pressure, suppression pool temperature, and battery depletion. As such, RCIC could be lost before this time. If RCIC trips, restart is not considered (as a simplifying assumption).

[2] Depressurization following battery depletion would require additional actions to locally operate the SRVs, as they require dc power for other-than-pressure relief operation.

[3] At 110 psig, the FLEX pump is able to inject to the RPV at a rate of approximately 129 m^3/hr (570 gpm). The licensee provided a pump curve to generate the nominal pressure-dependent flow rate.

[4] Required venting refers to the PCPL of EOP-2 venting action of maintaining 0.31–0.37 MPa (45–53 psig) in the wetwell. "Anticipatory" venting refers to maintaining a pressure band of 0.03–0.07 MPa (5–10 psig) in SEP 301.3.

Upon a loss of all ac power, operators enter AOP 301.1 for an SBO. This procedure directs operators to begin a rapid depressurization of the reactor, not surpassing a cooldown rate of 44.4–55.6 degrees C/hr (80–100 degrees F/hr). This must be initiated within 30 minutes, regardless of whether an ELAP has been declared. Hence, for the simulations in the calculation matrix of Table 4-2**,** there is a 55.6-degree-C/hr (100-degree-F/hr) cooldown that begins 30 minutes after the loss of all ac power. The EOPs contain a warning for operators to maintain RPV pressure greater than 150 psig to prevent RCIC loss on low steam pressure; therefore, a lower bound of 150 psig is enforced while RCIC is available for injection. Operators are permitted by EOP-2 to exceed the 55.6-degree-C/hr (100-degree-F/hr) cooldown limit, should this rate be insufficient in staying below the HCL curve. However, the cooldown limit is sufficient in all of the calculations in Table 4-2.

AOP 301.1 directs operators to declare an ELAP if (1) it is determined that ac power may not be restored within the coping time of 4 hours, or (2) if the plant has been in an SBO condition for 1 hour. Therefore, it is reasonable to assume that an ELAP is declared 1 hour after loss of all ac, and operators enter a beyond-design-basis event at this time. Operators then perform load-shedding actions (within 2 hours) to extend the battery life of the safety-related station batteries. During this time, RCIC (or HPCI if RCIC is unavailable) provides core makeup from either the CST or the suppression pool (depending on availability but with preference given to the CST). CST availability is varied in the calculation matrix with RCIC taking suction on either the CST or the wetwell.

RCIC/HPCI failure in the SPAR SBO sequence occurs upon battery depletion since dc power is required for RCIC/HPCI control. As previously described, FLEX procedures include the staging of a 480V diesel battery charger for repowering the 125V dc battery chargers (1D12 and 1D120). If this is successful, dc power and control of RCIC/HPCI is not lost. There are, however, many other potential failure modes for RCIC/HPCI, such as high exhaust backpressure, loss of NPSH, and overheating of bearings. The range of failure times in Table 4-2 is intended to reflect these failure modes as well as the failure of the FSG-based use of a portable diesel generatorto supply power to station battery chargers. Note that “indefinite” RCIC availability implies that the battery recharging is successful. The other pump and turbine trips built into the model are still active.

The availability of a FLEX pump for injection following the loss of RCIC is also explored. The pump is assumed to have been staged for injection before the loss of dc power in accordance with the FSGs. Upon a loss of RCIC, two SRVs are used to rapidly lower pressure such that it remains below 50 psid between the RPV and wetwell. (EOP ED calls for RPV pressure less than 50 psig above torus pressure.) In the applicable scenarios, the FLEX pump begins injecting when RPV pressure falls below the pump’s 110 psig deadheadpressure.

This section also investigates venting actions. In the event of a loss of the UHS or an ELAP, operators would open the HCV to maintain an “anticipatory” pressure band of 5–10 psig to maintain RCIC injection. If anticipatory venting does not occur, when the wetwell pressure approaches 53 psig, the required PCPL of EOP-2 venting action of maintaining 45–53 psig would be enforced (see Appendix B).

Under normal conditions, RCIC injection is performed in “batch mode” wherein the RCIC pump is secured when the RPV level reaches the desired maximum level (normally Level 8) and then restarted when level falls below the minimum desired level (normally Level 2). EOP-1 grants operators the option to use RCIC in an expanded level band if loss of injection is a concern. This expanded band is 38 centimeters (15 inches) to 655 centimeters (258 inches) above the

TAF. Discussions with DAEC operations staff suggested that operators are unlikely to allow level to go below 303.5 centimeters (119.5 inches) (referred to as Level 2), even when it is procedurally permitted. Hence, batch RCIC injection for these calculations is taken to be RCIC cycling full on and full off to maintain a band of 303.5 centimeters (119.5 inches) to 655 centimeters (258 inches). The exception to this is scenarios with ac power available for the first 2 hours. In an early round of calculations, water level continued to increase even after RCIC was secured at the expanded high level because of ongoing injection from CRDHS. This led to water entering the steamlines and a loss of RCIC on a code-automatic trip signal of a high steamline water level. For this reason, the upper bound of the RCIC level band was reduced by 0.5 meters (20 inches) (from 6.55 meters [258 inches] to 6.05 meters [238 inches] above TAF) to prevent flooding of the steamlines and loss of RCIC. This was thought reasonable since RCIC could be expected to operate with some water entering the steamlines. The LOMFW scenarios in the next section explore this further.

FLEX guideline SAMP-730 recommends that operators not run RCIC in batch mode when taking suction on the wetwell with wetwell water temperature greater than 215 degrees F. The concern is degradation in pump performance and reliability at such an elevated temperature. Instead, operators are encouraged to throttle the pump within the permitted level band. If the CST is unavailable and suction is being taken on the wetwell, the current calculations model this throttled injection when the water temperature in the suppression pool reaches 215 degrees F. However, if RCIC is already secured when the temperature reaches 215 degrees F, it is assumed that injection does not start until level falls back to Level 2. The target level assumed here is the “normal” RPV level of 485 centimeters (191 inches) above TAF. This choice should be carefully evaluated since, although thought to be reasonable, the water level could procedurally be maintained anywhere between 38 and 655 centimeters (15 and 258 inches).

If wetwell water temperature is greater than 250 degrees F, SAMP-730 directs operators to throttle RCIC full open to run up the water level to just below the steamlines before swap-over to FLEX injection. This is not included in the staff’s model since, for one, the wetwell water temperature reaches this value after the swap-over to the FLEX pump has already occurred. In addition, procedurally, this runup of level only takes place when wetwell temperature exceeds 250 degrees F. There is no known procedure for running up water level when anticipating the loss of RCIC before this temperature is attained; however, the possibility of operators running up water level before the loss of dc power is investigated as a sensitivity calculation.

RCS depressurization following loss of dc power requires additional actions to locally operate the SRVs since they require dc power for operation other than automatic pressure relief. For all LOOP scenarios, it is assumed that depressurization is successful, regardless of whether RCIC failure was caused by dc power loss. SAMP-707 provides procedures for depressurizing the RPV by use of battery carts or battery packs, or both, to open the valves locally. Hence, RCS ED begins at the time of RCIC loss and the FLEX pump begins injecting when pressure falls below the pump’s 0.76 MPa (110 psig) deadhead pressure. It is important to note that, upon a loss of all dc power, without this local depressurization, the staged FLEX pump would be deadheaded, and core damage would occur.

Table 4-3 Initial and boundary conditions—mitigating strategies—LOOPGR

System	Condition
These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 4-2	
RCS	100% (full power). Reactor successfully trips on loss of offsite ac. Nominal[1] recirculation pump seal leakage. Number of SRVs available—two of six.
Balance of plant	Offsite power—unavailable. Onsite emergency ac—see Table 4-2. DC power—see Table 4-2. Support systems are available (if ac is available) unless specified otherwise. Turbine trip occurs upon loss of offsite ac. Feedwater and condensate fail upon loss of offsite ac. MSIV closure occurs upon loss of offsite ac.
ECCS/ESF	ESF signals successfully perform their functions until battery depletion. CST availability—see Table 4-2. HPCI is unavailable (by PRA sequence definition). RCIC availability—see Table 4-2. CRDHS and SLC are unavailable upon loss of ac. LPCI/core spray are unavailable upon loss of ac.
Containment	Suppression pool cooling is unavailable upon loss of offsite and onsite ac. Nominal drywell and wetwell initial conditions (see Table 2-6).
Other operator actions	If credited, LPCS may need to be disabled per EOP-1, if other low-pressure systems are available. Actions related to RPV depressurization—see Table 4-2. Actions related to containment venting—see Table 4-2. Actions to align alternate injection via a FLEX pump—see Table 4-2.

[1] In this context, this means 4.1 m^3/hr (18 gpm)/pump at the lowest SRV pressure setpoint.

4.2.2 MELCOR Simulation Results

Table 4-4 lists the results of the 16 LOOP calculations. In addition to this, APPENDIX D to this report includes figures for selected parameters of interest.

Table 4-4 LOOPGR results

Case #	RCIC suction source	Containment venting (hours)	FLEX pump injection begins (hours)	Core uncovery (hours)	Core damage (hours)
1.	CST	Required (20.7)	Yes (4.0)	No	No
2.	CST	Anticipatory (6.4)	Yes (4.0)	No	No
3.	WW	Required (17.7)	Yes (4.0)	No	No
4.	WW	Anticipatory (5.6)	Yes (4.0)	No	No
5.	CST	Required (20.6)	Yes (8.0)	No	No
6.	CST	Anticipatory (7.1)	Yes (8.0)	No	No
7.	WW	Required (16.3)	Yes (8.0)	No	No
8.	WW	Anticipatory (6.0)	Yes (8.0)	No	No
9.	CST	Required (21.0)	No	> 24	> 24

Table 4-4 LOOPGR results (continued)

Case #	RCIC suction source	Containment venting (hours)	FLEX pump injection begins (hours)	Core uncovery (hours)	Core damage (hours)
10.	CST	Anticipatory (7.1)	No	No	No
11.	WW	Required (12.4)	No	10.5	12.0
12.	WW	Anticipatory (6.0)	No	No	No*
13.	CST	Required (23.2)	Yes (4.0)	No	No
14.	CST	Required (22.6)	Yes (8.0)	No	No
15.	CST	Anticipatory (7.8)	No	No	No
16.	WW	Anticipatory (6.9)	No	No	No*

*Although core damage is not predicted in these calculations, RCIC is operating for an extended period of time (>16 hours) with suction on the wetwell and low NPSH available. Pump damage caused by cavitation is likely and the success of the scenario is questionable at best.

In many cases, during the first cycle of RCIC, the RPV water level dips significantly lower than Level 2 before RCIC injection raises the level. The cause of this is multifaceted. First, there is a 30-second delay in RCIC injection following level falling through Level 2. In addition, the temperature of the water injected by RCIC is significantly cooler than the water already in the feedwater line (105 degrees F versus 430 degrees F). The density of the water is increasing rapidly both here and in the RPV. This change of density is likely a factor in the slow-to-respond water level. Additionally, early on in the sequence progression, the decay heat is high enough to significantly influence the efficacy of RCIC injection.

In those cases where all ac power is lost at time zero, the reactor trips and the RPV cycles on the lowest pressure SRV. After 30 minutes, the 55.6 degree C/hr (100 degree F/hr) cooldown is initiated. The model used a PID controller to attain this cooldown rate. Hence, there are times when the rate is exceeded (particularly when RCIC injection takes place), but on average, the desired rate is maintained.

In the scenarios in which all ac power is lost at time zero and RCIC is lost at 4 hours (Cases 1–4 and 14), there is ample cooling from RCIC injection to the RCS from either the wetwell or the CST. The RCS is depressurized to 1.03 MPa (150 psig) to allow for prolonged RCIC injection. RCIC makes it through one full cycle and part of a second. At 4 hours, RCIC is secured, the RPV is rapidly depressurized to 0.34 MPa (50 psig), and FLEX begins injection at the nominal rate. Whether operators perform anticipatory venting or not is of no consequence to the success of these sequences, since wetwell pressure is below 0.07 MPa (10 psig) at 4 hours when the FLEX pump begins to inject. RCIC performance is not in question, and the success of FLEX pump injection is not contingent upon the pressure or temperature in the wetwell. However, the hardened vent must still be opened eventually to allow for the expulsion of decay heat from the wetwell, which occurs in these cases at either the anticipatory or the required setpoints of 0.07 MPa (10 psig) or 0.37 MPa (53 psig), respectively.

The NPSH available for RCIC suction on the wetwell is estimated for those scenarios in which the CST is unavailable (Case 3 and 4). At 4 hours, the NPSH is well above the 6.1 meters (20 feet) of head that is required for RCIC pump suction according to the UFSAR. This implies that pump cavitation is not a concern when swap-over occurs at 4 hours.

In the scenarios with RCIC lost at 8 hours (Cases 5–8), RCIC makes it through three cycles before it is lost, and operators switch to FLEX injection. When the CST is available (Cases 5 and 6), RCIC injection remains in batch mode for the entire 8 hours. As in the analogous 4-hour cases, anticipatory venting has little impact on the outcome when CST is available, although venting is necessary for decay heat rejection to the environment. In the cases where the CST is unavailable (Cases 7 and 8), RCIC injection is throttled around 5.1 hours when the wetwell temperature rises above 215 degrees F. Not long after this, the NPSH available for RCIC falls below 6.1 meters (20 feet) and some cavitation in the pump is possible (although it is not modeled). When the hardened vent is opened around 6 hours in the case with anticipatory venting, the NPSH drops even further. As of 8 hours, the NPSH available to RCIC is 3.41 meters (11.2 feet) in the case without anticipatory venting and 1.7 meters (5.6 feet) in the case with anticipatory venting.

In the cases where RCIC is available indefinitely (Cases 9–12), a swap-over to FLEX pump injection is assumed not to occur, and RCIC remains the source of long-term injection. It is perhaps not intuitive that core damage occurs in the case with RCIC suction from the CST and “required” HCL venting (Case 9), since RCIC is injecting cool water from the CST. Although CST inventory has not been exhausted, RCIC still trips around 20.2 hours. The cause of this loss of injection is a RCIC turbine trip on high backpressure in the wetwell of 0.34 MPa (50 psig). Since the wetwell pressure is allowed to increase to 0.37 MPa (53 psig) with the “required” PCPL venting, this trip is inevitable. Since dc power is available in this scenario, the automatic protection system is active and RCIC cannot be restarted. This is similar to what is thought to have happened at Fukushima Unit 3. There, dc power was available and RCIC injection was lost at 21 hours because of the high backpressure trip (Sandia, 2014a).[8] With dc assumed to be available in these scenarios, the trip is active, and they are assumed to go to core damage because of a loss of RCIC injection when wetwell pressure reaches 0.34 MPa (50 psig). Operator action to vent the wetwell at the “anticipatory” setpoint of 0.07 MPa (10 psig) in Case 10 prevents this trip of RCIC from occurring and core uncovery and damage are not predicted to occur so long as the CST is available. As of 24 hours, there is ample water still available in the CST.

When RCIC suction is on the wetwell, as in Cases 11 and 12, the pressure in the wetwell and operator venting action is also important. Without anticipatory venting, the wetwell pressure and temperature continue to rise as the RPV vents into the wetwell. The bulk water temperature in the wetwell reaches 250 degrees F at 7.9 hours, and RCIC is assumed to fail. Without an injection source, core uncovery and damage occur. Conversely, in Case 12, venting of containment begins at 6.0 hours. The anticipatory venting is successful in keeping the wetwell pressure low and therefore keeping the water temperature under the 250 degrees F threshold for loss of RCIC. Hence, there is no hard trip of RCIC, and injection continues with RCIC being throttled for makeup. However, the NPSH available to the pump drops below 6.1 meters (20 feet) at 5.5 hours, and cavitation is possible. Once wetwell venting begins and the pressure drops, the NPSH falls and is at 1.6 meters (5.1 feet) at 8 hours. Operating RCIC out beyond 8 hours while taking suction on a saturated pool is therefore beyond what RCIC is designed for, and this scenario should not be considered a success. Hence, with long-term RCIC injection on the wetwell, wetwell venting has the positive effect of keeping the suction water temperature below 250 degrees F and reducing concern for RCIC failure on high bearing temperature, but it has the negative effect of reducing the NPSH available to the pump by reducing the pressure within the wetwell. According to the DAEC UFSAR (Section 1.8.1), the maximum wetwell

[8] If dc power had not been available, SAMP-703 discusses RCIC operation during loss of electrical power. It states that, if turbine exhaust pressure reaches 50 psig, operators are to close the RCIC throttling valve; however, there is a warning statement that the automatic initiation and isolation features will not be available. In this case then, the 50-psig turbine isolation on backpressure requires a manual action and operators could reopen the RCIC valve when pressure drops below 50 psig.

pressure that can be credited for NPSH is 0.15 MPa (22 psia). Hence, the lower NPSH from anticipatory venting is more in line with the licensee's assumptions.

In summary, "anticipatory" venting and CST availability become critical when dc power is not lost, long-term injection from RCIC is relied upon, and there is no FLEX swap-over. Core damage was averted when CST injection was combined with early venting (Cases 10 and 15). For these scenarios, the combination of cool water from the CST and expulsion of decay heat out the HCV by means of anticipatory venting led to success. Without this early venting (Case 9), the RCIC turbine trips on high backpressure in the wetwell and damage occurs. All cases with long-term RCIC suction on the wetwell cannot be assumed to be in a safe and stable state at 24 hours. If anticipatory venting does not occur, RCIC is lost because of high wetwell water temperature and fuel damage occurs. With anticipatory venting, the NPSH available to the pump is low enough that damage to the pump could occur and the source of injection would be lost.

In those scenarios in which ac power is available for the first 2 hours from the diesel generators (Cases 13-16), the emergency diesels power the wetwell cooling from the RHR system and injection from CRDHS and both are therefore available for the first 2 hours. Since MFW relies on offsite power, RPV makeup is provided by RCIC. MSIVs close on a LOOP and the SRVs open, relieving pressure to the wetwell. Upon a complete loss of ac at 2 hours, CRDHS injection and wetwell cooling are lost. Operators then begin a cooldown of the reactor at the maximum allowed rate.

When compared to the analogous scenarios with ac power lost at the start of the transient (Cases 1, 5, 10, and 12), since the wetwell is initially cooled by RHR, action to vent the wetwell through the hardened containment vent is delayed in these scenarios. In the cases with FLEX pump swap-over and indefinite RCIC injection from the CST (Cases 13–15), this has little impact on the scenario results, apart from shifts in timing, and RPV water level is successfully maintained. In the case with indefinite RCIC injection on the wetwell and anticipatory containment venting (Case 16), the NPSH available to the pump is still a concern although it falls below the required head at 7.7 hours rather than at 5.5 hours in Case 12. Again, the pump never trips on high wetwell water temperature, but long-term cavitation in the pump is a concern.

Sensitivity Calculations

In addition to these results, additional sensitivity studies were run to investigate specific issues, documented in Table 4-5.

Table 4-5 Sensitivity study matrix—mitigating strategies—SBO

Case #	Sensitivity	Impact
7a 8a 9a	Availability of HPCI, in lieu of RCIC	With the much greater injection rate of HPCI, the water level recovers at a greater rate during the first duty cycle and there is more overshooting of RPV level past the point when HPCI is secured. Steamline flooding occurs in all three cases. This occurs since relatively cold water is being injected rapidly up to the setpoint, which then heats up and expands. In all three cases, HPCI is lost on a code-automatic trip of HPCI when the steamline floods to a certain level. This trip is meant to capture the phenomena of turbine damage when a large volume of water enters the steamlines. There is uncertainty as to whether the pump would be lost since the Terry turbine is designed to handle some liquid water ingress.

Table 4-5 Sensitivity study matrix—mitigating strategies—SBO (continued)

Case #	Sensitivity	Impact
		Without HPCI injection, water level falls quickly with core uncovery occurring before 2 hours in all three cases. Since the FLEX pump is not yet available for injection, RPV level does not recover in time and core damage occurs in all three cases.
8b	FLEX delivered flow reduced by 50%	The reduced flow has very little impact on the long-term state of the reactor water level. It takes a little longer for the water level to turn around following RCIC failure, allowing water level to drop slightly further before it is recovered. Note that this is 50% of the rated flow (~114 m^3/hr [500 gpm]) and not 50% of the committed flow (68.1 m^3/hr [300 gpm]) and that injection is taking place after 8 hours, when the decay heat is significantly less. This sensitivity highlights the sufficiency of normal FLEX pump injection to provide adequate makeup for long-term cooling.
8c	Increased recirculation seal leakage (13 m^3/hr (60 gpm) per pump)	The increased leakage led to an increased demand for RCIC injection. In the base case, the vacuum breakers open repeatedly to equalize pressures in the wetwell and drywell as the wetwell pressure rises because of RPV depressurization. There is less need for this pressure equalization in the sensitivity since the drywell is pressurized from the additional seal leakage into containment. As a result, less heat from the wetwell enters the drywell and the hardened vent opens 6 minutes sooner. Overall, there is not a significant difference when compared to the base case, other than modest timing shifts. Importantly, core damage still does not occur.
8d	No recirculation seal leakage	There was little difference in the results of this calculation. The timing of key events shifted slightly. Without water leaking into the drywell, wetwell and drywell pressures rise somewhat more slowly and venting begins 7 minutes later. Nominal seal leakage appears not to play a significant role in the outcome of this scenario.
8e	Run up the water level to the steamlines before FLEX swap-over	SAMP-730 directs operators to run up the water level before securing RCIC. In this sensitivity, at 8 hours, RCIC is throttled fully open until water level is just below the steamlines. RPV ED is then initiated. Wetwell water level is at +5.6m (220 inches). It takes 18 minutes for water level to reach 0.25 meters (10 inches) below the steamlines (the level given in the EOPs). ED brings the level down by 2.4 meters (94 inches) to roughly the “normal” water level and then FLEX injection maintains the level.
8f	Alternate decay heat formulation using the built-in ANS decay heat standard	Little to no difference in the simulation since the two decay heat formulations are very similar, with the ANS curve being nearly identical in the first 2 hours, slightly lower from 2 to 9 hours, and slightly greater after 9 hours. Because of this, wetwell venting occurs 7 minutes later than the base case, but the long-term temperature in the wetwell is slightly higher in this sensitivity and the wetwell pressure at 24 hours was about 0.007 MPa (1 psid) greater than the base case.

[1] In earlier versions of the MELCOR deck, there was a low primary side pressure trip setpoint of 1.03 MPa (150 psid) between the wetwell and RPV steamlines (taken from UFSAR Table 15.0-6 p124/141 for P_rpv = 1.14 MPa (165 psia) while Figure 5.4-10 tells us P_ww is 0.14 MPa (19.8 psia) in this case). This was changed in later versions of the deck since it did not appear to agree with what is in the EOPs (they state that RCIC is available down to RPV pressure of 1.03 MPa (150 psig)). Also, the RCIC system description gives RPV pressure of 0.517 MPa (75.0) psig as the trip setpoint for the RCIC turbine. Even though a differential pressure setpoint is more realistic, the RCIC system description and the PB precedent were followed with a trip setpoint of 0.52 MPa (75 psig).

4.3 Loss-of-Main-Feedwater Sequence

4.3.1 Calculation Matrix Development

Table 4-6 describes the PRA sequence that is the focus of this section.

Table 4-6 LOMFW sequence of interest for FLEX-based diverse injection

PRA Sequence	Event	Description
LOMFW-25	Initiator	A loss of all MFW occurs.
	/RPS	Reactor is successfully shut down.
	/OEP	Offsite power is available.
	/SRV	SRVs successfully reclose (if demanded).
	/HPI	HPI succeeds (RCIC or HPCI).
	SPC	Suppression pool cooling (RHR) fails (e.g., common-cause failure of suppression pool strainers)
	/DEP	Manual depressurization of the reactor occurs (e.g., two of six SRVs opened by operator).
	CRDHS	CRDHS fails to provide makeup (e.g., one of two trains out for testing and maintenance).
	CDS	CDS fails to provide makeup (e.g., common-cause failure of pump discharge check valves).
	LPI	No trains of CS or LPCI succeed at providing LPI (e.g., common-cause failure of suppression pool strainers).
	/VA	Alternate LPI is successful (to be investigated here using the FLEX pump).
	Shutdown cooling	Shutdown cooling fails (e.g., operator error).
	CSS	Containment spray cooling mode of RHR fails (e.g., operator error dependent on failure to align shutdown cooling).
	PCSR	The PCS failure is not recovered (e.g., inability to recover the pump discharge check valve common-cause failure).
	/CVS	Containment venting operations are successful.
	/LI	Injection continues after containment venting.
	OK	Core damage is averted.

Table 4-7 provides the calculation matrix for the subsequent MELCOR calculations, while Table 4-8 gives the calculation boundary and initial conditions. A discussion of the key modeling assumptions made for these calculations follows.

Table 4-7 Calculation matrix—mitigating strategies—LOMFW-25

Case #	Time of RCIC failure[4]	Time and method of RPV depressurization[1,2,3]	Time/delivered flow of FLEX injection [5]
17.	t = 4 hours	Timing based on EOP-2 HCL/Follow HCL curve	t = 5 hours/nominal
18.			t = 6 hours/nominal
19.		Timing based on EOP-2 HCL/Rapid	t = 5 hours/nominal
20.			t = 5 hours/nominal—25%
21.			t = 6 hours/nominal

1 Depressurization following battery depletion would require additional actions to locally operate the SRVs, as they require dc power for other than pressure relief operation.
2 “Follow HCL curve” refers to the heat capacity limit curve (Graph 4) in EOP-2. The MELCOR model encodes the operator actions to achieve this depressurization and “walk down” the HCL curve. “Rapid” infers a single action wherein multiple SRVs are opened when the “action is required” regime in Graph 4 is first reached and a 55.6 degree C/hr (100 degree F/hr) cooldown is initiated.
3 The RC/P leg of EOP-1 includes a provision to stop depressurization before losing the pressure required to operate RCIC (i.e., 1.03 MPa (150 psig)).
4 RCIC may be lost before this time, based on, for example, high exhaust pressure or suppression pool temperature. In the calculations, if RCIC trips, restart will not be considered (as a simplifying assumption).
5 At 0.758 MPa (110 psig), the FLEX pump is able to inject to the RPV at a rate of approximately 129 m3/hr (570 gpm). A pump curve provided by the licensee generated the nominal pressure-dependent flow rate.

Table 4-7 Calculation matrix—mitigating strategies—LOMFW-25 (continued)

Case #	Time of RCIC failure[4]	Time and method of RPV depressurization[1,2,3]	Time/delivered flow of FLEX injection [5]
22.	t = 8 hours	Timing based on EOP-2 HCL/Follow HCL curve	t = 9 hours/nominal
23.		Timing based on EOP-2 HCL/Rapid	
24.			t = 10 hours/nominal
25.			t = 10 hours/nominal—25%

1 Depressurization following battery depletion would require additional actions to locally operate the SRVs, as they require dc power for other than pressure relief operation.

2 "Follow HCL curve" refers to the heat capacity limit curve (Graph 4) in EOP-2. The MELCOR model encodes the operator actions to achieve this depressurization and "walk down" the HCL curve. "Rapid" infers a single action wherein multiple SRVs are opened when the "action is required" regime in Graph 4 is first reached and a 55.6 degree C/hr (100 degree F/hr) cooldown is initiated.

3 The RC/P leg of EOP-1 includes a provision to stop depressurization before losing the pressure required to operate RCIC (i.e., 1.03 MPa (150 psig)).

4 RCIC may be lost before this time, based on, for example, high exhaust pressure or suppression pool temperature. In the calculations, if RCIC trips, restart will not be considered (as a simplifying assumption).

5 At 0.758 MPa (110 psig), the FLEX pump is able to inject to the RPV at a rate of approximately 129 m^3/hr (570 gpm). A pump curve provided by the licensee generated the nominal pressure-dependent flow rate.

The LOMFW scenarios begin with an LOMFW. The reactor scrams on low RPV level and RCIC begins injection after the water level falls below Level 2. HPI is the only form of makeup available, as prescribed by the PRA sequence definition.

The turbine trips upon a loss of feedwater, and the turbine bypass valves open to pass steam directly to the condenser in the hotwell. However, a train of feedwater/condensate is necessary for long-term availability of the PCS since the condenser tubes will eventually be covered with water and rendered ineffective. Hence, the assumption is that turbine bypass valves are initially open and pass steam to the hotwell but would eventually be lost with a closure of the MSIVs. In these calculations (and in the LOMFW scenarios in subsequent chapters), the MSIVs close on a low RPV pressure trip. This trip was later determined to not be plant-actual since it is only active when the turbine is running. However, the net result; namely, the initial availability of the condenser with an eventual loss of the PCS when MSIVs close, is likely to mimic the actual plant response but with great uncertainty in the timing. In the series of calculations in this chapter, MSIV closure occurs at 30 minutes. Table 4-10 includes a sensitivity with MSIV closure (and loss of the condenser) occurring at time zero. Upon MSIV closure, the RPV pressure rises to the SRV relief setpoint.

When the RPV pressure and wetwell temperature reach the "action is required" region of the HCL curve (Graph 4 in EOP-2), operators are directed to depressurize the RPV. At this point, operator action to depressurize the reactor is modeled in one of two ways. Operators either perform an ED and fully open two SRVs in a rapid RPV depressurization, or they modulate an SRV open (along with a second, as necessary) to follow the HCL curve. This depressurization continues until RPV pressure is 0.34 MPa (50 psi) above the wetwell pressure. However, EOP-1 instructs operators to keep pressure above 1.03 MPa (150 psig), if RCIC or HPCI, or both, are required for injection.

In contrast to the LOOPGR scenarios, offsite power is available. While CRDHS injection fails to provide makeup according to the PRA sequence definition, it continues to inject at the preaccident flow rate of a single pump. Both trains of RHR fail from common-cause failure so there is no suppression pool cooling available to remove decay heat from the wetwell and LPCI/core spray are not available for LPI. Recirculation pump seal leakage is assumed not to occur since seal cooling is available.

In an early round of calculations, the water level continued to increase significantly even after RCIC was secured at the expanded high level caused by thermal expansion, ongoing injection from CRDHS, and RPV depressurization. This led to water entering the steamlines and a loss of RCIC on a code-automatic trip signal of high steamline water level. For this reason, the upper bound of the RCIC level band was reduced by 0.5 meters (20 inches) (from 6.55 meters [258 inches] to 6.05 meters [238 inches] above TAF) to prevent flooding of the steamlines and loss of RCIC. This is thought to be reasonable since RCIC can still be expected to run with some water in the steamlines. The possibility of steamline flooding and subsequent loss of RCIC is investigated as a sensitivity calculation.

In the LOMFW scenarios, anticipatory venting is not credited, and the hardened containment vent is opened at the "required" PCPL setpoint of 0.37 MPa (53 psig). The reasoning is that (1) this will aid understanding of the failure versus success space (since crediting venting is expected to routinely lead to success), and thus the sensitivity of the PRA criterion to this assumption, and (2) the operators are less likely to do the anticipatory venting in a situation where they are both taking RCIC suction from the CST and in a scenario that in no way approximates an ELAP.

In those cases where RCIC is lost, these scenarios differ from the LOOPGR calculations in that the FLEX pump is not assumed immediately available for injection since its use following a non-ELAP event is not yet proceduralized. This could likely lead to a delay in diagnosis and staging. The lag time in injection between the loss of RCIC and the start of FLEX pump injection is explored for this reason. As for the necessary ED down to 0.34 MPa (50 psig) to allow for the swap-over to FLEX injection, a "midpoint" between the time RCIC is lost and the start of FLEX injection is used. These diagnoses and execution lags are appropriate for both actions. The delivered flow rate of the FLEX pump is also varied. A pump curve provided by DAEC dictates the nominal flow rate, and a diminished flow rate of 25 percent below the nominal rate puts the flow rate close to the committed flow rate of 68.1 m^3/hr (300 gpm) outlined in the FSGs.

Table 4-8 Initial and boundary conditions—mitigating strategies—LOMFW

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 4-7.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on first-in RPS signal. No recirculation pump seal leakage. Number of SRVs available—two of six.
Balance of plant	OFFSITE POWER is available. Support systems are available unless specified otherwise. Turbine trip occurs upon loss of feedwater.
ECCS/ESF	ESF signals successfully perform their functions. CST is available. HPCI is unavailable (by PRA sequence definition). RCIC availability—see Table 4-7. CRDHS and SLC are available. LPCI/core spray are unavailable.
Containment	Suppression pool cooling is unavailable (by PRA sequence definition). Nominal drywell and wetwell initial conditions (see Table 2-6).
Other operator actions	Actions related to RPV depressurization—see Table 4-7. Containment venting occurs at wetwell pressure of 0.37 MPa (53 psig). Actions to align alternate injection via a FLEX pump—see Table 4-7.

4.3.2 MELCOR Simulation Results

Table 4-9 lists the results of the nine LOMFW calculations. In addition to this, Appendix D to this report includes results for selected parameters of interest.

Table 4-9 LOMFW results and key timings

Case #	RCIC lost (hrs.)	ED begins (hrs.)	Core uncovery (hrs.)	FLEX injection begins (hrs.)	Level when RCIC is lost (centimeters [inches] above TAF)	Level when FLEX begins (centimeters [inches] above TAF)	Maximum PCT[1] degrees C (degrees F)
17.	4.0	4.5	4.8	5.0	563.4 (222.0)	-22 (-8.7)	322 (611)
18.	4.0	5.0	5.0	6.0	566.4 (223.0)	-210 (-82.7)	791 (1455)
19.	4.0	4.5	4.8	5.0	563.4 (222.0)	-155 (-60.9)	421 (790)
20.	4.0	4.5	4.8	5.0	563.4 (222.0)	-151 (-59.5)	438 (820)
21.	4.0	5.0	5.3	6.0	563.4 (222.0)	-263.7 (-103.8)	1106 (2023)
22.	8.0	8.5	No	9.0	534.4 (210.4)	338.1 (133.1)	-
23.	8.0	8.5	No	9.0	386.1 (152.0)	258.6 (101.8)	-
24.	8.0	9.0	No	10.0	384.8 (151.5)	125 (49.1)	-
25.	8.0	9.0	No	10.0	1384.8 (151.5)	123 (48.5)	-

[1]Recall that a PCT of 1,204 degrees C (2,200 degrees F) is the core damage surrogate.
[2]The maximum cladding temperature occurred during steady state (i.e., no heatup during the transient).

The pressure in the RPV in the LOMFW scenarios before depressurization requires some explanation. Upon a reactor trip, RPV pressure initially falls as the turbine bypass valves open to pass steam to the condenser. However, as mentioned before, the assumption is that condenser tubes will eventually cover with water and be ineffective at steam condensation. MSIV closure occurs at 30 minutes (on low steamline pressure, which is not a plant-actual trip with the turbine tripped) and mimics a loss of the PCS for steam condensation. There is some uncertainty on the timing of this loss of the condenser (DAEC assumes that it is lost immediately in its PRA) since it is not clear how long it would take water to fill the hotwell and cover the condenser tubes. An impact of this assumption will be on the amount of decay heat that is deposited in the wetwell versus in the hotwell, which will subsequently affect the timing of reaching the HCL curve and containment venting. A number of sensitivity calculations are described in Table 4-10 wherein MSIVs are assumed to close at the start of the transient to elucidate the impact of this assumption.

Following MSIV closure, the RPV pressure begins to rise until there is another decrease in pressure that takes place around 0.6 hours. This is caused in part by the cool RCIC water filling the RPV. Water from RCIC enters the Downcomer and subcools the water there. The water level increases in both the Downcomer and the riser but at different rates since the cooler Downcomer water is denser. When the level in the standpipes reaches the threshold of the flowpath going from the riser to the Downcomer, the warmer water spills over into the Downcomer and begins to raise its temperature. The water level in the Downcomer then catches up to the water level in the standpipes and begins to cool the water there as well. This reduces both steam flow and the pressure in the dome. When the first RCIC cycle ends, heatup resumes, thus increasing the pressure back to the relief setpoint. A similar pattern occurs during the second RCIC cycle from 2.5 to 3.0 hours. Until 4 hours, all scenarios are the same.

RPV pressure reaches the "action is required" region of the HCL curve at 4.3 hours. At this point, operator action to depressurize the reactor is modeled by either fully opening two SRVs in a "rapid" depressurization, or by modulating an SRV open to "follow the HCL curve." In those cases where HPI is no longer available (Cases 17–21) and FLEX pump injection is in the process of being staged, the depressurization continues until RPV pressure is less than 0.34 MPa (50 psid) above the wetwell pressure. Otherwise, the depressurization ends at 1.03 MPa (150 psig).

Core damage does not occur in any of the LOMFW calculations. However, the core is uncovered in all cases where dc power is lost at 4 hours. In the 4-hour cases, even though they end in "success" with no core damage, it is important to note the water level at the time of RCIC loss. As seen in Table 4-9, in each of the simulations where the core is uncovered, water level is around the "normal" water level when RCIC is lost. In actuality, water level could be as low as 3.04 meters (119.5 inches) above TAF at the time of RCIC failure, which would lead to a more significant uncovering of the core. Table 4-10 includes two sensitivity calculations with RCIC failure when RPV level is at Level 2. These sensitivities demonstrate that success is uncertain when there is a significant delay (more than an hour) in FLEX injection. Without procedures in place that would ensure the prior staging of FLEX equipment, the 4-hour scenarios (Cases 17–21) should be considered to go to core damage.

Depressurization by following the HCL curve has a more favorable impact on the loss of inventory than a rapid depressurization. When RCIC fails at 4 hours and operators follow the HCL curve (Case 18), there is a gradual depressurization from 4.3 to 5 hours and then a rapid depressurization at 5 hours. In contrast, in the analogous case with rapid depressurizations at and 5 hours (Case 20), the RCS level falls more than half a meter further and nearly goes to core damage.

None of the 8-hour cases have core uncovery since, by the time RCIC fails, the RCS has already been depressurized down to 1.03 MPa (150 psig) to stay below the HCL curve, and the subsequent ED at either 8.5 or 9 hours does not have as significant an impact (this combined with the fact that the decay heat is lower at this point). This points to the importance of the RCS being depressurized before RCIC failure.

The 25-percent reduction of FLEX injection extends the time to level recovery by 14 minutes when RCIC is lost at 4 hours and by 8 minutes when RCIC is lost at 8 hours. Hence, a 25-percent reduction in FLEX injection (caused by, for example, partial freezing in the hose, clogging of the FLEX pump suction, or diverted flow to the SFP) would not affect the success of these scenarios. A further diminished flow rate of 50 percent is explored as a sensitivity.

Sensitivity Calculations

In addition to these results, additional sensitivity studies investigated specific issues, documented in Table 4-10.

Table 4-10 Sensitivity study matrix—mitigating strategies—LOMFW

Case #	Sensitivity	Impact
19a 22a	Availability of HPCI, in lieu of RCIC	In Case 19a, HPCI goes through two cycles but is then lost on a code-automatic trip on high steamline water level. HPCI is lost at 2.2 hours, and water level begins to fall. At 3.3 hours, wetwell temperature and RPV pressure reach the “action is required” region of the HCL curve, operators begin a rapid ED down to 1.03 MPa (150 psig), and the core is briefly uncovered at this time. Because of high wetwell water level, there is a swap-over of HPCI to suction on the wetwell. HPCI recovers from the trip in this case since the steamline water level drops below an assumed recovery setpoint, begins injecting, and recovers the RPV water level. HPCI again floods the steamlines and is lost again at 3.3 hours when the ED begins. This trip cycles on and off repeatedly while the ED takes place. Water level is recovered and HPCI has its final cycle at 3.7 hours, with a turbine trip from low steamline pressure. From here, the scenario proceeds the same as in the base case, with FLEX injection precluding core damage. It is uncertain what the plant-actual response would be in this case. Although the loss and recovery of HPCI on a flooded steamline may be analogous to the self-regulated injection that was seen at Fukushima (Sandia, 2014a). In Case 22a, HPCI again cycles twice and is then lost around 2 hours on a code-automatic trip on the high steamline water level. In this case, HPCI does not recover from the steamline flooding and core damage occurs at 5.7 hours.
22b	50% reduction in delivered FLEX pump flow	The reduced injection is still sufficient to provide enough makeup to the RPV. This is especially true since injection begins 8 hours into the transient when inventory loss through the SRVs is small.
23a	SRV fails open	In the base scenarios, operators are assumed to modulate the SRVs open to prevent continuous cycling on the lowest pressure SRV with pressure held around 7.58 MPa (1,100 psig). If operators did not take this action, the lowest pressure SRV would cycle repeatedly. In this sensitivity, no action is taken to modulate the valves open and the lowest pressure SRV reaches 270 cycles at 3.5 hours and is then assumed to stick open. RCS water level happens to be just below the steamlines at this time. The rapid depressurization leads to expansion of the water in the RCS and water floods the steamlines. RCIC is lost on a code-automatic trip on high water level in steamline. RCS pressure and water level drop quickly at this point. RCIC is shortly recovered at 4.3 hours in this case since the steamline water level drops below an assumed recovery setpoint. However, after 17 minutes of injection, the RCIC turbine trips on low primary side pressure. The FLEX pump in this scenario is not assumed to be staged until 8 hours so only CRDHS is injecting at this time and core damage occurs at 7.9 hours. With 3.6 hours between the loss of RCIC and core damage, there should be ample time for FLEX equipment to be staged and core damage could be avoided.
22c	RCIC delivered flow reduced by 10%	The reduced flow has little effect on the scenario. On its first cycle, water level dips a little lower before RCIC can recover the RPV water level.
22d	Failure of FLEX injection at 24 hours	FLEX injection is assumed to be lost at 24 hours. Because CRDHS is still injecting from the CST, water level decreases slowly, reaching TAF at 40 hours. The water level continues to decrease to the 2/3 fuel height and levels off. The fuel heats up some, but there is sufficient cooling to prevent core damage. CRDHS continues to inject, maintaining this level until CST is depleted down to the reserve level around 62 hours, at which point it trips automatically. Without operator action to continue this injection, the core immediately begins to heat up and core damage occurs 2 hours later, around 64 hours.
22e	Alternate decay heat formulation using the built-in American Nuclear Society (ANS) decay heat standard	There is little to no difference in the simulation. While there are slight differences in the timing of injection and venting, the decay heat curve used in the base model is similar enough to the ANS standard that there is little impact on the results.
22f	Increased level band with steamline flooding and loss of RCIC	RCIC is lost at 3.9 hours on a code-automatic trip of a flooded steamline. The simulation ended unexpectedly at 4.5 hours because of a calculational issue in the steamline and could not be restarted. Since FLEX injection is assumed to not be available until 10 hours, this sensitivity would likely have gone to core damage.

Table 4-10 Sensitivity study matrix—mitigating strategies—LOMFW (continued)

Case #	Sensitivity	Impact
17a	Begin cooldown at 0.5 hours at the maximum allowed rate (55.6degrees C/hr [100 degrees F/ hr])	Depressurization begins at 0.5 hours at a controlled 55.6 degrees C/hr (100 degrees F/hr) cooldown rate and reaches 1.03 MPa (150 psig) around 1.5 hours. RCIC is secured at 4.0 hours while RPV water level is at its highest point. ED begins at 4.5 hours, but pressure is already low and level falls from 599 centimeters (236 inches) at 4 hours to 378 centimeters (149 inches) at 5 hours, when FLEX injection begins at 5 hours. Hence, the early, controlled depressurization is successful in preventing core uncovery.
19b 21a	RCIC is lost with water level at Level 2 (lost at 4.0 hours and then FLEX at 5.0 and 6.0 hours, respectively)	Instead of operating RCIC in batch mode in these sensitivity calculations, RCIC injection is throttled to maintain RPV level at Level 2. In the first case, RCIC fails at 4.0 hours. Incidentally, operators also reach the “action is required” region of the HCL curve at this time and perform an ED (ceasing at 1.03 MPa (150 psig) with the hopes that they might recover RCIC injection). An ED down to 0.34 MPa (50 psig) begins at 4.5 hours and FLEX injection begins at 5.0 hours. With the water level much lower than in the base case, depressurization brings the water level well below the TAF. The core begins to heat up with PCT reaching 543 degree C (1,009 degree F) before FLEX injection recovers level and cools the core. Case 19b, therefore, ends in success, although by a tight margin. In the second case, RCIC also fails at 4.0 hours with a simultaneous ED down to 1.03 MPa (150 psig). However, ED down to 0.34 MPa (50 psig) begins at 5.0 hours and FLEX injection begins at 6.0 hours. The extended time between RCIC loss and FLEX injection here gives time for the core to be significantly uncovered. FLEX injection begins too late to avoid core damage, which occurs at 6.0 hours.
22g	CST unavailable	Since the CST is unavailable, RCIC suction is taken from the wetwell. This also means that CRDHS injection is not available. MSIVs close at 16 minutes on low level (14 minutes sooner than the assumed closure on loss of PCS steam in the base case). In addition, there is no cool water from the CST being injected to the RPV, so more steam is passing to the wetwell. Both differences mean more heat is deposited in the wetwell. Available RCIC NPSH falls below 20 feet at 6.4 hours and its availability, therefore, becomes questionable. At 7.5 hours, RCIC begins its last cycle and is throttled since the wetwell temperature at this time is greater than 102 degrees C (215 degrees F) (see discussion in Section 4) and operators maintain the “normal” RPV level. RCIC is lost at 8 hours by scenario definition and RPV depressurization begins at 8.5 hours. FLEX injection starting at 9 hours successfully prevents any core uncovery or damage.
19c 22h	MSIV closure at start of transient	In both scenarios, MSIVs close at the start of the transient. Because of this, there is a greater amount of decay heat deposited in the wetwell. The HCL curve is reached at 2.7 hours (1.7 hours sooner than the base case), and operators are forced to begin depressurizing the RPV at that time. In the first case, the depressurization is rapid. Since RCIC is available until 4 hours, the loss in inventory from the depressurization is offset by the injection from RCIC. Unlike the base case, the core is not uncovered during the depressurization. In this case, reaching the HCL curve earlier is beneficial, as it prevented ED from being necessary when RCIC was unavailable. In the second case, RCIC is available until 8 hours and operators “walk down” the HCL curve starting at 2.7 hours. As in the base case, RPV pressure has been reduced to 1.03 MPa (150 psig) by the time RCIC is lost. While the HCL curve is reached 1.7 hours sooner than in the base case, there is not a large difference in the net result between this scenario and the base case. RCIC is lost after the depressurization has occurred, whether MSIV closure is at 30 minutes or at time zero. By chance, the RPV water level when RCIC is lost at 8 hours is at its lowest point (instead of being near the “normal” water level in the base case). Hence, the water level falls lower than the base case but still not low enough to uncover the core.

4.4 Conclusions Drawn from MELCOR Results

The staff makes the following observations about the MELCOR results with regard to LOOPGR:

- Without manual depressurization following loss of both dc power and RCIC injection, the FLEX pump would be unable to inject and core uncovery and fuel damage would be inevitable.
- FLEX injection led to success in all scenarios for which FLEX credit was given, regardless of timing of RCIC loss and HCV ventingactions.
- If FLEX is not available, success is only possible with both anticipatory venting and CST availability. The combination of cool water from the CST, combined with expulsion of decay heat out of the HCV through anticipatory venting, led to success. Without CST water, the RCIC could be damaged by cavitation. Without anticipatory venting, the RCIC would trip on high wetwell backpressure.
- The loss of NPSH is of concern when RCIC is taking suction from the wetwell.
- The use of two valves for ED is sufficient for RPV depressurization in all scenarios
- In total, these calculations demonstrate that FLEX pump injection can ensure that core damage does not occur. This supports the conclusion that FLEX pumps should beable to mitigate in SBO scenarios, whether anticipatory venting occurs or not. Additionally, it is important to note that, without FLEX, almost all SBO scenarios end in core damage, despite the availability of large amounts of water from the CST.

The staff makes the following observations about the MELCOR results with regard to LOMFW:

- Success was not sensitive to a lower delivered flow rate of the FLEX pump.

  One impact on core uncovery was the initial water level and pressure before depressurization down to 0.34 MPa (50 psig) in the RCIC to FLEX swap-over. It is optimal to depressurize the RCS while HPI is available. Although core damage does not occur in all cases, the amount of core uncovery is lessened the earlier the depressurization occurs.

  Core uncovery occurs in all cases where RCIC is lost at 4 hours (before RPV ED) and could go to core damage if the water level were lower at the time of RCIC loss and FLEX injection were not staged rapidly. This is because operators were assumed to wait to depressurize until pressure reached the HCL curve. However, as discussed above, if operators initiated depressurization before the loss of RCIC, core uncovery could be avoided.

- Steamline flooding occurs at the expanded level band with HPCI but may also occur with RCIC. This is because the thermal expansion of the water causes spillover into the steamlines. Over time, this could cause degradation of the turbine and the possible loss of the injection source.

- In those cases in which no procedures are in place for the staging of FLEX equipment, timely injection cannot be assumed and early failure of RCIC/HPCI may result in core damage.

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5 EMERGENCY CORE COOLING SYSTEM INJECTION FOLLOWING CONTAINMENT FAILURE OR VENTING

5.1 Issue Description

Many licensee BWR PRAs credit coolant injection following containment venting and containment failure caused by the slow overpressurization of containment resulting from a loss of containment heat removal. The key characteristic of these sequences is the failure of containment (or the venting of containment) before core damage occurs. These sequences often involve a loss of ac power and are generally known as “TW” sequences. Although, historically, the SPAR models have not given credit for injection following containment failure, recently some of the new revisions to the SPAR models include some credit for late (postcontainment failure) injection, based in part on insights gained during the implementation of the mitigating systems performance indicator and, in part, on evaluations provided by individual licensees to support an upgrade of their own models. Whether or not credit for coolant injection is given after containment failure (or venting) can significantly affect CDF.

There are several concerns about emergency coolant injection performance during the time leading up to and immediately after containment failure (or venting). These issues are primarily associated with accident sequences that include failure of long-term heat removal (TW) or ATWS, where heat removal is simply inadequate for the heat being generated. The progression of these sequences includes the effects of high pressure inside containment and then the consequences of subsequent containment failure or venting. Specifically, as the containment atmosphere pressurizes, some injection systems might cease working because of increased backpressure on the turbine steam exhaust. Additional concerns arise when the containment fails or is vented. In this case, the severely adverse environment produced in the reactor building as a result of containment failure (or venting, depending on the configuration of the vent path used) could cause needed safety equipment to fail. Also, at the time of containment failure (or venting), the rapid depressurization of the suppression pool water could generate boiling in the suppression pool, and ECCS pumps not designed for two-phase flow could fail, while significant flashing of suppression pool water could lower the level to the point of introducing vortexing or suction line uncovery concerns. Finally, rupture of containment could directly affect continued ECCS operation, if injection or suction lines were damaged. Each of these mechanisms has the potential to result in failure of some or all coolant injection and lead to core damage.

The generic concerns above can lead to the need for plant-specific evaluations, in that plant designs can vary in several key aspects. First, plants use ECCS pumps with varying capabilities in their response upon seeing two-phase flow.[1] Second, the response of the containment to overpressure failure can vary by design (most notably in terms of where the containment is likely to fail and whether it is likely to fail in a catastrophic versus liner tearing fashion). Finally, there is plant-to-plant variability in the layout of equipment (not only the pumps themselves but also the other components required for successful operation) in the reactor and control buildings, and in the way that equipment is protected from flooding and high temperatures and humidity.

[1] Note that containment accident pressure analyses investigated the performance of pumps under these types of conditions (e.g., (BWROG, 2012a) and (BWROG, 2012b)).

An additional issue that has received attention in recent years concerns the reliance on containment overpressure when assessing the operability of emergency coolant injection during a postulated design-basis accident (i.e., containment accident pressure). This issue is not considered further here per se, as the focus is on the response of the system during the actual predicted conditions (e.g., operation of ECCS when the containment pressure is elevated). However, the same basic considerations apply here once containment has been vented or has failed, or if a containment isolation failure prevented containment pressurization. APPENDIX F to this report includes more information on gradual overpressurization of Mark I, Mark II, and Mark III containments.

In the past, there were concerns that the ADS valves could be forced closed by the high ambient pressure; however, as seen in APPENDIX F , even at low temperatures, the containment would fail at 0.97 MPa (140 psig). Given that the SRVs open at pressures much higher than this, the containment would likely fail before the ADS valves would be forced to close.

Finally, this issue also has a philosophical aspect, which is whether a cooled core, but failed containment, should be considered an acceptable ("OK") end state for Level 1 PRA purposes. On the one hand, this is a clear loss of defense in depth, and the failure of containment with successful continued ECCS injection could be viewed as a "benevolent failure," in that containment failure has prevented the further containment pressurization that would affect SRV operation and low-pressure ECCS injection flow rates. On the other hand, the core is still cooled, and a significant radiological release is not expected within the considered sequence mission time. Some types of evaluations (e.g., SDP) would allow one to consider the large early release frequency aspects of this end state (despite the lack of core damage). For context, also note that Level 1 PRAs typically neglect consideration of containment isolation failure, which has some analogous aspects. A unique aspect of the ECCS late injection situation, relative to containment isolation failure, is the greater uncertainty in where and how the containment will fail and what effect this will have on the injection systems.

The uncertainties of interest for late injection following containment venting or containment failure are as follows:

- the leakage path from primary containment to the reactor building or environment
- the extent of "normal leakage" or containment isolation impairment at the time of the initiator and resulting containment isolation signal
- the mode of containment failure in terms of the speed of drywell depressurization
- the timing (and associated pressure) of venting
- the vent path used
- the point at which the vent path is closed
- the response of the SRVs and ECCS pumps to the elevated pressure and the depressurization

With regard to PRA sequences, the same two sequences identified in Section 4 of this report are used as anchors for the investigation.

Note that all simulations in this chapter are extended to 48 hours to better explore the long-term performance of RCIC in debilitated containment conditions.

5.2 Station Blackout Sequence

5.2.1 Calculation Matrix Development

Table 5-1 provides the calculation matrix for the subsequent MELCOR calculations, while Table 5-2 provides the calculation boundary and initial conditions. Note that the PRA sequence used here is the same as that of Section 4.2, which includes a more detailed explanation. This section discusses the key modeling assumptions made for these calculations as they differ from those in Section 4.2.

Table 5-1 Calculation matrix—ECCS injection—SBO sequence

Case #	Sequence	Venting action or containment failure	Vent path used	Response of ECCS pumps to pressure change
1.	Based around LOOPGR-38-9	Anticipatory venting per SEPs	Drywell—2-inch vent bypass[1]	Functional
2.				50% Degraded
3.			Drywell—18-inch main vent[1]	Functional
4.				50% Degraded
5.				Nonfunctional
6.			Hard pipe vent[2]	Functional
7.				50% Degraded
8.		Failure at 0.37 MPa (53 psig)	Drywell—2-inch vent bypass[1]	Functional
9.				50% Degraded
10.			Drywell—18-inch main vent[1]	Functional
11.				50% Degraded
12.				Nonfunctional
13.			Hard pipe vent[2]	Functional
14.				50% Degraded

[1] SEP 301.2 dictates a targeted torus pressure band of 0.07–0.10 MPa (10–15 psig).
[2] SEP 301.3 dictates a targeted torus pressure band of 0.03–0.07 MPa (5–10 psig).

Upon a loss of all ac power, operators enter AOP 301.1. It is assumed here that, at 30 minutes, operators begin a cooldown of the reactor. An RPV depressurization down to 1.03 MPa (150 psig) at the maximum cooldown rate of 55.6 degrees C/hr (100 degrees F/hr) is assumed.

The purpose of this analysis is to explore long-term RCIC performance during an SBO. Consequently, the analysis did not consider FLEX injection. It assumes that dc power in the form of batteries is available indefinitely, which is necessary for RCIC level control. Where "degraded" RCIC performance is assumed, the RCIC injection rate is reduced by 50 percent when the containment vent first opens.

As in the previous chapter, containment venting actions are also investigated. In the event of a loss of the UHS or an ELAP, operators would open the hard pipe vent to maintain an "anticipatory" wetwell pressure band of 0.03–0.07 MPa (5–10 psig) to maintain RCIC injection in accordance with SEP 301.3. If this vent path is unavailable, operators would vent the wetwell using the old wetwell vent in SEP 301.1, maintaining an "anticipatory" pressure band of 0.07–0.10 MPa (10–15 psig). If both wetwell vents are unavailable, operators would vent using the drywell main vent in SEP 301.2, maintaining an "anticipatory" pressure band of 0.07–0.10 MPa (10–15 psig). These latter two procedures instruct operators to first open the corresponding 2-inch bypass lines and then open the full 18-inch main line if this proves insufficient in maintaining the desired pressure. The calculation matrix in Table 5-1 includes venting using the 2-inch bypass and 18-inch main drywell lines, as well as the wetwell hard pipe vent. This is to explore RCIC performance following containment failure at low containment pressures caused by venting.

Even though the required PCPL venting action of maintaining 0.31–0.37 MPa (45–53 psig) would be enforced if anticipatory venting does not occur and the wetwell pressure approaches 0.37 MPa (53 psig), researchers decided not to investigate this venting action here. In Section 4.2.2, in the cases in which containment venting occurs at 0.37 MPa (53 psig) in the wetwell, CST was available and dc power was indefinitely available, the RCIC turbine trips on high turbine exhaust pressure at 0.34 MPa (50 psig) and is never recovered since pressure remains relatively high (in the 0.31–0.37 MPa (45–53 psig) pressure band assumed for required venting). This trip requires manual operator action for RCIC to be reset. Hence, venting at a pressure band of 0.31–0.37 MPa (45–53 psig) would lead to RCIC tripping and core damage occurring in all these scenarios. Chapter 4 describes this important result, while this section investigates the possibility of containment failure. Rather than operators maintaining a pressure band of 0.31–0.37 MPa (45–53 psig), the Chapter 5 analysis assumes the respective vent fails irreversibly open when wetwell pressure reaches 0.37 MPa (53 psig). The intent here is to explore the performance of ECCS injection following containment failure. In these cases, RCIC trips on high backpressure of 0.34 MPa (50 psig) but operator action to recover RCIC when wetwell pressure falls below 0.28 MPa (40 psig) is assumed. This recovery setpoint is an assumption and not based on any procedures. It merely seeks to credit operators who successfully restart RCIC when wetwell pressure is sufficiently low.

The model assumes that venting through the old drywell or wetwell vents opens a flowpath directly to the reactor building because of an assumed ductwork failure. The old vents are unhardened and could therefore leak or rupture when demanded. This conservative choice is made to better understand the possible conditions of the reactor building for inhabitability and flooding should a rupture occur.

The CST is assumed to be available for RCIC injection. This choice was made in order to focus on the impact of containment failure and because it is more likely that the CST would be available for injection. Table 5-4 includes a series of sensitivities where RCIC suction is on the wetwell.

Calculations are carried out to 48 hours to investigate the long-term performance of RCIC and inhabitability of the reactor building.

Table 5-2 Initial and boundary conditions—ECCS injection—SBO sequence

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 5-1.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on first-in RPS signal or loss of offsite ac. Nominal[1] recirculation pump seal leakage. Number of SRVs available—two of six.
Balance of plant	OFFSITE POWER is lost at time zero. DC power is available indefinitely. Support systems are available (if ac is available) unless specified otherwise. Turbine trip occurs at time zero. Feedwater and condensate fail at time zero. MSIV closure occurs upon loss of offsite ac (for loss-of-ac scenarios). RPV depressurization begins at 0.5 hours at the maximum cooldown rate (55.6 degrees C/hr [100 degrees F/hr]). CST is available for injection until depleted and then injection switches to wetwell.
ECCS/ESF	ESF signals successfully perform their functions (while dc power exists). HPCI is unavailable. RCIC is available indefinitely. FLEX injection is unavailable. CST is available. CRDHS and SLC are unavailable. LPCI/core spray are unavailable.[2]
Containment	Suppression pool cooling is unavailable.[2] Nominal drywell and wetwell initial conditions (see Table 2-6).
Other operator actions	If credited, LPCS may need to be disabled as in EOP-1, if other low-pressure systems are available.

[1] In this context, this means 4.1 m^3/hr (18 gpm/hr)/pump at the lowest SRV pressure setpoint.
[2] The exception to this is before loss of all offsite and onsite ac in the loss-of-ac power scenarios.

5.2.2 MELCOR Simulation Results

Table 5-3 lists key timings from the 17 LOOP calculations. In addition to this, APPENDIX E includes figures for selected parameters of interest.

Table 5-3 LOOPGR results

Case #	Vent path used	Response of ECCS pumps to pressure change	Venting (hours)	Core uncovery (hours)	Core damage (hours)
1.	Drywell—2-inch vent bypass	Functional	9.6	28.2	30.5
2.		50% Degraded	9.6	25.5	27.8
3.	Drywell—18-inch main vent	Functional	9.6	No	No
4.		50% Degraded	9.6	No	No
5.		Nonfunctional	9.6	14.0	15.8
6.	Hard pipe vent	Functional	7.1	No	No
7.		50% Degraded	7.1	No	No

Table 5-3 LOOPGR results (continued)

Case #	Vent path used	Response of ECCS pumps to pressure change	Venting (hours)	Core uncovery (hours)	Core damage (hours)
8.	Drywell—2-inch vent bypass	Functional	20.6	24.3	26.6
9.		50% Degraded	20.6	24.3	26.6
10.	Drywell—18-inch main vent	Functional	20.6	No	No
11.		50% Degraded	20.6	No	No
12.		Nonfunctional	20.6	24.3	26.6
13.	Hard pipe vent	Functional	20.6	No	No
14.		Degraded	20.6	No	No

In those cases in which the 2-inch vent is used for anticipatory venting (Cases 1 and 2), containment pressure and, consequently, wetwell pressure, continue to rise as the size of the bypass vent proves to be insufficient in competing with the SRVs venting into the wetwell. RCIC trips inevitably on high exhaust backpressure as the torus pressure rises above the 0.34 MPa (50 psig) setpoint. With no other injection source available, the core eventually is uncovered, and core damage occurs. The reduced RCIC flowrate in Case 2 serves only to speed the onset of core uncovery and damage. Note that SEP 301.2 calls for operators to vent initially on the 2-inch vent bypass line but switch to the 18-inch main vent line if they are unable to achieve the desired pressure. In these scenarios, then, operators, if able, would have opened the main line when it became apparent that the pressure was rising in containment.

When the 18-inch main drywell vent is used for anticipatory venting (Cases 3–5), operators are able to achieve a 0.07–0.10 MPa (10–15 psig) wetwell pressure band (as in SEP 301.2 direction) since the vacuum breakers (which operate on dc power) keep the differential pressure between the drywell and wetwell within 0.003 MPa (0.5 psid). The reduced RCIC injection rate has no impact on the success of the scenario. The combined rate of inventory loss through the SRVs and seals at 9.6 hours when the venting begins is about 7.2 kg/s and RCIC injects at a rate of 25 kg/s at rated flow and 12.5 kg/s at the "degraded" rate. When RCIC is lost entirely at the time of venting (Case 5), there is a slow rate of inventory loss that eventually leads to core uncovery and core damage.

When the hardened vent is used, operators maintain a pressure band of 0.04–0.07 MPa (7–10 psig) in the wetwell. Note that the nominal RCIC injection (Case 6) is similar to Case 16 from Section 4.2.2, where CST is available and anticipatory venting is successful. In addition, when there is degraded RCIC injection, the scenario still ends in success for the same reason as the analogous drywell vent case.

In the containment failure cases (Cases 8–14), the RCIC turbine trips when wetwell pressure rises through 0.34 MPa (50 psig) on high wetwell backpressure and before the opening of any of the containment failure paths, which are all assumed to occur at 0.37 MPa (53 psig). This trip requires manual action to be reset. When there is a 2-inch break (Cases 8 and 9), it is once again not sufficient to bring wetwell pressure down, and RCIC remains unavailable. Since the failure path opens after RCIC has already tripped, a degraded pump performance (in Case 9) has no impact on the scenario. In both cases, then, core uncovery and damage occurs. Since venting began much later, RCIC failure on high backpressure occurs sooner and core damage 4 hours sooner than in the analogous venting cases (Cases 1 and 2).

In the 18-inch failure cases (Cases 10–12), wetwell pressure drops quickly with the stuck-open valve, and pressure quickly falls below the assumed reset value for RCIC injection. Wetwell pressure reaches atmospheric pressure around 26 hours and brings the wetwell water temperature down to 100 degrees C (212 degrees F). In both the functional and degraded RCIC cases (Cases 10 and 11), the trip and reset occur in between RCIC cycles and, therefore, injection is never lost. As in the analogous venting case, the degraded RCIC injection is sufficient to maintain level, allowing for long-term level control. Without the assumed reset on RCIC injection, core uncovery and damage would occur as demonstrated in the “nonfunctional” case (Case 12).

When the drywell vent opens either for venting purposes or containment failure, the ductwork is assumed to rupture, and steam enters the reactor building. The blowout panels on top of the reactor building open soon after to relieve pressure. Steam condenses on the relatively cool walls and structures of the reactor building and water begins to accumulate on the ground. The DAEC flood analysis reveals that this condensed water makes its way into the southeast and southwest stairwells and from there into the other basement rooms. The HPCI and RCIC rooms are at this basement level and if water rises above 0.9 meter (3 feet), the pumps inside may become inoperable. The RCIC room is protected by a sealed door and never has more than a few inches of water in any of the cases. This water is the result of condensing steam that enters the room through vents. Hence, RCIC is not affected by the rising water level in the basement, and its long-term availability in all cases is not in question. HPCI, on the other hand, has a fire door between it and the stairwell that is assumed to fail when 0.9 meter (3 feet) of water accumulates in the stairwell. In the cases with the small, 2-inch vent, the amount of water entering the basement is relatively small, and the water level in the HPCI room remains well below the 3-foot level. For the 18-inch venting cases (Cases 3–5), however, the water level in the HPCI room is just below the 0.9-meter (3-foot) level at 48 hours. HPCI availability is questionable beyond this time. In the 18-inch failure cases (Cases 10–12), even though the pathway opens much later in the transient, the HPCI room fills to nearly the same level by 48 hours as in the vented cases, since the vent is stuck open. Because of this, if RCIC were unavailable, HPCI availability beyond 48 hours is doubtful.

There is RCIC (and HPCI) isolation on high torus area or RCIC area temperature. Thermocouples are set up within the respective rooms to measure the ambient temperature. If the RCIC or HPCI room rises to 79.4 degrees C (175 degrees F), then an isolation signal is produced for the respective pump. In addition, if the torus area vent air temperature reaches 65.6 degrees C (150 degrees F), an isolation signal is produced for both pumps (after a 30-minute delay for RCIC and a 15-minute delay for HPCI). The ambient temperature in the HPCI and RCIC rooms does not reach 79.4 degrees C (175 degrees F) in any of the scenarios since they are relatively isolated from the torus room. However, the torus room temperature exceeds the 65.6-degree-C (150-degree-F) isolation setpoint in all cases. The model does not include these isolation signals since EOP-1 directs operators to bypass them if necessary. Hence, ongoing RCIC operation in these cases assumes operator action to bypass the high torus area vent temperature trip.

The CST remains unexhausted at 48 hours in all cases. However, if the CST were not available for some reason and RCIC were forced to take suction from the wetwell, RCIC long-term performance becomes questionable. This is because the wetwell eventually becomes saturated, and RCIC would be taking suction on a boiling pool. Table 5-4 includes a sensitivity with CST unavailability.

Sensitivity Calculations

In addition to these results, Table 5-4 documents additional sensitivity studies that investigated specific issues.

Table 5-4 Sensitivity study matrix—ECCS injection—SBO sequence

Case #	Sensitivity	Impact
3a 10a	Availability of HPCI, in lieu of RCIC	As in the Chapter 4 HPCI sensitivity cases, the increased flow of HPCI makes flooding of the steamlines a greater possibility when running the water level up to just below the steamlines. A lower target high level is assumed here to determine the long-term impact of HPCI should steamline flooding not be a concern. In Case 3a, HPCI takes suction from the CST until 1.3 hours, at which point HPCI automatically swaps to the wetwell because of the high wetwell water level. The wetwell continues to heat up but anticipatory venting keeps the wetwell temperature below the 121 degrees C (250 degrees F) assumed setpoint for pump failure and HPCI maintains level indefinitely. However, the NPSH available to the HPCI pump falls below the 6.4 meters (21 feet) required at 5.6 hours. Long-term availability of the pump is questionable at best, and this scenario should not be considered a success. Case 10a is identical to 3a except that anticipatory venting does not occur and wetwell pressure and temperature continue to rise. When the wetwell bulk water temperature reaches 121 degrees C (250 degrees F) at 8.7 hours, HPCI is lost and core damage soon follows.
1a 3b 8a 10b	CST unavailable	All four calculations end in core damage. Without CST availability, RCIC is required to take suction from the suppression pool. Performing anticipatory venting is irrelevant with the 2-inch vent (Case 1a); the wetwell pressure is not able to be sufficiently relieved and the water temperature rises above 121 degrees C (250 degrees F). The SEPs state that RCIC should remain available below this wetwell temperature but its performance is questionable beyond. RCIC is lost at 7.9 hours and core damage occurs at 11.9 hours. This is nearly identical to what occurs in both cases without anticipatory venting (Cases 8a and 10b). RCIC is lost on high wetwell temperature and core damage occurs at 11.9 hours. Containment failure at 0.37 MPa (53 psig) occurs after this at 12.5 hours. When suction is on the wetwell and anticipatory venting occurs through the 18-inch vent (Case 3b), the wetwell water temperature does not rise above the 121 degree C (250 degree F) assumed failure setpoint and provides long-term injection and RPV level control. However, RCIC is taking long-term suction on a saturated pool with NPSH well below the 6.1 meters (20 feet) required. Hence, cavitation and pump failure are possible if not likely and core damage would likely occur.

Table 5-4 Sensitivity study matrix—ECCS injection—SBO sequence (continued)

3c	No venting of containment occurs.	Without containment venting, the wetwell and drywell pressures continue to rise unchecked. RCIC trips on high backpressure at 0.34MPa (50 psig) at around 20 hours. Water level is 0.25 meter (10 inches) above the “high” level at the time of the trip so it takes several hours for water to reach the TAF. Immediately before core damage, the pressure in the wetwell/drywell is well below the failure pressure for the given ambient temperature that is described in APPENDIX F . Hence, there is no concern for containment failure or SRV failure before core damage. Core damage occurs at 26.6 hours. It is possible that SRVs could seize open or closed at high drywell pressures. This would cause the RCS to either pressurize or depressurize rapidly. However, this would simply exacerbate an already certain failure since RCIC has been lost.
3d	Increased seal leakage (34.1 m^3/hr [150 gpm] total, 17 m^3/hr [75 gpm] per pump)	The water level initially dips lower than the base case, but RCIC injection can recover level quickly since RCIC is injecting at a rate of 90.8 m^3/hr (400 gpm). Containment venting is required 2 hours sooner than the base case because of the increased leakage into the drywell. The CST is depleted around 41 hours and RCIC swaps over to inject from the wetwell. Since the bulk wetwell water temperature is around 121 degrees C (250 degrees F), RCIC reliability in recirculation mode is questionable at best.
3e	Increased seal leakage (68.1 m^3/hr [300 gpm] total, 34.1 m^3/hr [150 gpm] per pump)	With the increased leakage, water level drops significantly low initially, nearly reaching the TAF. However, RCIC is sufficient in recovering level. There is little impact here on the pressure in the RCS since the seal leakage is a water level break, and RCIC injection eventually makes up the inventory loss. The cooling of the RCS brought on by the colder CST water does so slowly, and RCIC performance on low RPV pressure is never a concern. RCIC never loses required steam supply pressure because of the leakage. There is a significant impact on the drywell pressure, since all the water is flashing to steam and pressurizing the containment. Containment venting occurs at 5.5 hours, 4.5 hours sooner than the base case. CST is depleted at 29 hours and swaps to recirculation mode, taking suction off the wetwell. The water in the suppression pool is at saturation and sitting around 121 degrees C (250 degrees F). RCIC operation beyond this time is questionable at best.
3f	Increased seal leakage starting at 17 minutes (34.1 m^3/hr [150 gpm] total, 17 m^3/hr [75 gpm] per pump)	The difference here is only 2,550 gallons of water. Compared to the 390,000 gallons available in the CST, this not significant. While there is a minor shift in timing of containment venting and RCIC injection, the delay in seal leakage has little impact on the scenario.
3g	Increased seal leakage starting at 17 minutes (68.1 m^3/hr [300 gpm] total, 34.1 m^3/hr [150 gpm] per pump)	The difference here is only 5,100 gallons of water. The delay in leakage has a bit more of an impact here with water level not dipping quite as low before RCIC injection. Besides this, the results are similar to the base case with minor shifts in timing.

5.3 Loss-of-Main-Feedwater Scenario

5.3.1 Calculation Matrix Development

Table 5-5 provides the calculation matrix for the subsequent MELCOR calculations, while Table 5-6 provides the calculation boundary and initial conditions. A discussion of the key modeling assumptions made for these calculations follows.

Table 5-5 Calculation matrix—ECCS injection—LOMFW sequence

Case #	Sequence	Venting action or containment failure	Vent path used	Response of ECCS pumps to pressure change
15.	LOMFW-25	Anticipatory venting per SEPs	Torus—2-inch vent bypass[1]	Functional
16.				Degraded
17.			Torus—18-inch main vent[1]	Functional
18.				Degraded
19.				Nonfunctional
20.			Drywell—2-inch vent bypass[1]	Functional
21.				Degraded
22.			Drywell—18-inch main vent[1]	Functional
23.				Degraded
24.				Nonfunctional
25.			Hard pipe vent[2]	Functional
26.				Degraded
27.		Failure at 0.37 MPa (53 psig)	Torus—2-inch vent bypass[1]	Functional
28.				Degraded
29.			Torus18-inch main vent[1]	Functional
30.				Degraded
31.				Nonfunctional
32.			—	Functional
33.				Degraded
34.			Drywell—18-inch main vent[1]	Functional
35.				Degraded
36.				Nonfunctional
37.			Hard pipe vent[2]	Functional
38.				Degraded

[1]SEPs 301.1 and 301.2 dictate a targeted torus pressure band of 0.07–0.10 MPa (10–15 psig).
[2]SEP 301.3 dictates a targeted torus pressure band of 0.03–0.07 MPa (5–10 psig).

Table 5-6 Initial and boundary conditions—ECCS injection—LOMFW sequence

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 5-1.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on first-in RPS signal. Nominal[1] recirculation pump seal leakage. Number of SRVs available—two of six.
Balance of plant	Offsite power is available. Support systems are available unless specified otherwise. Turbine trip occurs upon loss of feedwater. Feedwater and condensate fail at time zero.
ECCS/ESF	ESF signals successfully perform their functions (while dc power exists). HPCI is unavailable. RCIC is available indefinitely. CRDHS and SLC are available. LPCI/core spray are unavailable. CST is available for injection until depleted and then injection switches to wetwell. RPV depressurization is a "walk down" of the HCL curve.
Containment	Suppression pool cooling is unavailable. Nominal drywell and wetwell initial conditions (see Table 2-6).
Other operator actions	If credited, LPCS may need to be disabled as in EOP-1, if other low-pressure systems are available.

[1] In this context, this means no seal leakage.

Upon an LOMFW, the reactor scrams on low level and RCIC begins injection after the water level falls below Level 2. MSIVs close at 30 minutes, at which point the RPV pressure increases to the SRV relief setpoint. Operator action to depressurize the RPV is assumed only when action is required according to the HCL curve, at which point operators "walk down" the curve.

As in the LOMFW scenarios in the previous chapter, MSIVs are initially open with steam being sent to the condenser. MSIVs close on a low RPV pressure trip, which was later found to not be plant-actual. However, the net result; namely, the initial availability of the condenser with an eventual loss of the PCS when MSIVs close, is likely to mimic the actual plant response. In this series of calculations, MSIV closure occurs at 30 minutes. Table 5-8 includes sensitivity cases with MSIV closure (and loss of the condenser) occurring at time zero.

This analysis does not explore the availability of the FLEX pump for injection. The CRDHS is assumed to inject at the preaccident flow rate of a single pump, and no recirculation pump seal leakage is assumed. The level band for RCIC injection is reduced by 20 centimeters to avoid flooding the steamlines (see the explanation in Section 4.3.1).

As for the LOOP scenarios, this report does not explore containment venting at the "required" PCPL setpoint of 0.37 MPa (53 psig) since it is understood that this would lead to failure of RCIC and, eventually, core uncovery. Instead, it assumes containment failure at 0.37 MPa (53 psig) wetwell pressure at various hole sizes. It explores the loss of RCIC at various times as a series of sensitivity calculations.

5.3.2 MELCOR Simulation Results

Table 5-7 lists key timings from the 17 LOOP calculations. In addition to this, APPENDIX E to this report includes figures for selected parameters of interest.

Table 5-7 LOMFW results

Case #	Vent path used	Response of ECCS pumps to pressure change	Venting (hours)	Core uncovery (hours)	Maximum PCT degrees C (degrees F)
15.	Torus—2-inch vent bypass	Functional	12.0	33.9	,
16.		Degraded	12.0	-	-
17.	Torus—18-inch vent bypass	Functional	12.0	-	-
18.		Degraded	12.0	-	-
19.		Nonfunctional	12.0	23.1	696 (1,285)
20.	Drywell—2-inch vent bypass	Functional	12.0	-	-
21.		Degraded	12.0	-	-
22.	Drywell—18-inch main vent	Functional	12.0	-	-
23.		Degraded	12.0	-	-
24.		Nonfunctional	12.0	23.0	698 (1,288)
25.	Hard pipe vent	Functional	9.4	-	-
26.		Degraded	9.4	-	-
27.	Torus—2-inch vent bypass	Functional	23.4	33.9	558 (1,036)
28.		Degraded	23.4	33.9	558 (1,036)
29.	Torus—18-inch vent bypass	Functional	23.4	-	-
30.		Degraded	23.4	-	-
31.		Nonfunctional	23.4	34.0	556 (1,033)
32.	Drywell—2-inch vent bypass	Functional	23.4	33.9	558 (1,036)
33.		Degraded	23.4	33.9	558 (1,036)
34.	Drywell—18-inch main vent	Functional	23.4	-	-
35.		Degraded	23.4	-	-
36.		Nonfunctional	23.4	33.9	557 (1,035)
37.	Hard pipe vent	Functional	23.4	-	-
38.		Degraded	23.4	-	-

Core damage does not occur in any of the LOMFW calculations. While the core is uncovered in cases where RCIC injection is lost, the loss occurs late enough in the accident that decay heat is low and nominal CRDHS injection is sufficient to provide makeup to the RCS.

In those cases with a small 2-inch vent, the vent opens as wetwell pressure rises through 0.10 MPa (15 psig). However, the wetwell pressure continues to rise despite the open valve. This is true regardless of whether the torus (Cases 15 and 16) or wetwell bypass valve (Cases 20 and 21) is opened. Except for Case 16, they have very similar behavior with small differences in timing. RCIC is tripped on high wetwell backpressure, the level slowly begins to fall, and core uncovery occurs at 33.9 hours. However, core damage does not occur since the RPV water level remains at 2/3 fuel height until the end of the calculation. This is because the ongoing CRDHS injection can provide sufficient makeup to the RCS.

In the “degraded” injection case with venting through the bypass 2-inch torus vent (Case 16), core uncovery does not occur before 48 hours. It is not immediately intuitive that the 2-inch scenario with degraded RCIC injection should have a more successful result with no core uncovery. The cause is simply fortunate timing. The slower ramp-up of the level causes an additional cycle of RCIC to occur before RCIC is lost on high wetwell backpressure. The water level is just above TAF at 48 hours when the calculation ends.

In the 18-inch drywell venting case with anticipatory venting (Case 17), venting begins at 12.0 hours when pressure reaches 0.10 MPa (15 psig). The 18-inch vent is sufficient to keep wetwell pressure within the desired pressure band of 0.07–0.10 MPa (10–15 psig) for anticipatory venting. With suction on the CST, RCIC is not threatened by a loss of NPSH and is able to run out to 48 hours without issue. When debilitated pump performance is assumed (Case 18), a 50-percent reduction in RCIC injection has no impact on the success of this scenario. When venting begins at 12.0 hours, the rate of RPV inventory loss is slow and the combined makeup from CRDHS and 50-percent RCIC injection is more than sufficient to maintain the RPV level. When RCIC is lost entirely at the time of containment venting (Case 19), the water level decreases slowly since CRDHS is still injecting. While core uncovery occurs 10 hours after RCIC loss, core damage never occurs since the water level remains at 2/3 fuel height from ongoing CRDHS injection.

The preferred venting path is either the 18-inch wetwell vent or the hardened pipe vent. However, if for some reason the wetwell vent is unavailable or if the wetwell water level is too high, operators would use the drywell vent. Since the SRVs are venting into the wetwell and there is no leakage into containment, it is the torus, not the drywell, that is heating up and pressurizing. The vacuum breakers between the wetwell and drywell open if wetwell pressure rises more than 0.003 MPa (0.5 psid) over that of the drywell. Hence, as the wetwell pressure rises, vacuum breakers open to the drywell and increase the pressure there as well. When wetwell pressure reaches 0.10 MPa (15 psig), the drywell vent opens, reducing pressure, which also causes the vacuum breakers to open, effectively depressurizing the wetwell. For this reason, the results in the drywell venting cases (Cases 22–24) behave very similarly to the corresponding wetwell venting cases (Cases 17–19), with small differences in timing.

There is little difference in the results between the 2-inch anticipatory venting cases and the cases with 2-inch vent failure (Cases 27–28 and 32–33). In the venting cases, the valve opens at 12.0 hours and never closes, while in the failure cases, the valve opens at 23.4 hours and never closes. Even without the vent being open for those first 11.4 hours, the overall behavior is similar. Core uncovery occurs at 33.9 hours regardless and core damage is averted once again.

The location of the break (torus or drywell) again does not have a significant impact, apart from small timing differences.

For the 18-inch wetwell vent failure case (Case 29), RCIC is lost when pressure rises through 0.34 MPa (50 psig) on high wetwell backpressure. When the wetwell reaches 0.37 MPa (53 psig), the valve sticks open and both wetwell and drywell pressure fall. Operators are assumed to take action to restart RCIC, and the pump is reset locally when wetwell pressure falls through 0.28 MPa (40 psig). RCIC injection continues at this point, recovering the RPV water level, and the scenario ends in success. The two subsequent scenarios (Cases 30 and 31) with debilitated and nonfunctional RCIC demonstrate that CRDHS is sufficient for RCS makeup, even if RCIC is not recovered. The sensitivity analyses explore this further. The location of the break (torus or drywell) again does not have a significant impact, apart from small timing differences.

The hardened pipe vent calculations serve as a baseline comparison since the hardened vent is the preferred method of containment venting. The results are similar to those found in Section 5.3.1, which includes more information.

Sensitivity Calculations

In addition to these results, Table 5-8 includes additional sensitivity studies that were run to investigate specific issues.

Table 5-8 Sensitivity study matrix—ECCS injection—LOMFW sequence

Case #	Sensitivity	Impact
17a 29a	Availability of HPCI, in lieu of RCIC	In both cases, allowing the water level to go up to the extended level band before turning off HPCI would lead to significant water entering the steamlines. As is the case for RCIC in the base calculations, the extended high level is reduced by 0.51 meter (20 inches). However, thermal expansion still causes a significant amount of water to enter the steamline, HPCI fails on high steamline water level, and core damage occurs at 5.7 hours in both cases. Both sensitivity cases are repeated here with the HPCI level band set to the MELCOR default (from just below Level 2 to just below Level 8). This is meant to determine whether HPCI can provide long-term makeup if steamline flooding were not a concern. Unlike RCIC, HPCI automatically switches from CST to wetwell suction if the wetwell water level becomes too high. HPCI suction switches to the wetwell on high wetwell water level in the first calculation at 2.2 hours. The first case assumes anticipatory venting through the 18-in torus vent and operators act to keep wetwell pressure in the 0.07–0.10 MPa (10–15 psig) range. Because of this venting, the wetwell temperature remains below the 121 degree C (250 degree F) temperature at which the pump is threatened and a loss of HPCI injection does not occur. The core never uncovers, and core damage does not occur. However, HPCI is taking suction on a saturated pool and the NPSH available falls below that required for operation (6.4 meters [21 feet]) at 5.4 hours. Therefore, unless operators are credited with swapping HPCI suction back to the CST, this scenario should be considered to go to core damage. Without anticipatory venting, the temperature in the wetwell rises above 121 degrees C (250 degrees F) at 9.5 hours and HPCI injection is assumed lost. It is not until the vent fails open that the wetwell water temperature cools. Operators are credited here with restarting HPCI recirculatory injection when the temperature falls below 102 degrees C (215 degrees F). The PCT reaches 931 degrees C

Table 5-8 Sensitivity study matrix—ECCS injection—LOMFW sequence (continued)

Case #	Sensitivity	Impact
		(1,708 degrees F) before HPCI injection recovers level and averts core damage. However, suction of HPCI is again on the wetwell at this time, NPSH is well below the required head for the HPCI pump, and HPCI performance at this time is questionable at best. This scenario should be considered to go to core damage.
17b	SRV fails open	In the base scenarios, operators are assumed to modulate the SRVs open to prevent continuous cycling on the lowest pressure SRV with pressure held around 7.58 MPa (1,100 psig). If operators did not take this action, the lowest pressure SRV would cycle repeatedly. In this sensitivity, the MSIVs again close at 30 minutes and the lowest pressure then begins to cycle since no action is taken to modulate the valve open. The lowest pressure SRV reaches 270 cycles at 3.5 hours and is assumed to stick open. RPV pressure falls over the course of an hour with RCIC maintaining level. RCIC trips on low RPV pressure at 4.6 hours. Nominal CRDHS is not a sufficient source of injection at this time and the RPV level falls. Core damage occurs at 7.8 hours.
17c	RCIC lost after 3 complete cycles	RCIC's final cycle ends at 5.3 hours. Since RPV depressurization is still occurring at this time, the RPV water level reaches TAF at 8.5 hours and continues to fall. Even though the CRDHS is injecting at the nominal flow rate, it is not sufficient to prevent significant core uncovery. Core damage occurs at 12.1 hours.
17d	RCIC lost after 4 complete cycles	RCIC's final cycle ends at 6.7 hours. Since the RPV is depressurized down to 1.03 MPa (150 psig) at this point, it takes longer for the level to fall. The RPV water level reaches TAF at 15.6 hours. At this point, CRDHS can provide sufficient makeup to the RCS to avert core damage. However, the core does heat up after it is uncovered, reaching a PCT of 876 degrees C (1,609 degrees F) at 22.5 hours before cooling back down. It is doubtful that nominal CRDHS injection could provide sufficient makeup if the water level reached TAF before 15.6 hours.
17e 29b	CST unavailable	Until the timing of containment venting, the two scenarios are identical. With the CST unavailable, the CRDHS is not available for injection. The MSIVs close 15 minutes sooner than the base case (because of the low RPV pressure trip later found to not be plant-actual). As the wetwell temperature rises, operators depressurize the RPV as necessary to stay below the HCL curve. Without CRDHS injection, RCIC cycles more frequently than in the base scenarios since level falls more quickly between each cycle. Note that the version of the deck used in this and the base scenario (Revision 7) does not include logic for throttled RCIC injection when the wetwell water temperature rises above 102 degrees C (215 degrees F). In the first case, operators perform anticipatory venting starting at 8.8 hours. This venting prevents the wetwell water temperature from rising to the assumed high wetwell water temperature RCIC trip. However, NPSH falls below the 6.1 meters (20 feet) required at 6.3 hours. Note that the actual time this occurs is sensitive to the timing of MSIV closure. However, in any case, long-term performance (out to 24 hours) of the pump is not likely. This scenario should be considered to go to core damage. In the second case, operators do not perform anticipatory venting and the wetwell pressure and temperature continue to rise. RCIC is assumed to fail when the wetwell temperature reaches 121 degrees C (250 degrees F) at 9.3 hours. Both RCIC and CRDHS injection are then unavailable and water level falls with core uncovery 2.6 hours later. Core damage is predicted at 13.6 hours. At this time, the wetwell pressure has not yet reached the assumed 0.37 MPa (53 psig) failure setpoint.
17f 19a	Nominal seal leakage	Seal leakage does not have significant impact on these scenarios. There are minor differences in event timing from the base case but RCIC can keep up with the nominal leakage. As in the base case, core damage does not occur.
17g	Increased seal leakage to (34.1 m^3/hr [150 gpm] total, 17 m^3/hr [75 gpm] per pump)	When the recirculation pump seal leakage is increased, more RCIC injection is required to offset the inventory loss through the seals. The CST water level reaches the RCIC reserve level around 24.7 hours, at which point CRDHS injection ends. RCIC switches to wetwell injection on low CST level at 37.5 hours and provides level control until the scenario ends at 48 hours. Without wetwell cooling, however, the NPSH available to the RCIC pump is insufficient to support long-term suction on the wetwell. This scenario is in a safe and stable state as of 24 hours, but RCIC availability out to 48 hours is not likely.

Table 5-8 Sensitivity study matrix—ECCS injection—LOMFW sequence (continued)

Case #	Sensitivity	Impact
17h	Rapid RPV depressurization at HCL curve	When the wetwell temperature and RPV pressure reach the "action is required" region of the HCL curve, operators perform an ED of 2 SRVs full open. However, EOPs warn operators to cease depressurization if it may threaten injection. Hence, operators maintain pressure at 1.03 MPa (150 psig) to prevent the loss of RCIC injection. The core uncovers very briefly at 4.3 hours during the depressurization. However, RCIC injection is more than sufficient to recover the level and no core heatup is observed.
15a 19b 31a	CRDHS unavailable	Without CRDHS injection, MSIV closure happens sooner at 17.0 minutes. Recall that this is not a plant-actual response but the result of including a MSIV closure trip on low wetwell pressure that is not active. In the first case, the start of containment venting is similar to the base case. Without CRDHS injection, level falls more quickly in between RCIC cycles, requiring that RCIC inject more frequently. As in the base case, when the wetwell pressure rises to 0.34 MPa (50 psig), RCIC trips on high backpressure and water level begins to fall. Without CRDHS injection, however, level falls quickly with core uncovery at 28.0 hours and core damage at 30.2 hours. In the second case, RCIC is assumed lost entirely at the time of containment venting. This occurs at 11.3 hours and RPV water level begins to fall. Without CRDHS injection, level does not remain at 2/3 fuel height and core damage occurs at 17.0 hours. In the third case, without CRDHS injection, level again falls more quickly in between RCIC cycles and RCIC injects more frequently. When the wetwell pressure rises to 0.34 MPa (50 psig), RCIC trips at 21.6 hours and is assumed unrecoverable. RPV water level begins to fall, and without CRDHS injection core, uncovery occurs at 24.6 hours and core damage at 26.7 hours.
15b 17i 19c	MSIVs close at start of transient.	A difference of 30 minutes for MSIV closure has a 2.7-hour difference in the timing of containment venting. This demonstrates the large uncertainty in timing of wetwell conditions inherent in the LOMFW scenarios. In the first case, with more decay heat deposited into the wetwell early in the transient, RCIC fails on high backpressure sooner than the base case (at 20.8 hours). However, at this time, RCIC has recently completed a cycle of injection and RPV water level is high. This contrasts with the base case, where RCIC fails when RPV level is relatively low. Core uncovery occurs 7.1 hours later in the sensitivity case than in the base case. This highlights the fact that the uncertainty in timing is not only in MSIV closure but also in the RPV level being anywhere in a wide level range when and if RCIC fails. In the second case, the HCL curve is crossed at 2.7 hours, 100 minutes sooner than the base case, and a slow depressurization begins. This moves up the timeline of the scenario with containment venting beginning at 9.3 hours (2.7 hours sooner). However, this scenario still ends in success. In the third case, the HCL curve is again crossed at 2.7 hours. This moves up the timeline of the scenario with containment venting (coincident with RCIC failure) beginning at 9.3 hours (2.7 hours sooner). At this time, the RPV water level is relatively high and the CRDHS is still injecting. Water level falls slowly with core uncovery at 18.8 hours. As in the base case, CRDHS injection is still able to maintain level at the 2/3 height and core damage does not occur.

5.4 Conclusions Drawn from MELCOR Results

The staff makes the following observations about the MELCOR results with regard to LOOPGR:

- The 2-inch bypass vent is insufficient to keep the wetwell pressure low enough such that RCIC does not trip on high wetwell backpressure.

- Venting through the 18-inch drywell vent successfully controls wetwell pressure and temperature. However, the reactor building becomes uninhabitable and has significant flooding.

- Depending upon the size of containment failure, wetwell and drywell pressure will fall, potentially to the point of allowing RCIC restart following its loss on high wetwell backpressure. However, this requires operator action to reset the RCIC turbine, and without injection, core damage would ensue with a resulting uncontrolled release directly to the environment.

- Venting through the containment vent, which is the preferred method of containment pressure control, led to no adverse reactor building conditions and better RCIC performance. This was also demonstrated in the previous section.

- Conditions (i.e., water level and ambient temperature) in the basement are such that HPCI remains available out to but not beyond 48 hours. Since RCIC is protected from internal flooding conditions, its failure from environmental conditions is not a concern.

- Although all equipment is anticipated to be operable following internal flooding from vent failure, operator access to the reactor building would be severely affected.

- Increased seal leakage is a concern in that it will deplete the CST at a greater rate and force the swap-over of HPI suction to the saturated wetwell where there are concerns for available NPSH; however, increased seal leakage does not significantly affect RPV pressure and available steam pressure for early RCIC performance.

- Significant flashing of the wetwell volume such that wetwell water level was a concern did not occur any of the cases.

- If the CST were not available, the RCIC pump would eventually experience two-phase flow because of wetwell boiling from containment venting. Thus, long-term performance and scenario success is questionable at best.

- Again, steamline flooding occurs at the expanded level band with HPCI but may also occur with RCIC. This is because the thermal expansion of the water causes spillover into the steamlines. Over time, this could cause degradation of the turbine and the possible loss of the injection source.

The staff makes the following observations about the MELCOR results with regard to LOMFW:

- Venting through the wetwell versus the drywell has no impact on success if vacuum breakers are available.

- There is an important distinction between HPCI and RCIC injection in that HPCI has a swap-over to wetwell injection if level there rises 0.13 meter (5 inches) above the nominal level. With no operator action to prevent this swap-over, long-term HPCI injection does not lead to a success path because of NPSH concerns.

- Again, conditions (i.e., water level and ambient temperature) in the basement are such that HPCI remains available out to but not beyond 48 hours. Since RCIC is protected from internal flooding conditions, its failure from environmental conditions is not a concern.

- Again, steamline flooding is a concern in these scenarios.

- Significant flashing of the wetwell volume such that wetwell water level was a concern did not occur any of the cases.

- CRDHS injection plays a critical role in success in these cases following RCIC failure. A single train of CRDHS injection is sufficient for RCS makeup after 16 hours.

6 SAFE AND STABLE END-STATE CONSIDERATIONS

6.1 Issue Description

(ASME, 2013a) defines a safe and stable state as “a plant condition, following an initiating event, in which RCS conditions are controllable at or near desired values.” Requirement AS-A2 states, “For each modeled initiating event, IDENTIFY the key safety functions that are necessary to reach a safe, stable state and prevent core damage.” Requirement SC-A5 elaborates by requiring (for Capability Category II/III) that, for sequences where stable plant conditions are not achieved at 24 hours, additional evaluations must be performed. Examples of appropriate evaluation techniques include assigning an appropriate plant damage state for the sequence, extending the mission time until an acceptable end state is reached, or modeling additional system recovery or operator actions. Only in the definition of “success path” does the standard provide a later backstop time (that being 72 hours), and the success path concept is only invoked in the seismic margins assessment (Section 10). Meanwhile, NUREG-2122, (NRC, 2013d), defines a safe stable state as the “Condition of the reactor in which the necessary safety functions are achieved.” NUREG-2122 goes on to state, “In a PRA, safe stable states are represented by success paths in modeling of accident sequences. A safe stable state implies that the plant conditions are controllable within the success criteria for maintenance of safety functions.”

Historically, Level 1 PRA models (including the SPAR models) have typically assumed a mission time of 24 hours, unless core damage was imminent at that time. The analysis in this portion of the report scopes the additional operator actions or system functionality that would be required to extend the sequence duration to a longer period of time (e.g., 48 or 72 hours). Examples of common events of interest in this regard are refill of the CST, recovery of suppression pool cooling, alignment of additional alternative RPV injection water sources, and additional containment venting operations.

The SPAR development team is undertaking a symbiotic effort to formulate guidance for upgrading the suite of SPAR models to more closely conform with ASME/ANS RA-S-2013 in this regard (INL, 2016). The report identifies the following issues relevant to the BWR/4 Mark I design:

- If battery charging (dedicated charging diesel) is successful during an SBO event, should the SPAR model mandate that power be recovered within 24 hours be retained?
- Should CST refill always be queried when the CST is the source of long-term makeup? If not, under what conditions should refill be queried?
- Is suppression pool inventory adequate as a long-term source for injection when the suppression pool cooling system is failed and containment venting is successful?
- How should recirculation pump leakage or failure be considered when relying on isolation condensers or CRDHS injection?

The following uncertainties are of interest for safe and stable end-state modeling:

- room heatup concerns for long-term equipment operation (e.g., the potential that equipment performance will degrade, or operators will be unable to access equipment because of environmental conditions)
- the leakage path from primary containment to the reactor building or environment
- the extent of “normal leakage” or containment isolation impairment at the time of the initiator and resulting containment isolation signal
- the initial volumes of water in the CST and suppression pool
- thermal-hydraulic uncertainties affecting the rate of containment pressurization
- decay heat formulation in the MELCOR model (the default adopted from a different plant versus the built-in ANS curve)
- recirculation pump seal leakage

6.2 <u>Station Blackout Sequence</u>

6.2.1 Calculation Matrix Development

Table 6-1 provides the calculation matrix for the subsequent MELCOR calculations, while Table 6-2 gives the calculation boundary and initial conditions. This analyses uses the same PRA sequence as that in Section 4.2, which includes a more detailed explanation. The following discusses the key modeling assumptions made for these calculations as they differ from those in Section 4.2.

Table 6-1 Calculation matrix—safe and stable—SBO sequence

Case #	Sequence	RCIC injection source	Initial volume in CST	Initial level in suppression pool	Recirculation pump seal leakage
1.	Based around LOOPGR-38-9	CST	24-foot MELCOR level (i.e., 240,000 gallons)	N/A	Nominal
2.					45.4 m^3/hr (200 gpm)
3.			36-foot MELCOR level (i.e., 360,000 gallons)		Nominal
4.					45.4 m^3/hr (200 gpm)
5.		WW	N/A	10.1 feet	Nominal
6.					45.4 m^3/hr (200 gpm)
7.				10.4 feet	Nominal
8.					45.4 m^3/hr (200 gpm)
9.				N/A	Nominal

Table 6-1 Calculation matrix—safe and stable—SBO sequence (continued)

Case #	Sequence	RCIC injection source	Initial volume in CST	Initial level in suppression pool	Recirculation pump seal leakage
10.		CST switching to FLEX after battery depletion at 7 hours	24-foot MELCOR level		45.4 m^3/hr (200 gpm)
11.		WW switching to FLEX after battery depletion at 7 hours	N/A	10.4 feet	Nominal
12.					45.4 m^3/hr (200 gpm)

[1]As discussed previously, nominal recirculation pump seal leakage is 4.1 m^3/hr (18 gpm) from each seal. The technical specification maximum for the seals is 14 m^3/hr (61 gpm) total.

The first parameter explored in this section is the initial volume of the water available in either the CST or wetwell depending upon the injection source of RCIC. The intention is to identify how sensitive the success of the SBO sequence is to the initial conditions in the wetwell and CST. In the case of CST injection, the initial volume of water will dictate when a swap-over to wetwell injection is required. For the wetwell, the minimum and maximum limiting conditions for operation for wetwell water level are 3.08 and 3.17 meters (10.1 and 10.4 feet), respectively. The volume of water within the wetwell contributes positively to the available NPSH for RCIC/HPCI pumps and as a heat sink for RPV depressurization.

Recirculation pump seal leakage is the other parameter that is varied in this analysis. The nominal pump seal leakage is typically taken to be 4.1 m^3/hr (18 gpm) per pump. However, the possibility of an enhanced seal leakage following a catastrophic seal failure cannot be ruled out. A seal leakage of 22.7 m^3/hr (100 gpm) per pump is explored to determine if RCIC can successfully provide long-term makeup to the reactor while simultaneously losing significant inventory through the seals.

As in Chapter 4, these simulations include a 55.6-degree-C/hr (100-degree-F/hr) cooldown that is assumed to begin 30 minutes after the loss of all ac power. Also, as noted previously, battery power is required for control of the RCIC turbine as well as for SRV manipulation. Hence, the indefinite availability of RCIC in Cases 1–8 assumes indefinite battery life, implying that the FSG-based use of a portable diesel generator to supply power to station battery chargers has been successful.

Four of the cases also explore the availability of a FLEX pump for injection following the loss of RCIC. The pump is assumed to have been staged for injection before the loss of RCIC injection, in accordance with the FSGs. RCIC is assumed to be lost at 7 hours, and two SRVs are used for RPV ED such that it remains below 0.34 MPa (50 psid) between the RPV and wetwell pressures. (EOP-ED calls for RPV pressure less than 0.34 MPa (50 psi) above torus pressure.) In the applicable scenarios, the FLEX pump begins injecting when pressure falls below the pump's 0.76 MPa (110 psig) deadhead pressure. These cases also vary in CST availability, as well as pump seal leakage. As noted previously, the depressurization of the reactor following battery loss in these cases implies local manipulation of the SRVs to lower and maintain pressure. Without this depressurization, FLEX would be deadheaded, level would fall, and core damage would ensue.

If the UHS or an ELAP is lost, operators would open the hardened containment vent to maintain an "anticipatory" pressure band of 0.03–0.07 MPa (5–10 psig) to maintain RCIC injection. This action is assumed successful in these cases. As in previous sections, batch RCIC injection is assumed with RCIC cycling full on and full off to maintain a band of 3.04 meters (119.5 inches) to 6.55 meters (258 inches). If suction is on the wetwell, RCIC is assumed to be throttled when wetwell water temperature is greater than 215 degrees F. The target level assumed here is the "normal" RPV level of 4.85 meters (191 inches) above TAF. This choice should be carefully evaluated since, although thought to be reasonable, the water level could procedurally be maintained anywhere between 0.38 meter (15 inches) and 6.55 meters (258 inches).

Table 6-2 Initial and boundary conditions—safe and stable—SBO sequence

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 6-1.	
System	**Condition**
RCS	100% (full power). Reactor successfully trips on loss of offsite ac. Seal leakage—see Table 6-1. Number of SRVs available—two of six. RPV depressurization begins at 0.5 hours at the maximum cooldown rate (55.6 degrees C/hr [100 degrees F/hr]).
Balance of plant	OFFSITE POWER is lost at time zero. DC power is available unless specified otherwise. Support systems are available (if ac is available) unless specified otherwise. Turbine trip occurs upon loss of ac. Feedwater and condensate fail at time zero. MSIV closure occurs upon loss of offsite ac.
ECCS/ESF	ESF signals successfully perform their functions (while dc power exists). HPCI is unavailable. RCIC is available unless specified otherwise. CRDHS and SLC are unavailable upon loss of offsite ac. LPCI/core spray are unavailable.
Containment	Suppression pool cooling is unavailable.[1] Nominal drywell and wetwell initial conditions (see Table 2-6) are present. Anticipatory containment venting through the HCV.
Other operator actions	If credited, LPCS may need to be disabled per EOP-1, if other low-pressure systems are available.

[1] The exception to this is before loss of all offsite and onsite ac.

6.2.2 MELCOR Simulation Results

Table 6-3 lists the results of the 12 LOOP calculations. In addition to this, APPENDIX G to this report includes figures for selected parameters of interest.

Table 6-3 LOOPGR results

Case #	Source of RCIC suction	NPSH[1] available <6.1 meters (20 feet) (hours)	Containment venting (hours)	Core damage (hours)
1.	CST	7.1	7.1	No
2.	CST	8.4	4.4	No[2]
3.	CST	7.1	7.1	No
4.	CST	8.3	4.4	No
5.	WW	5.3	5.8	No[3]

Table 6-3 LOOPGR results (continued)

Case #	Source of RCIC suction	NPSH[1] available <6.1 meters (20 feet) (hours)	Containment venting (hours)	Core damage (hours)
6.	WW	6.1	4.4	No[3]
7.	WW	5.7	6.1	No[3]
8.	WW	6.3	4.6	No[3]
9.	CST->FLEX	7.1	7.1	No
10.	CST->FLEX	7.9	4.4	No
11.	WW->FLEX	5.7	6.1	No
12.	WW->FLEX	6.3	4.6	No

[1]NPSH is approximated using conditions in the wetwell. Table 2-1 in Section 2.1 contains more information.

[2] The CST is depleted and swap-over to the wetwell occurs immediately after 24 hours. Pump damage from cavitation is likely, and the success of the scenario is questionable at best.

[3] Although these calculations do not predict core damage, RCIC is operating for an extended period (more than 16 hours) with suction on the wetwell and low NPSH available. Pump damage from cavitation is likely, and the success of the scenario is questionable at best.

As of 24 hours, all cases taking suction from the CST are in a safe and, seemingly, stable state. CST inventory has not been exhausted, even with the enhanced seal leakage and limited initial inventory of CST in Case 2. The wetwell water level, while high, has not yet threatened the vacuum breakers, RCIC exhaust, and hardened vent. However, these calculations were extended from 24 to 48 hours to determine the stability of the results. As time goes on, conditions become less stable. In the cases with low initial CST inventory, swap-over of RCIC suction to the wetwell occurs at 38.1 hours in the case with nominal seal leakage (Case 1) and at 24.1 hours in the case with increased seal leakage (Case 2). This has the positive benefit of reducing the high wetwell water level threat. However, the NPSH available to RCIC is less than the 6.1 meters (20 feet) of head required for the pump to operate. Cavitation is likely to occur, and prolonged injection from the RCIC pump could lead to pump damage and loss of injection. In the cases with greater CST inventory, the swap-over to the wetwell occurs much later. When there is only nominal seal leakage (in Case 3), the CST is still not exhausted as of 48 hours. When there is increased seal leakage (in Case 4), the CST is exhausted and swap-over occurs at 42.1 hours. While the wetwell water level still does not reach the wetwell vacuum breakers in these cases, it comes right up to them before swap-over occurs in the increased seal leakage case. The impact of initial CST water level, then, is on the timing of swap-over of RCIC to the wetwell. In addition, the increased rate of pump seal leakage serves to speed the loss of CST inventory.

When the CST is unavailable, and suction is on the wetwell, the available NPSH becomes important in determining the long-term availability of the pump. Anticipatory venting is assumed successful in all cases, which keeps the wetwell water saturated and water temperature below 121 degrees C (250 degrees F). However, the pressure in the wetwell also remains relatively low, reducing the head available to the pump. Additional inventory in the wetwell in Cases 7 and 8 results in two benefits to NPSH. First, the additional water weight itself provides more head to the pump. Second, the additional wetwell water acts as a slightly better heat sink and the wetwell water temperature does not increase as quickly. In the cases with nominal seal leakage, the increased wetwell water level leads to a 20-minute delay in the available NPSH dropping below the 6.1 meters (20 feet) required for RCIC operation (5.7 hours versus

5.3 hours). In the cases with increased seal leakage, a significant amount of decay heat is going to the drywell rather than the wetwell through the leaking seals. Hence, the wetwell water temperature receives less of the decay heat and leads to a slower loss of the available NPSH for RCIC. NPSH drops below 6.1 meters (20 feet) at 6.1 and 6.3 hours in Cases 6 and 8, respectively. The availability of RCIC beyond the time when available NPSH falls below the required head is questionable at best. Cases 5–8 are not in a safe and stable state as of 24 hours. Two sensitivity calculations are provided with loss of RCIC occurring when NPSH falls below 6.1 meters (20 feet).

As in the analogous Chapter 4 cases, FLEX pump injection can provide a means of long-term cooling following the switch at 7 hours. This is the case regardless of the method of injection, initial CST and wetwell inventory before the switch, and seal leakage. Even though available NPSH falls below that required for RCIC before the swap-over to FLEX injection, it is for a relatively short period of time (1.7 hours or less). RCIC would not be immediately lost, and it would take time for the core to uncover. Because of the safe and stable state as of 24 hours, these calculations were not extended to 48 hours.

Sensitivity Calculations

In addition to these results, Table 6-4 documents additional sensitivity studies to investigate specific issues.

Table 6-4 Sensitivity study matrix—safe and stable—SBO scenario

Case #	Sensitivity	Impact
1a 5a	Availability of HPCI, in lieu of RCIC, for multiple scenarios	With the much greater injection rate of HPCI, the water level recovers at a greater rate during the first cycle of HPI. However, there is more overshooting of RPV water level after the pump is switched off at the expanded upper level setpoint. Steamline flooding occurs in both cases. This occurs since relatively cold water is being injected rapidly up to the setpoint (just below the steamlines) which then heats up and expands. HPCI is tripped code-automatically on an assumed trip from the high steamline water level. Water level falls quickly and, since the FLEX pump is not assumed available in either case, RPV level does not recover. The core uncovers with core damage occurring at 2.0 hours in both cases. Even with FLEX pumps available, it is unlikely that they could be staged and injecting in time to preclude core damage.
5b 11a	RCIC is lost upon NPSH available < 20ft	In the first scenario, the NPSH available to RCIC falls below the required head at 5.3 hours and RCIC is assumed lost. RPV water level at this time is relatively high (214 inches above TAF) since RCIC has recently completed a cycle. Therefore, it takes time for water level to fall below the TAF. The core uncovers at 8.1 hours and core damage occurs at 9.4 hours. Even if level had been lower at the time of RCIC failure, it takes 1.6 hours for the level to fall from Level 2 to TAF and an additional 1.3 hours for core damage to occur. Hence, there is ample time for FLEX injection to begin. This is seen in the second case, where FLEX injection becomes available at 7 hours. Operators begin depressurizing the RPV with 2 SRVs and FLEX begins injecting soon after. Level recovers and core uncovery and damage are precluded.

6.3 Loss-of-Main-Feedwater Scenario

6.3.1 Calculation Matrix Development

Table 6-5 provides the calculation matrix for the subsequent MELCOR calculations, while Table 6-6 gives the calculation boundary and initial conditions. This analysis uses the same PRA sequence as that in Section 4.3 , which includes a more detailed explanation. The following discusses the key modeling assumptions made for these calculations as they differ from those in Section 4.3.

Table 6-5 Calculation matrix—safe and stable—LOMFW sequence

Case #	Sequence	Time of RCIC failure	CRDHS[1]	Recirculation pump seal leakage[2]
13.	LOMFW-25	4 hours	Nominal	Nominal
14.				45.4 m^3/hr (200 gpm)
15.			1-train, maximized	Nominal
16.				45.4 m^3/hr (200 gpm)
17.		6 hours	Nominal	Nominal
18.				45.4 m^3/hr (200 gpm)
19.			1-train, maximized	Nominal
20.				45.4 m^3/hr (200 gpm)

[1]Nominal CRDHS injection is roughly 9.61 m^3/hr (42.3 gpm). The maximized, postscram injection rate to the vessel depends on RPV pressure. The rate is 51.1 m^3/hr (225 gpm) for vessel pressure below 1.245 MPa-absolute (abs), 40.2 m^3/hr (177 gpm) for vessel pressure above 6.05 MPa-abs; for intermediate pressures, a linear dependence is assumed.
[2]As discussed previously, nominal recirculation pump seal leakage is 4.1 m^3/hr (18 gpm) from each seal. The technical specification maximum for the seals is 14m^3/hr (61 gpm) total.

This series of simulations explored the sufficiency of the CRDHS to provide long-term makeup following the loss of HPI. In many analyses (e.g., UFSAR Chapter 15 analyses), the prescram injection rate of the CRDHS is assumed even after reactor trip. However, the CRDHS can be a significant source of injection if the increased postscram flow is assumed. The assumption is that, when operating at the enhanced CRDHS injection rate, the CRDHS operates in batch mode between L2 and L8. Unlike with the steam-driven pumps, the EOPs do not appear to give guidance for an expanded level band with an electric pump. While procedures direct operators to put the pump into automatic mode, there is no indication that the pump operates automatically in batch mode. Hence, the code-automatic cycling assumed here models and credits operator action to maintain level in a desired band.

The level band for RCIC injection is reduced by 20 centimeters to avoid flooding the steamlines (see the explanation in Section 4.3.1). The FLEX pump is assumed unavailable in these simulations.

This analysis also explored the timing of dc power loss (resulting in loss of RCIC injection) and the recirculation pump seal leakage rate. The intention is to determine how sensitive CRDHS success in providing makeup is to the amount of decay heat present and the rate of inventory loss.

When RPV pressure reaches the “action is required” region of the HCL curve, operators are assumed to “walk down” the curve. Since the HPI systems are unavailable when the curve is reached, the assumption is that operators do not cease the depressurization at 1.03 MPa (150 psig) but continue to depressurize to 0.34 MPa (50 psid). Table 6-8 includes a sensitivity wherein the pressure is held at 1.03 MPa (150 psig).

As in the LOMFW scenarios in the previous chapters, MSIVs are initially open with steam being sent to the condenser. MSIVs close on a low RPV pressure trip, which was later found to not be plan-actual. However, the net result, namely, the initial availability of the condenser with an eventual loss of the PCS when MSIVs close, is likely to mimic the actual plant response. In this series of calculations, MSIV closure varies depending upon the amount of CRDHS injection and seal leakage and is therefore included in the results table. Table 6-8 includes sensitivity cases with MSIV closure (and loss of the condenser) occurring at time zero.

Table 6-6 Initial and boundary conditions—safe and stable—LOMFW sequence

These conditions are in addition to the generic modeling conditions from Table 2-6 and the calculation-specific conditions from Table 6-5.	
System	**Condition**
RCS	100% full power. Reactor successfully trips on first-in RPS signal. Recirculation pump seal leakage—see Table 6-5. Number of SRVs available—two of six.
Balance of plant	OFFSITE POWER is available. Support systems are available, unless specified otherwise. Turbine trip occurs upon loss of feedwater. Feedwater and condensate fail at time zero.
ECCS/ESF	ESF signals successfully perform their functions. HPCI is unavailable. RCIC—see Table 6-5. CRDHS and SLC are available. LPCI/core spray are unavailable. CST is available for injection until depleted and then injection switches to wetwell. RPV depressurization is a “walk down” of the HCL curve.
Containment	Suppression pool cooling is unavailable. Nominal drywell and wetwell initial conditions (see Table 2-6) are present.
Other operator actions	If credited, LPCS may need to be disabled per EOP-1, if other low-pressure systems are available.

6.3.2 MELCOR Simulation Results

Table 6-7 lists the results of the eight LOMFW calculations. In addition to this, APPENDIX G to this report includes figures for selected parameters of interest.

Table 6-7 LOMFW results

Case #	CRDHS	Recirculation pump seal leakage	MSIV closure (mins)	Core uncovery (hours)	Core damage (hours)
13.	Nominal	8.1 m^3/hr (36 gpm)	30.0	5.4	6.7
14.		45.4 m^3/hr (200 gpm)	10.7	5.4	6.5
15.	1-train, maximized	8.1 m^3/hr (36 gpm)	23.2	-	-
16.		45.4 m^3/hr (200 gpm)	21.3	6.7	-
17.	Nominal	8.1 m^3/hr (36 gpm)	30.0	7.4	10.3
18.		45.4 m^3/hr (200 gpm)	10.7	7.3	8.6
19.	1-train, maximized	8.1 m^3/hr (36 gpm)	23.2	-	-
20.		45.4 m^3/hr (200 gpm)	21.3	-	-

In all cases where CRDHS injection is at a nominal flow rate (Cases 13, 14, 17, and 18), core damage occurs following the loss of RCIC. The relatively low rate of injection from CRDHS is not able to compensate for the combined inventory loss through the SRVs and from the seal leakage. When there is increased seal leakage, the water level falls faster following the loss of RCIC. However, the water level at the time of RCIC failure is slightly higher in both cases, and thus core uncovery occurs at roughly the same time as in the analogous nominal leakage cases.

When there is enhanced CRDHS injection and nominal seal leakage (Cases 15 and 19), there is more than enough makeup to the RPV following RCIC failure. A single CRDHS at maximized flow offers sufficient makeup to the RPV so that the core is never uncovered, and batch mode injection of the CRDHS leaves the plant in a safe and stable state at 24 hours.

When there is enhanced CRDHS injection and increased seal leakage (Cases 16 and 20), depressurization of the reactor becomes important. At high pressures, the seals are leaking at a rate of about 45.4 m^3/hr (200 gpm), the CRDHS is injecting at rate of about 40.2 m^3/hr (177 gpm), and additional inventory is being lost through the SRVs to the wetwell. The net result is a decrease in RPV water inventory and water level. Depressurizing the RPV reduces the rate of seal leakage, and the CRDHS can inject at a higher rate (51.1 m^3/hr [225 gpm] when RPV pressure is below 1.14 MPa (166 psig)).

This effect is seen in the case with RCIC lost at 4 hours (Case 16). Level is high from the last RCIC cycle. The CRDHS begins injecting once RPV water level hits L2 and is, initially, not sufficient to make up for loss from the SRVs and seal leakage, since pressure is still high. As a result, the water level begins to fall. At 5.3 hours, RPV pressure reaches the HCL curve and depressurization begins with operators slowly following the HCL curve. Initially, the additional loss of inventory from depressurization causes level to fall even further, dropping below TAF at 6.7 hours. At 7.4 hours, RPV pressure reaches a break-even point in inventory loss versus gain with seal leakage sufficiently reduced and CRDHS injection increased so that level begins to recover and core damage is averted. A similar progression occurs in the 6-hour case (Case 20). Table 6-8 includes a sensitivity wherein ED occurs when pressure reaches the HCL curve rather than walking down the curve.

Sensitivity Calculations

In addition to these results, Table 6-8 documents additional sensitivity studies that were run to investigate specific issues.

Table 6-8 Sensitivity study matrix—safe and stable—LOMFW scenario

Case #	Sensitivity	Impact
17a	Availability of HPCI, in lieu of RCIC	Using an extended level band before turning off HPCI leads to significant water entering the steamlines. As is the case for RCIC in the base calculations, the extended high level is reduced by 0.51 meters (20 inches). However, thermal expansion still causes a significant amount of water to enter the steamline and HPCI failed on high steamline water level. Soon after, the code failed unexpectedly and was not able to be recovered. Had the scenario run to completion, core damage would have ensued with no source of injection.
17b	SRV fails open	The base scenarios assume that operators modulate the SRVs open to prevent continuous cycling on the lowest pressure SRV with pressure held around 7.58 MPa (1,100 psig). If operators did not take this action, the lowest pressure SRV would cycle repeatedly. In this sensitivity, the MSIVs again close at 30 minutes and the lowest pressure SRV then begins to cycle, since no action is taken to modulate the valve open. The lowest pressure SRV reaches 270 cycles at 3.7 hours and is then assumed to stick open. The level is relatively high at this point, and the open SRV causes water to flood the steamlines. RCIC is lost on a code-automatic trip from a flooded steamline. With the stuck-open valve and no injection source, water level falls quickly. At 4.3 hours, RCIC recovers from its trip as water level in the steamlines falls below an assumed setpoint. RCIC can inject for 19 minutes before it is lost again when the turbine trips on low RPV pressure. The core uncovers at 5.8 hours and core damage occurs at 7.7 hours.
15a 19a	Injection from wetwell	In these scenarios, RCIC takes suction on the wetwell instead of the CST. Since RCIC is lost early in the scenarios (at 4 and 6 hours in Case 15a and 19a, respectively), NPSH in the wetwell has not yet fallen below the 6.1 meters (20 feet) required for the pump, and there is no concern for pump cavitation while it is operating. Both scenarios progress similarly to the base case with increased CRDHS injection providing sufficient makeup to the RPV after RCIC is assumed to fail.
15b	Cease RPV depressurization at 1.03 MPa (150 psig)	With the pressure held at 1.03 MPa (150 psig) following depressurization, the rate of seal leakage is increased slightly in the long term. The CRDHS is still able to provide RPV makeup, and no uncovery or damage occurs.
15c 19b	ED when the HCL curve is reached	In both cases, as in the corresponding base scenarios, MSIVs close at 23.2 minutes after which steam is condensed in the wetwell. The HCL curve is reached in both cases at 4.3 hours. In the first case, RCIC is no longer available when ED begins and the RPV water level falls quickly with core uncovery soon after. The CRDHS is operating at the increased injection rate and can keep the core covered sufficiently to prevent any heatup. The RPV water level slowly recovers, and the CRDHS maintains long-term level control, as in the base case. In the second case, RCIC is available when ED begins. However, there is a 30-second delay in the start of RCIC injection, and RCIC starts after the water level has reached TAF. Once it starts, recovery of water level is much faster than with CRDHS injection alone. After RCIC is lost at 6 hours, the CRDHS maintains RPV level, as in the base case.

Table 6-8 Sensitivity study matrix—safe and stable—LOMFW scenario (continued)

15d 16a 19c	MSIV closure at start of transient	The biggest impact of the timing of MSIV closure is when the RPV depressurization begins. With no decay heat being passed to the condenser, the wetwell receives significantly more heat in the early part of the transient. Hence, the HCL curve is reached 1.7 hours sooner in Cases 15d and 19c and 1.2 hours sooner in Case 16a. This has a positive impact on the transient in that the seal leakage is reduced and CRDHS injection is increased sooner. Water level does not fall as far after RCIC failure. In Case 16a, core uncovery does not occur as it did in the base case. This is not to say that early MSIV closure is preferred, since decay heat going to the condenser is always preferred over decay heat within containment. Instead, early depressurization is preferred over late.

6.4 Conclusions Drawn from MELCOR Results

The staff makes the following observations about the MELCOR results with regard to LOOP:

- In scenarios in which the CST is unavailable, the available NPSH for RCIC falls below the 6.1 meters (20 feet) required early in the scenario. Long-term availability of the pump is therefore questionable at best. This is also the case for HPCI taking suction on the wetwell. Without FLEX injection to provide long-term makeup, or the recovery of power, core damage would likely occur. This is the case even for nominal seal leakage.

- Given significant recirculation pump seal leakage, the CST will deplete more quickly and, if the CST level is low, swap-over of RCIC to the wetwell will occur around 24 hours. Because of NPSH concerns, RCIC availability is questionable and core damage could occur.

- In those cases that credit it, FLEX injection is successful in preventing core damage.

- Again, steamline flooding occurs at the expanded level band with HPCI but may also occur with RCIC. This is because the thermal expansion of the water causes spillover into the steamlines. Over time, this could cause degradation of the turbine and the possible loss of the injection source.

The staff makes the following observations about the MELCOR results with regard to LOMFW:

- Nominal CRDHS injection is not sufficient in providing makeup following RCIC failure at or before 6 hours. However, increased postscram CRDHS injection is adequate for RPV makeup.

- The rate of seal leakage has little impact on scenario success. Failure occurs regardless of leakage rate for nominal CRDHS injection, and success occurs for increased injection.

- Timely depressurization of the RPV (in this case, walking down the HCL curve) is important since the rate of seal leakage as well as the rate of injection is pressure dependent.

- Again, steamline flooding is a concern in these scenarios, particularly given HPCI rather than RCIC injection.

7 APPLICATION OF MELCOR RESULTS TO SPAR MODEL

Table 7-1 maps the MELCOR calculations presented in Chapters 3–6 with the corresponding SPAR model sequence. APPENDIX H to this report includes all relevant event trees. It is important to note that SPAR models are most commonly used for event and condition assessments, meaning that the specific portions of the model have relatively more importance in specific applications than their baselines frequencies would suggest.

Table 7-2 summarizes the scenarios that have been investigated, recaps the boundary and initial condition variations studied using MELCOR, highlights relevant parts of the existing DAEC success criteria, and discusses the potential changes to the DAEC model based on the MELCOR analysis. In addition, the table identifies cases in which these results can be applied to SPAR models for other similar plants. This table is designed to be the starting point for subsequent evaluation by SPAR model developers to ensure that these changes are appropriate and assess whether the same changes can be made to SPAR models for similar plants.

Table 7-1 Mapping of MELCOR analyses to the DAEC SPAR (8.50) model

SPAR sequence	MELCOR calculations	Percentage as part of initiator class CDF (internal events)	Percentage as part of total internal event CDF
Chapter 3—Degraded High-Pressure Injection and Relief Valve Criteria (non-ATWS)			
TRANS-30	Cases 1–16	N/A—success path	N/A—success path
TRANS-49	Cases 17–20	0.27%	0.15%
SLOCA-25	Cases 21–30	N/A—success path	N/A—success path
Chapter 4—Mitigating Strategies Usage in Loss of AC Power and Other Scenarios			
LOOPGR-38-9	Cases 1–16	N/A—success path	N/A—success path
LOMFW-25	Cases 17–25	N/A—success path	N/A—success path
Chapter 5—ECCS Injection Following Containment Failure or Venting			
LOOPGR-38-9	Cases 1–14	N/A—success path	N/A—success path
LOMFW-25	Cases 15–38	N/A—success path	N/A—success path
Chapter 6—Safe and Stable End-State Considerations			
LOOPGR-38-9	Cases 1–12	N/A—success path	N/A—success path
LOMFW-25	Cases 13–20	N/A—success path	N/A—success path

Table 7-2 Potential success criteria updates based on DAEC result (continued)

Initiator/aspect of interest	MELCOR variations for baseline cases	Expected insights	Proposed SPAR changes or application-specific considerations
TRANS—Degraded HPI and Relief Valve Criteria (non-ATWS)	CRDHS injection, manual actions to stabilize level and pressure, method of depressurization, timing of ADS initiation, number of SRVs during ADS	• What high pressure systems are required? • What operator actions are required? • How many ADS valves need to operate?	• A single SRV can depressurize the RPV and core damage is avoided. However, the uncertainty associated with the volume of water entering and leaving the vessel (i.e., seal leakage, CRDHS injection, feedwater line emptying) at this time makes the success of this scenario uncertain. A change to the SPAR models is not recommended because of this uncertainty. • CRDHS injection alone operating at the nominal, prescram rate is insufficient in providing makeup to the RPV following an unexpected reactor trip. Another source of HPI (such as RCIC) or LPI with successful ADS operation is necessary for success. This is consistent with the current SPAR logic. • A single CRDHS pump injecting at the postscram increased injection rate is sufficient for RPV water inventory makeup. However, this may not be sufficient to support RPV cooldown in the first few hours of the transient. Additionally, two CRDHS pumps injecting at the postscram injection rate provide more than enough makeup to the RPV and can facilitate a cooldown of the RPV to cold shutdown conditions if a train of RHR is available. This increased injection is currently not queried in the SPAR models and could be added.
SLOCA—Degraded HPI and Relief Valve Criteria (non-ATWS)	CRDHS injection, timing of ADS initiation, number of SRVs during ADS		• Given a small LOCA in the steamline, pressure and level fall but a single train of CRDHS at the increased postscram rate can maintain the RPV level. This is true for both a 1-inch and 1.8-inch equivalent break. Two trains provide more than enough injection to maintain the level and support a cooldown to cold shutdown conditions. This increased injection is currently not queried in the SPAR models and could be added. However, for a small, recirculation line LOCA, the loss of inventory is significant enough that even both CRDHS pumps operating at full capacity is insufficient to maintain the level. This is true even for a smaller 1-inch equivalent break and one train of the CRDHS. • As in the TRANS cases, two SRVs are necessary for the success of the ADS. This is consistent with the current success criteria.

Table 7-2 Potential success criteria updates based on DAEC result (continued)

Initiator/aspect of interest	MELCOR variations for baseline cases	Expected insights	Proposed SPAR changes or application-specific considerations
LOOP—Mitigating Strategies Usage	Timing of ac power loss, timing of RCIC loss, CST availability, venting actions	• What FLEX equipment can be used? • What FLEX strategies can be used? • What conditions need to be satisfied for FLEX to be successful?	• Without manual depressurization following a loss of both dc power and RCIC injection, the FLEX pump would be unable to inject and core uncovery and fuel damage would be inevitable. This is consistent with the current SPAR model assumptions made for firewater injection. • FLEX injection led to success in all scenarios that gave FLEX credit, regardless of timing of RCIC loss and HCV venting actions. Given the ability of FLEX to prevent core damage, this confirms that FLEX equipment should be added to the SPAR models. • If FLEX is not available, success is only possible with both anticipatory venting and CST availability. The combination of cool water from the CST combined with expulsion of decay heat out the HCV by anticipatory venting led to success. Without CST water, RCIC could be damaged by cavitation. Without anticipatory venting, RCIC would trip on high wetwell backpressure. Currently, the SPAR models do not query CST availability. This could be added for scenarios for which no alternate injection is available.
LOMFW—Mitigating Strategies Usage	Timing and method of RPV depressurization, time and delivered flow rate of FLEX injection		• Success was not sensitive to a lower delivered flow rate of the FLEX pump.

Table 7-2 Potential success criteria updates based on DAEC result (continued)

Initiator/aspect of interest	MELCOR variations for baseline cases	Expected insights	Proposed SPAR changes or application-specific considerations
LOOP—ECCS Injection Following Containment Failure or Venting	Venting action or containment failure, vent path used, response of ECCS pumps to pressure changes	• Can you inject after failure because of high backpressure? • Can you inject after failure because of high ambient pressure? • Does containment failure create wetwell boiling? • Does containment failure lead to two-phase flow in pumps? • Does containment failure lead to suction-line uncovering? • How does ECCS operate when containment pressure is elevated? • Does the type of containment failure change any of the outcomes?	• The 2-inch bypass vent is insufficient to keep the wetwell pressure low enough so that RCIC does not trip on high wetwell backpressure. This confirms the current SPAR model, which does not consider the bypass vent as a means to success. •If flooding occurs from venting the 18-inch vents, conditions (i.e., water level and ambient temperature) in the basement are such that HPCI remains available out to but not beyond 48 hours. Since RCIC is protected from internal flooding conditions, its failure from environmental conditions is not a concern. Given the nature of the current modeling of late injection, there is no distinguishing between HPI sources. If this modeling were expanded, RCIC and HPCI injection should be looked at separately. • Increased seal leakage is a concern in that it will deplete the CST at a greater rate and force the swap-over of HPI suction to the saturated wetwell where there are concerns for available NPSH. However, given that increased seal leakage does not significantly affect RPV pressure and available steam pressure for early RCIC performance, this is a candidate for inclusion in the SPAR models. • If the CST were not available, the RCIC pump would eventually experience two-phase flow by wetwell boiling from containment venting. Thus, long-term performance and scenario success are questionable at best. Given the nature of the current modeling of late injection, CST availability is not queried. If this modeling were expanded, CSTavailability should be considered.
LOMFW—ECCS Injection Following Containment Failure or Venting	Venting action or containment failure, vent path used, response of ECCS pumps to pressure changes		• Venting through the wetwell versus the drywell has no impact on success if vacuum breakers are available. This is consistent with the current SPAR model. • There is an important distinction between HPCI and RCIC injection in that HPCI has a swap-over to wetwell injection if level thererises 0.13 meter (5 inches) above the nominal level. With no operator action to prevent this swap-over, long-term HPCI injection does not lead to a success path because of NPSH concerns. Additionally, as mentioned above, environmental conditions differ between HPCI and RCIC. Given the nature of the current modeling of late injection, there is no

Table 7-2 Potential success criteria updates based on DAEC result (continued)

Initiator/aspect of interest	MELCOR variations for baseline cases	Expected insights	Proposed SPAR changes or application-specific considerations
			distinguishing between HPI sources. If this modeling were expanded, RCIC and HPCI injection should be looked at separately. • A single train of CRDHS injection is sufficient for RCS makeup after 16 hours. This again points to distinguishing injection sources if the late injection modeling were expanded.
LOOP—Safe and Stable End-State Considerations	RCIC injection source, initial volume in CST, initial volume in suppression pool, recirculation pump seal leakage	• If battery charging (dedicated charging diesel) is successful during an SBO event, should the SPAR model mandate that power be recovered within 24 hours be retained? • Should CST refill always be queried when the CST is the source of long-term makeup? If	• In scenarios in which the CST is unavailable, the available NPSH for RCIC falls below the 6.1 meters (20 feet) required early in the scenario. Long-term availability of the pump is therefore questionable at best. This is also the case for HPCI taking suction on the wetwell. Without FLEX injection to provide long-term makeup, or the recovery of power for wetwell cooling, core damage would likely occur. This is the case even with nominal seal leakage. This indicates that the CST should be queried when RCIC or HPCI is the source of long-term makeup. • Given significant recirculation pump seal leakage, the CST will deplete more quickly and, if the CST level is low, swap-over of RCIC to the wetwell will occur around 24 hours. Because of NPSH concerns, RCIC availability is questionable and core damage could occur. However, given that increased seal leakage does not significantly affect RPV pressure and available steam pressure for early RCIC performance, this is a candidate for inclusion in the SPAR models. • FLEX injection is successful in all cases. This again points to the appropriateness of adding FLEX to the SPAR models.

Table 7-2 Potential success criteria updates based on DAEC result (continued)

Initiator/aspect of interest	MELCOR variations for baseline cases	Expected insights	Proposed SPAR changes or application-specific considerations
		not, under what conditions should refill be queried?	
LOMFW—Safe and Stable End-State Considerations	Time of RCIC failure, CRDHS injection, recirculation pump seal leakage	• Is suppression pool inventory adequate as a long-term source for injection when the suppression pool cooling system has failed and containment venting is successful? • How should recirculation pump leakage or failure be considered when relying on isolation condensers or CRDHS injection?	• Nominal CRDHS injection is not sufficient to provide makeup following RCIC failure at or before 6 hours. However, increased postscram CRDHS injection is adequate for RPV makeup. This increased injection is a candidate for being added to the SPAR model. • Timely depressurization of the RPV is important since the rate of seal leakage, as well as the rate of injection, is pressure dependent. This depressurization is a candidate for consideration in the SPAR models.

8 CONCLUSIONS

This project performed MELCOR analyses for the DAEC, looking at various initiating events and sequences of interest. These results have either confirmed existing SPAR assumptions or provided a technical basis for a few specific model changes.

The study results provide additional timing information for several PRA sequences, confirm many of the existing SPAR model assumptions, and provide a technical basis for a few specific SPAR modeling changes. Potential SPAR model changes supported by this study include the following:

- Degraded HPI and Relief Valve Criteria (non-ATWS): For both the TRANS and SLOCA cases, a single CRDHS pump injecting at the postscram increased injection rate is sufficient for RPV water inventory makeup. Additionally, two CRDHS pumps injecting at the postscram injection rate provide enough makeup to the RPV and can facilitate a cooldown of the RPV to cold shutdown conditions. This increased injection is currently not queried in the SPAR models and could be added.

- Mitigating Strategies Usage: If FLEX is not available, the success of long-term cooling for these scenarios is only possible with both anticipatory venting and CST availability. Currently, the SPAR models do not query CST availability. This could be added for scenarios in which no alternate injection is available. For the LOOP scenarios, FLEX injection led to success in all scenarios that gave FLEX credit, regardless of timing of RCIC loss and HCV venting actions. Given the ability of FLEX to prevent core damage, this confirms that FLEX equipment should be added to the SPAR models.

- ECCS Injection Following Containment Failure or Venting: If the CST were not available, the RCIC pump would eventually experience two-phase flow by wetwell boiling from containment venting. If late injection modeling were expanded, CST availability should be considered. If flooding occurs from venting the 18-inch vents, conditions (i.e., water level and ambient temperature) in the basement are such that HPCI remains available out to but not beyond 48 hours. Since RCIC is protected from internal flooding conditions, its failure from environmental conditions is not a concern. Additionally, for the LOMFW case, a single train of CRDHS injection is sufficient for RCS makeup after 16 hours. If the late injection modeling were expanded, injection sources should be distinguished. Given that increased seal leakage does not significantly affect RPV pressure and available steam pressure for early RCIC performance, updated SBO modeling is a candidate for inclusion in the SPAR models.

- Safe and Stable End-State Considerations: In scenarios in which the CST is unavailable, long-term availability of the HPCI or RCIC pump is questionable at best. This is also the case for HPCI taking suction on the wetwell. The CST should be queried when RCIC or HPCI is the source of long-term makeup. Increased postscram CRDHS injection is adequate for RPV makeup. This increased injection is a candidate for inclusion in the SPAR model. Depressurizing the RPV when reaching the HCL curve is important since the rate of seal leakage, as well as the rate of injection, is pressure dependent. This depressurization is a candidate for consideration in the SPAR models.

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APPENDIX A
MELCOR VERSIONS

MELCOR VERSIONS

MELCOR is a computer code that is under active development, so it is important to mention the code version used for this analysis, if only to allow users to reproduce the results discussed in this NUREG. All calculations used MELCOR 2.2.9541, which was the latest available code version when the work documented in this NUREG began.

Similarly, the MELCOR input deck used for the calculations described in this report was under active development throughout the project. Numerous changes were made to correct input errors, to improve the performance of system logic (e.g., cooldown logic), or to reflect feedback received from internal and external stakeholders about plant design and operations. The following table lists the major input deck revisions used for the various calculations documented in this report, as well as any modifications that may have been made to the base input model to address specific scenarios. Note that, unless otherwise stated, sensitivity studies use the same input model as their base cases, with some minor modifications described in the various tables documenting the sensitivity analyses.

Table A-1 Input Models Used for Documented Calculations

Chapter—Scenario	Cases	Input Model Revision #	Comments
Shakedown calculations	N/A	Rev. 5	Includes cooldown logic to slowly depressurize the reactor pressure vessel (RPV) at a rate of 55.6 degrees Celsius (degrees C) per hour (/hr) (100 degrees Fahrenheit (degrees F)/hr) using a proportional-integral-derivative controller. Also includes the ability to throttle the FLEX to maintain a user-defined level.
Chapter 3—Transient		Rev. 7a*	Removes the main steam isolation valve closure on low RPV pressure.
Chapter 3—Small Loss of Coolant Accident		Rev. 7a*	Removes the main steam isolation valve closure on low RPV pressure.
Chapter 4—Station Blackout		Rev. 7a*	
Chapter 4—Loss-of-Main-Feedwater		Rev. 7a*	
Chapter 5— Station Blackout		Rev. 7a*	
Chapter 5— Loss-of-Main-Feedwater		Rev. 7	This revision of the deck contains no throttled reactor core isolation cooling injection with suction on the wetwell. This only affects the sensitivity cases with no condensate storage tank (CST) available.

Table A-1 Input Models Used for Documented Calculations (continued)

Chapter—Scenario	Cases	Input Model Revision #	Comments
Chapter 6— Station Blackout	1, 2, 9, 10	Rev. 7a*	Includes decreased initial CST level/volume and an altered recirculation pump seal leakage size.
	3, 4		Includes increased initial CST level/volume and an altered recirculation pump seal leakage size.
	5, 6		Includes decreased initial wetwell level/volume and an altered recirculation pump seal leakage size.
	7, 8, 11, 12		Includes increased initial wetwell level/volume and an altered recirculation pump seal leakage size.
Chapter 6— Loss-of-Main-Feedwater		Rev. 7a*	Includes an altered recirculation pump seal leakage size.

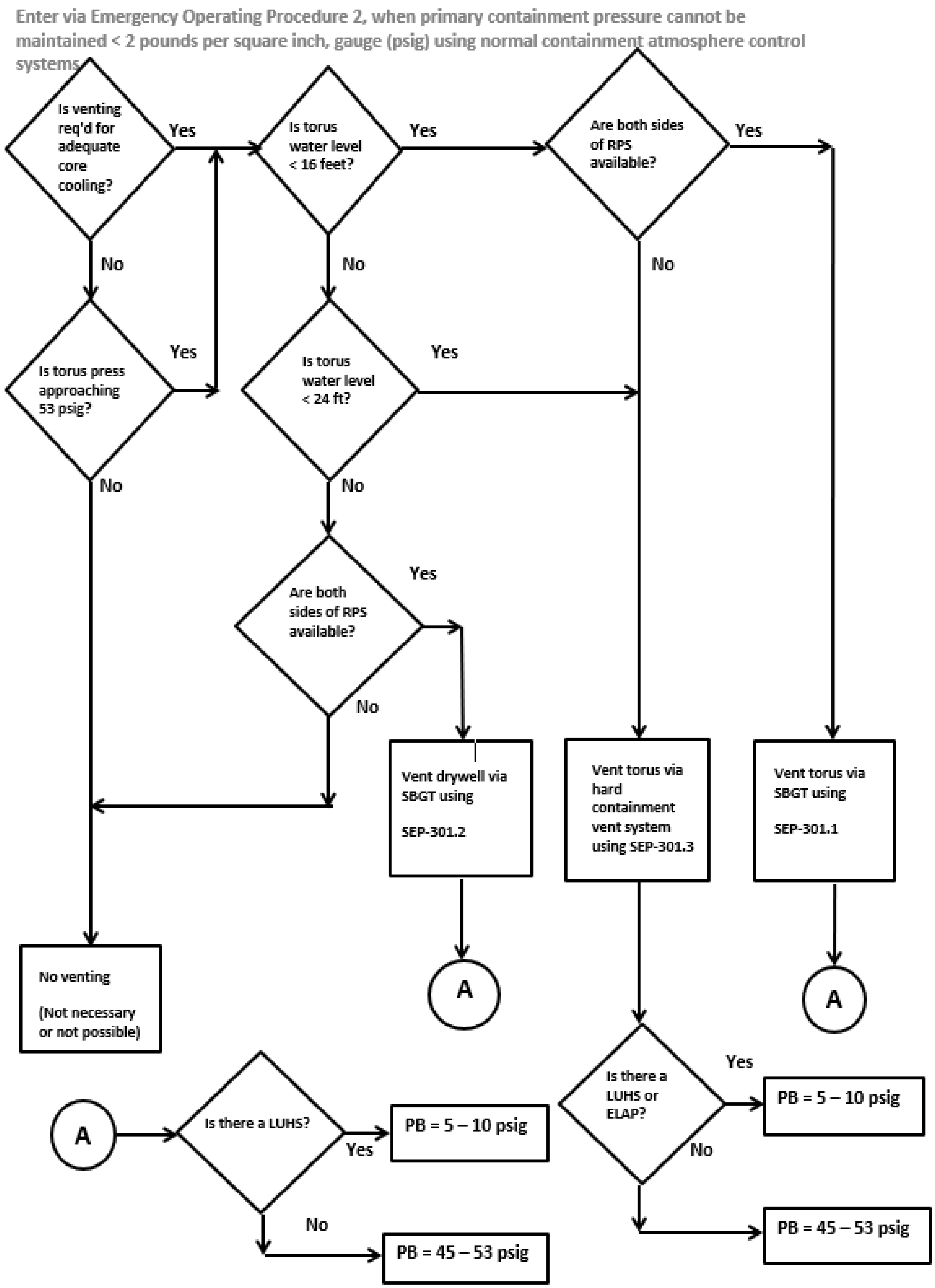
* Revision 7a is the same as Revision 7 with the following additional logic: (1) added the option for reactor core isolation cooling to be throttled when suction is on the wetwell and the water temperature is between 101.7 degrees C and 121.1 degrees C (215 degrees F and 250 degrees F), and (2) after depressurization, safety/relief valves can be throttled to maintain pressure rather than cycling fully open and closed.

Table A-2 Known Errors in Input Models Used for Documented Calculations

Input Model Revision #	Issue	Notes
Rev. 7/7a	Automatic depressurization system (ADS) can only initiate if level first falls below L2.	ADS has a logic control that waits for level to fall below L 2 before it can be actuated. CF304 can be manipulated in .cor to force ADS without the need for level to reach L2.
	Core spray control functions CF3131 and CF3132 do not call CF3130 as intended.	Core spray velocity CF3130 is not referenced in CF3131 and CF3132. This is corrected through the .cor file for the sensitivities that use core spray.
	Trip on low wetwell water level not plant-actual.	The trip does not actually exist and is more a surrogate for loss of net positive suction head. This trip is removed as needed through the .cor file for each relevant scenario (those with suction on the wetwell).
	While the total volume is consistent with the licensee’s Modular Accident Analysis Program model, the altitude/volume information for the reactor building corner rooms is off.	The result is that the rooms are narrower than is plant-actual and the water height rises rather quickly. This has no impact on scenario conclusions since the corner rooms are not modeled to contain any vital equipment.

APPENDIX B
CONTAINMENT VENTING

CONTAINMENT VENTING



[1]

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[1] ELAP: extended loss of alternating current power; LUHS: loss of ultimate heat sink; PB: pressure band; RPS: reactor protection system; SEP: site emergency plan; SBGT: standby gas treatment

APPENDIX C
DETAILED CHAPTER 3 ANALYSIS RESULTS

DETAILED CHAPTER 3 ANALYSIS RESULTS

C.1 TRANS Scenarios

C.1.1 Case 1: TRANS-30, Nominal CRDHS, MSIV Closure at 6 min., ADS at +15 in., One SRV

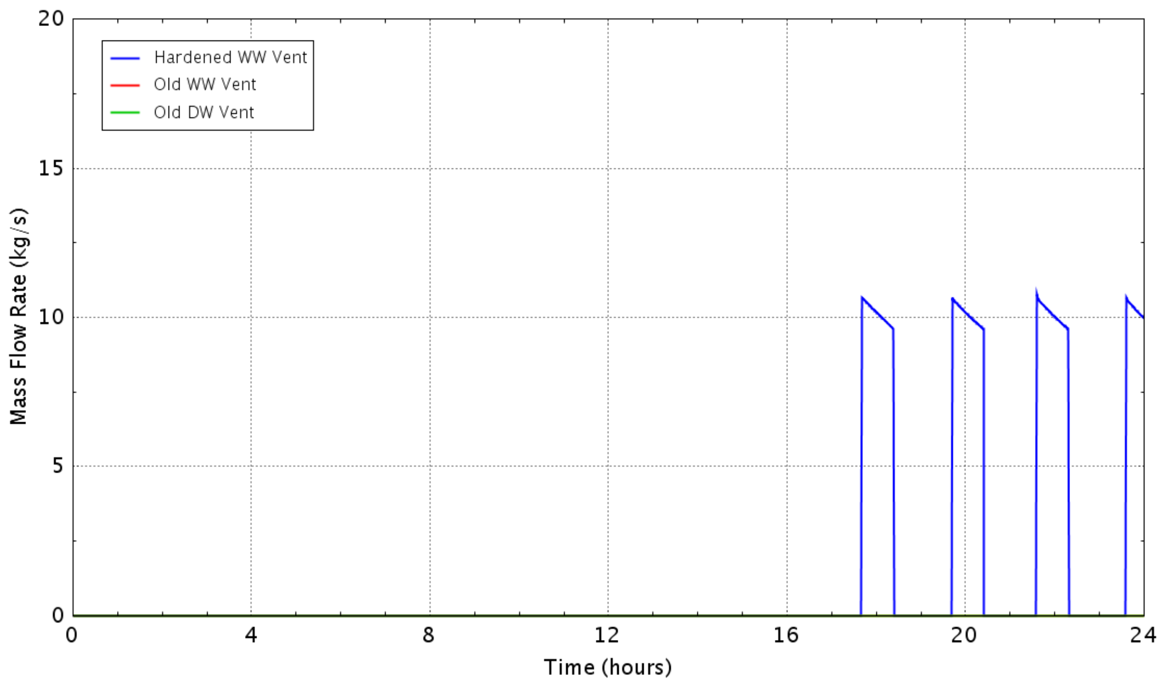

Figure C - 1 Flow rate of the containment vents

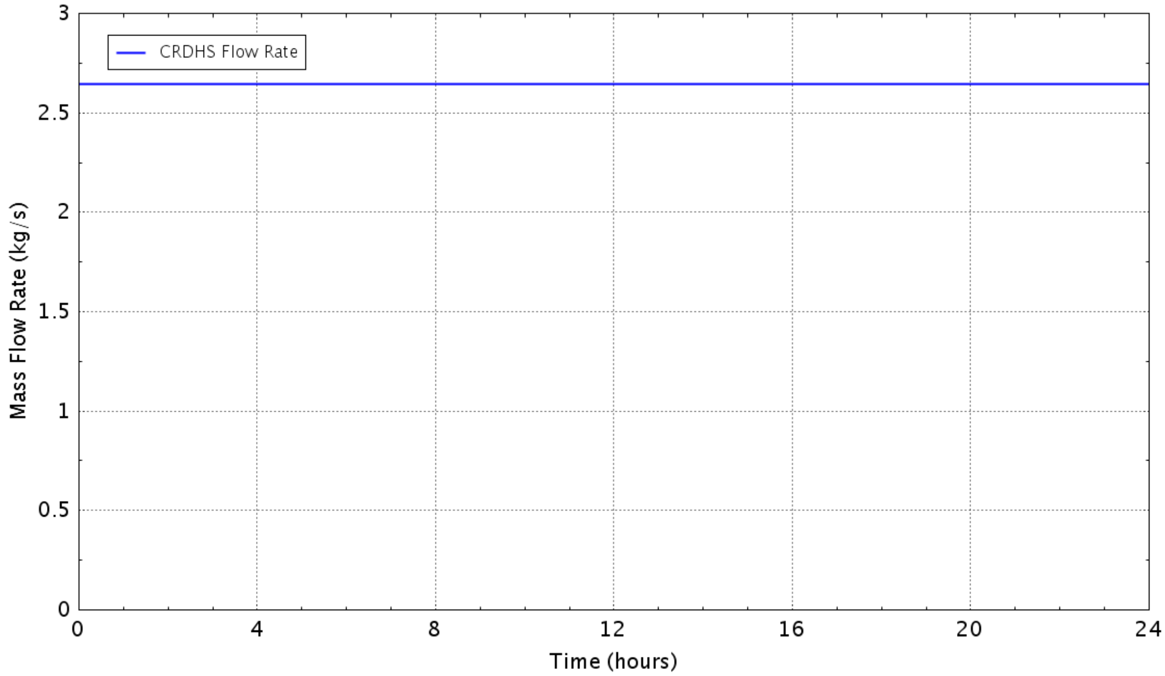

Figure C - 2 Flow rate of the control rod drive hydraulic system

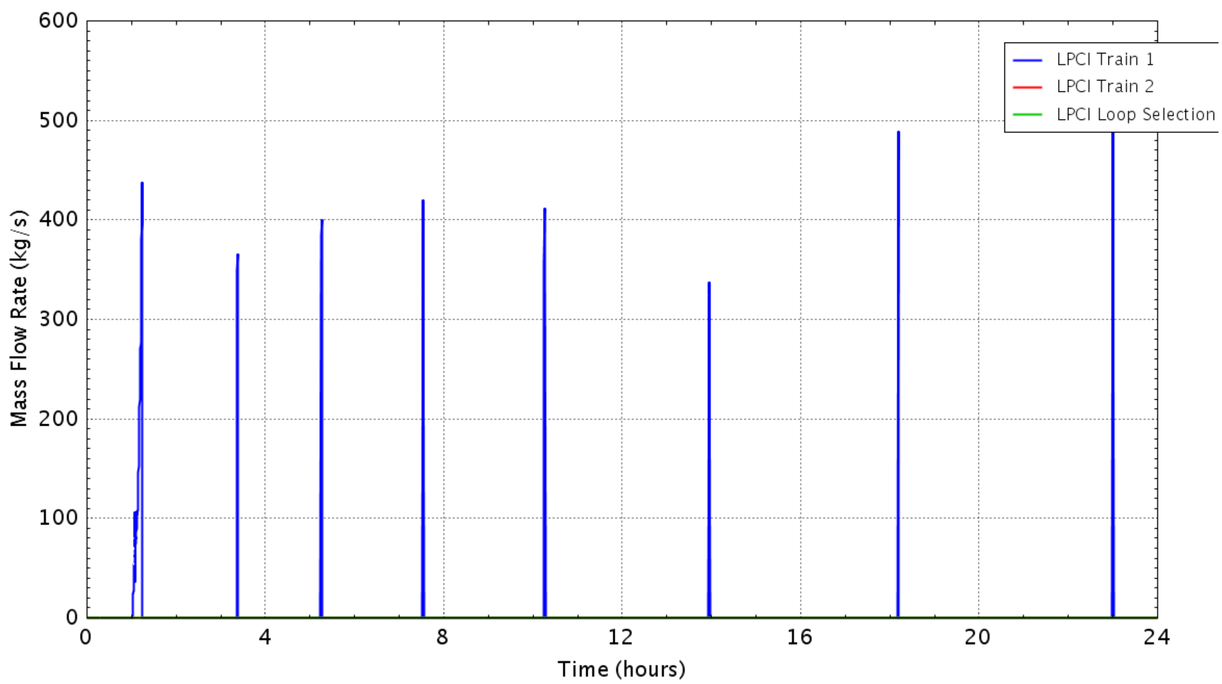

Figure C - 3 Flow rate of the LPCI pump

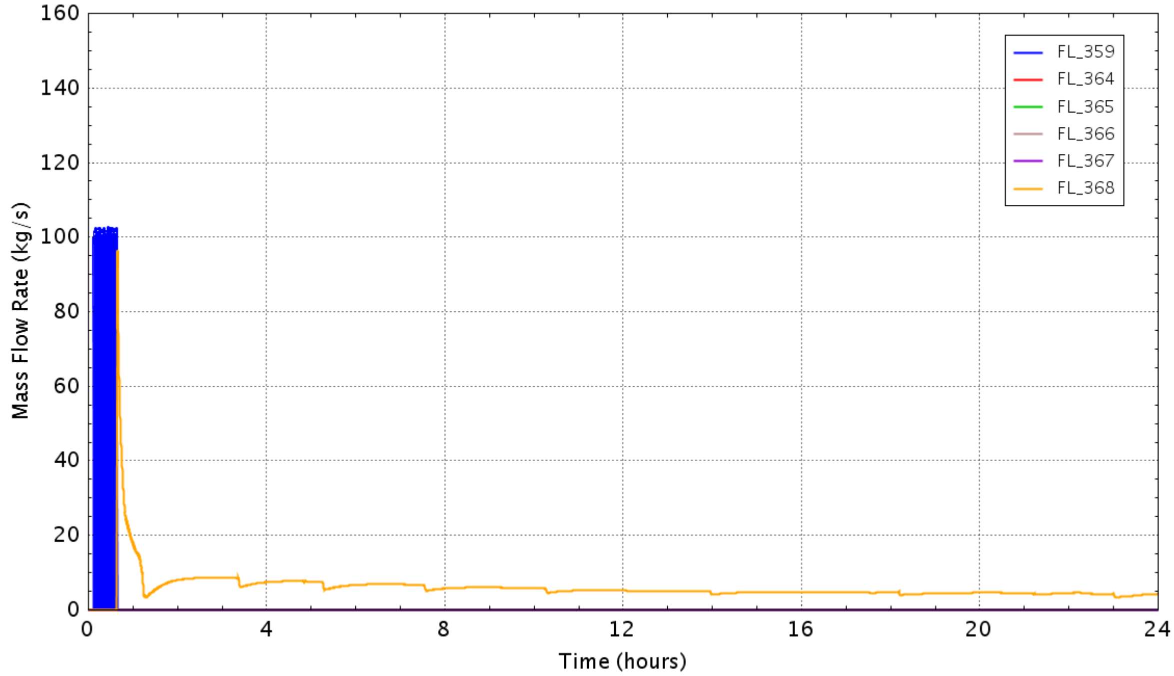

Figure C - 4 Flow rate of the SRVs

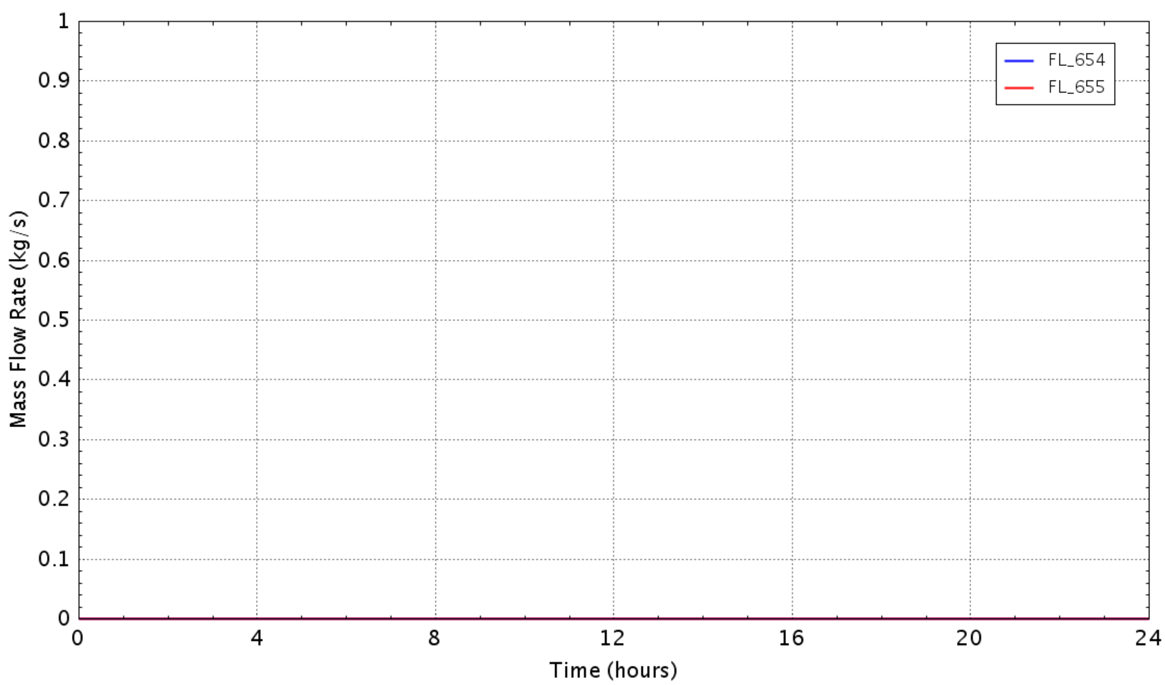

Figure C - 5 Flow rate of the wetwell cooling system

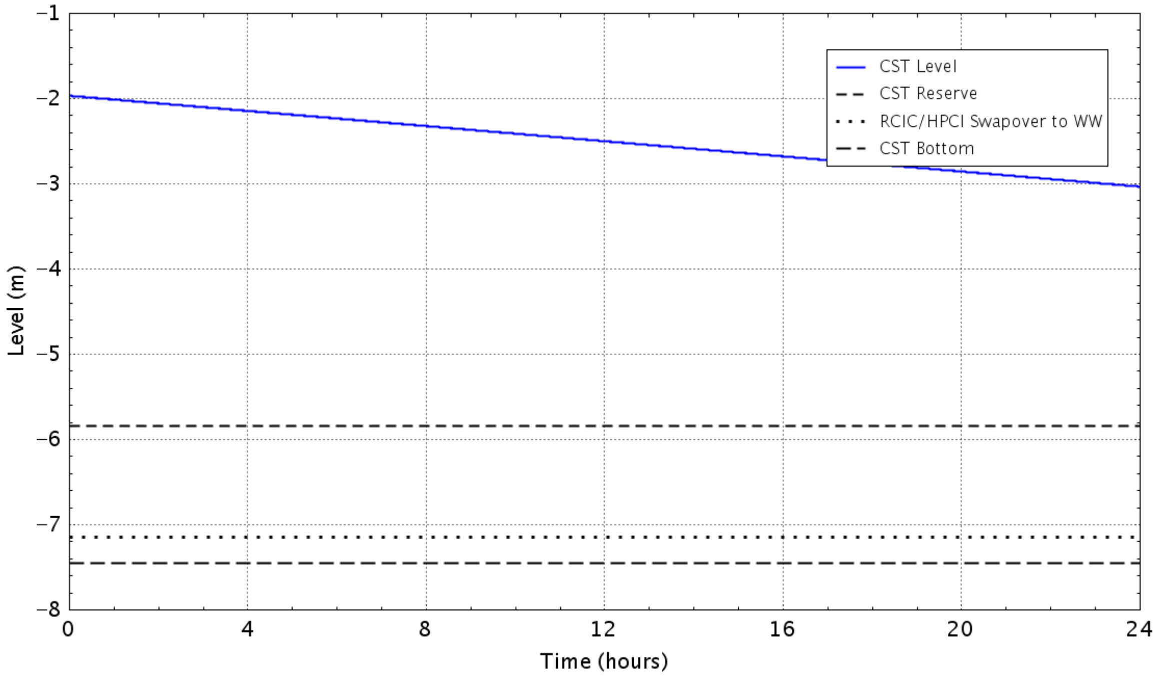

Figure C - 6 Water level in the CST

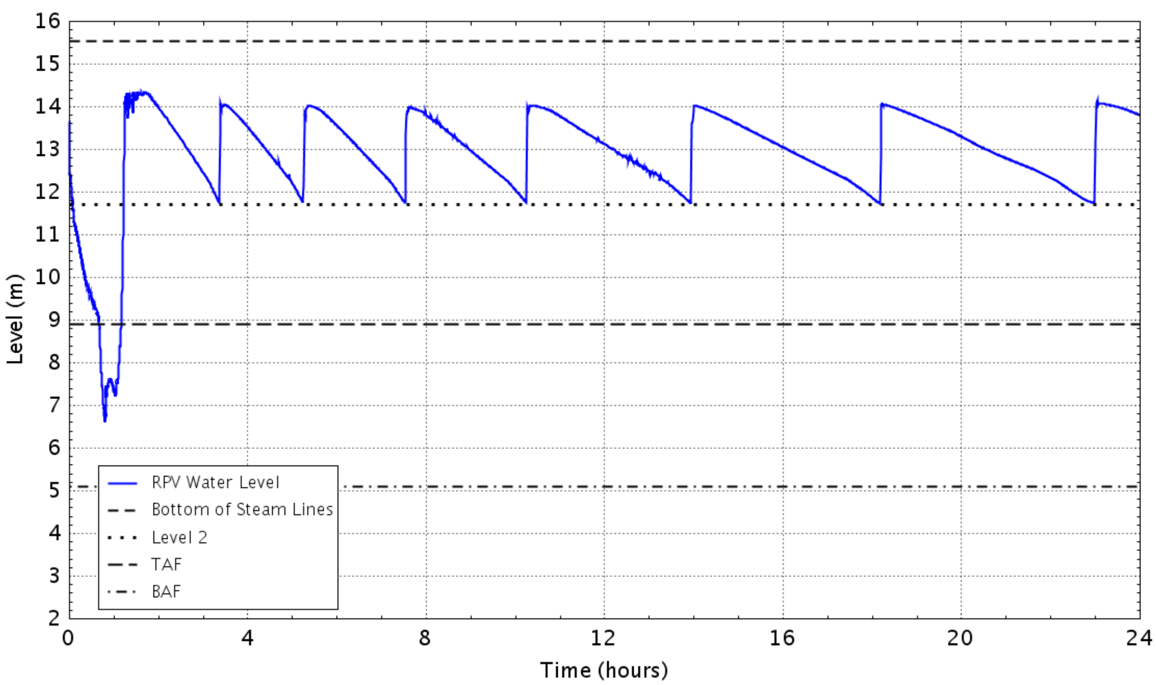

Figure C - 7   RPV Downcomer water level

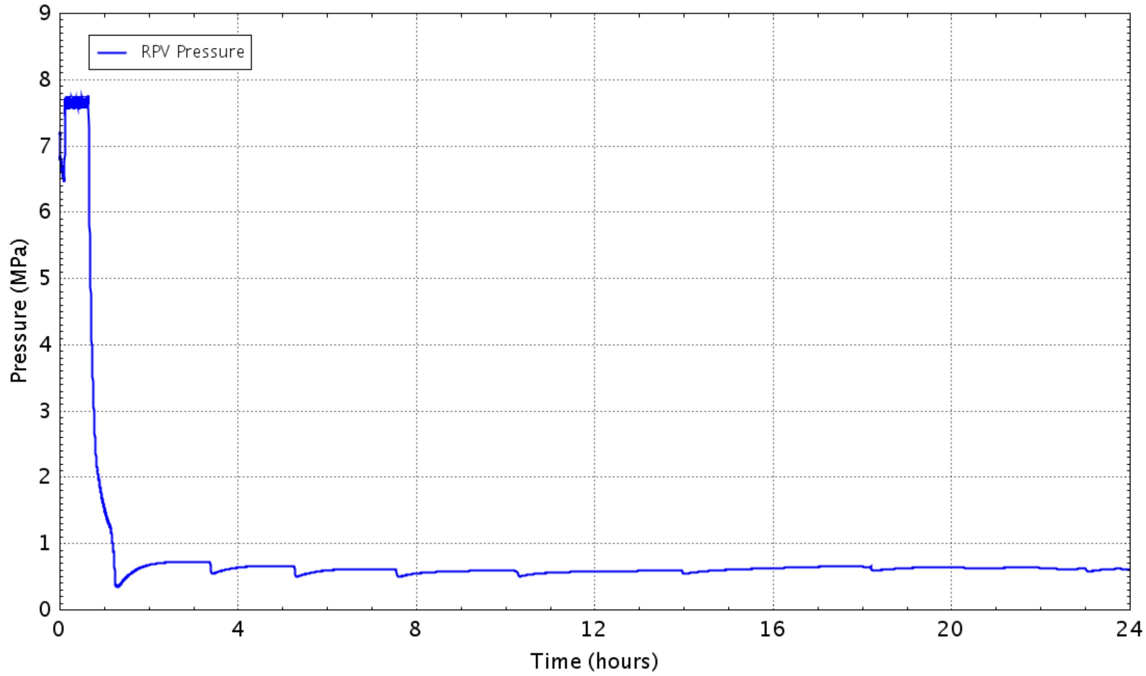

Figure C - 8 Pressure in the RPV

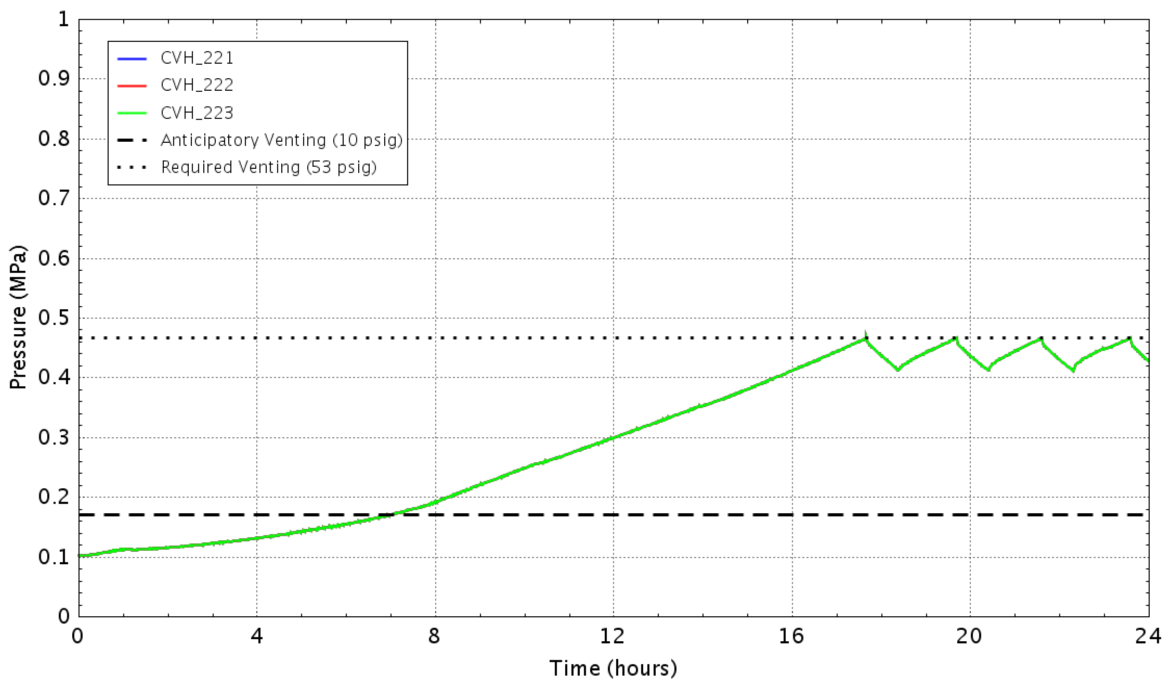

Figure C - 9 Pressure in the wetwell

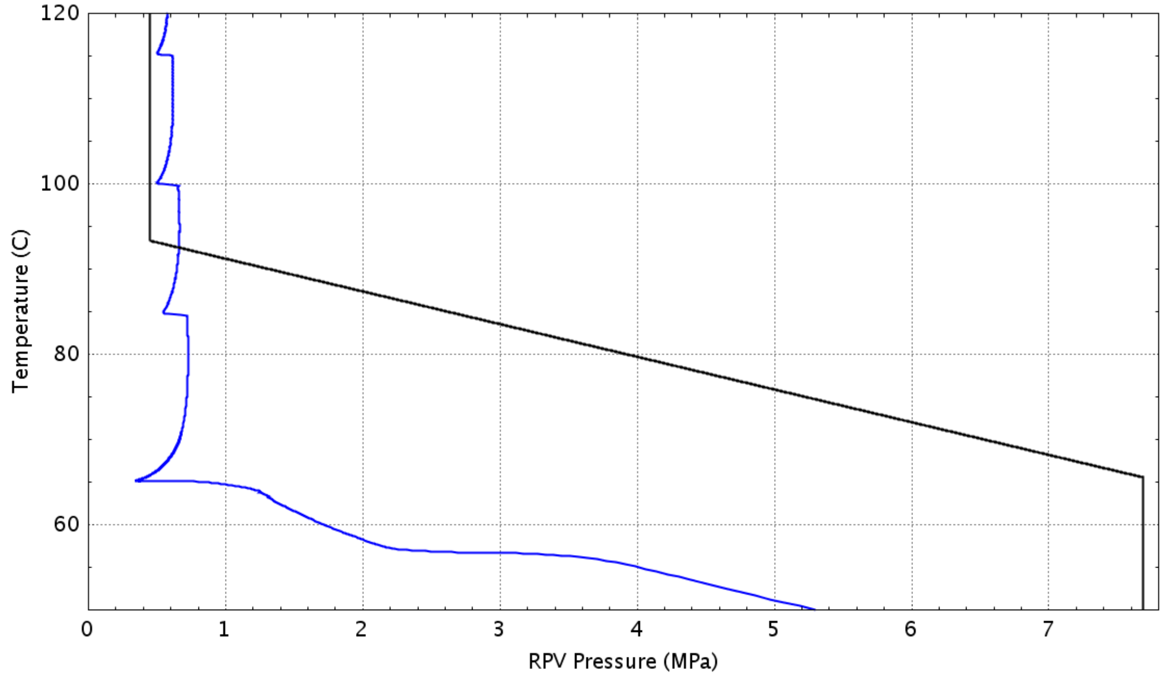

Figure C - 10 Plant status relative to the HCL curve (Graph 4 of the EOPs)

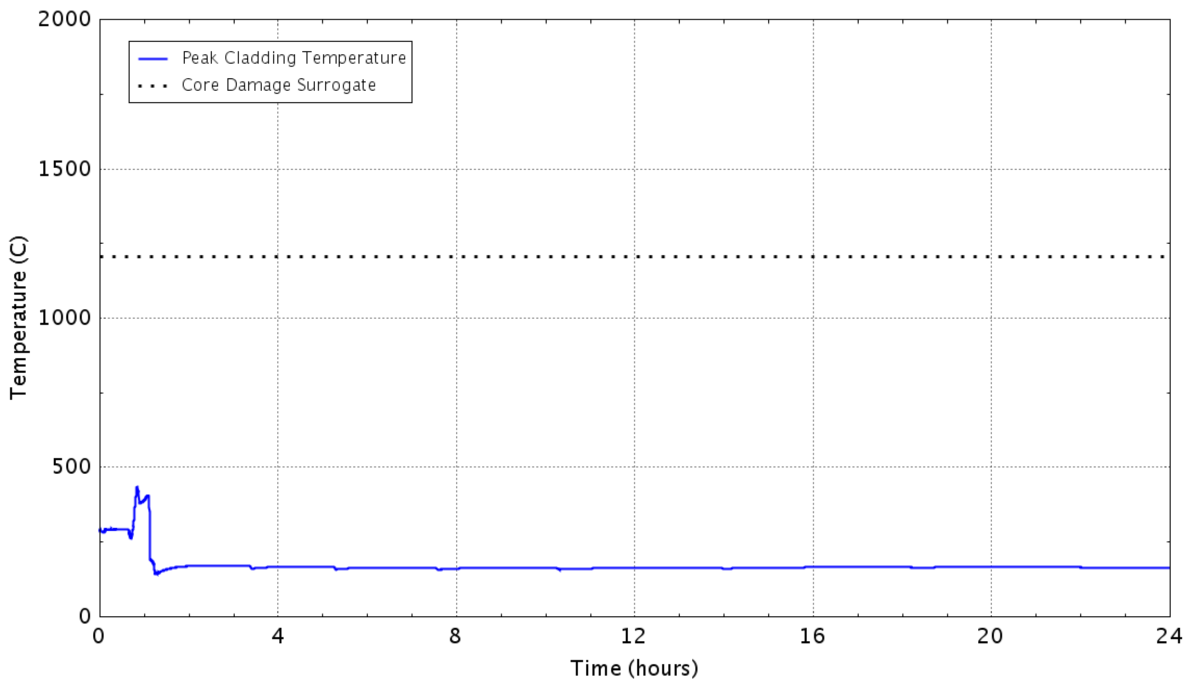

Figure C - 11 Peak temperature of the fuel cladding as a function of time

C.1.2 Case 2: TRANS-30, Nominal CRDHS, MSIV Closure at 6 min., ADS at +15 in., Two SRVs

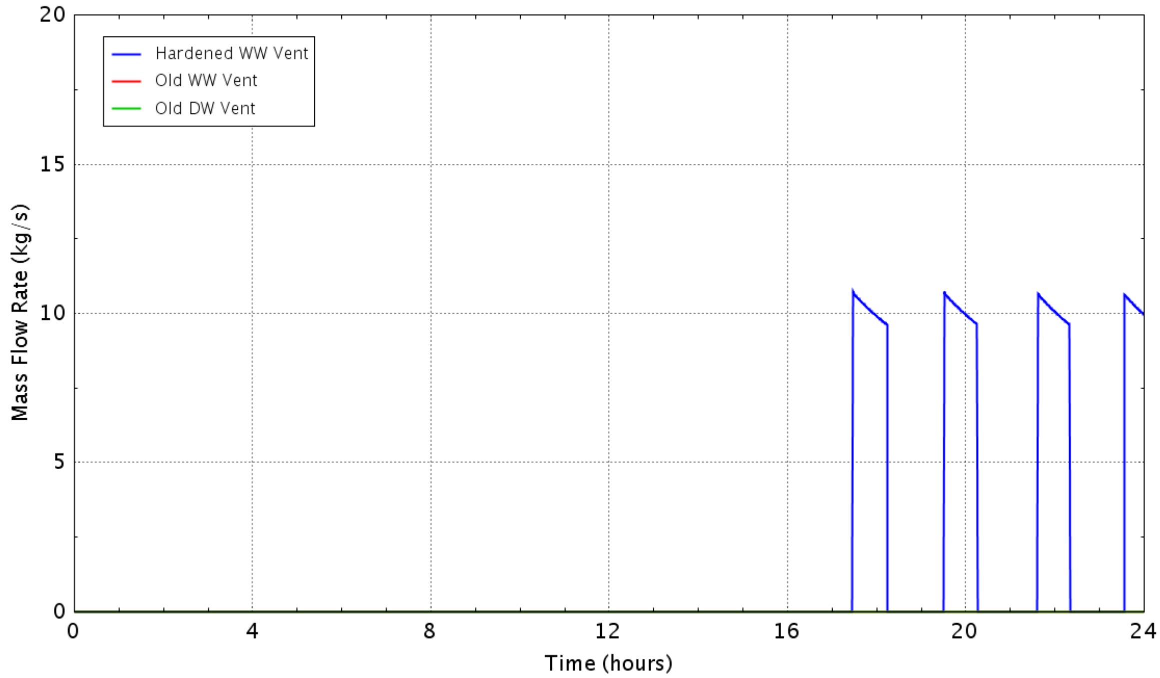

Figure C - 12 Flow rate of the containment vents

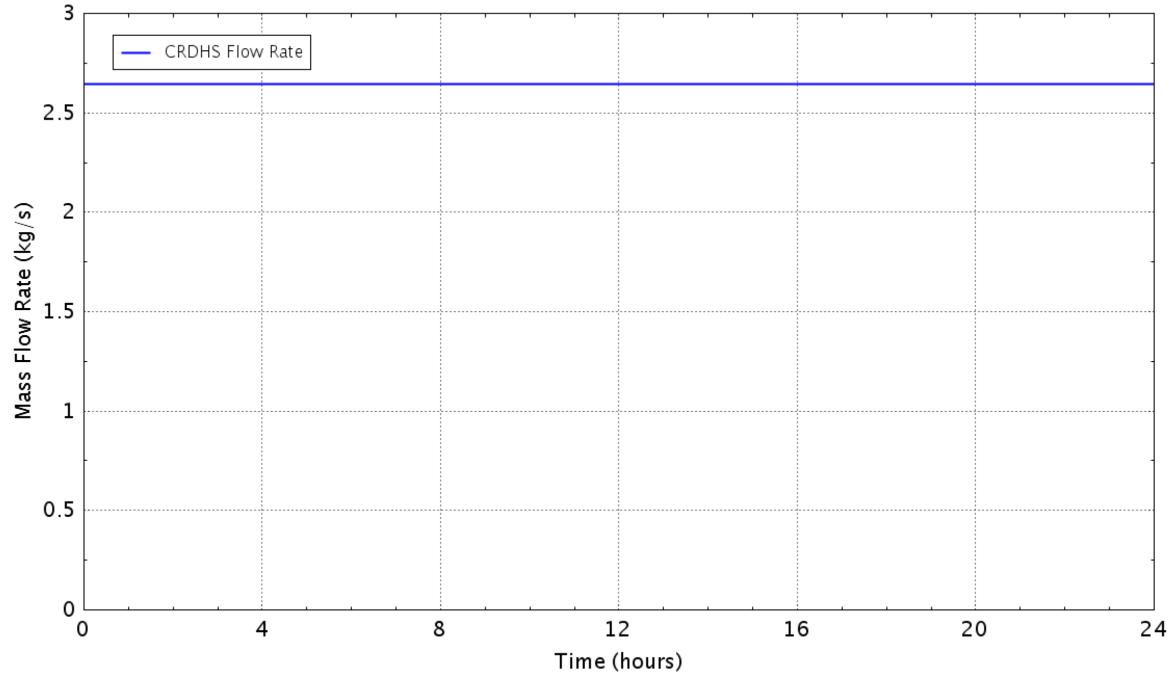

Figure C - 13 Flow rate of the control rod drive hydraulic system

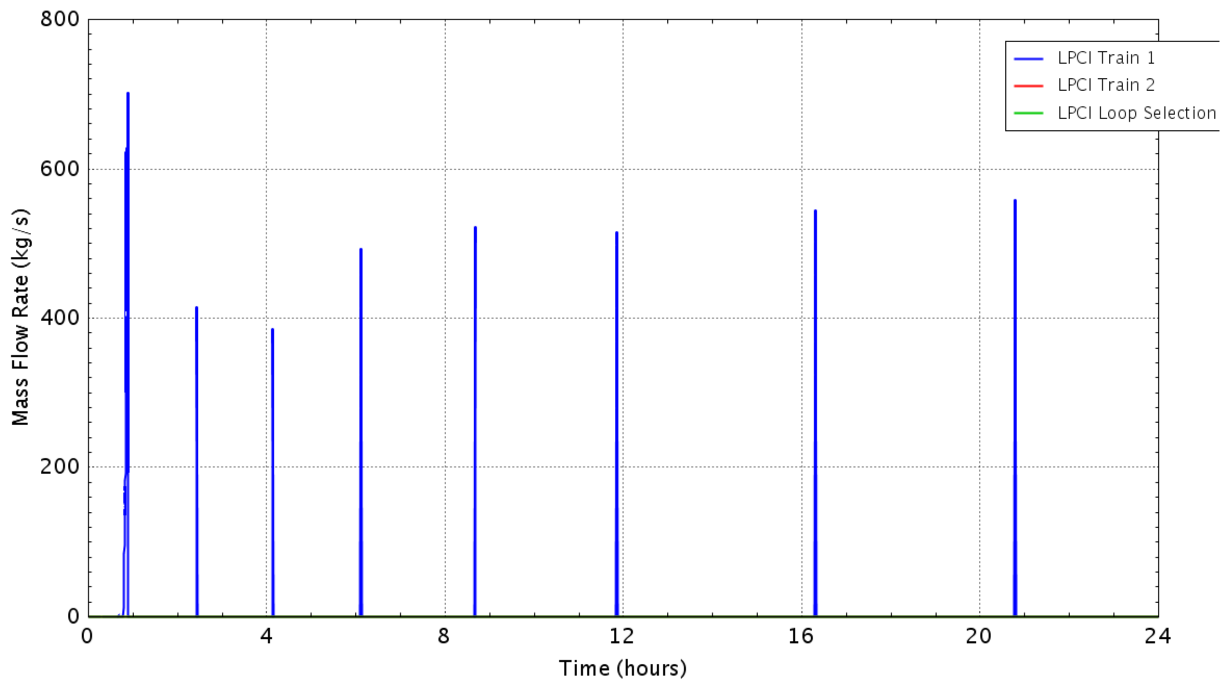

Figure C - 14 Flow rate of the LPCI pump

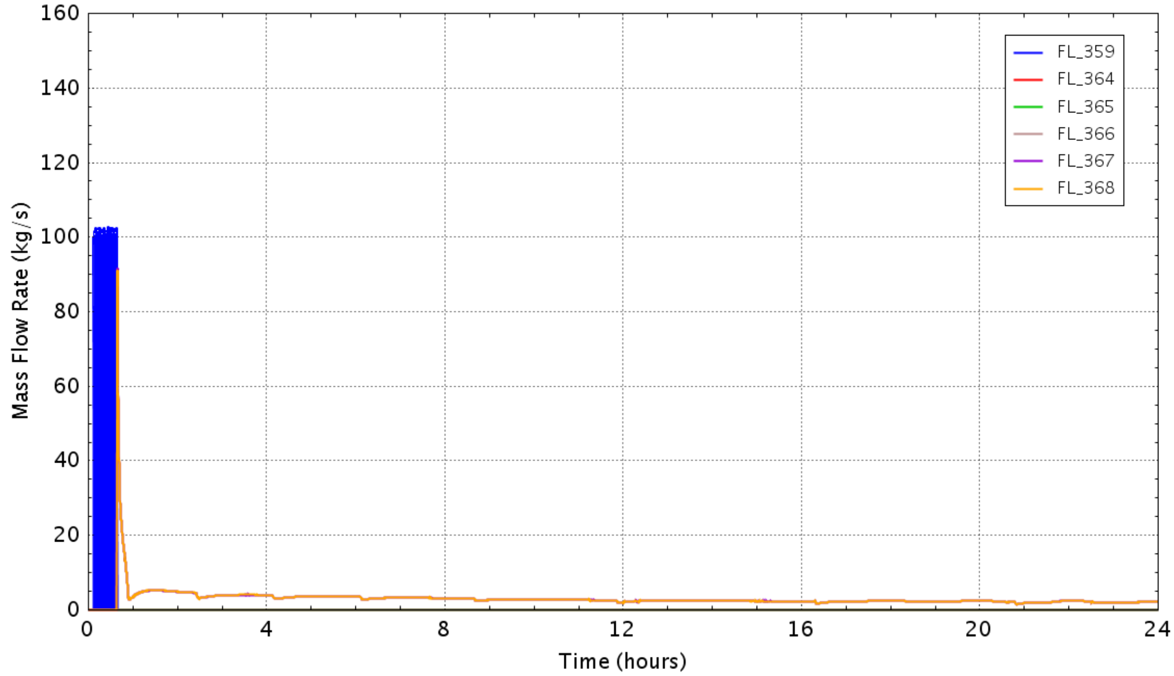

Figure C - 15 Flow rate of the SRVs

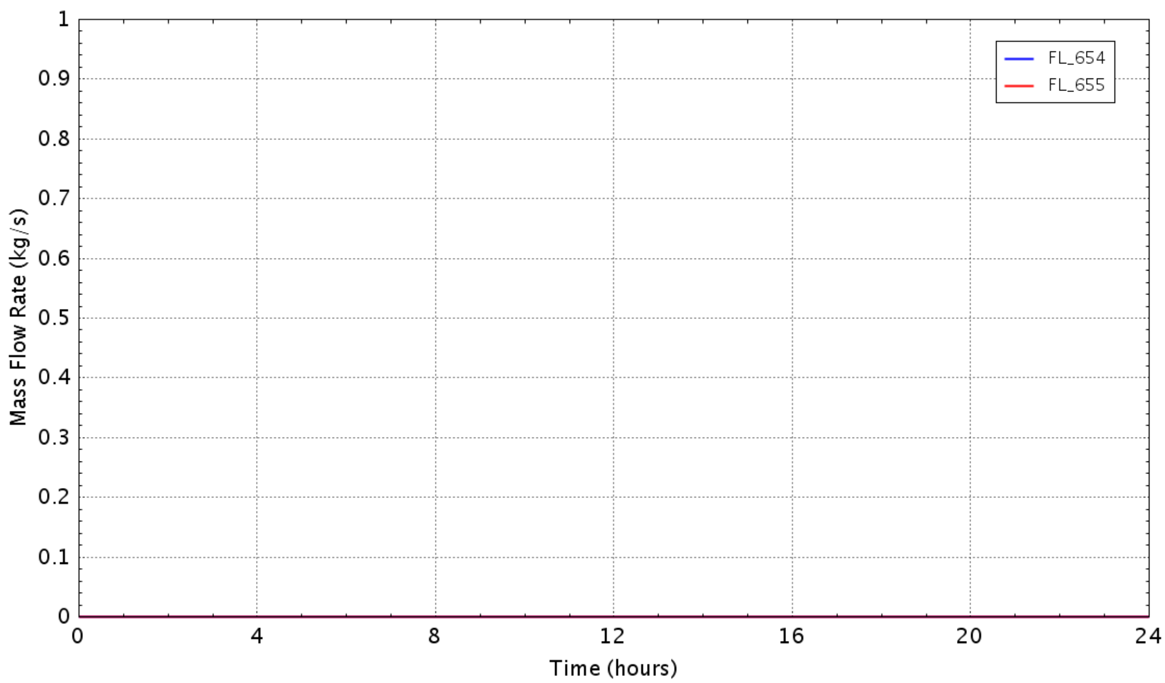

Figure C - 16 Flow rate of the wetwell cooling system

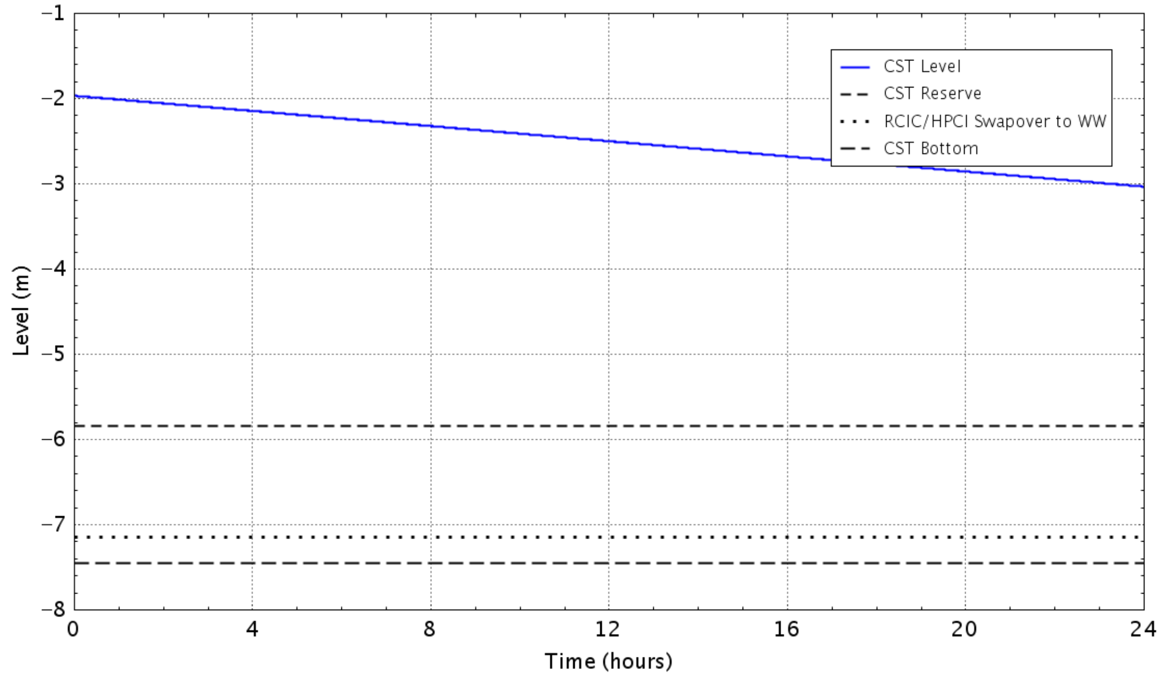

Figure C - 17 Water level in the CST

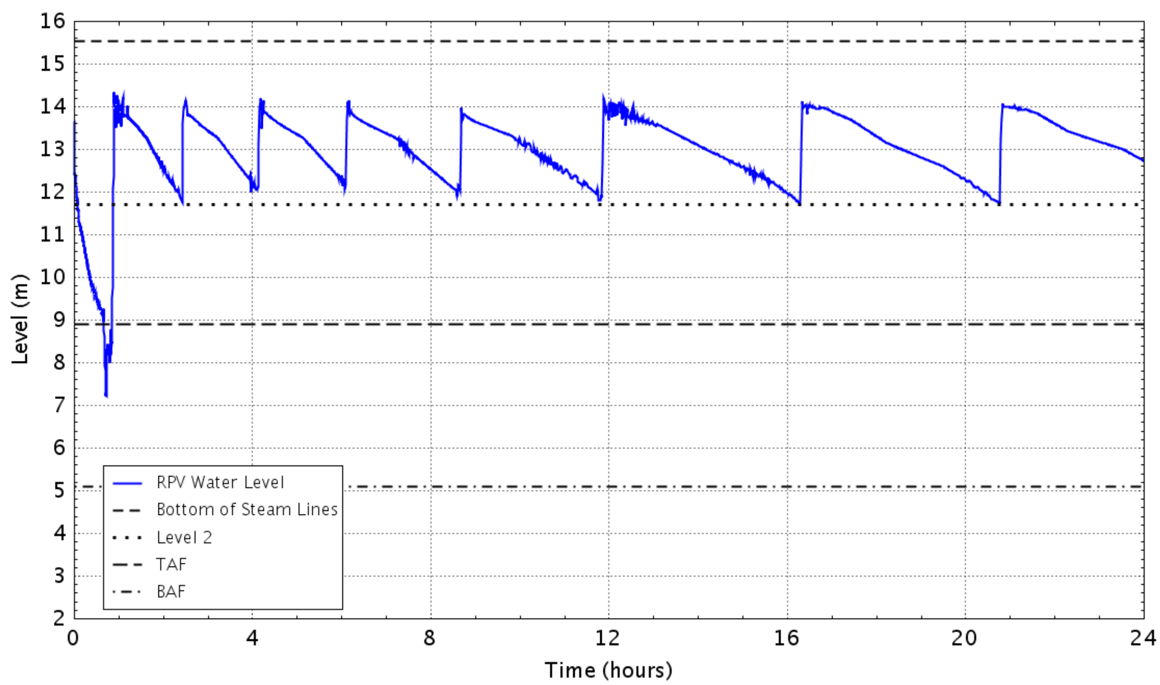

Figure C - 18 RPV Downcomer water level

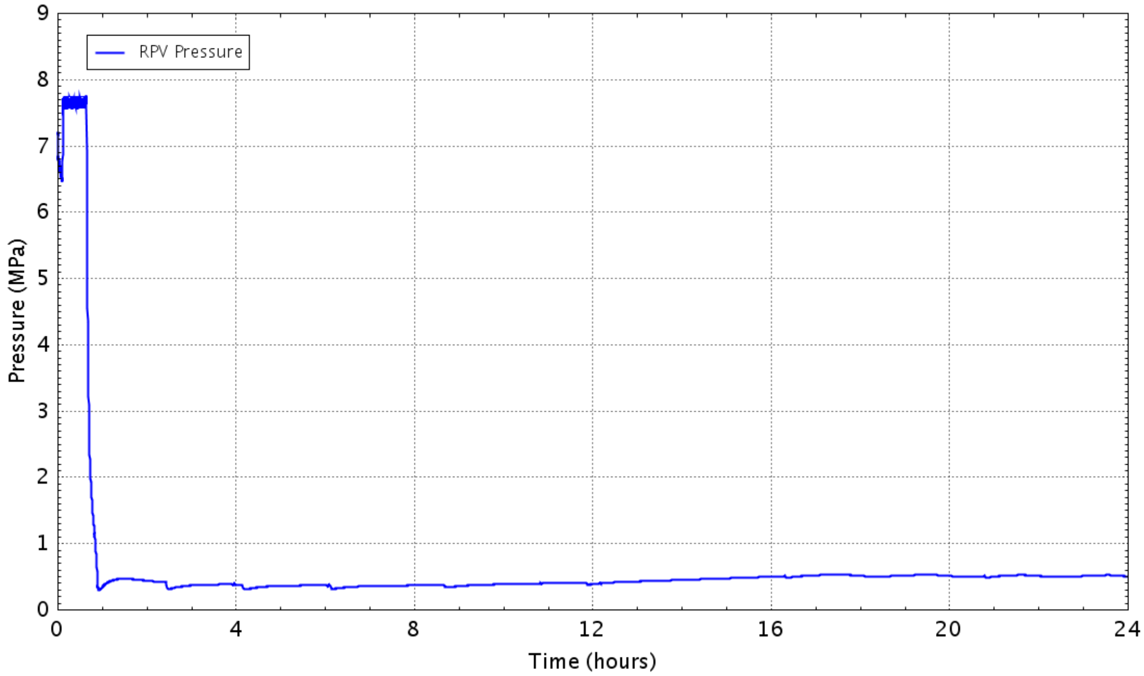

Figure C - 19 Pressure in the RPV

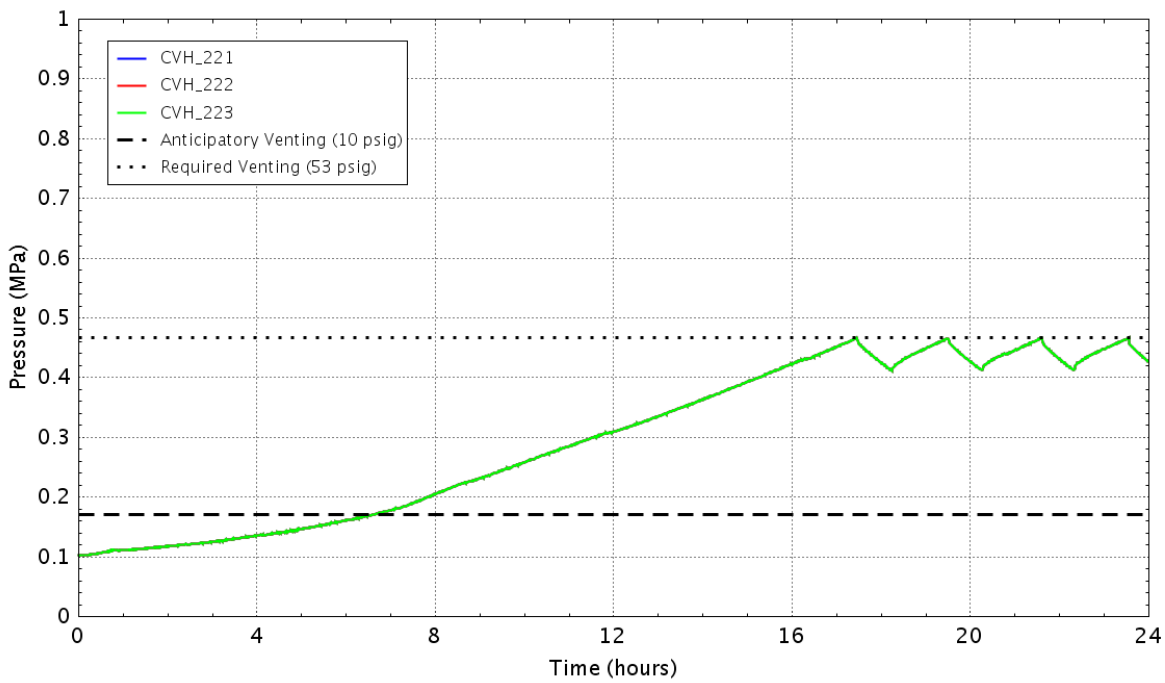

Figure C - 20 Pressure in the wetwell

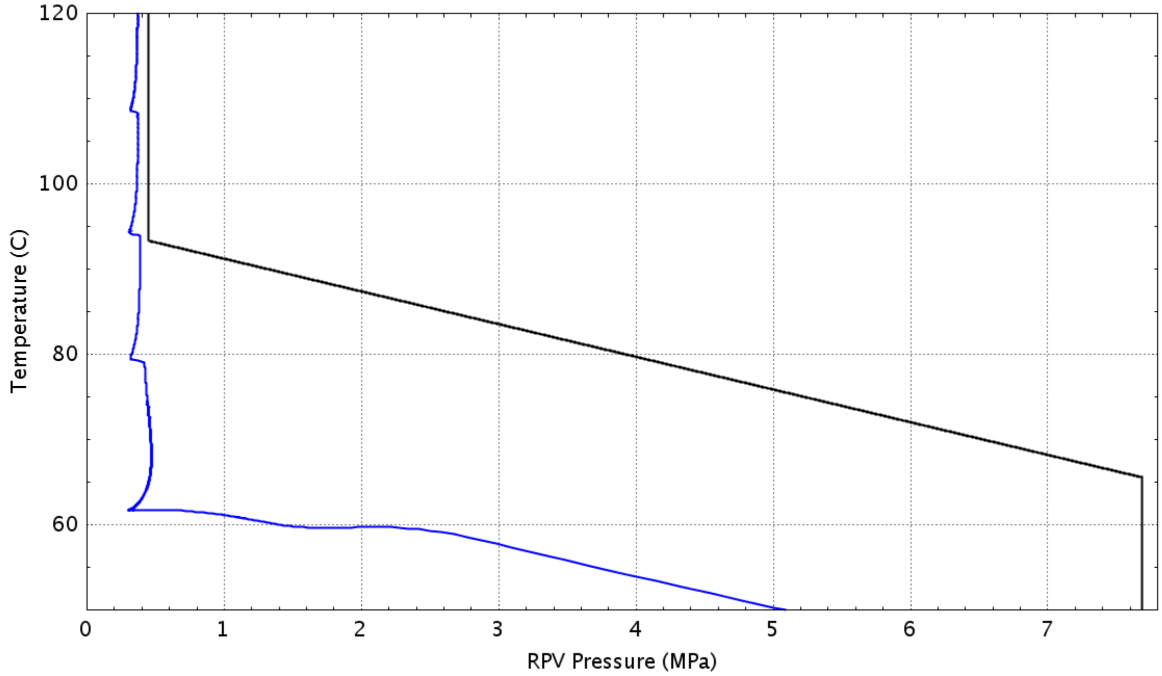

Figure C - 21 Plant status relative to the HCL curve (Graph 4 of the EOPs)

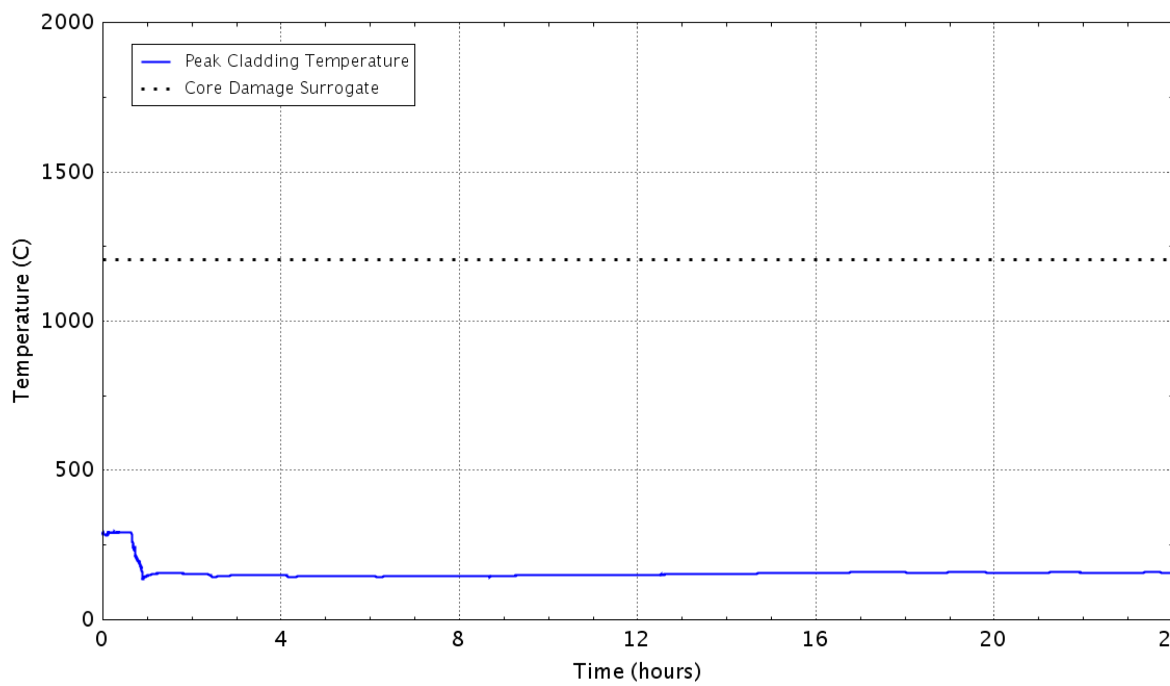

Figure C - 22 Peak temperature of the fuel cladding as a function of time

C.1.3 Case 3: TRANS-30, Nominal CRDHS, MSIV Closure at 6 min., ADS at -25 in., One SRV

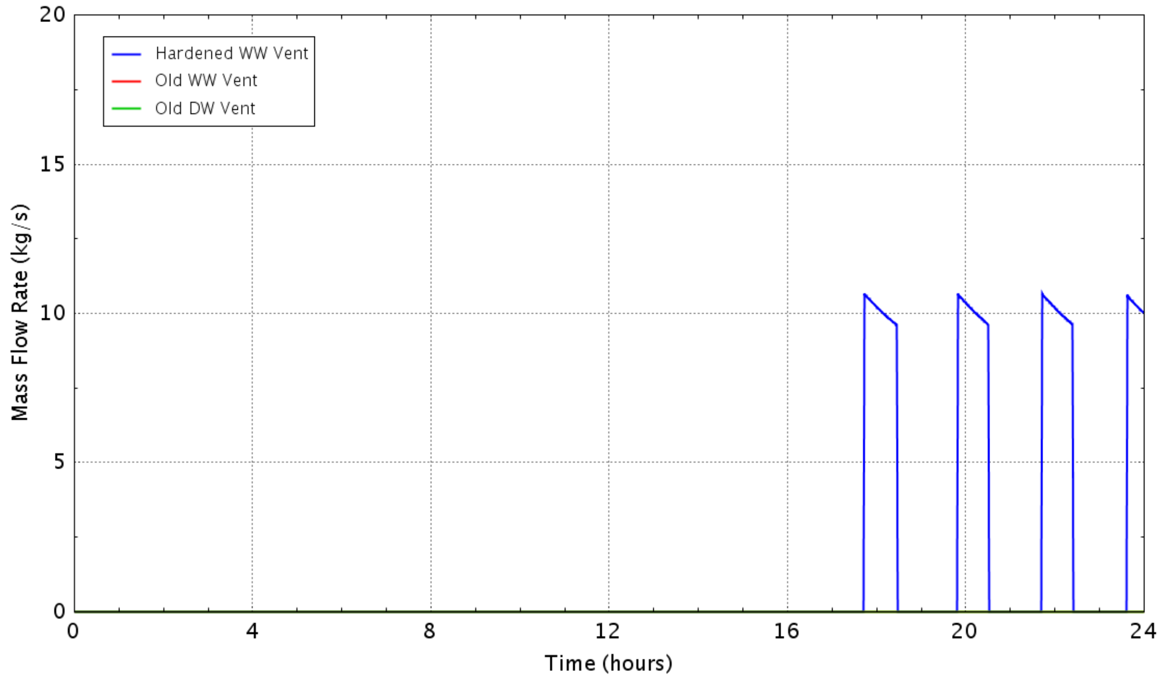

Figure C - 23 Flow rate of the containment vents

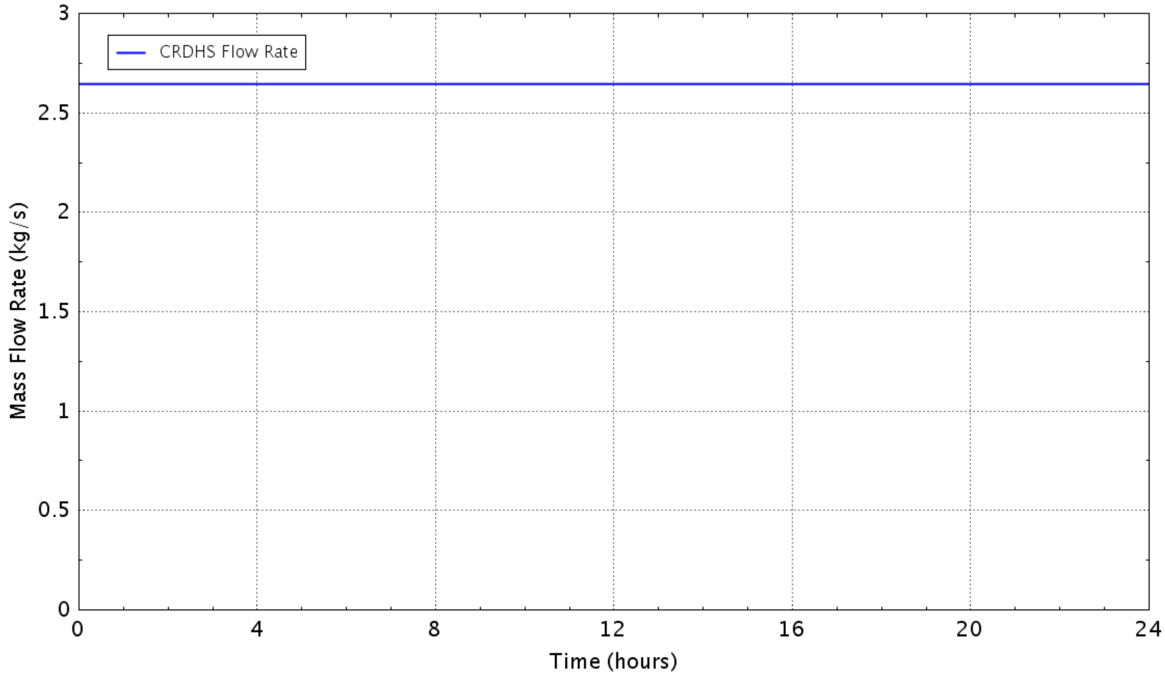

Figure C - 24 Flow rate of the control rod drive hydraulic system

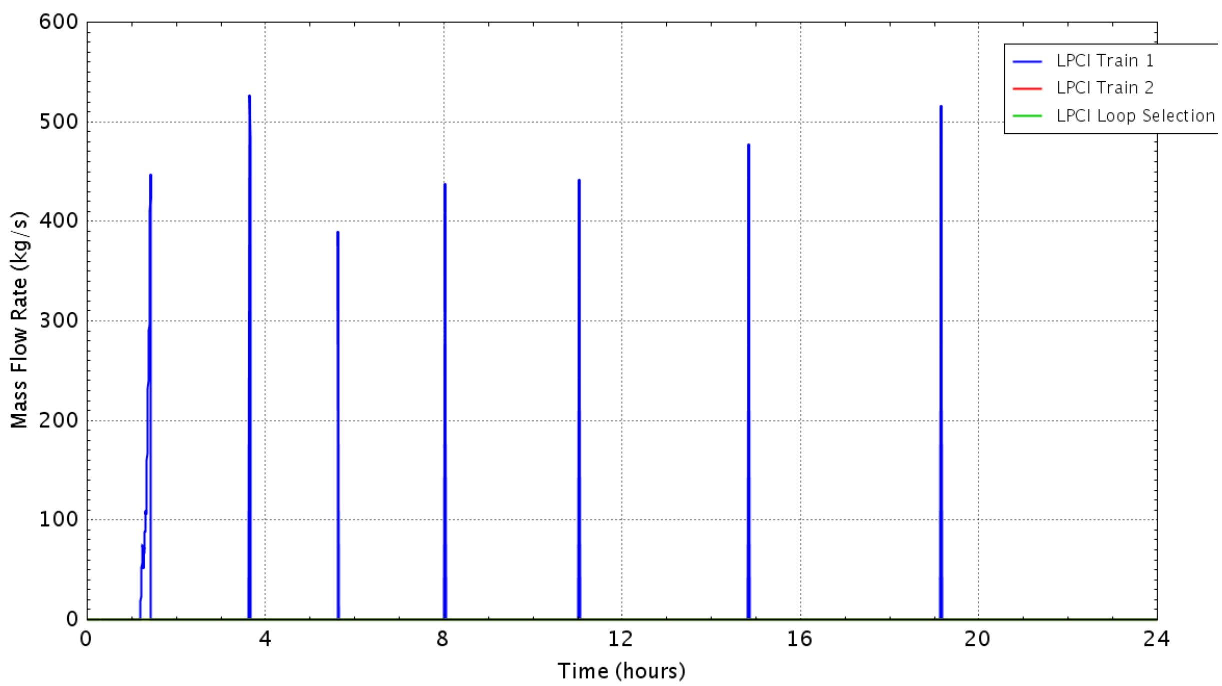

Figure C - 25 Flow rate of the LPCI pump

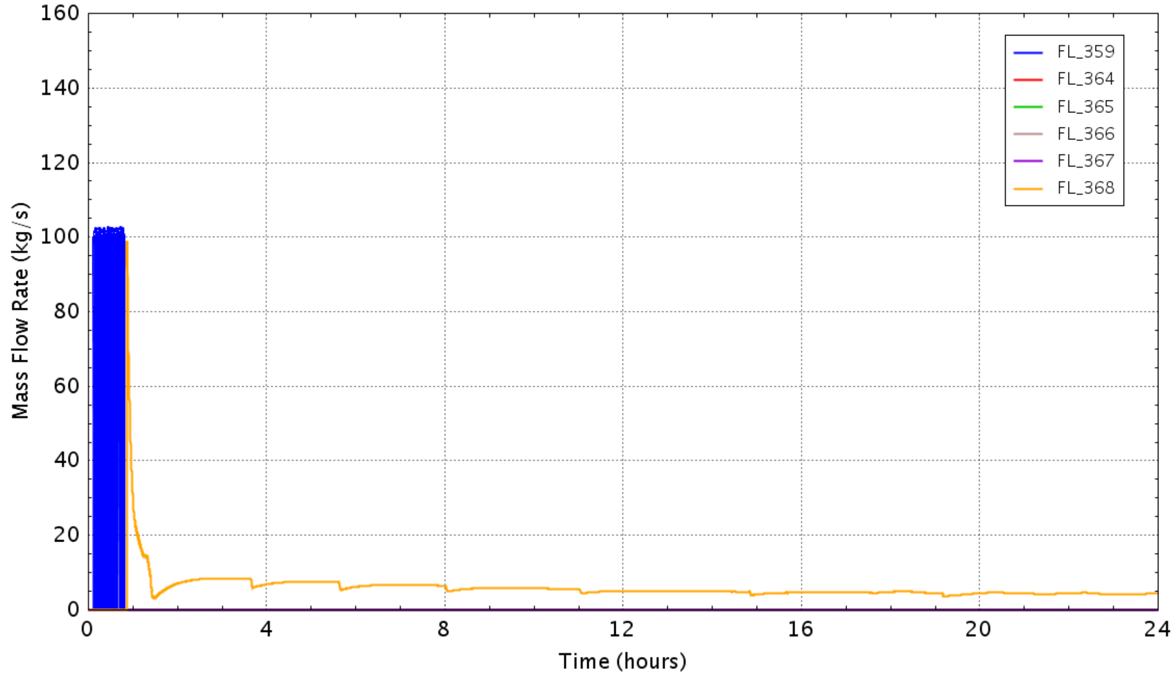

Figure C - 26 Flow rate of the SRVs

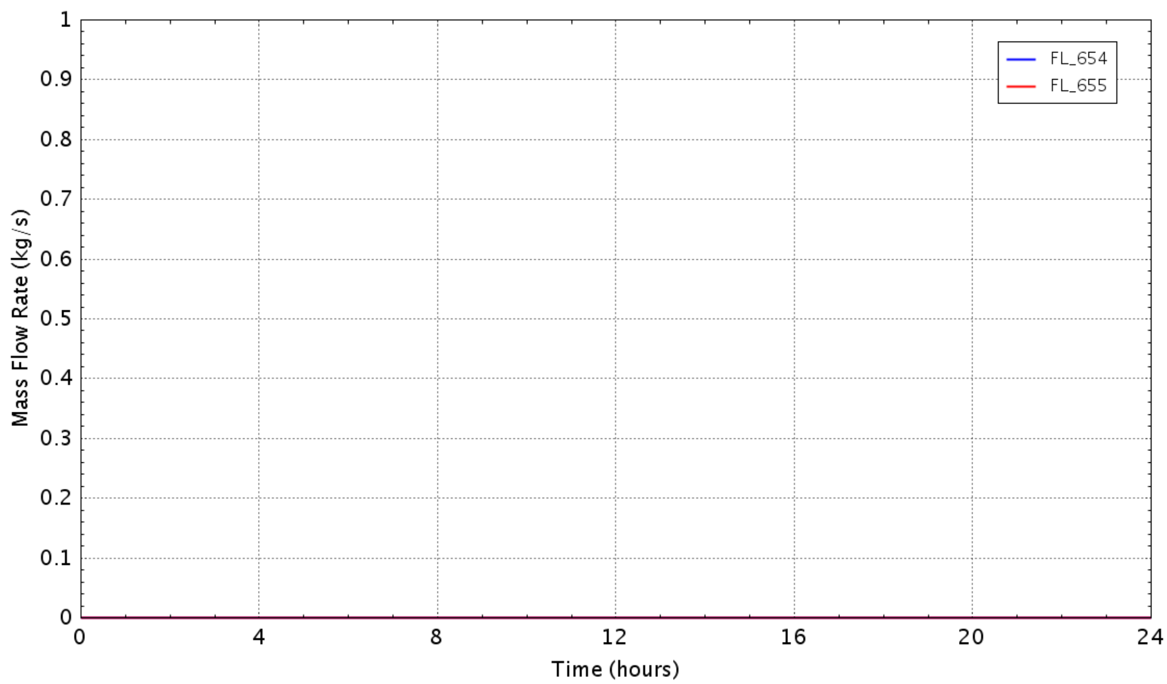

Figure C - 27 Flow rate of the wetwell cooling system

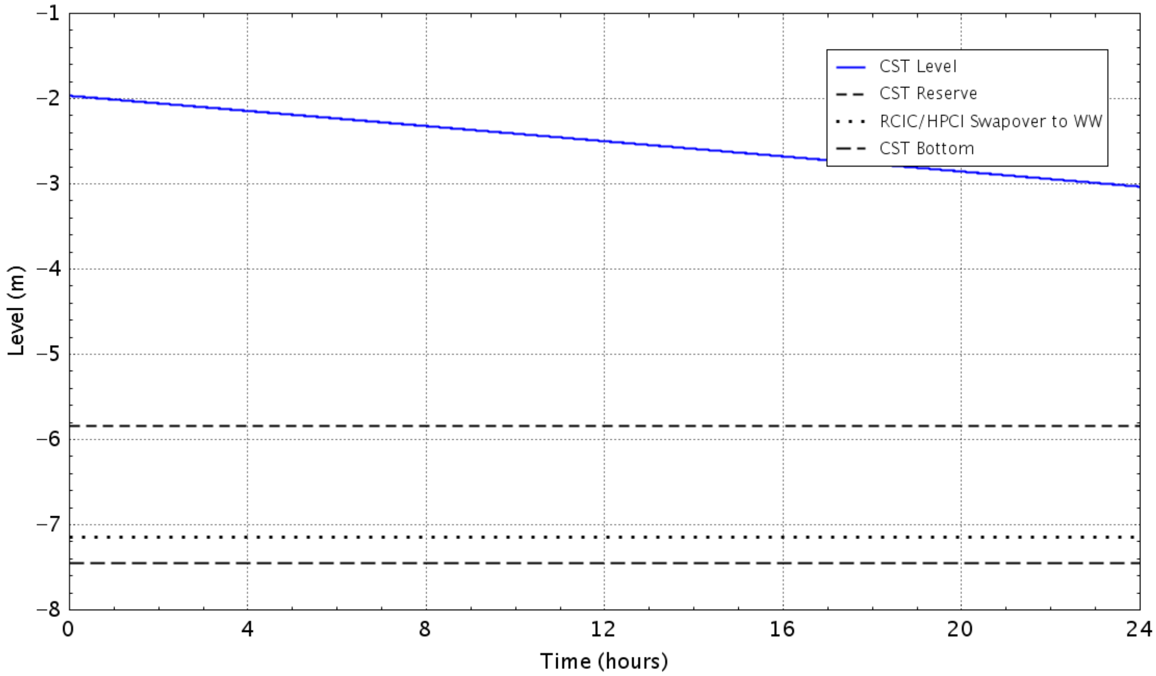

Figure C - 28 Water level in the CST

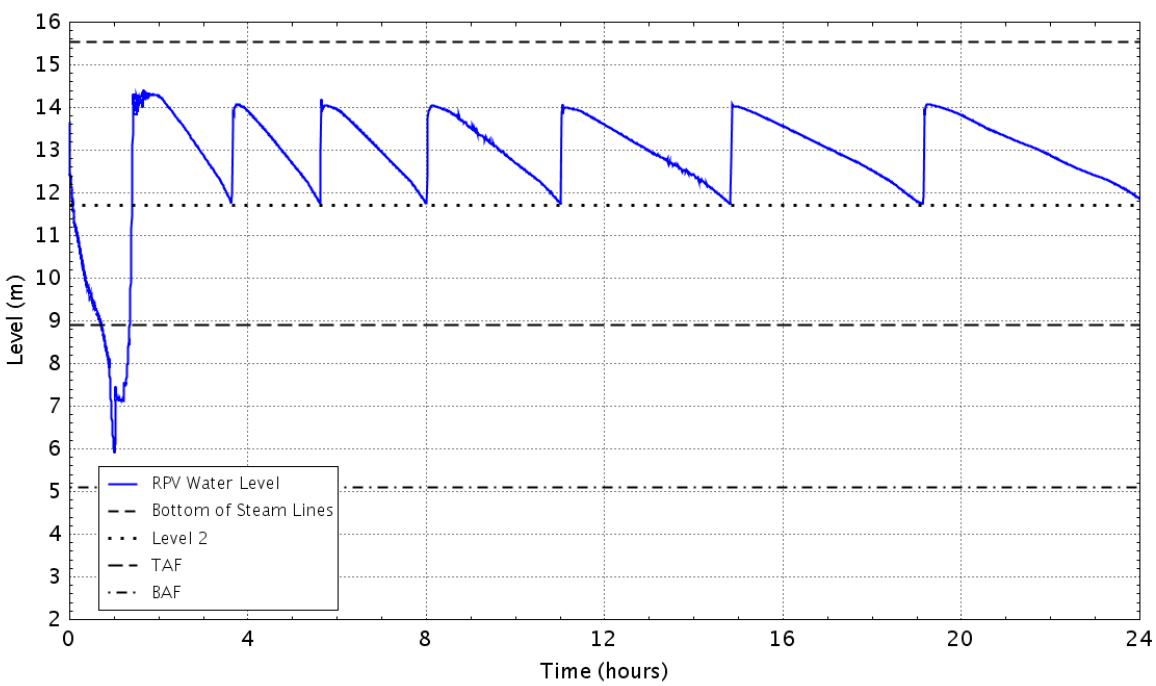

Figure C - 29   RPV Downcomer water level

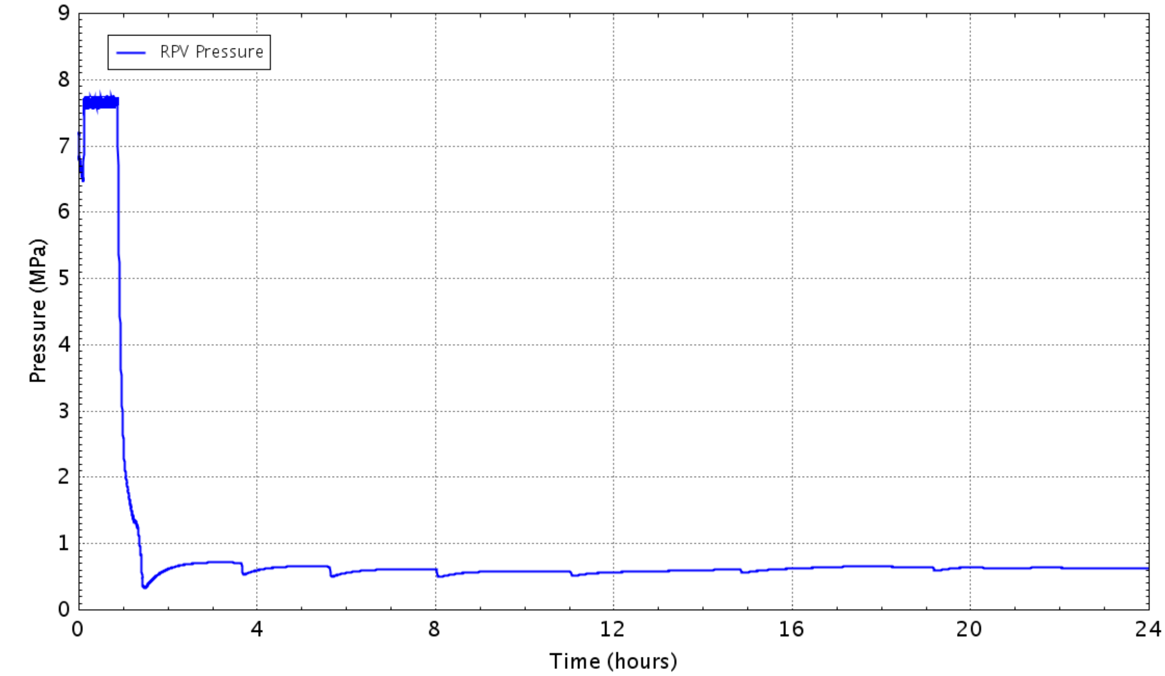

Figure C - 30 Pressure in the RPV

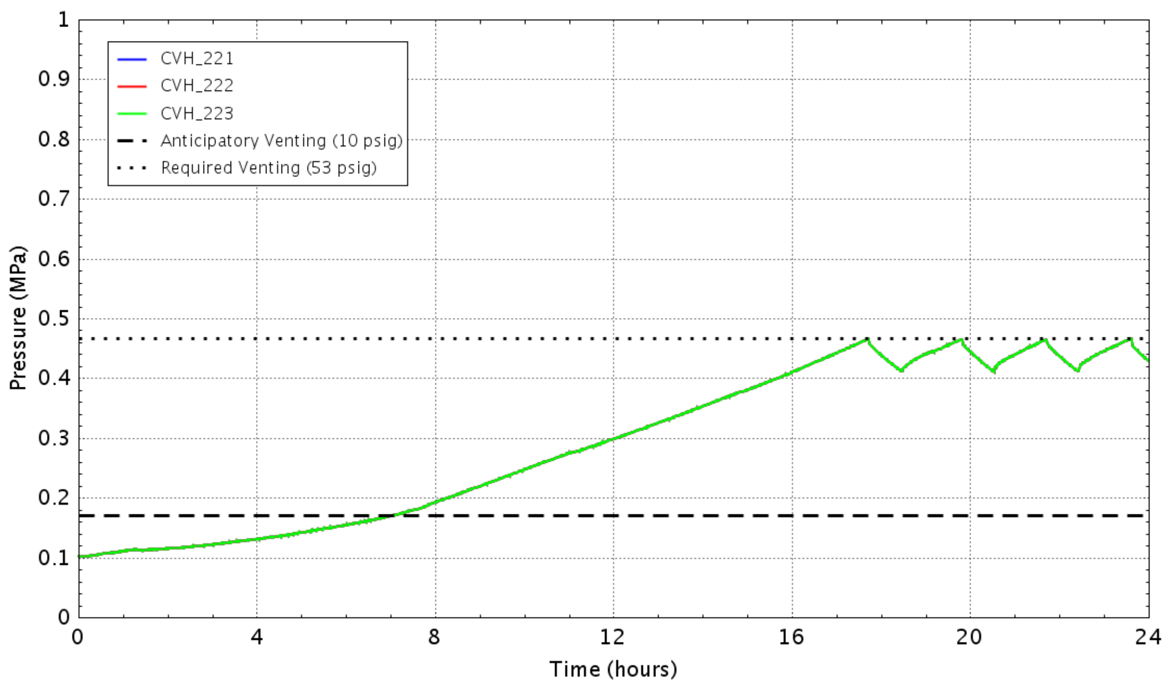

Figure C - 31 Pressure in the wetwell

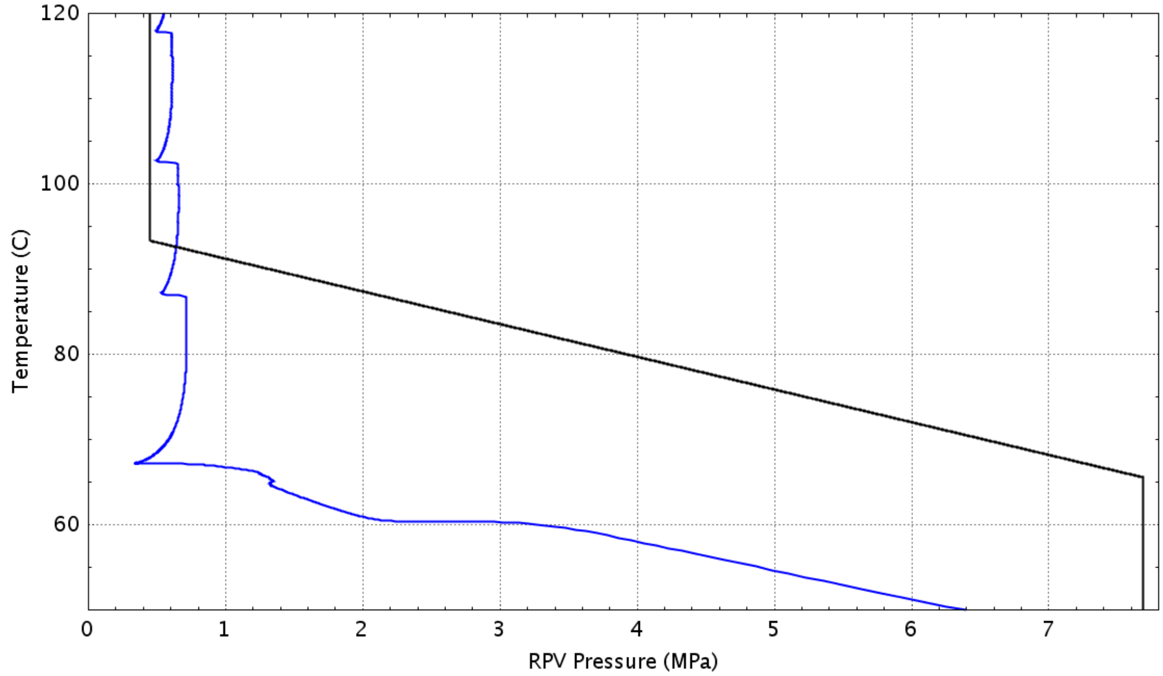

Figure C - 32 Plant status relative to the HCL curve (Graph 4 of the EOPs)

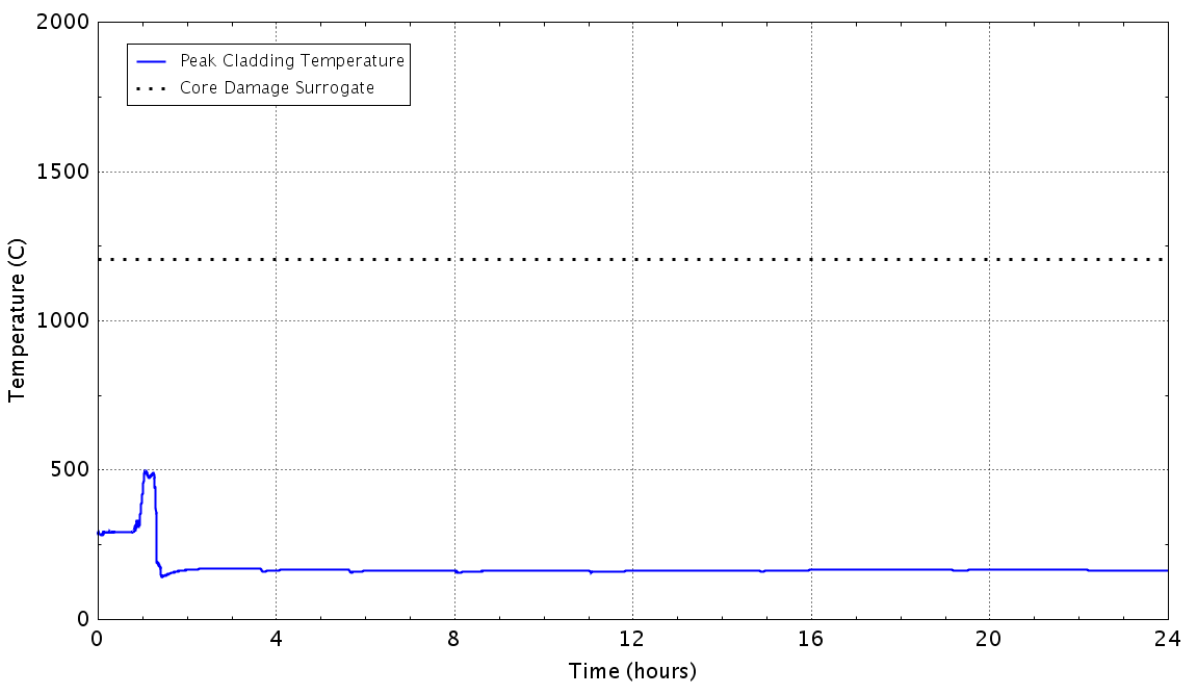

Figure C - 33 Peak temperature of the fuel cladding as a function of time

C.1.4 Case 4: TRANS-30, Nominal CRDHS, MSIV Closure at 6 min., ADS at -25 in., Two SRVs

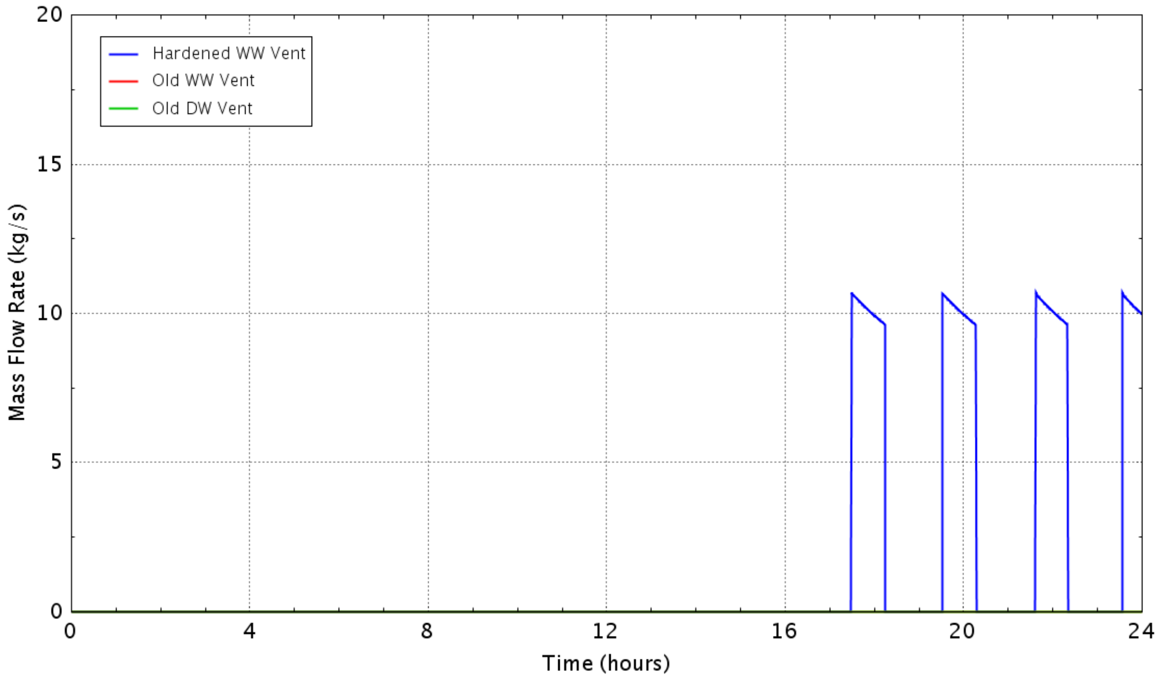

Figure C - 34 Flow rate of the containment vents

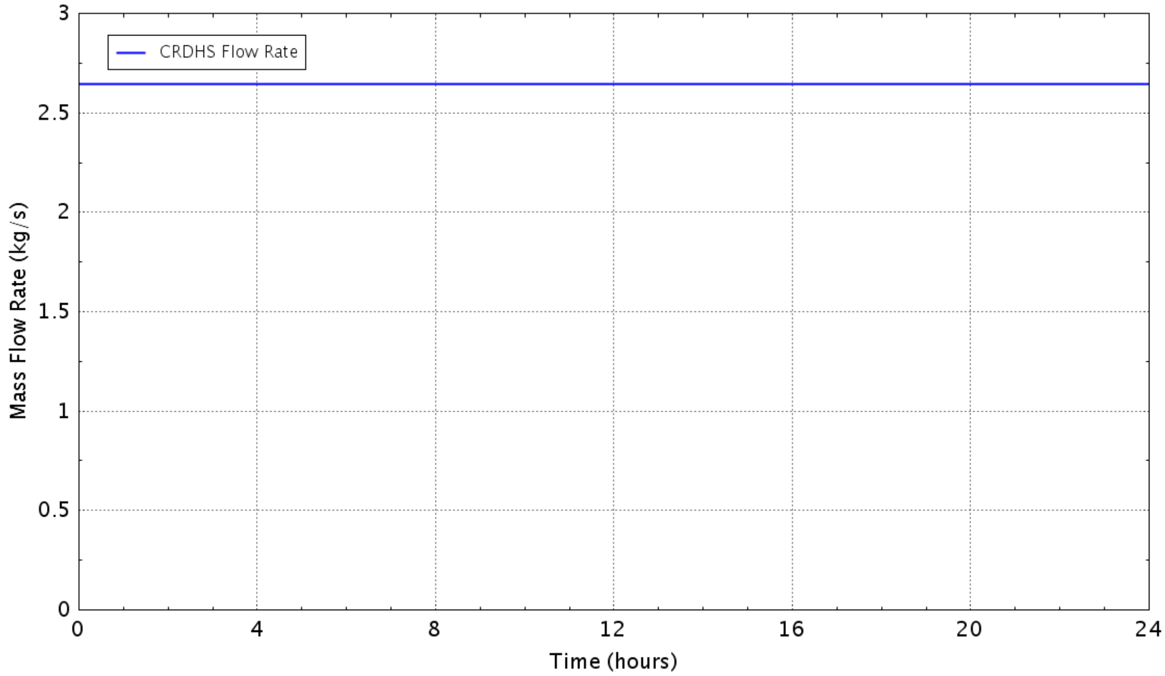

Figure C - 35 Flow rate of the control rod drive hydraulic system

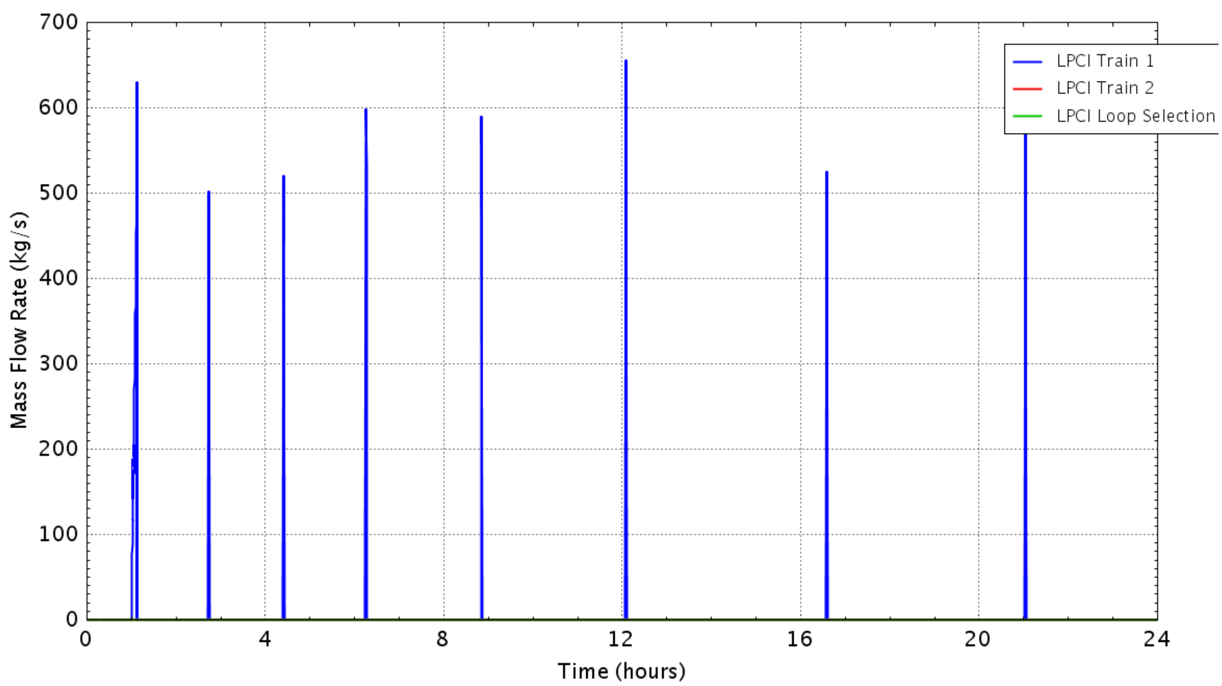

Figure C - 36 Flow rate of the LPCI pump

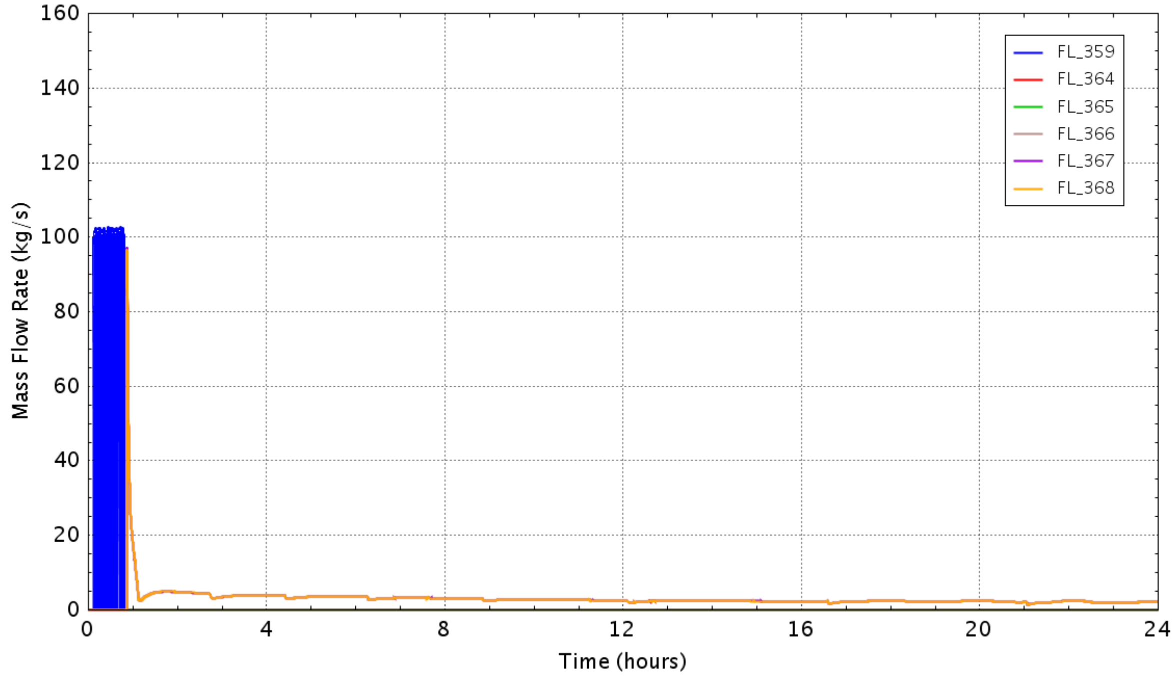

Figure C - 37 Flow rate of the SRVs

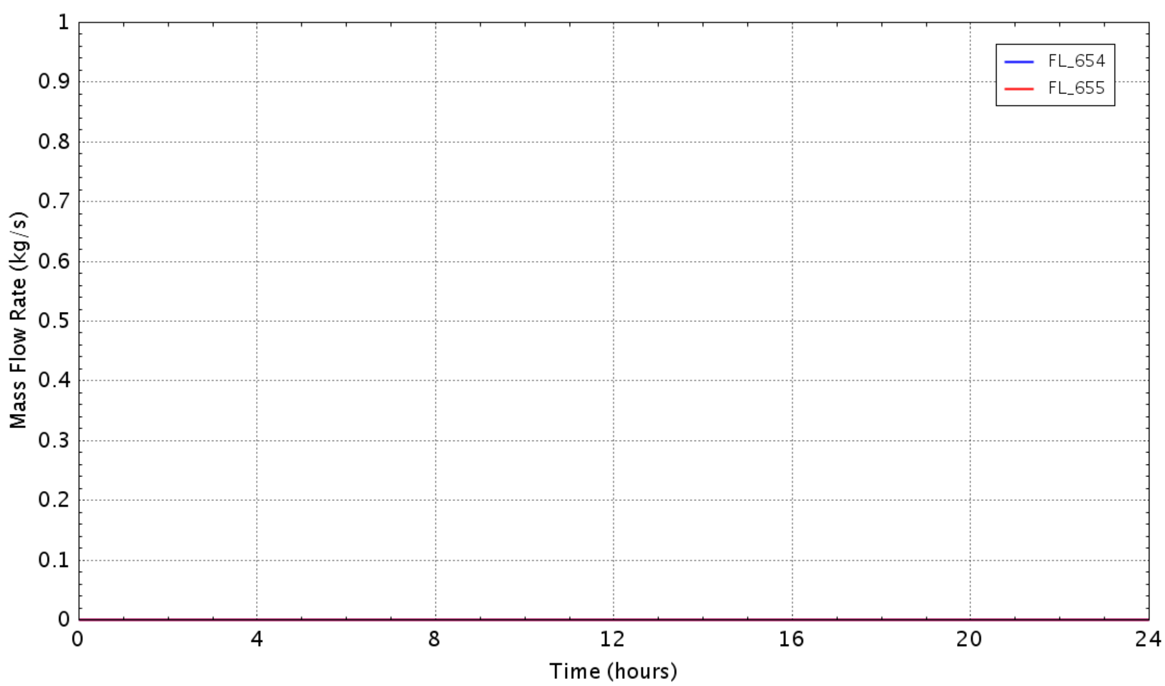

Figure C - 38 Flow rate of the wetwell cooling system

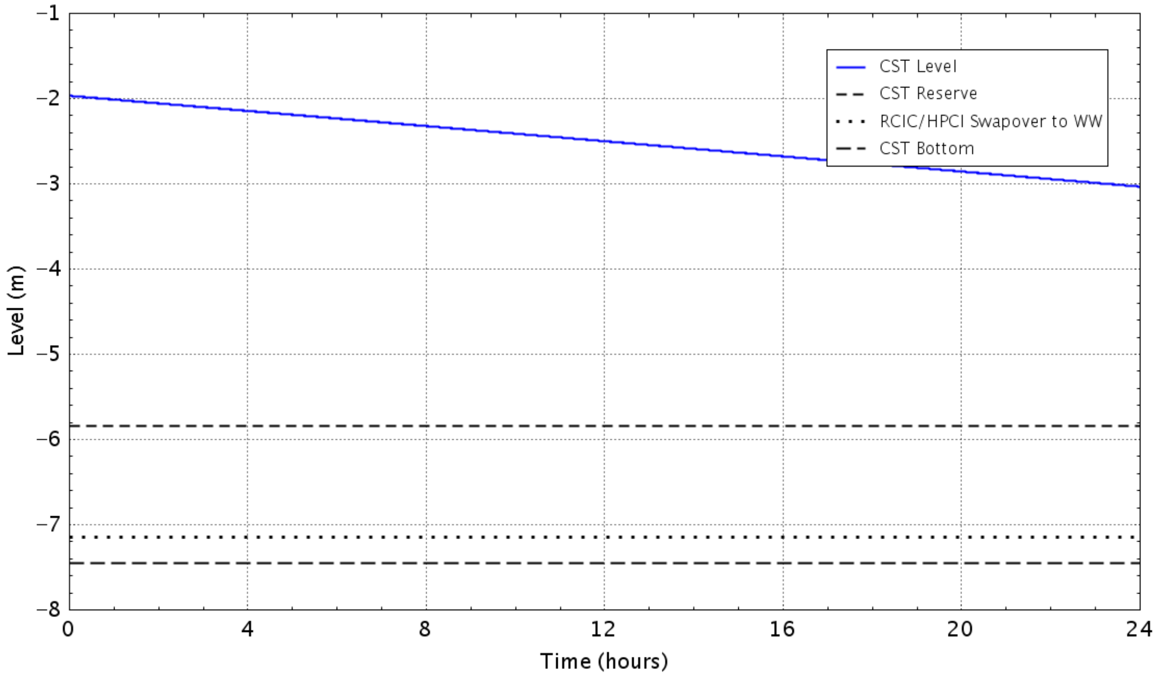

Figure C - 39 Water level in the CST

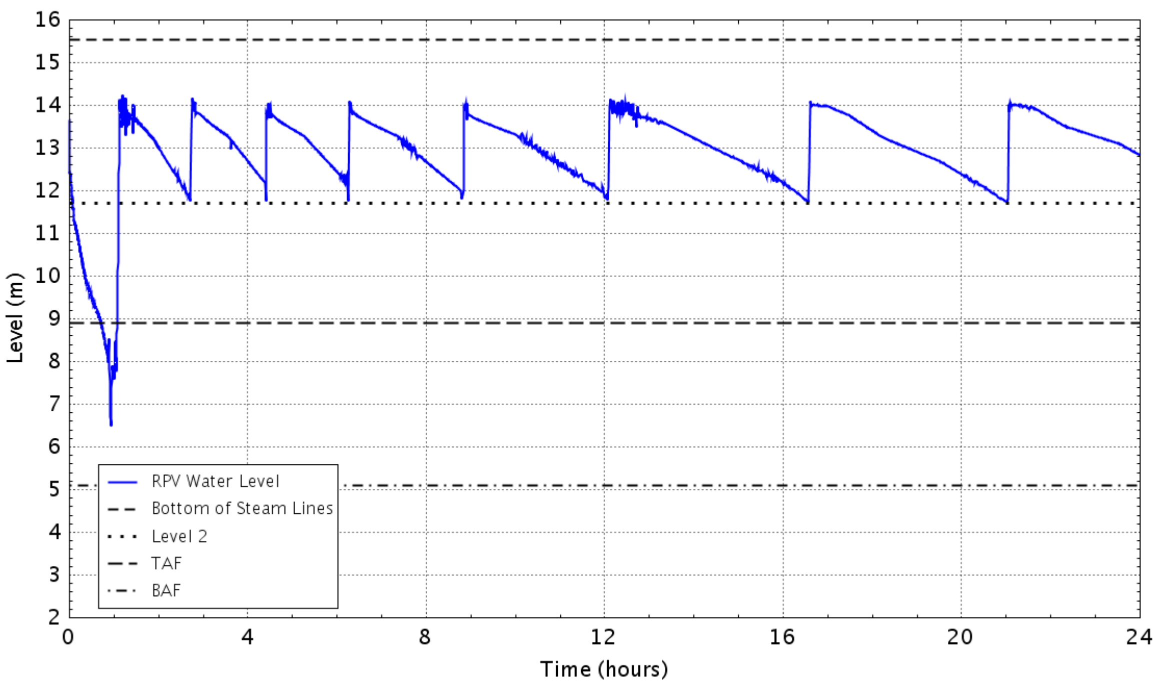

Figure C - 40   RPV Downcomer water level

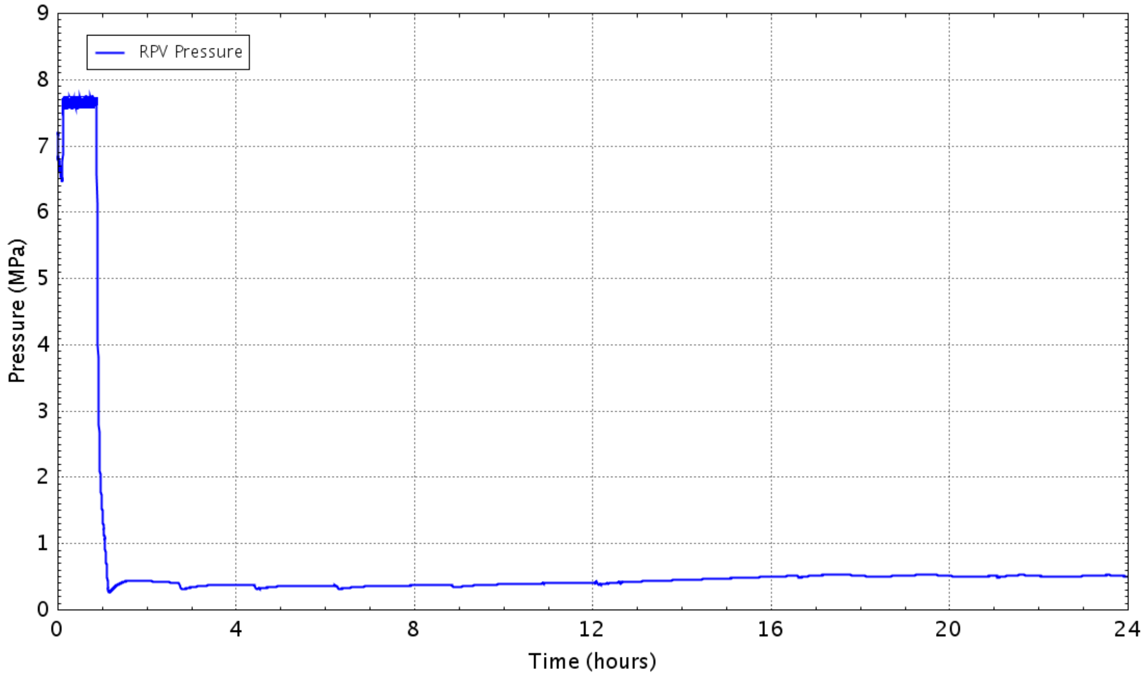

Figure C - 41 Pressure in the RPV

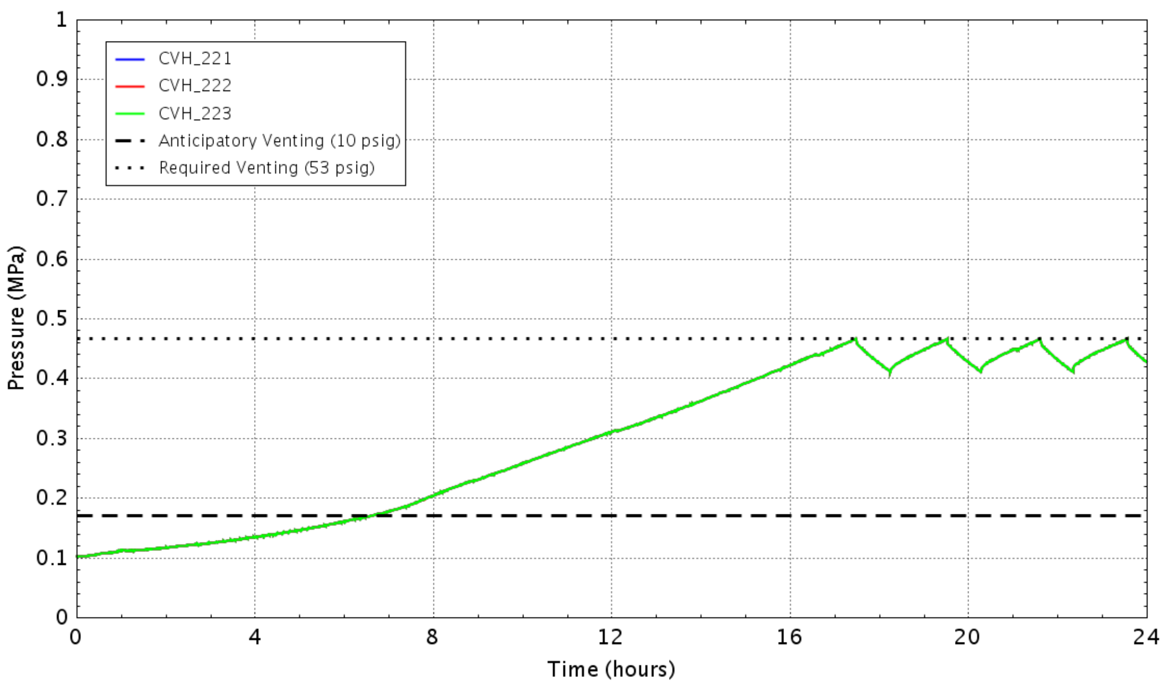

Figure C - 42 Pressure in the wetwell

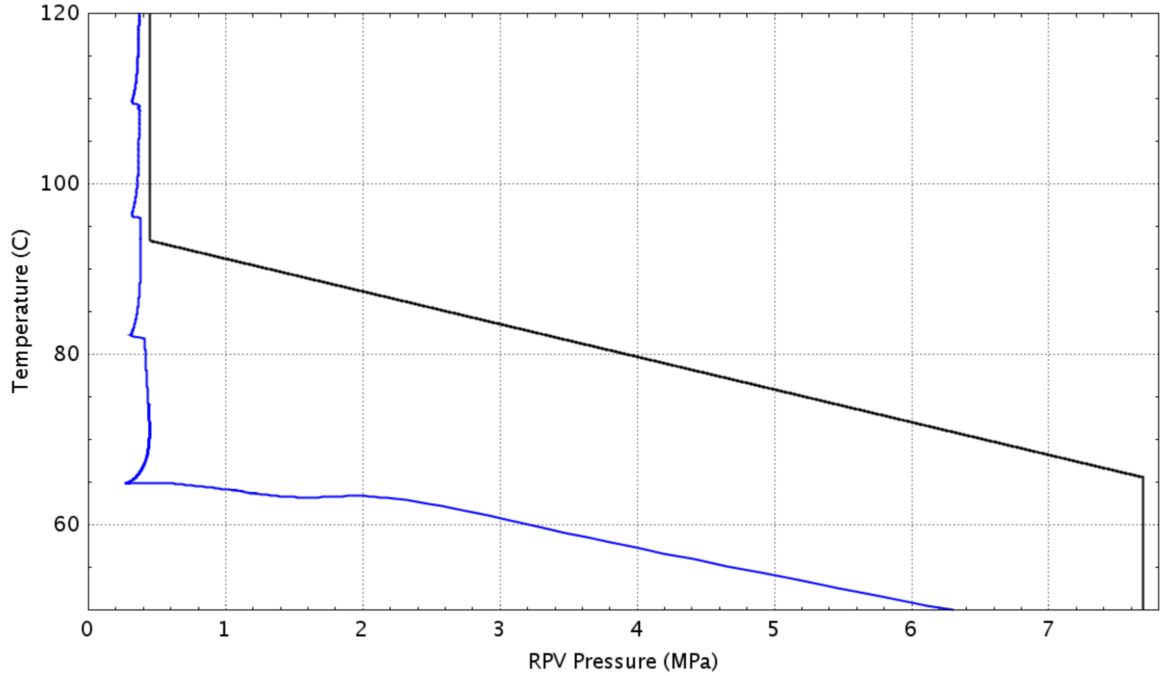

Figure C - 43   Plant status relative to the HCL curve (Graph 4 of the EOPs)

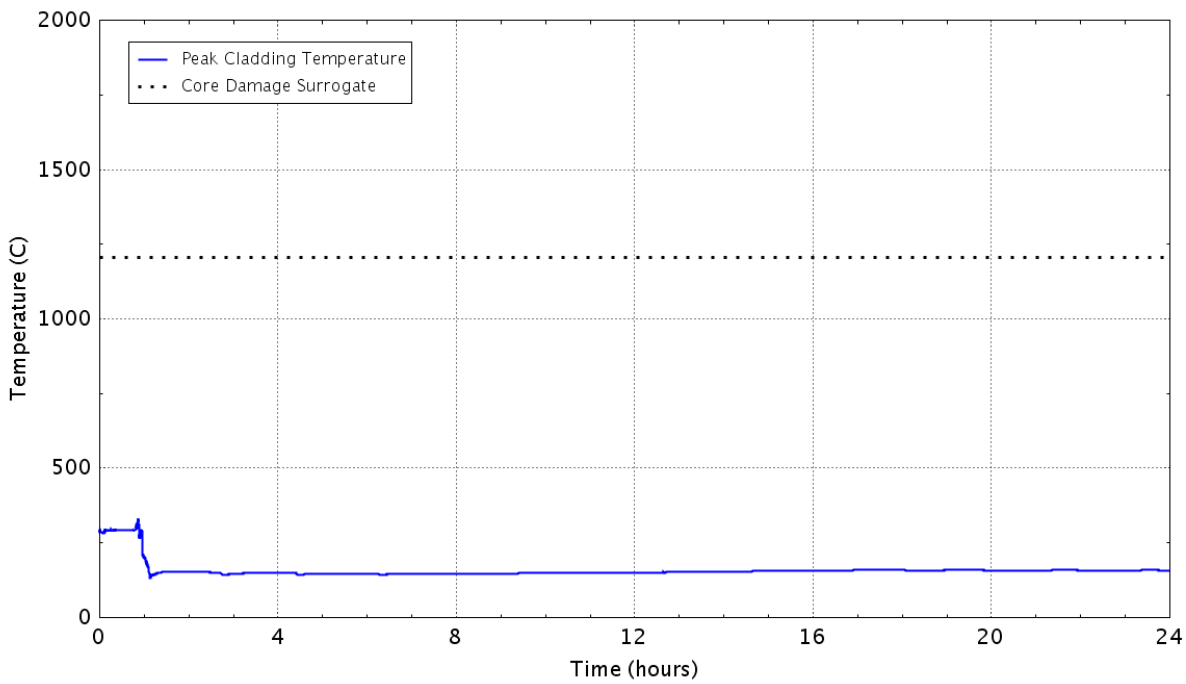

Figure C - 44 Peak temperature of the fuel cladding as a function of time

C.1.5 Case 5: TRANS-30, Nominal CRDHS, Automatic MSIV Closure, ADS at +15 in., One SRV

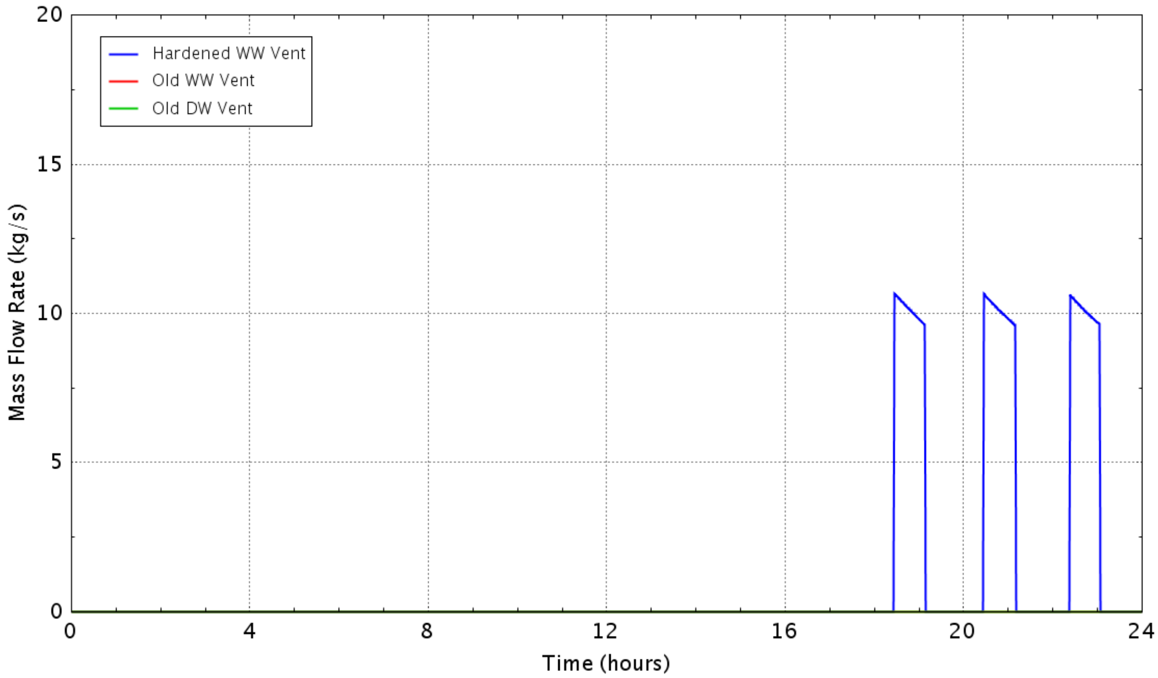

Figure C - 45 Flow rate of the containment vents

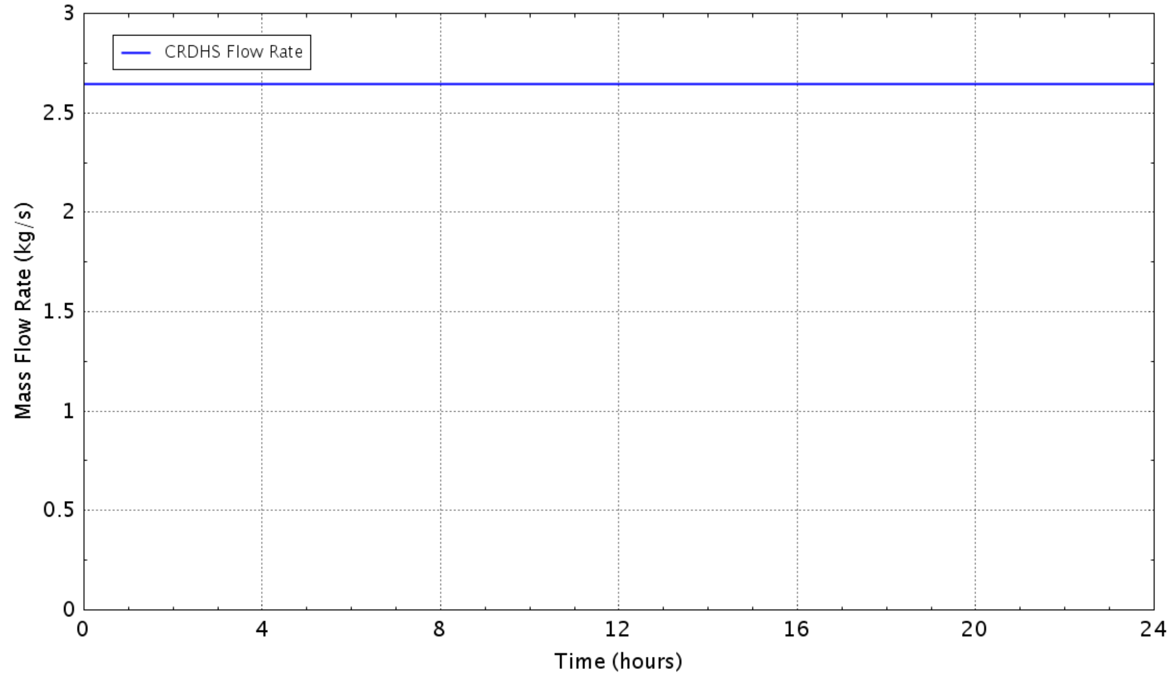

Figure C - 46 Flow rate of the control rod drive hydraulic system

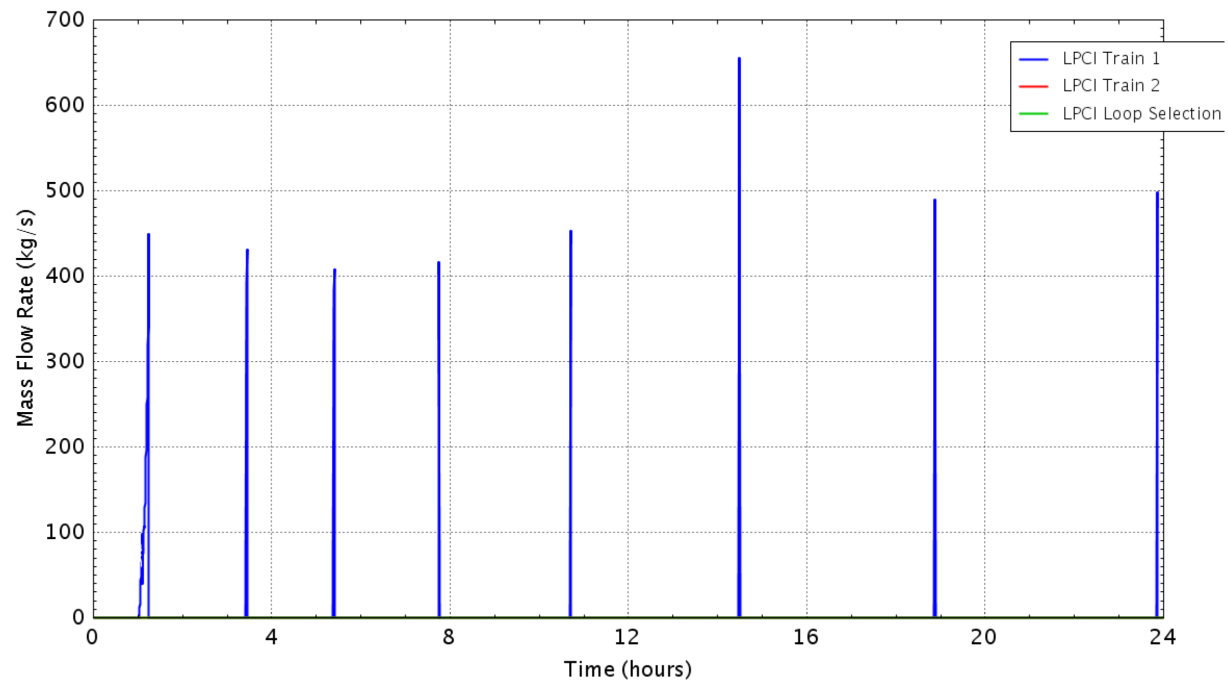

Figure C - 47 Flow rate of the LPCI pump

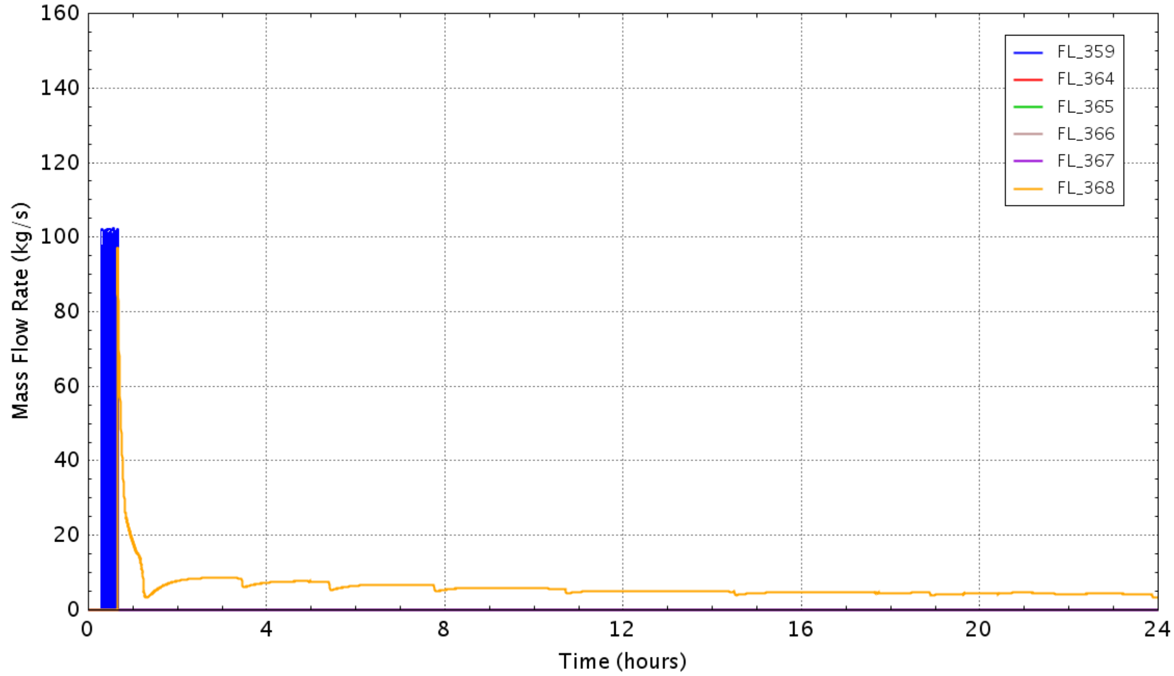

Figure C - 48 Flow rate of the SRVs

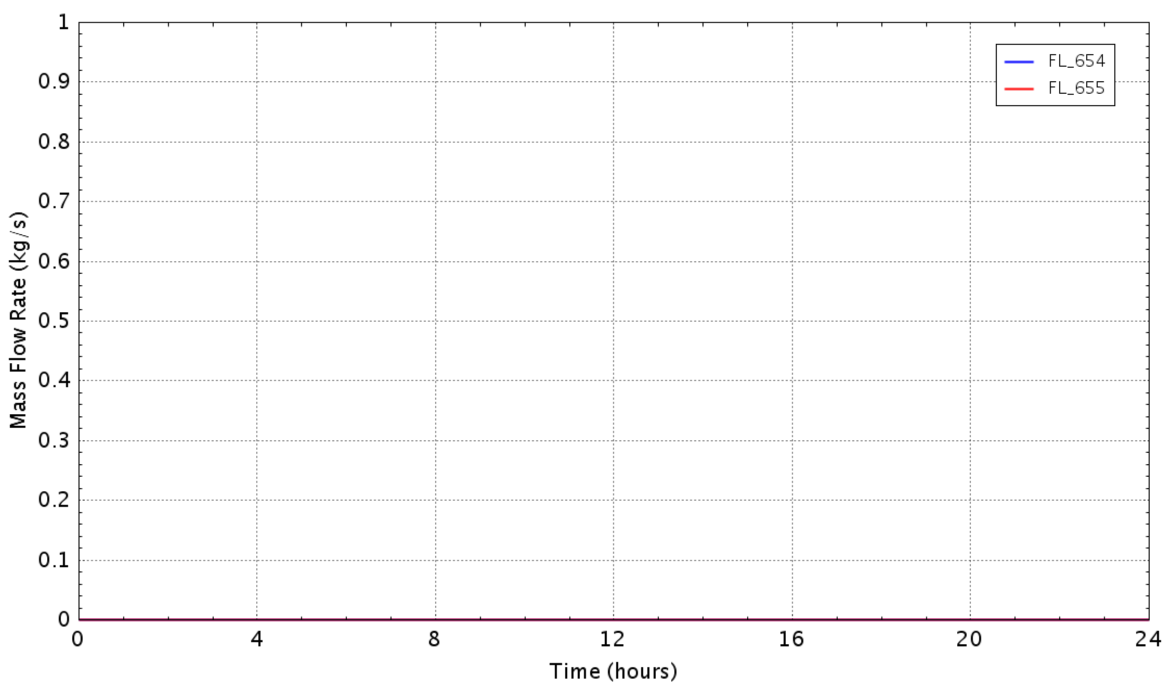

Figure C - 49 Flow rate of the wetwell cooling system

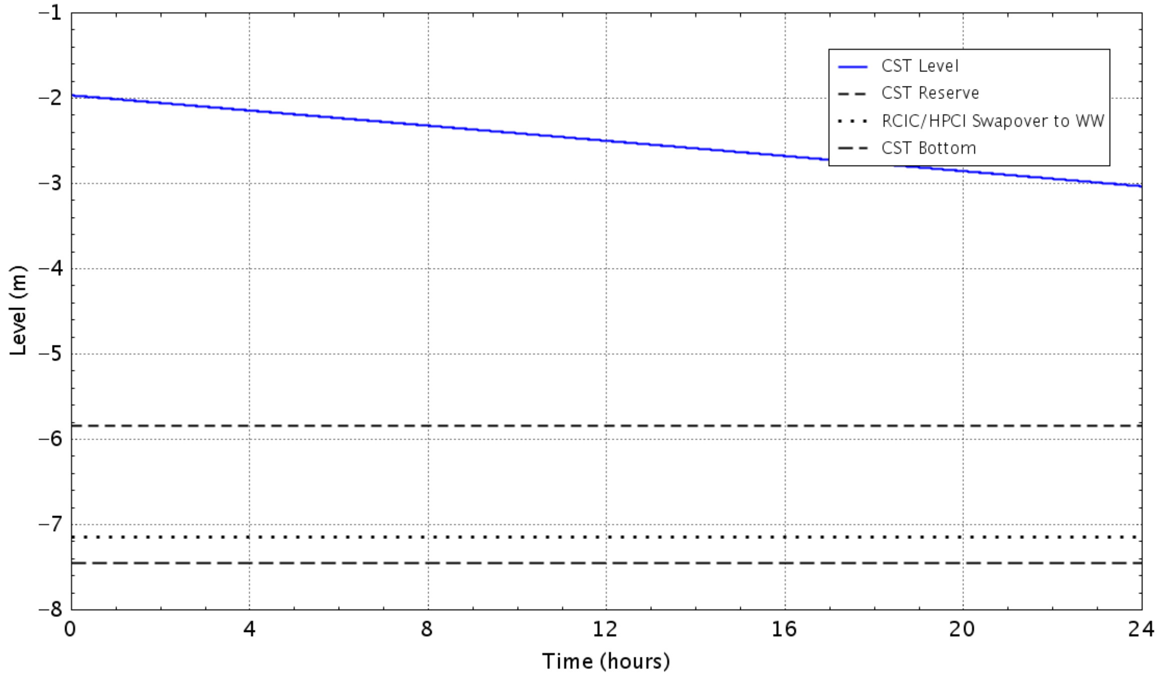

Figure C - 50 Water level in the CST

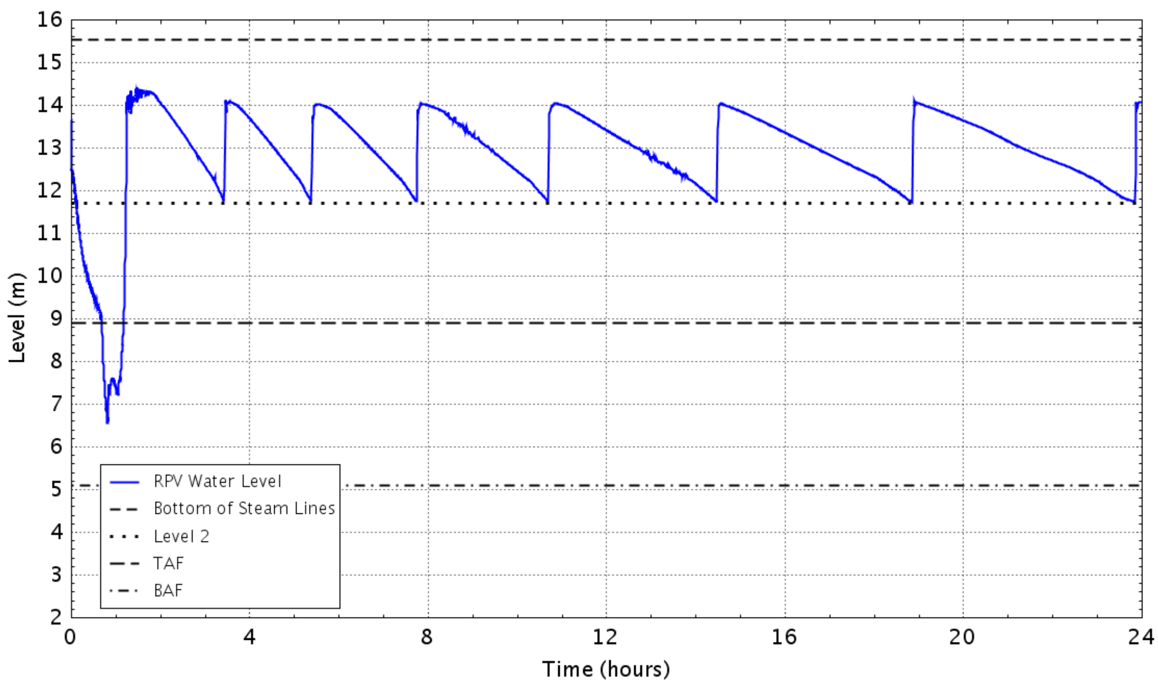

Figure C - 51 RPV Downcomer water level

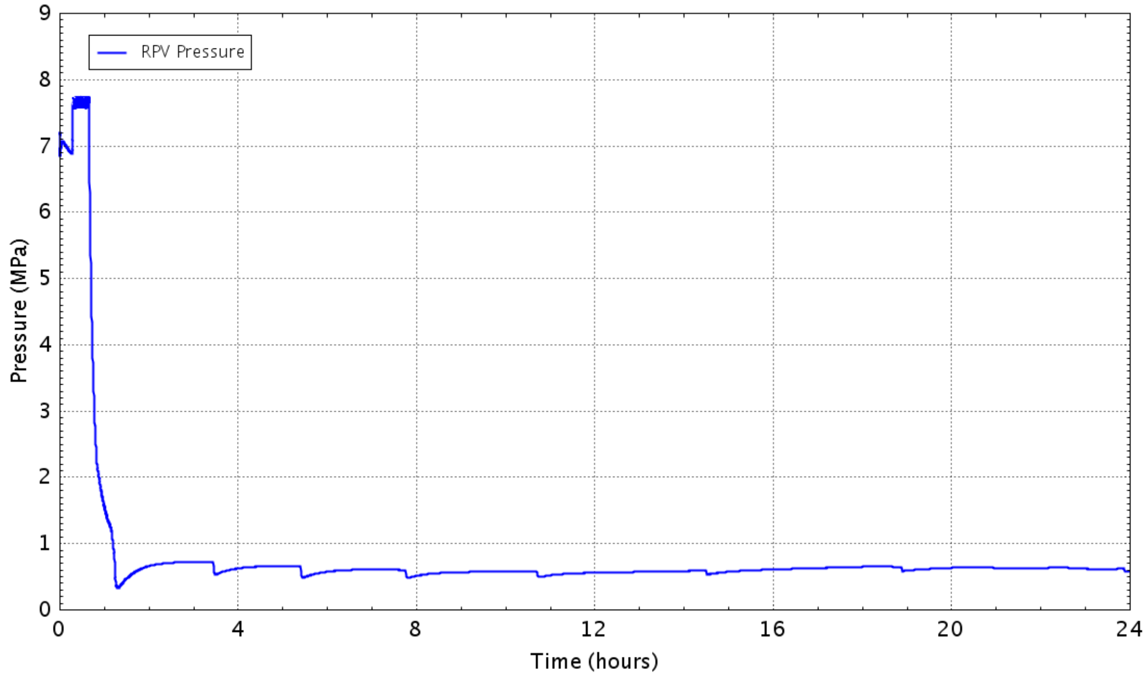

Figure C - 52 Pressure in the RPV

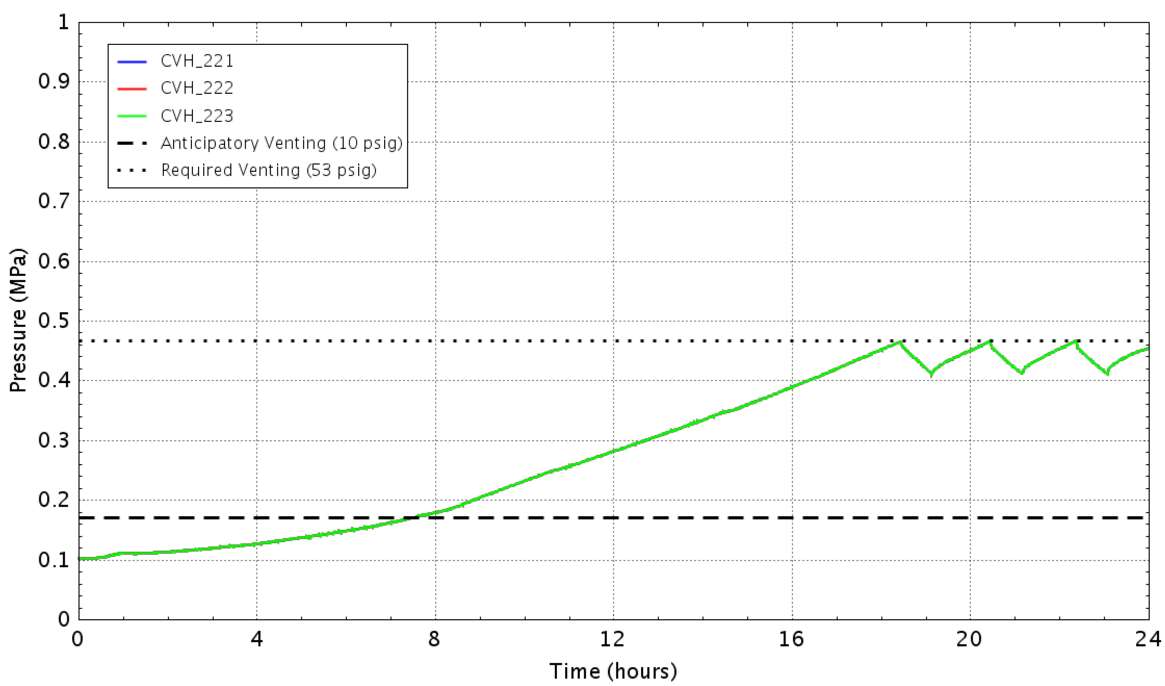

Figure C - 53 Pressure in the wetwell

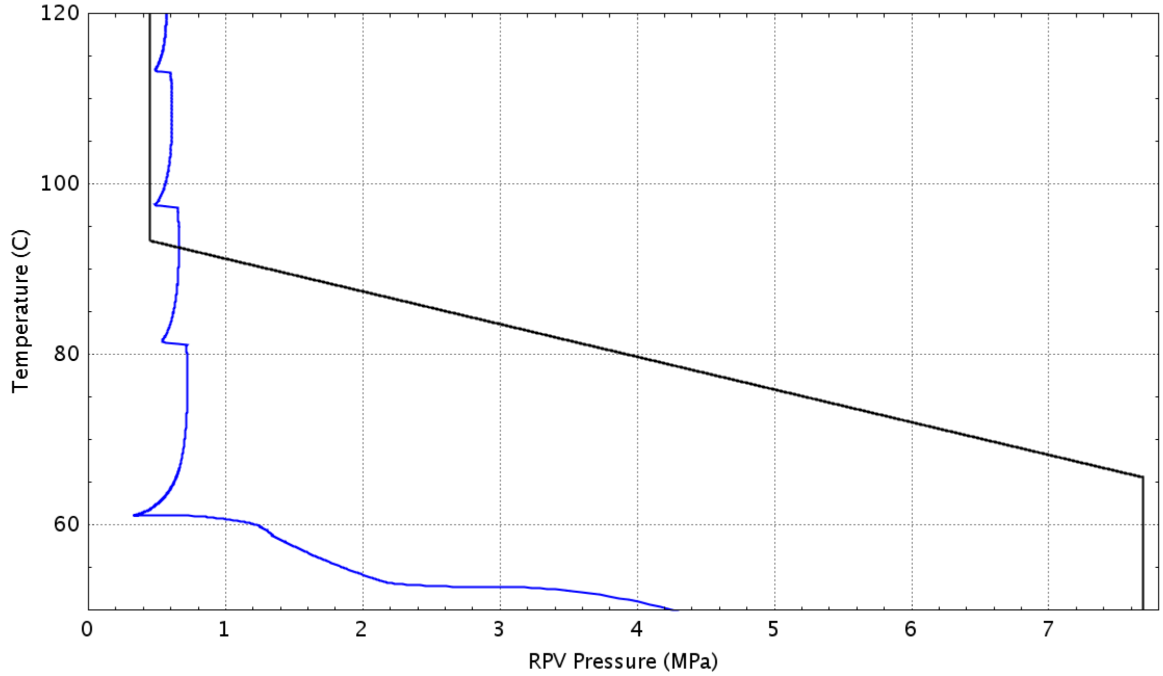

Figure C - 54 Plant status relative to the HCL curve (Graph 4 of the EOPs)

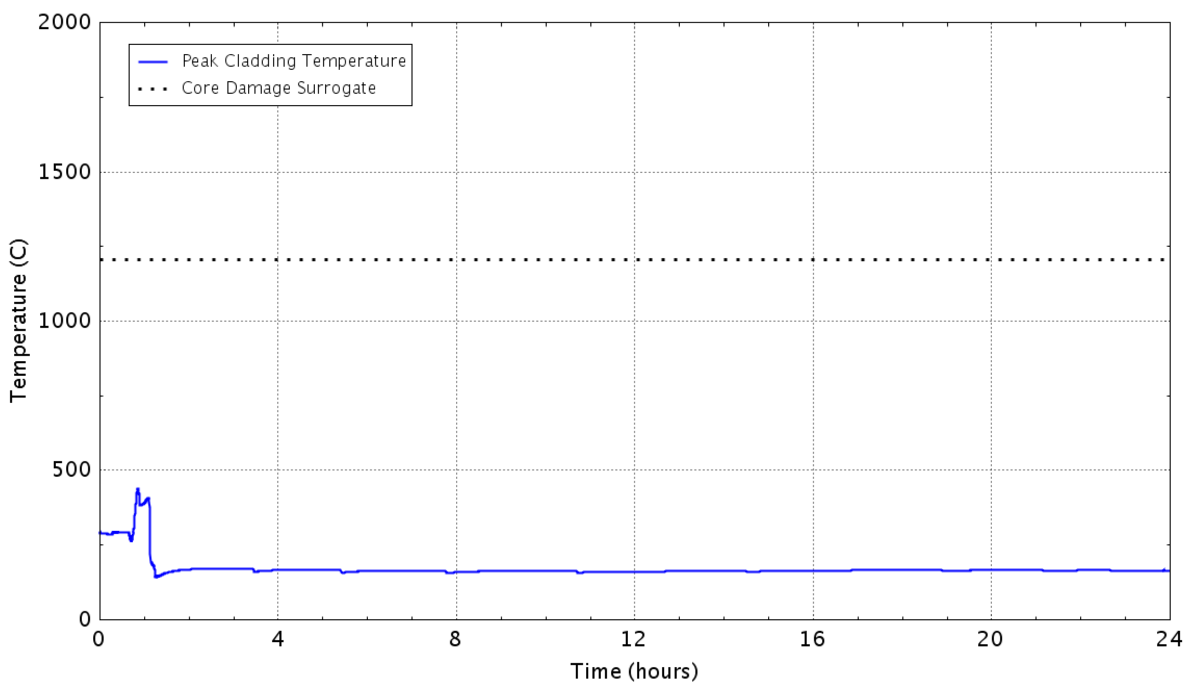

Figure C - 55 Peak temperature of the fuel cladding as a function of time

C.1.6 Case 6: TRANS-30, Nominal CRDHS, Automatic MSIV Closure, ADS at +15 in., Two SRVs

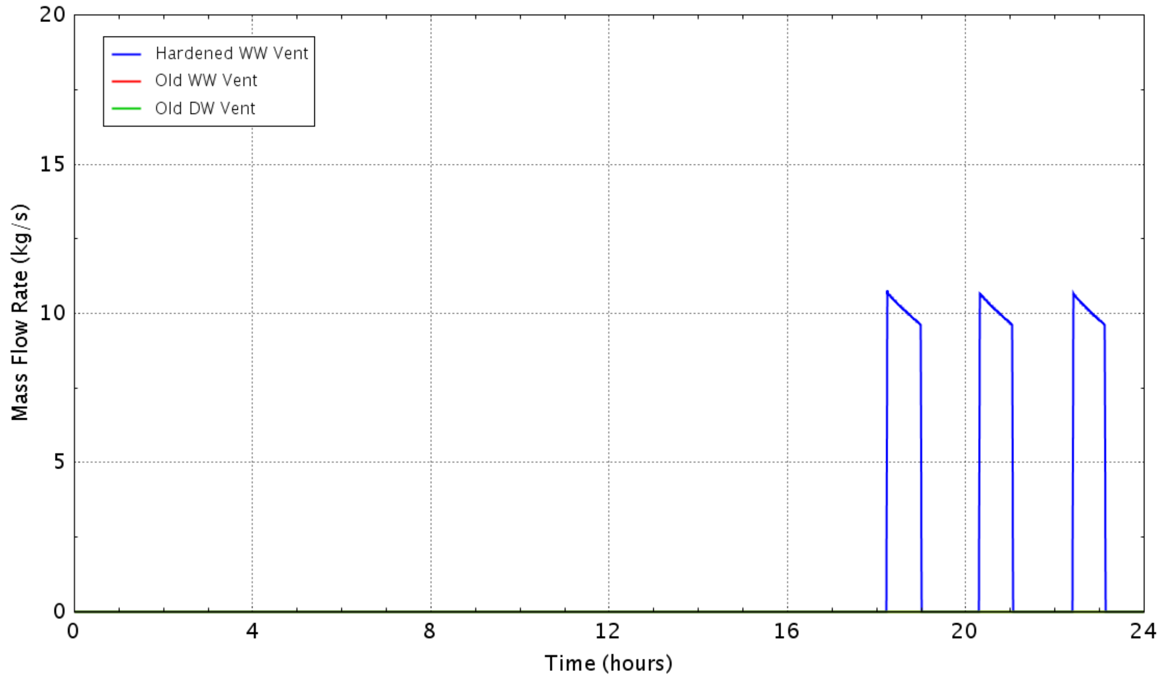

Figure C - 56 Flow rate of the containment vents

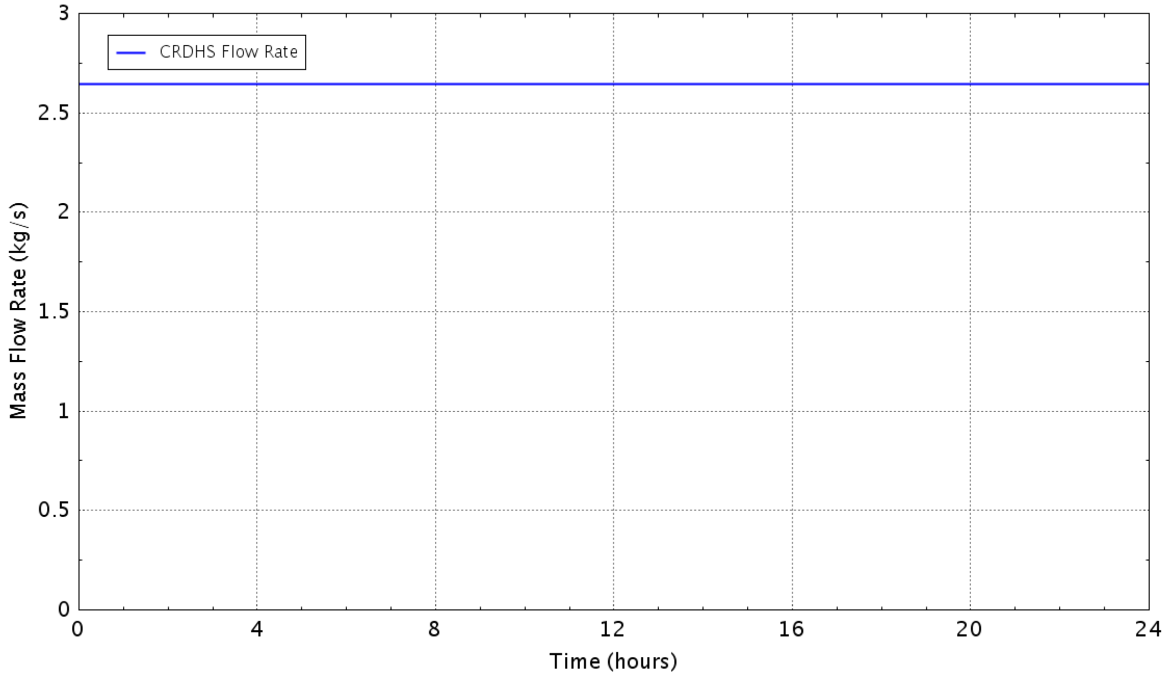

Figure C - 57   Flow rate of the control rod drive hydraulic system

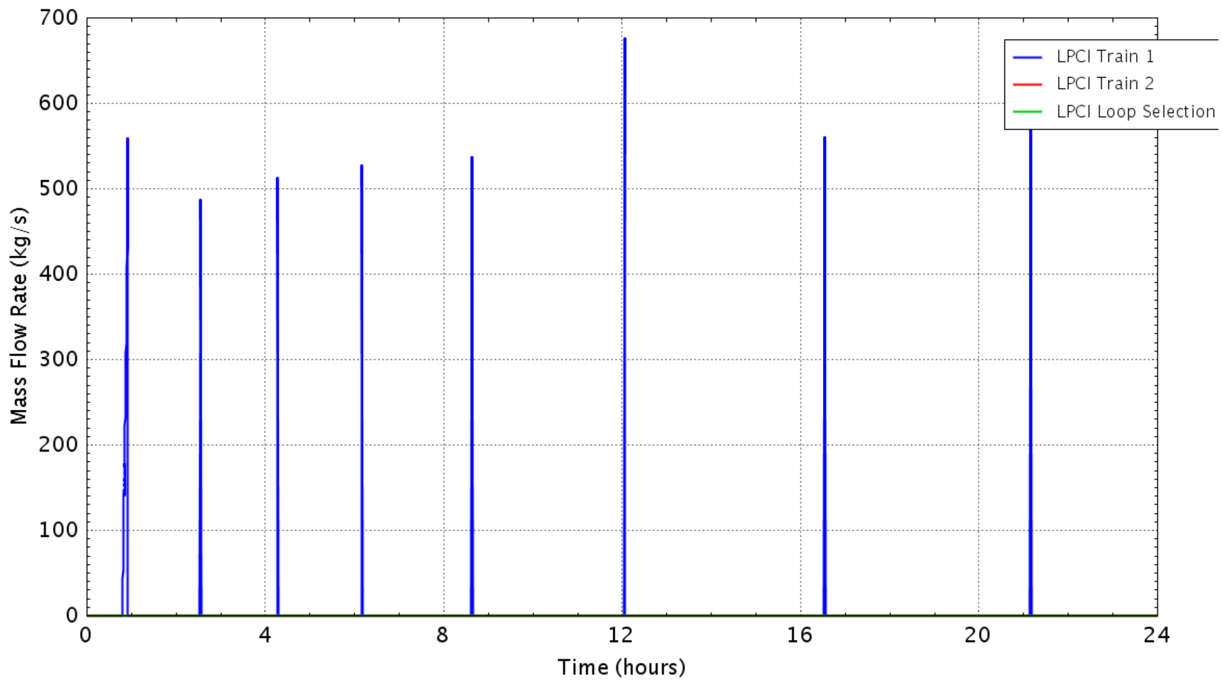

Figure C - 58   Flow rate of the LPCI pump

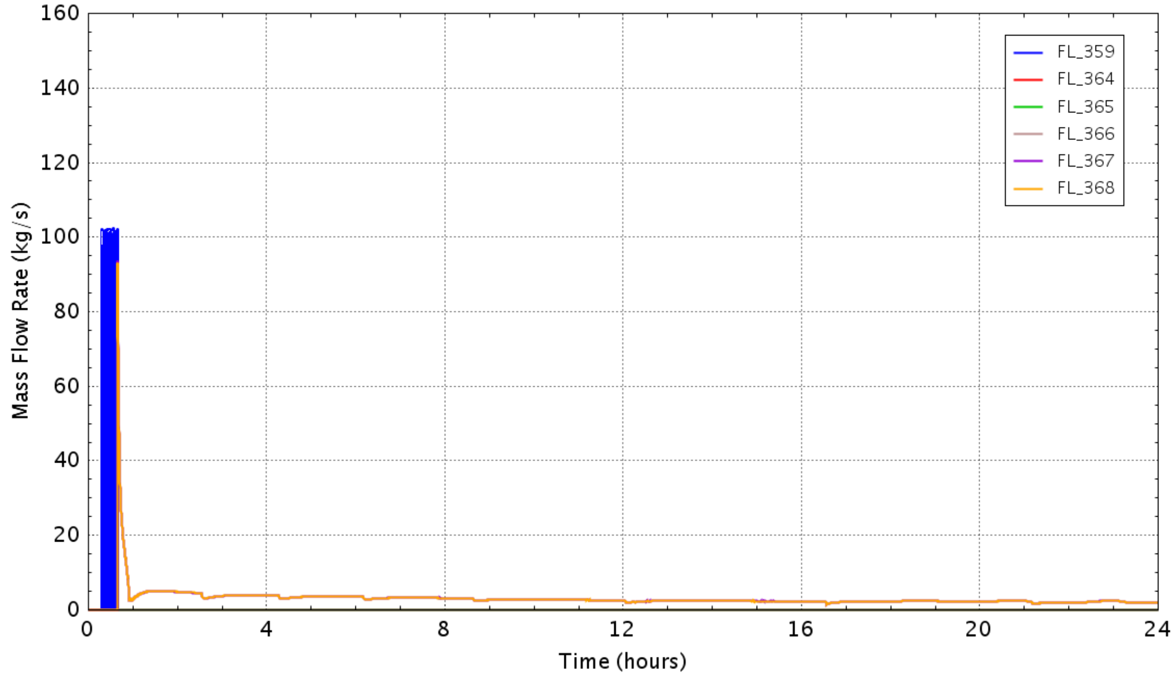

Figure C - 59 Flow rate of the SRVs

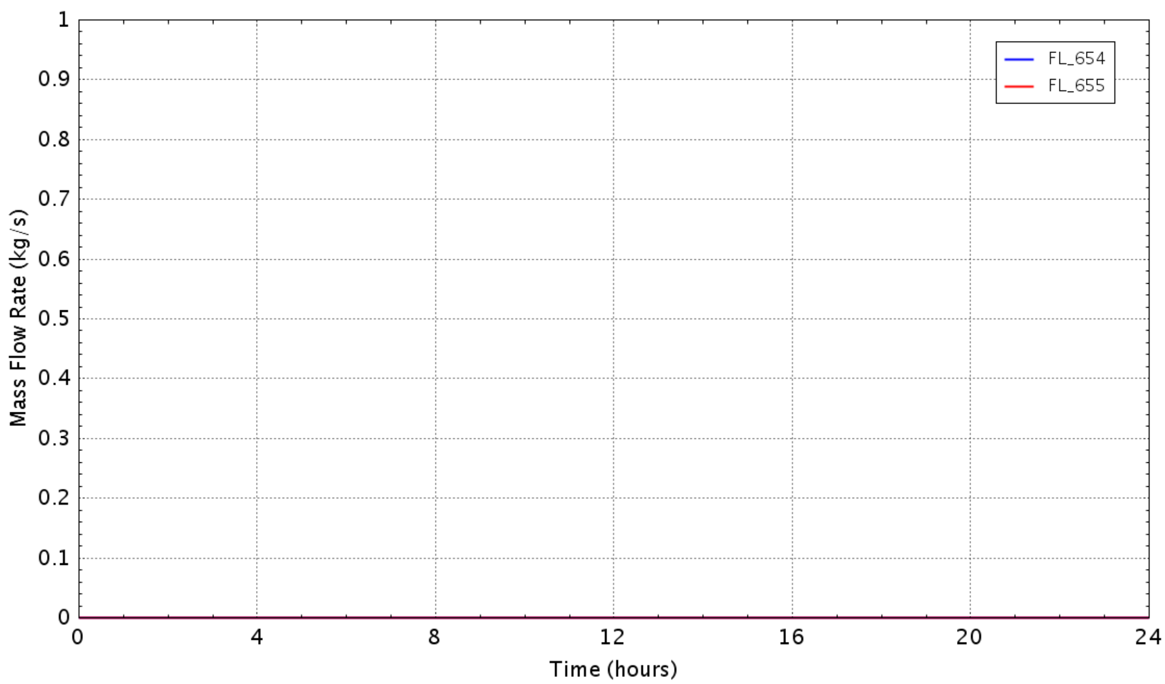

Figure C - 60 Flow rate of the wetwell cooling system

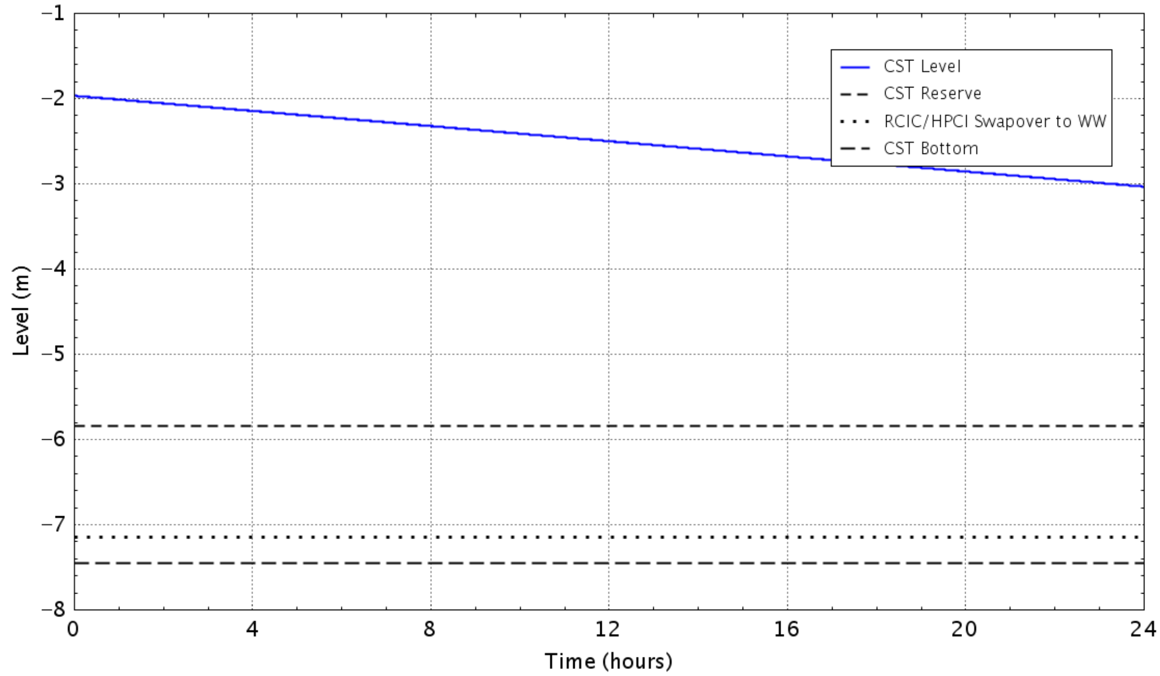

Figure C - 61 Water level in the CST

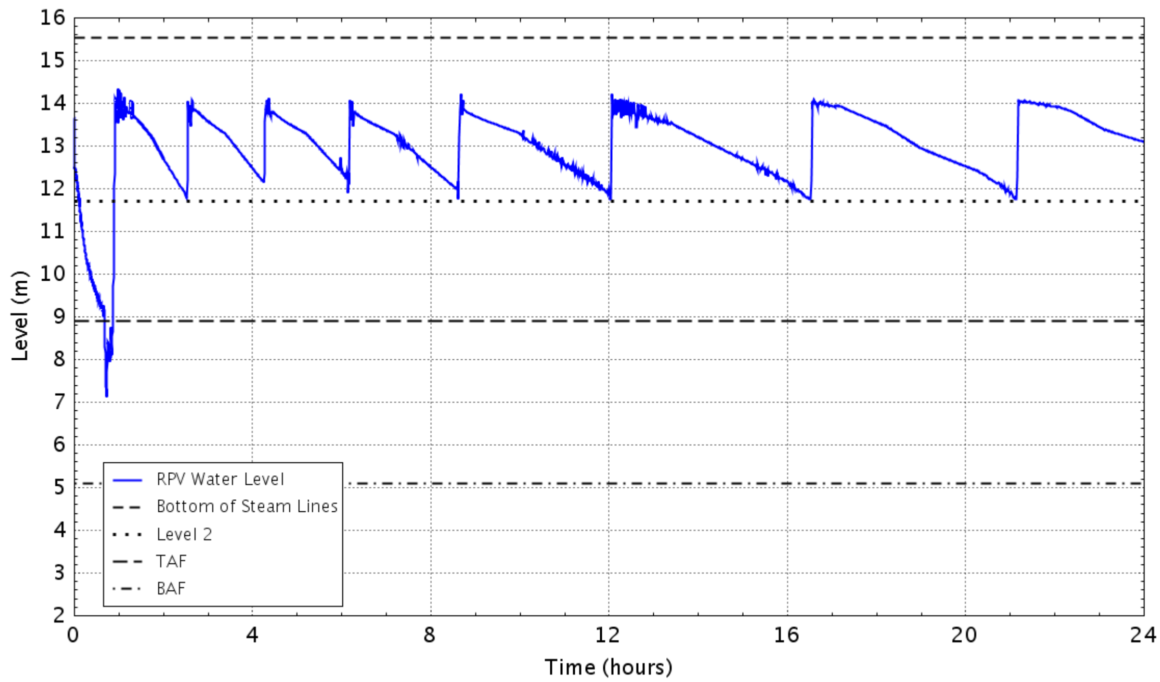

Figure C - 62   RPV Downcomer water level

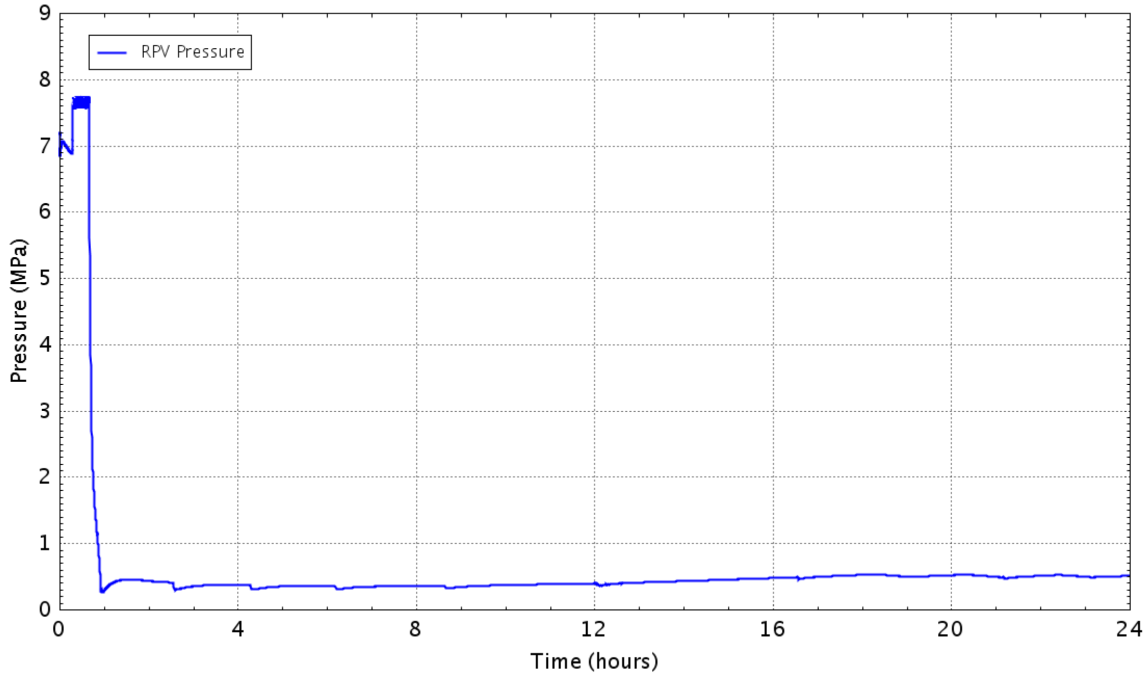

Figure C - 63 Pressure in the RPV

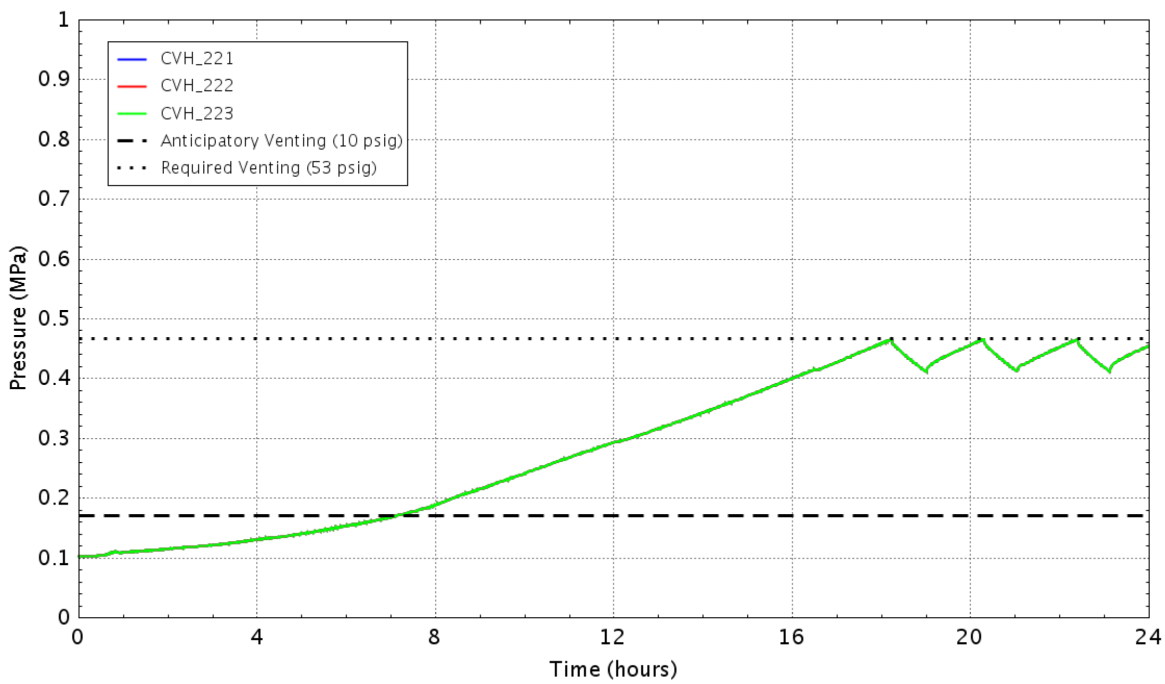

Figure C - 64 Pressure in the wetwell

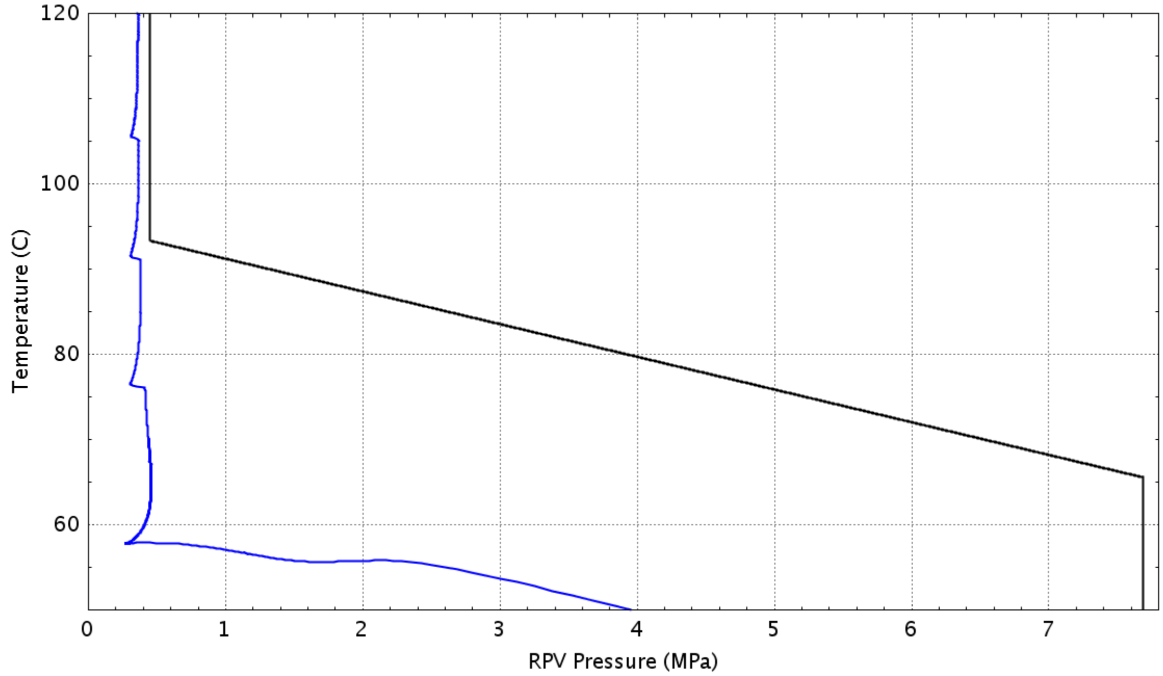

Figure C - 65 Plant status relative to the HCL curve (Graph 4 of the EOPs)

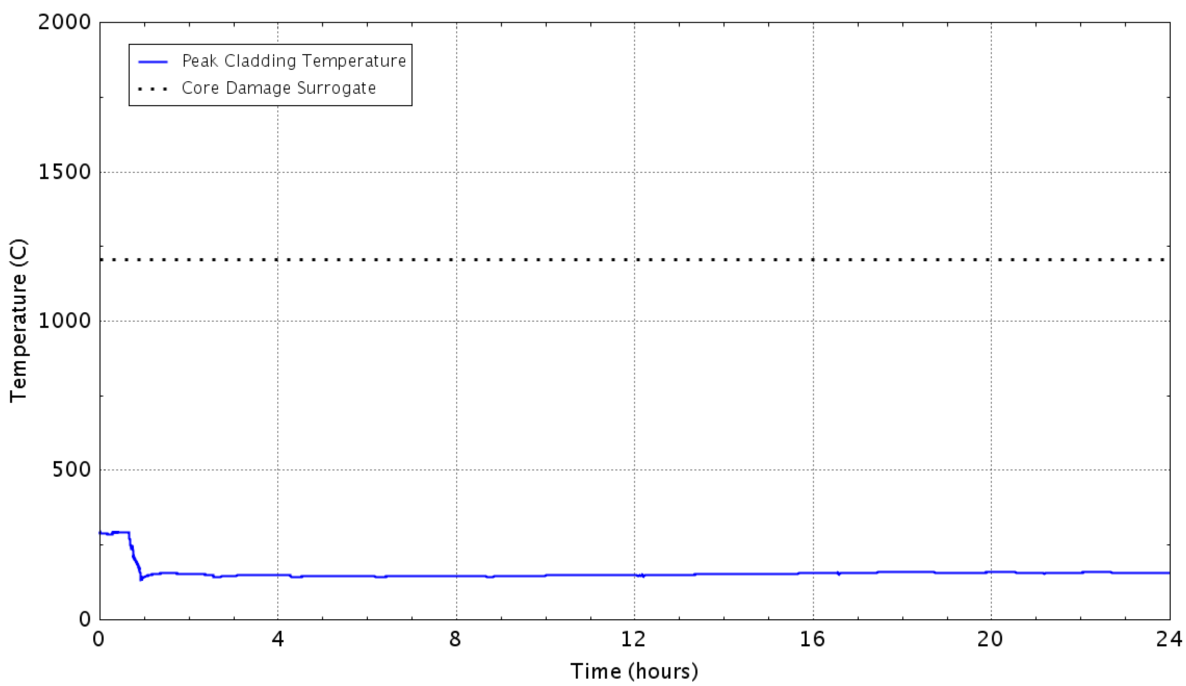

Figure C - 66 Peak temperature of the fuel cladding as a function of time

C.1.7 Case 7: TRANS-30, Nominal CRDHS, Automatic MSIV Closure, ADS at -25 in., One SRV

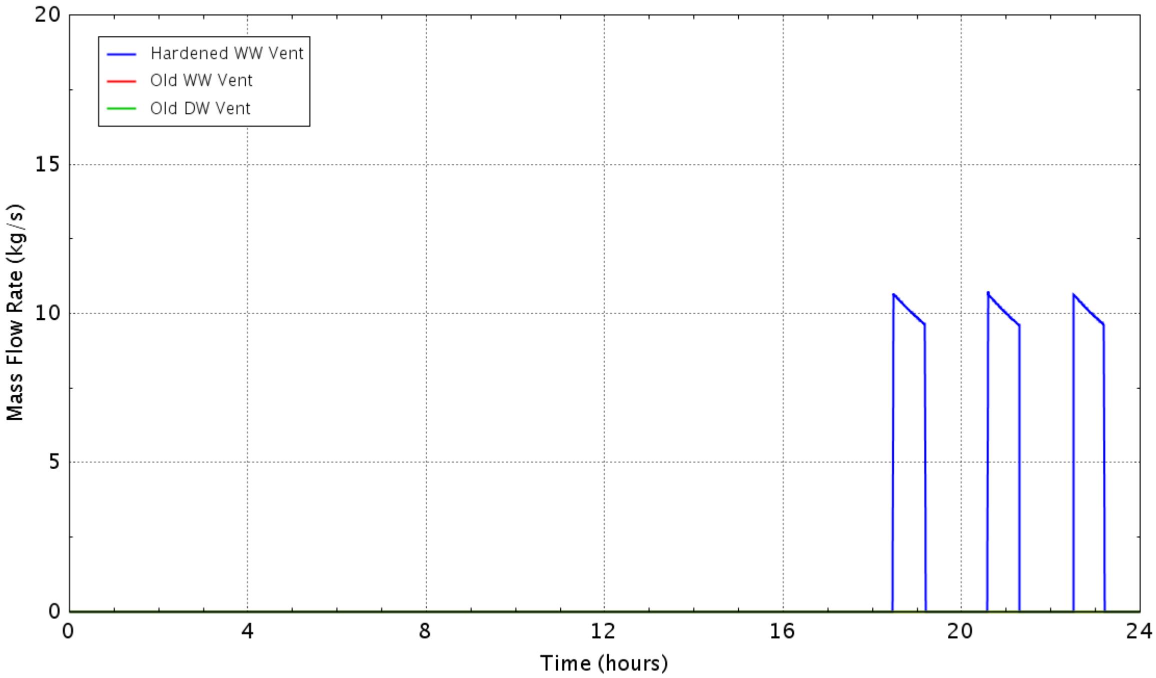

Figure C - 67 Flow rate of the containment vents

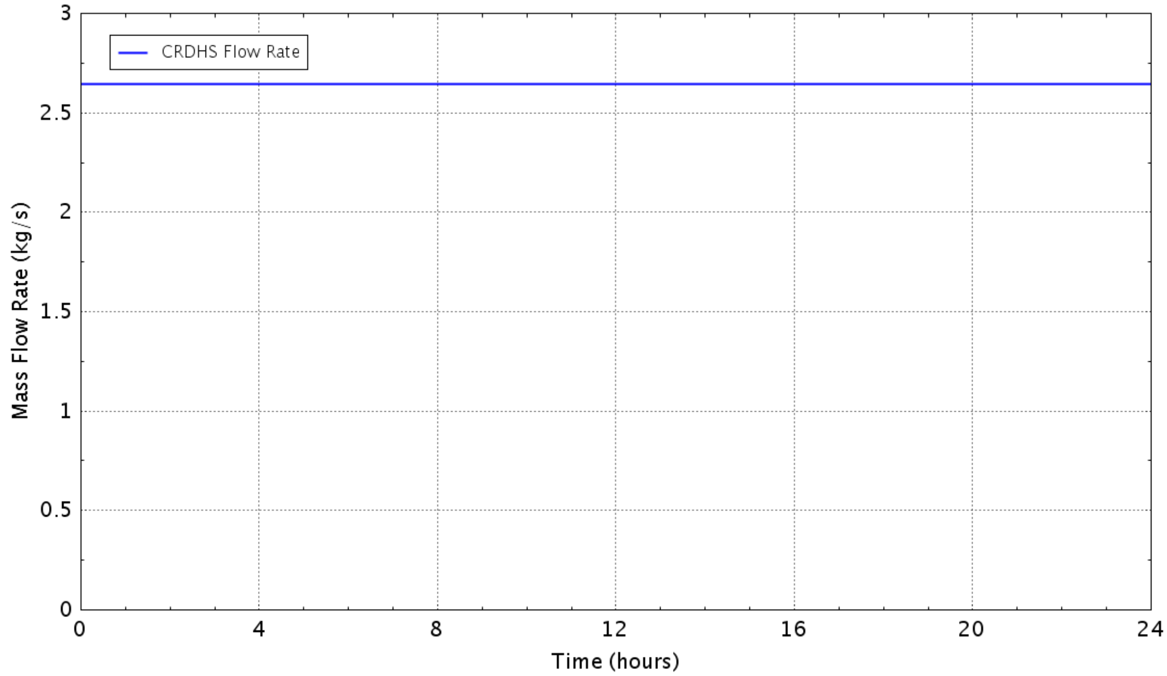

Figure C - 68   Flow rate of the control rod drive hydraulic system

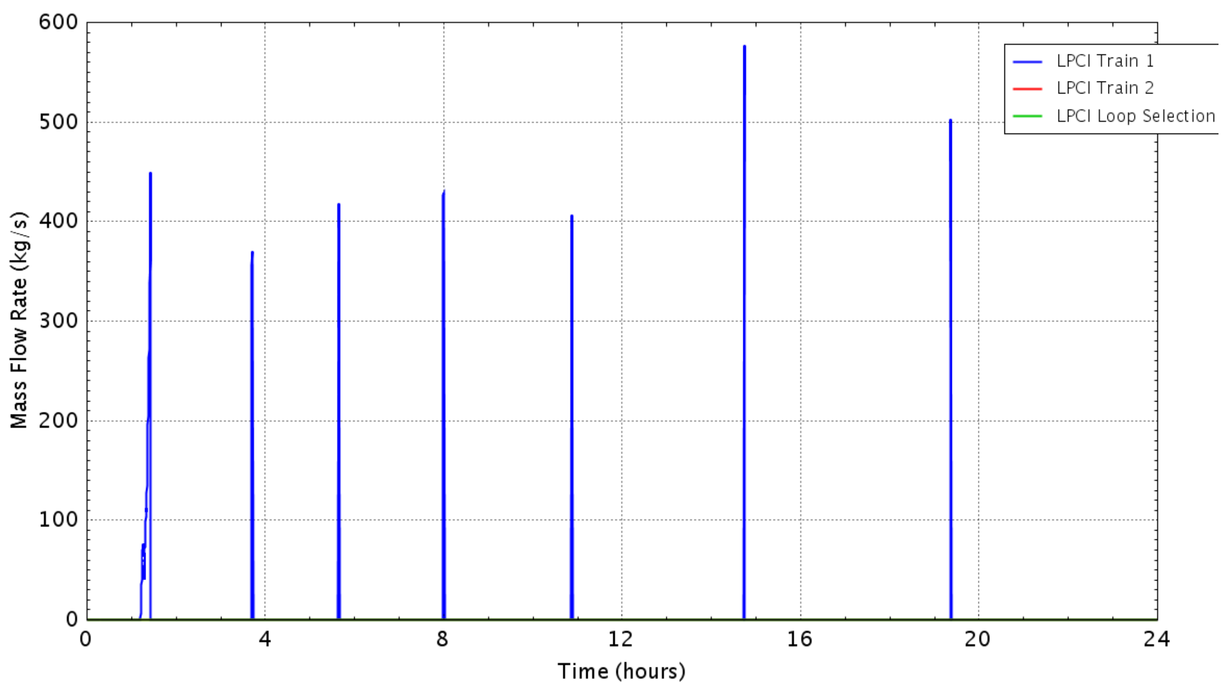

Figure C - 69   Flow rate of the LPCI pump

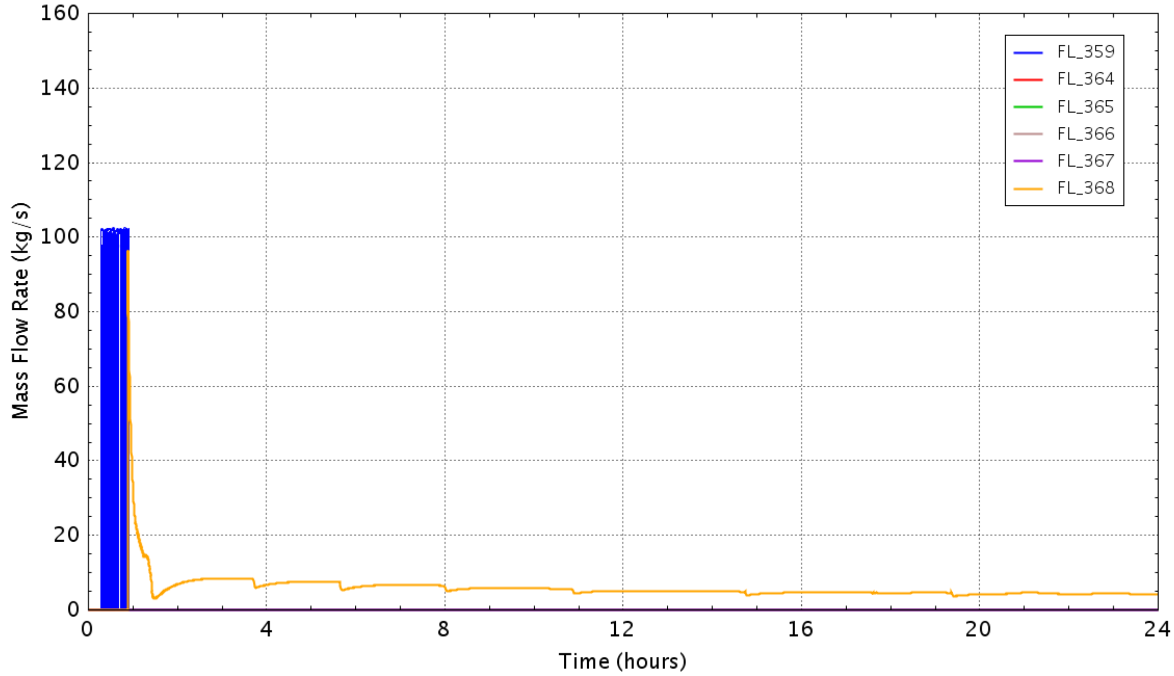

Figure C - 70 Flow rate of the SRVs

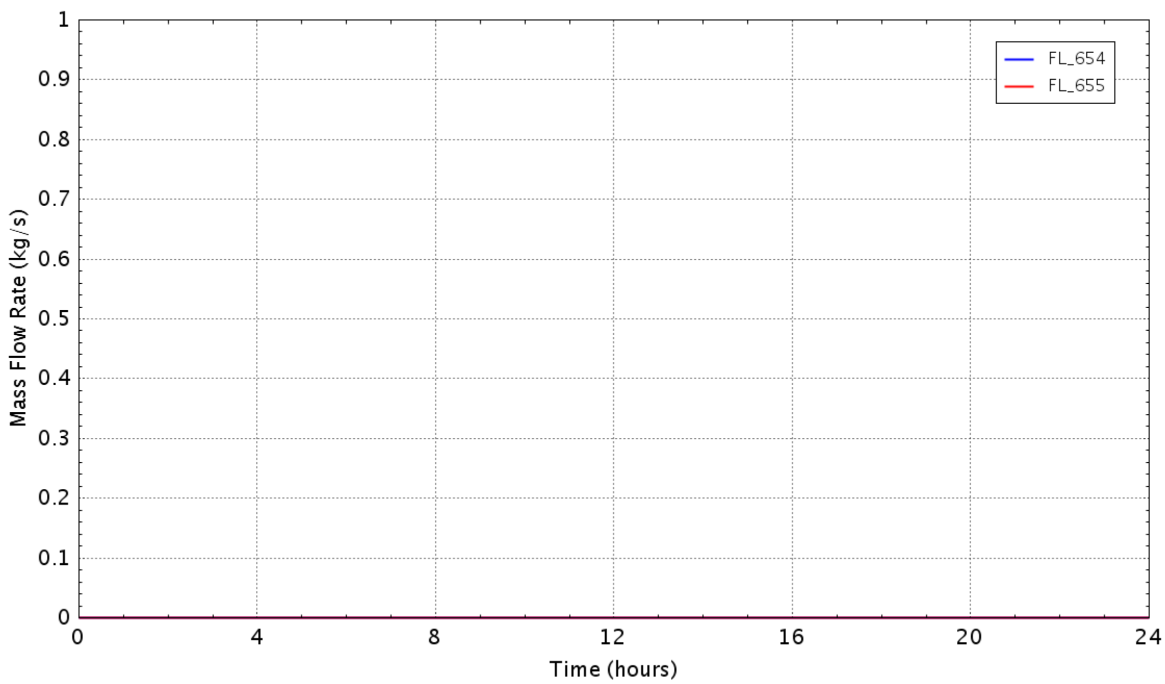

Figure C - 71 Flow rate of the wetwell cooling system

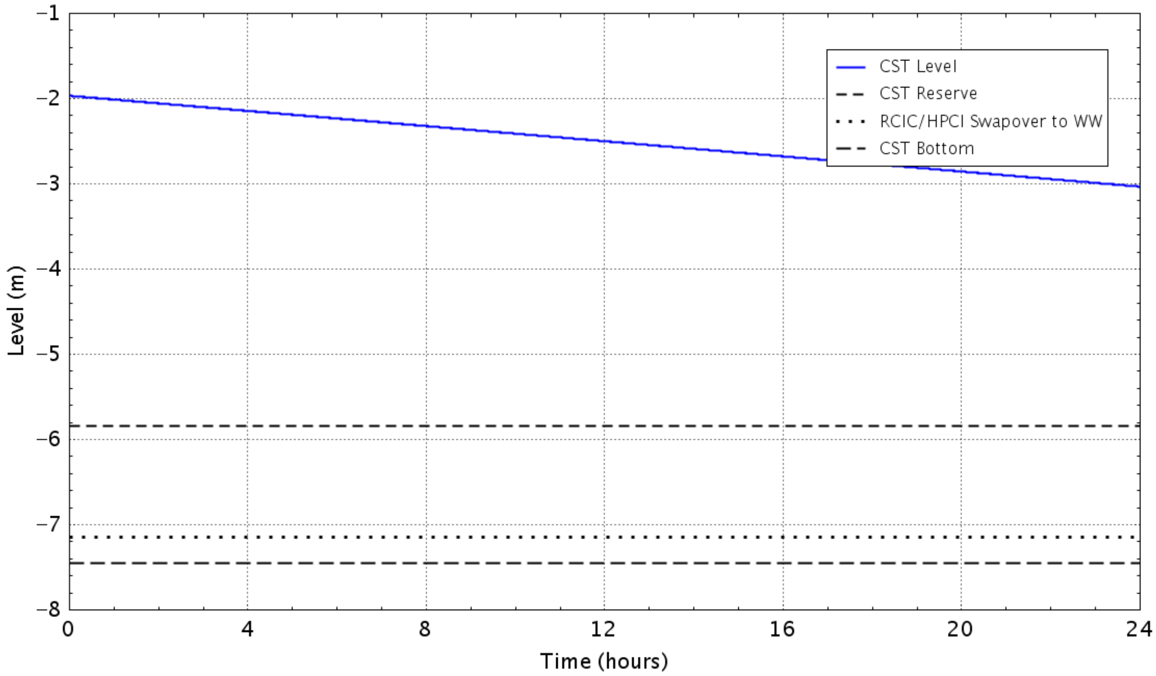

Figure C - 72 Water level in the CST

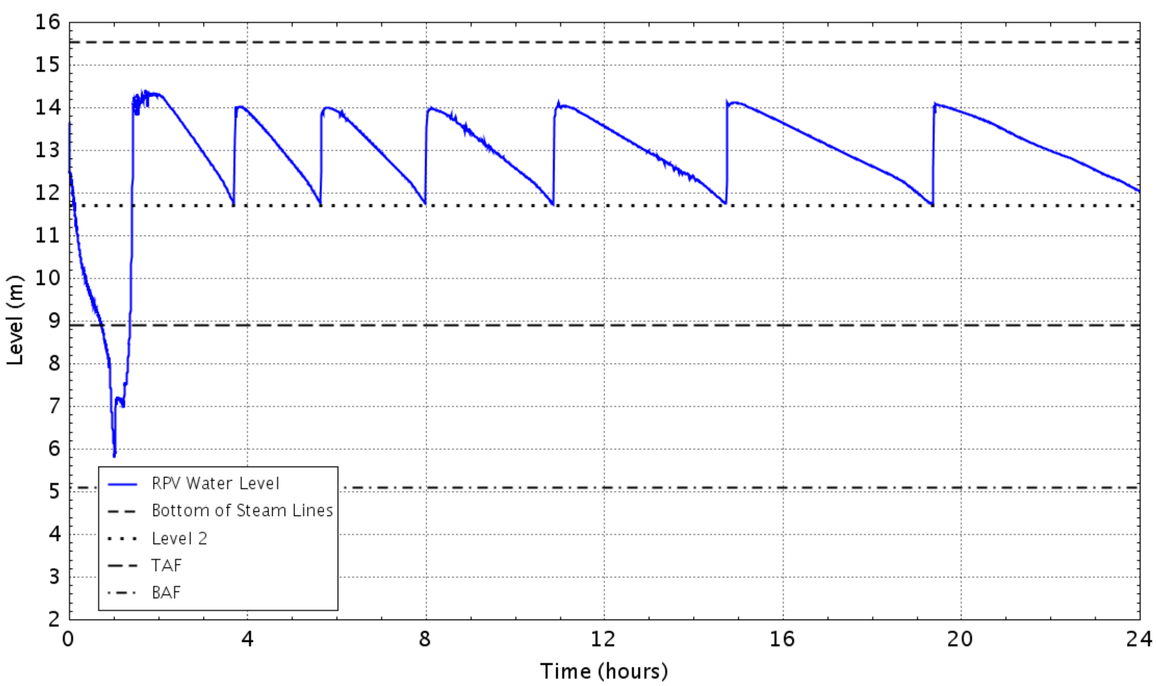

Figure C - 73 RPV Downcomer water level

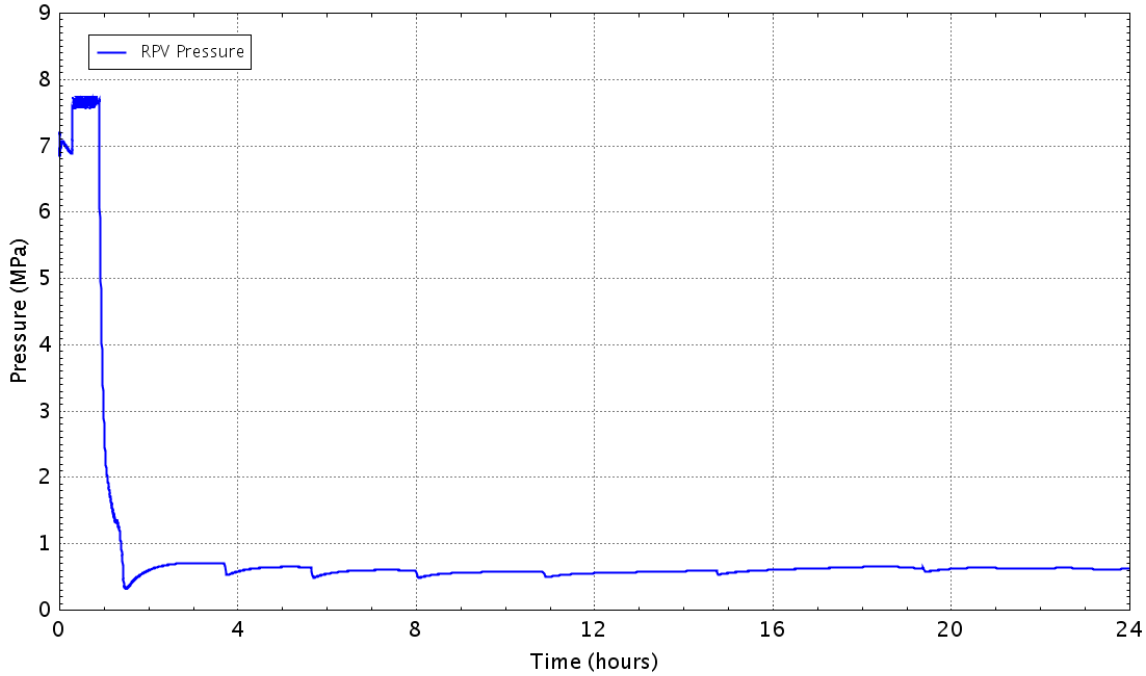

Figure C - 74 Pressure in the RPV

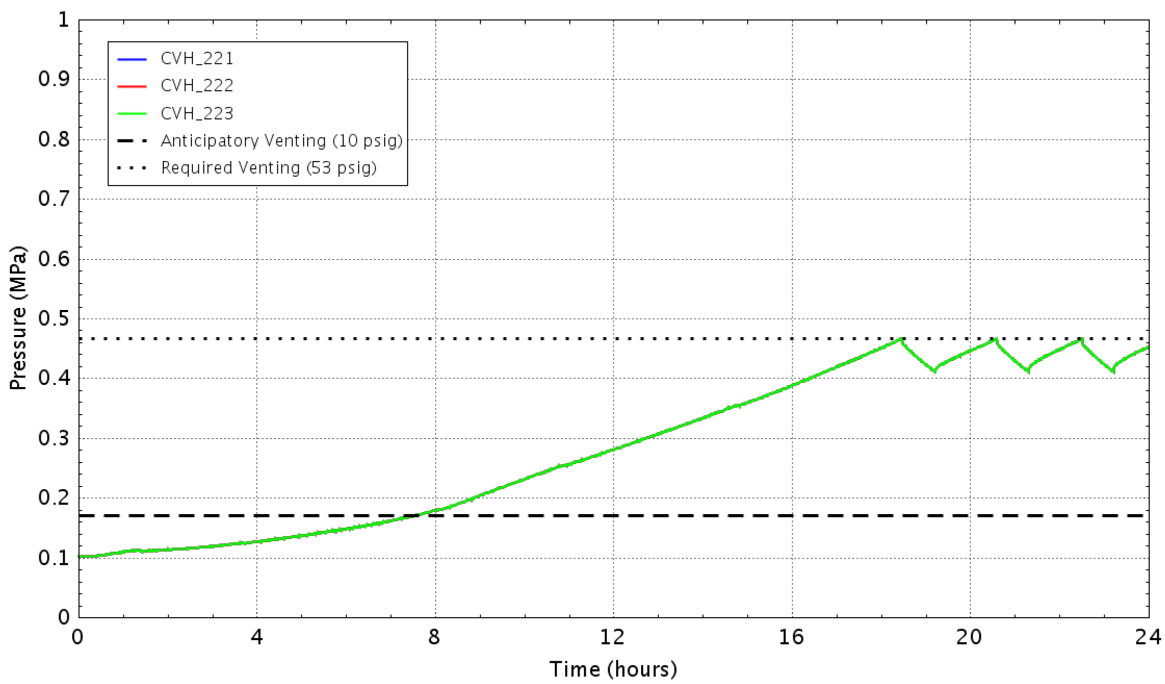

Figure C - 75 Pressure in the wetwell

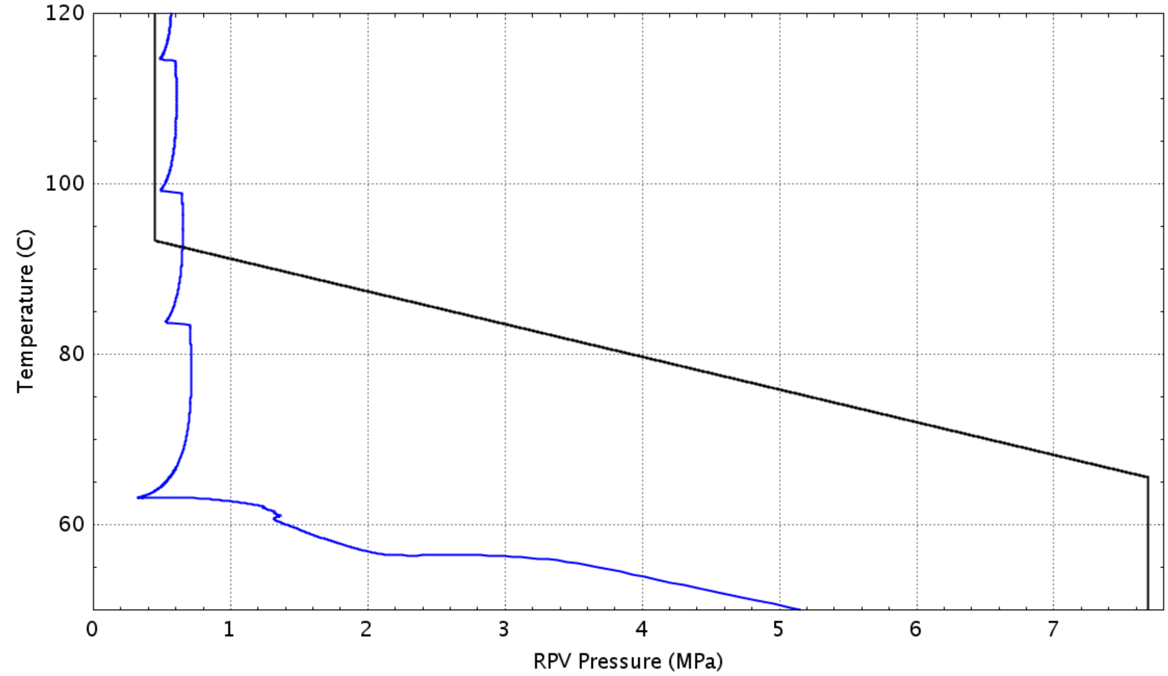

Figure C - 76 Plant status relative to the HCL curve (Graph 4 of the EOPs)

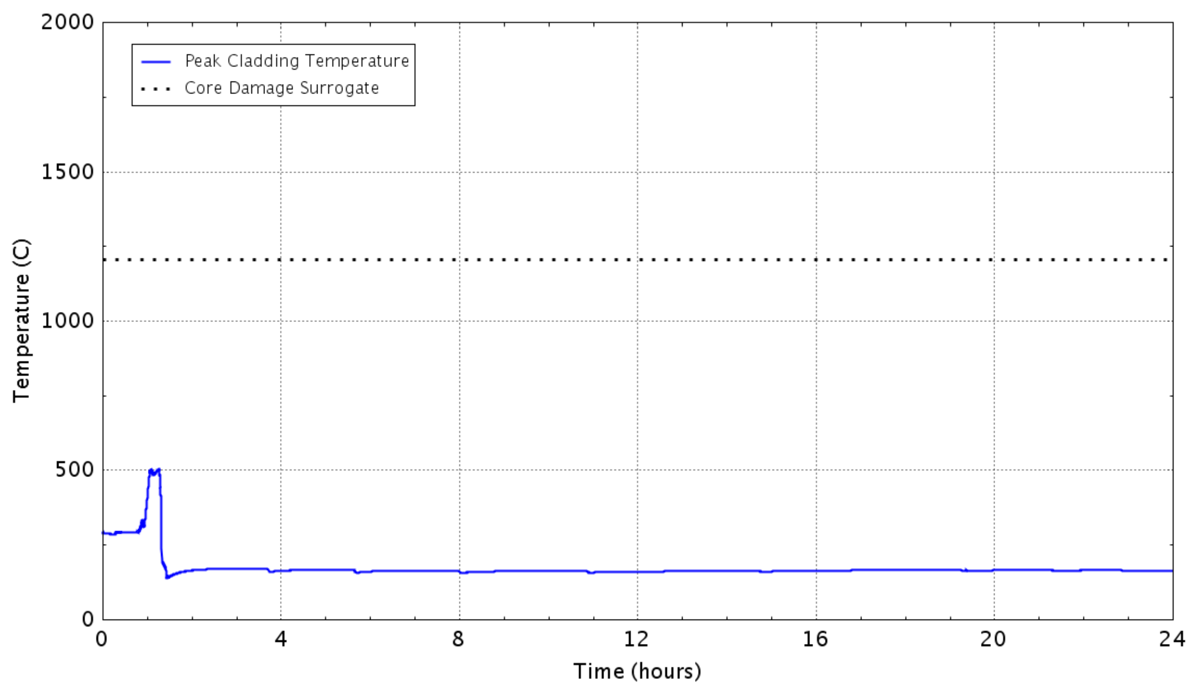

Figure C - 77 Peak temperature of the fuel cladding as a function of time

C.1.8 Case 8: TRANS-30, Nominal CRDHS, Automatic MSIV Closure, ADS at -25 in., Two SRVs

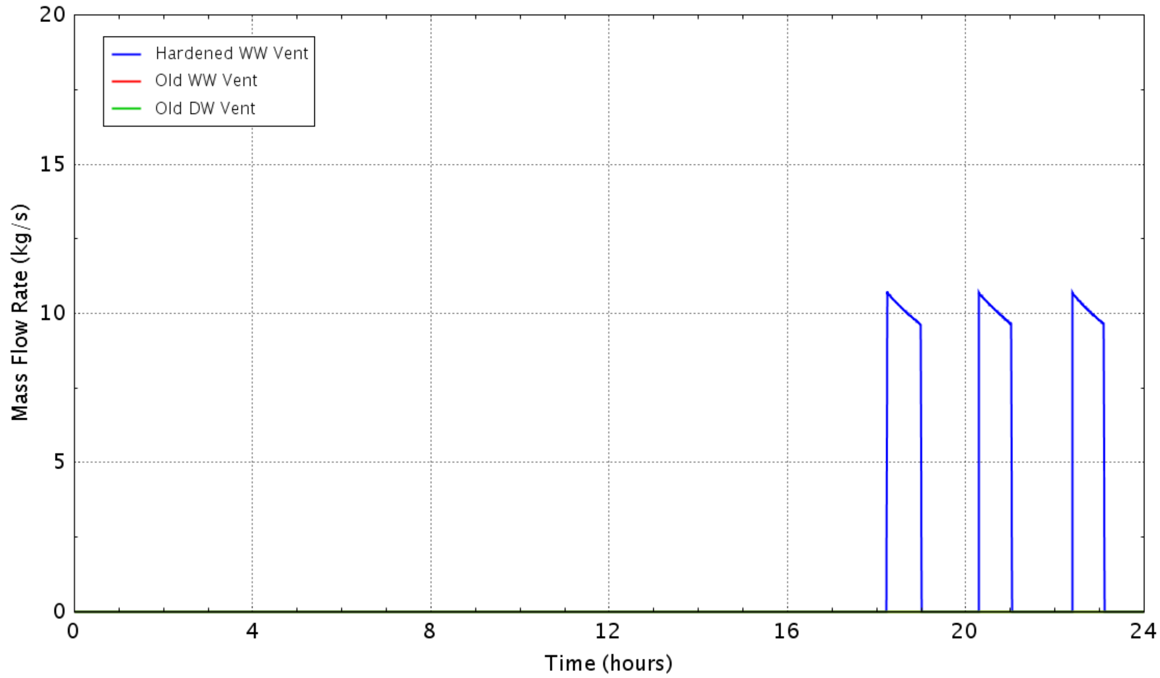

Figure C - 78 Flow rate of the containment vents

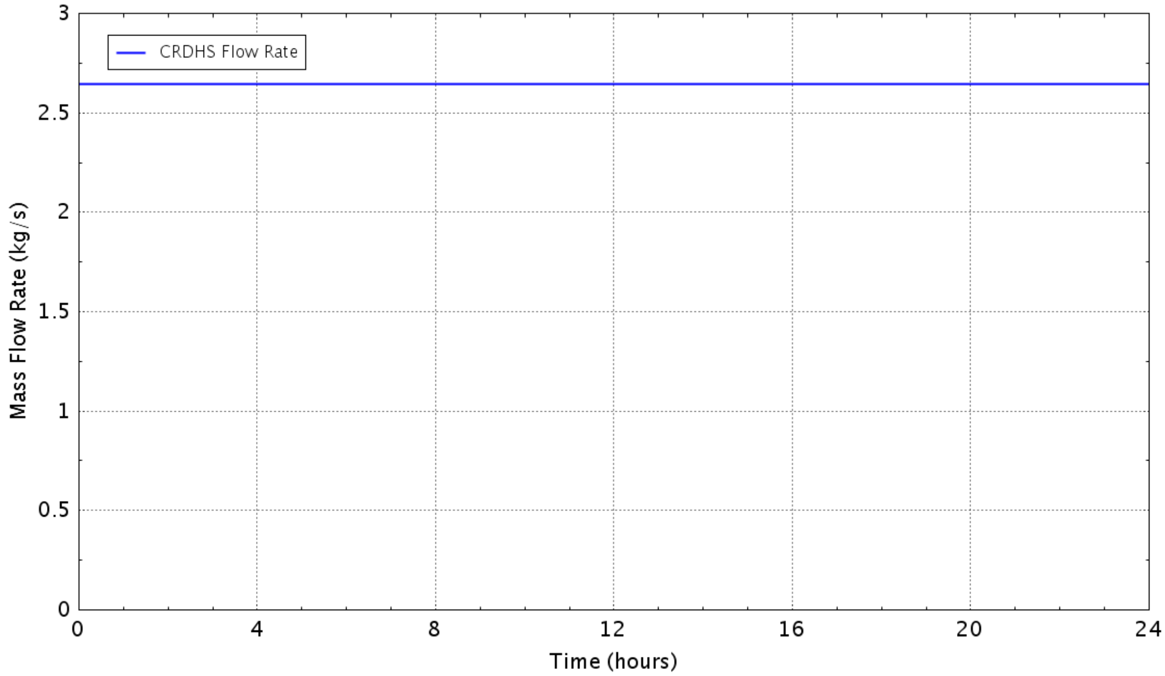

Figure C - 79 Flow rate of the control rod drive hydraulic system

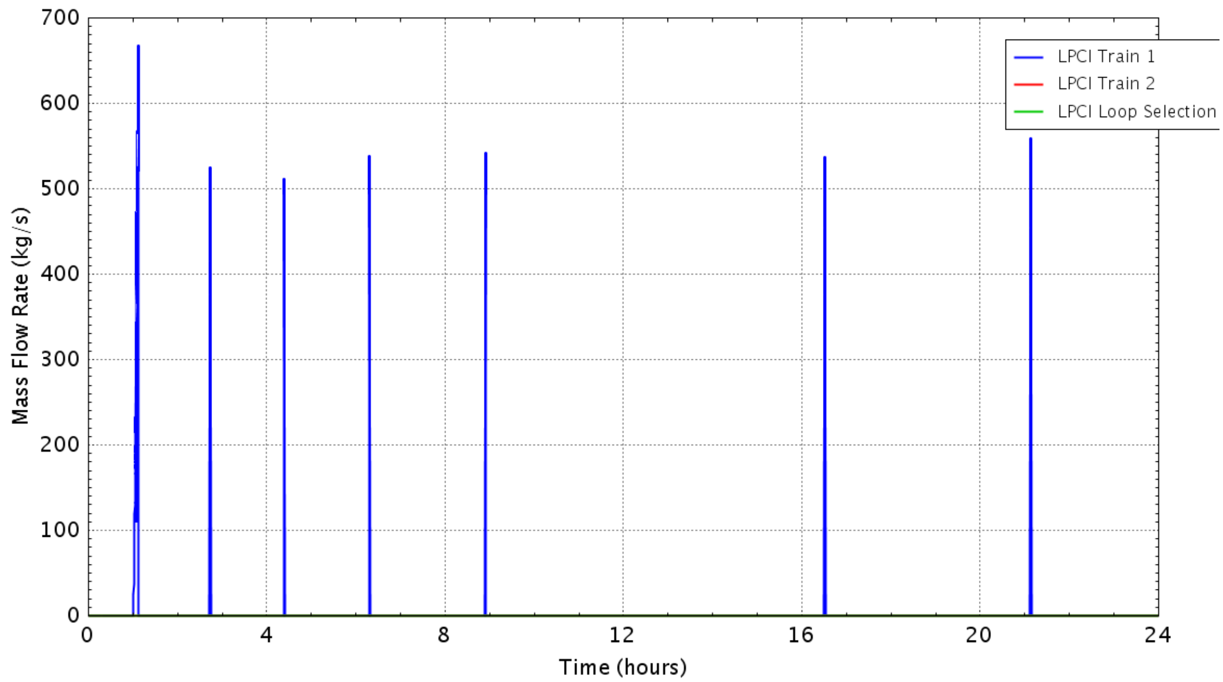

Figure C - 80 Flow rate of the LPCI pump

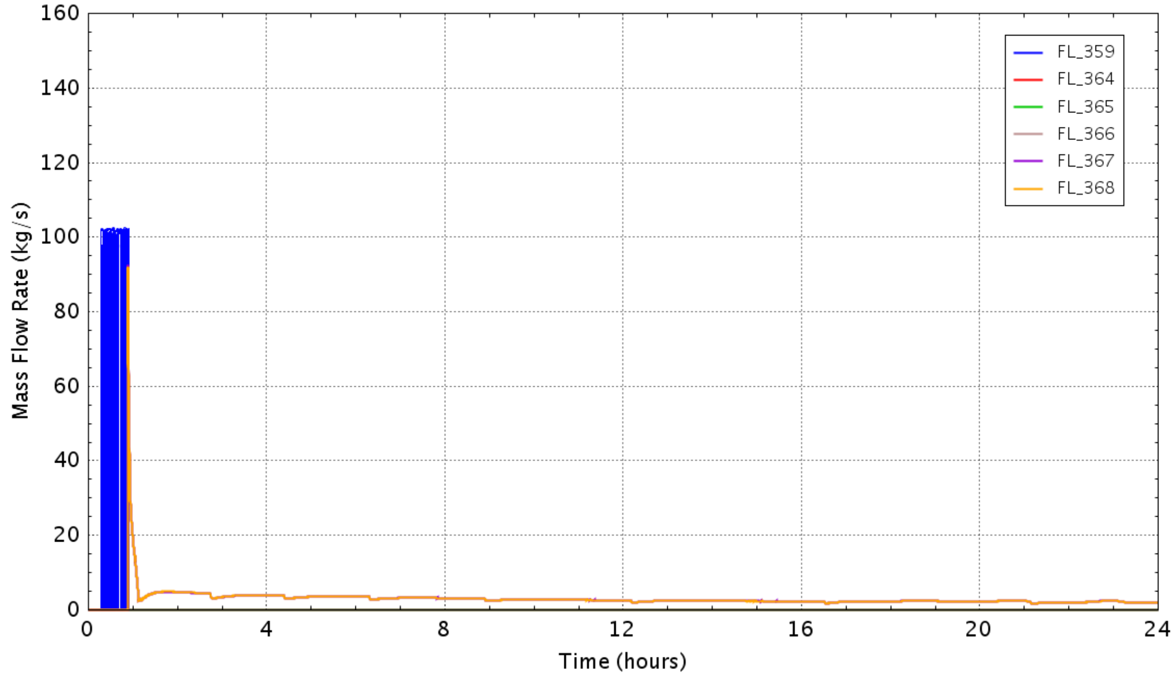

Figure C - 81 Flow rate of the SRVs

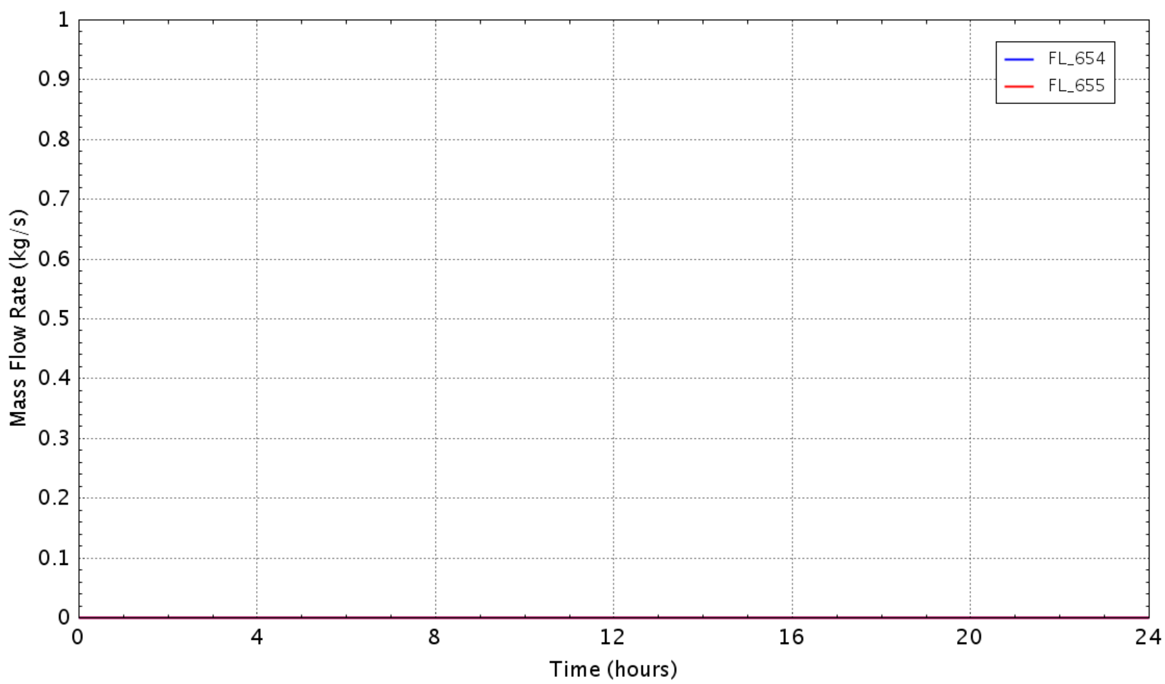

Figure C - 82 Flow rate of the wetwell cooling system

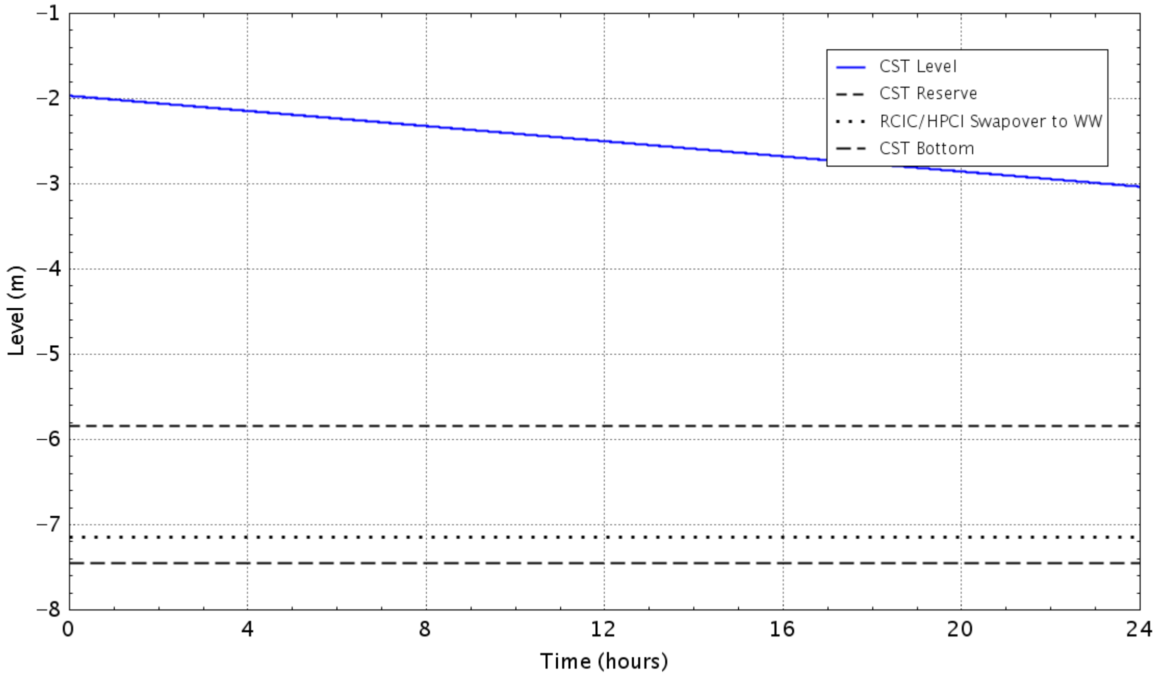

Figure C - 83 Water level in the CST

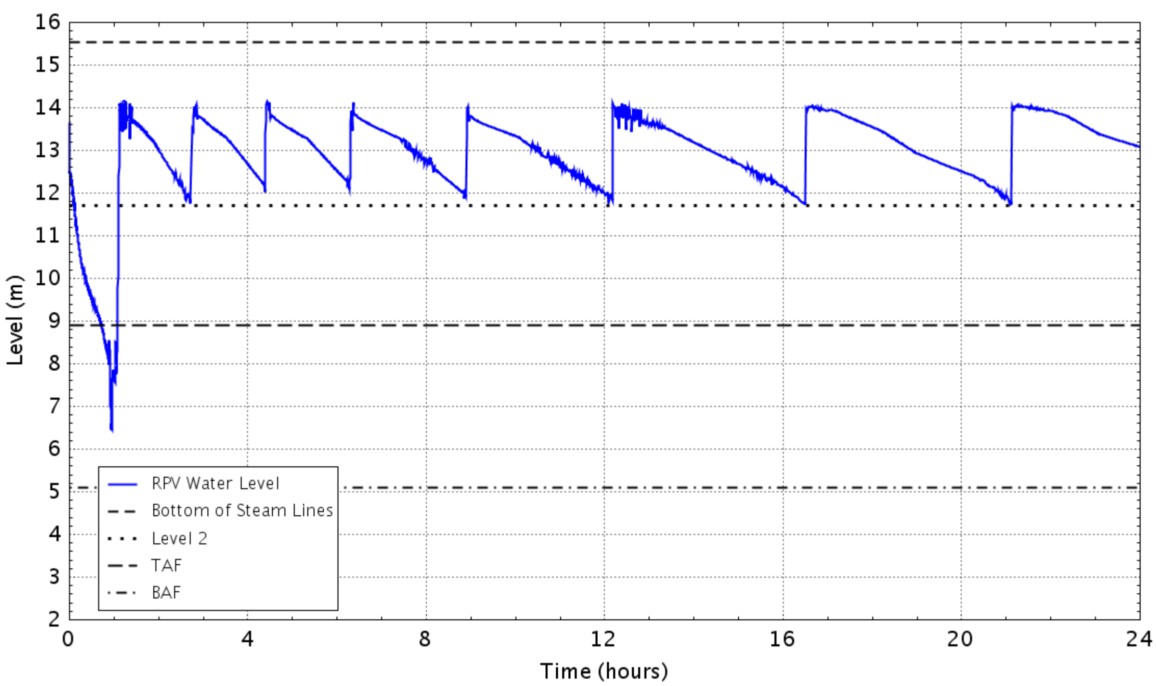

Figure C - 84   RPV Downcomer water level

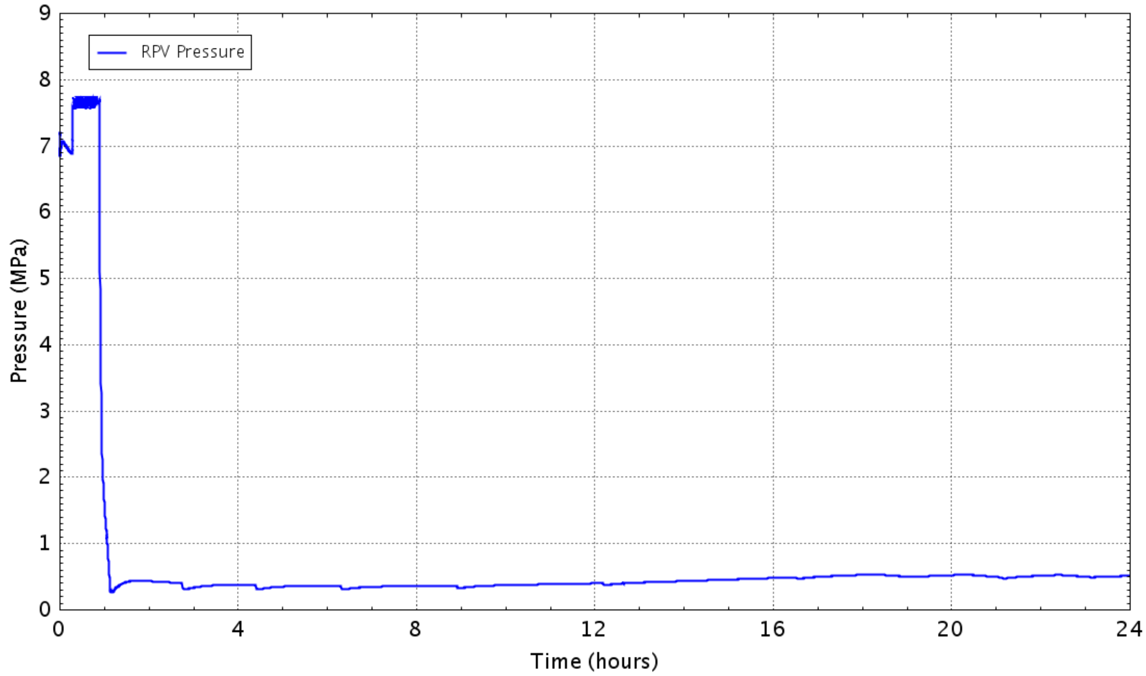

Figure C - 85 Pressure in the RPV

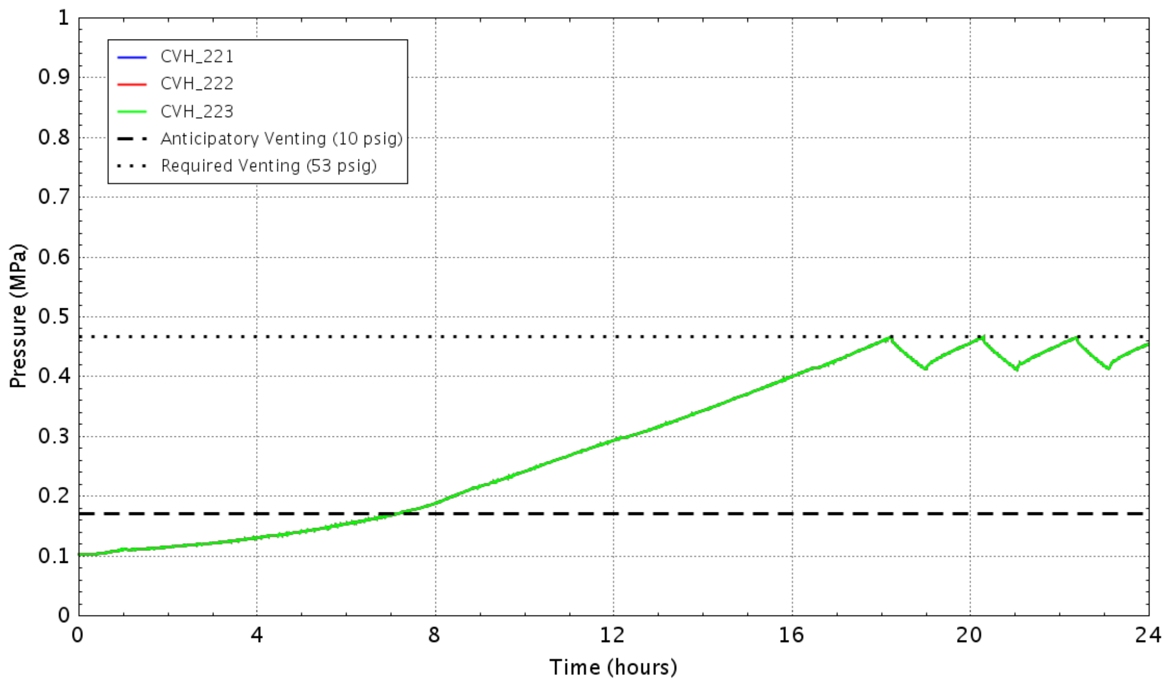

Figure C - 86 Pressure in the wetwell

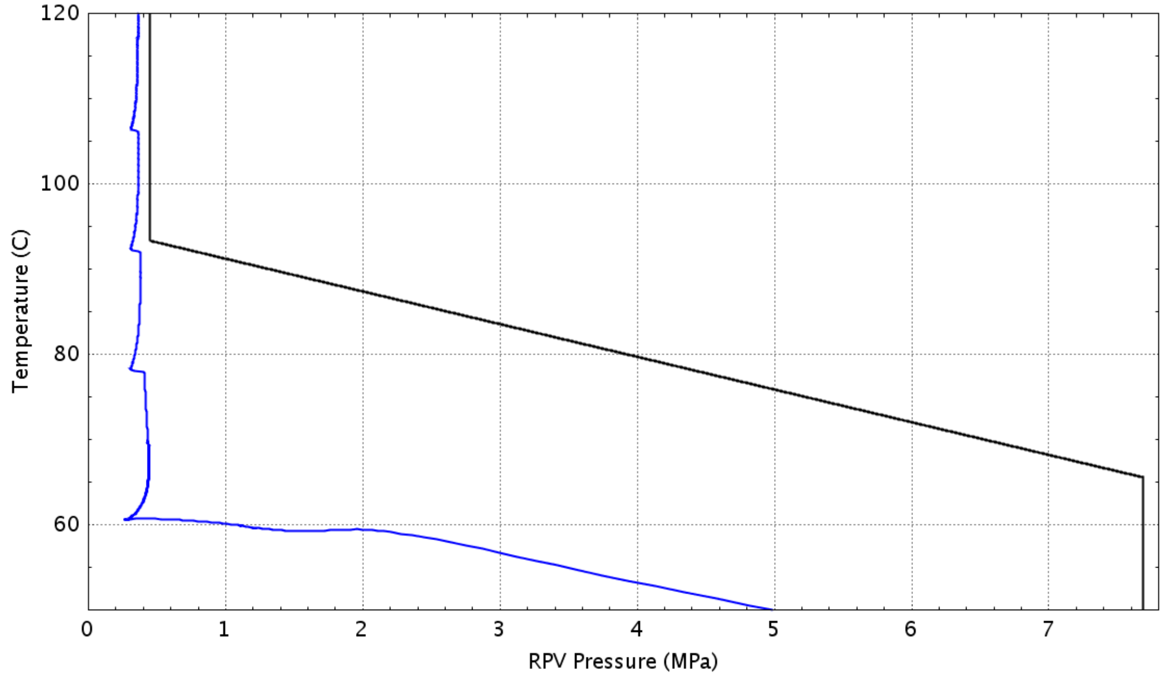

Figure C - 87 Plant status relative to the HCL curve (Graph 4 of the EOPs)

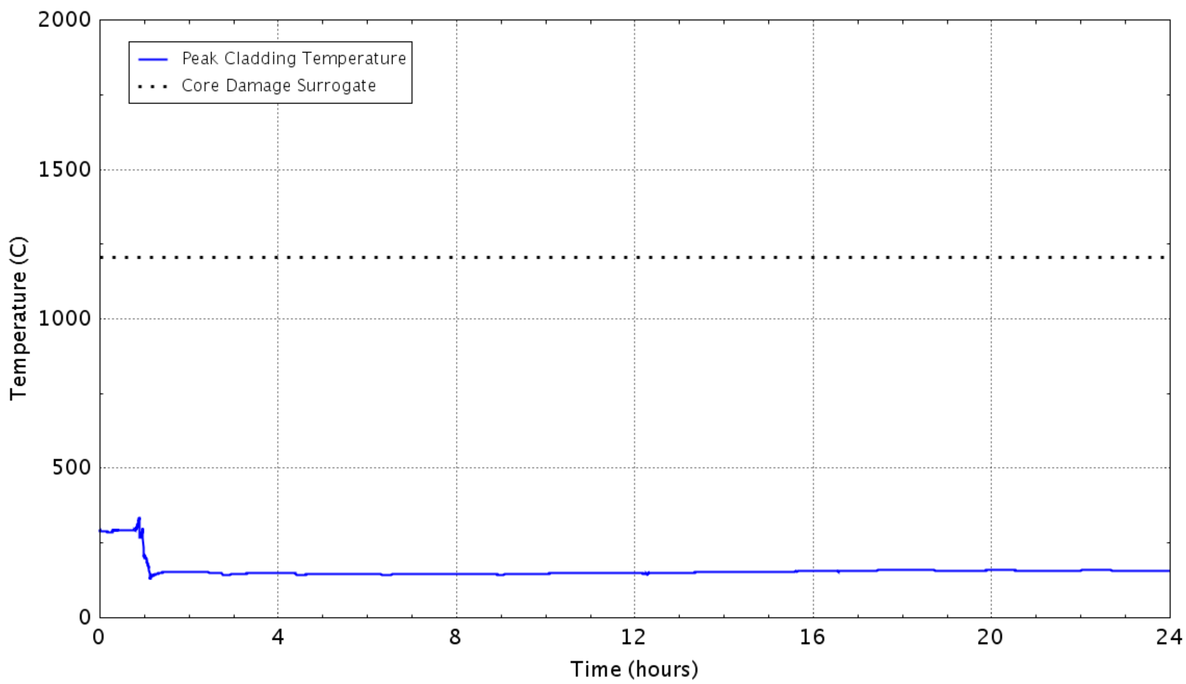

Figure C - 88 Peak temperature of the fuel cladding as a function of time

C.1.9 Case 9: TRANS-30, One Train of CRDHS, MSIV Closure at 10 min., RPV Pressure Follows HCL Curve

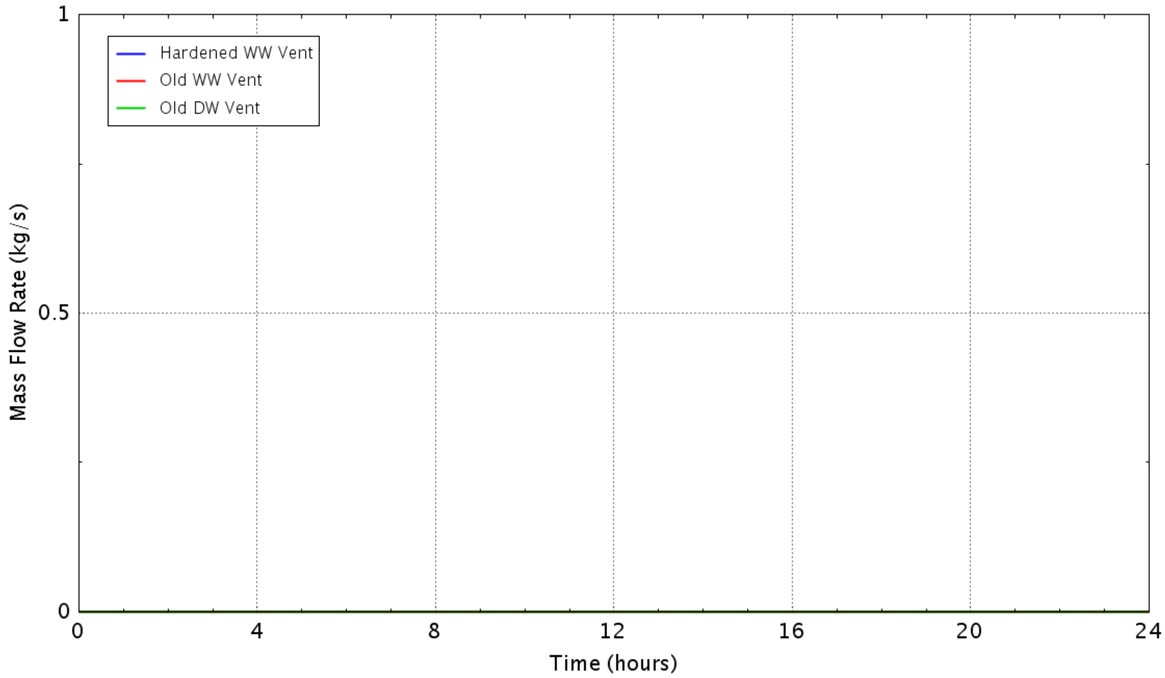

Figure C - 89 Flow rate of the containment vents

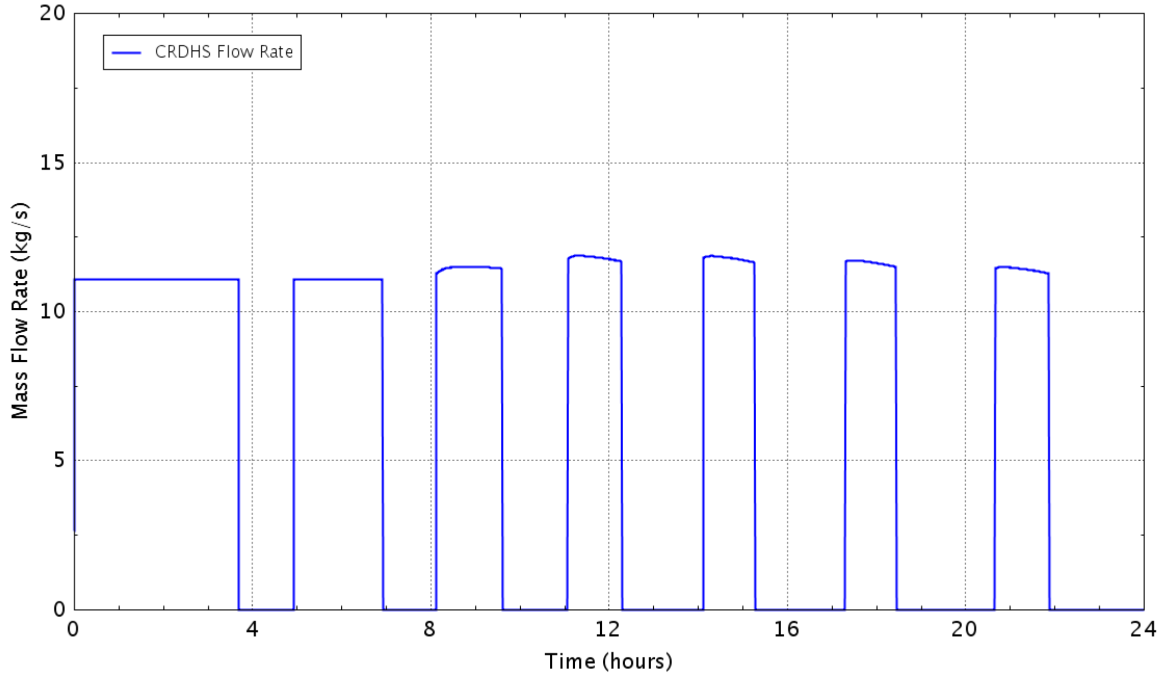

Figure C - 90 Flow rate of the control rod drive hydraulic system

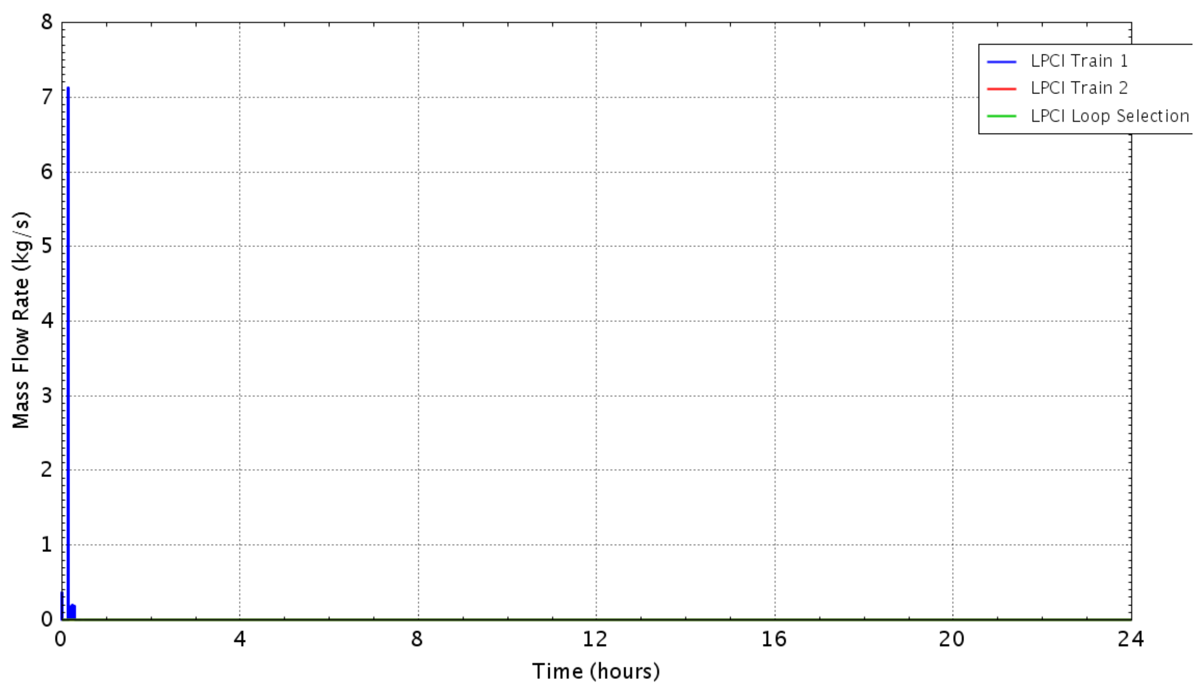

Figure C - 91 Flow rate of the LPCI pump

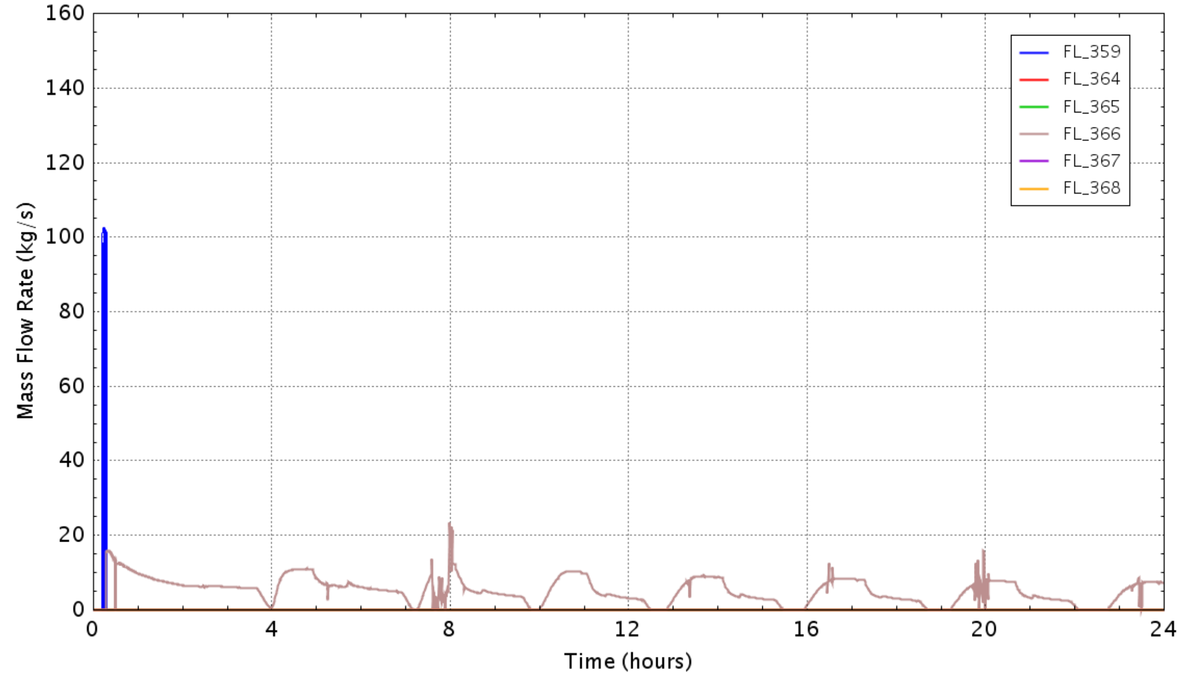

Figure C - 92 Flow rate of the SRVs

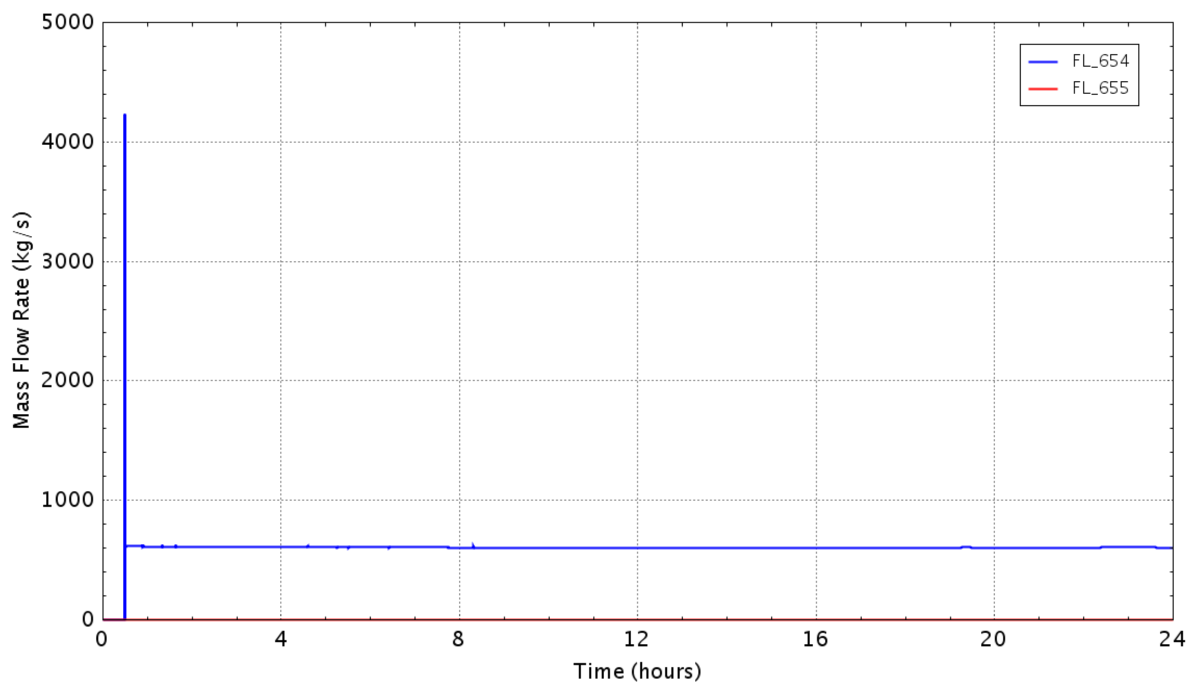

Figure C - 93 Flow rate of the wetwell cooling system

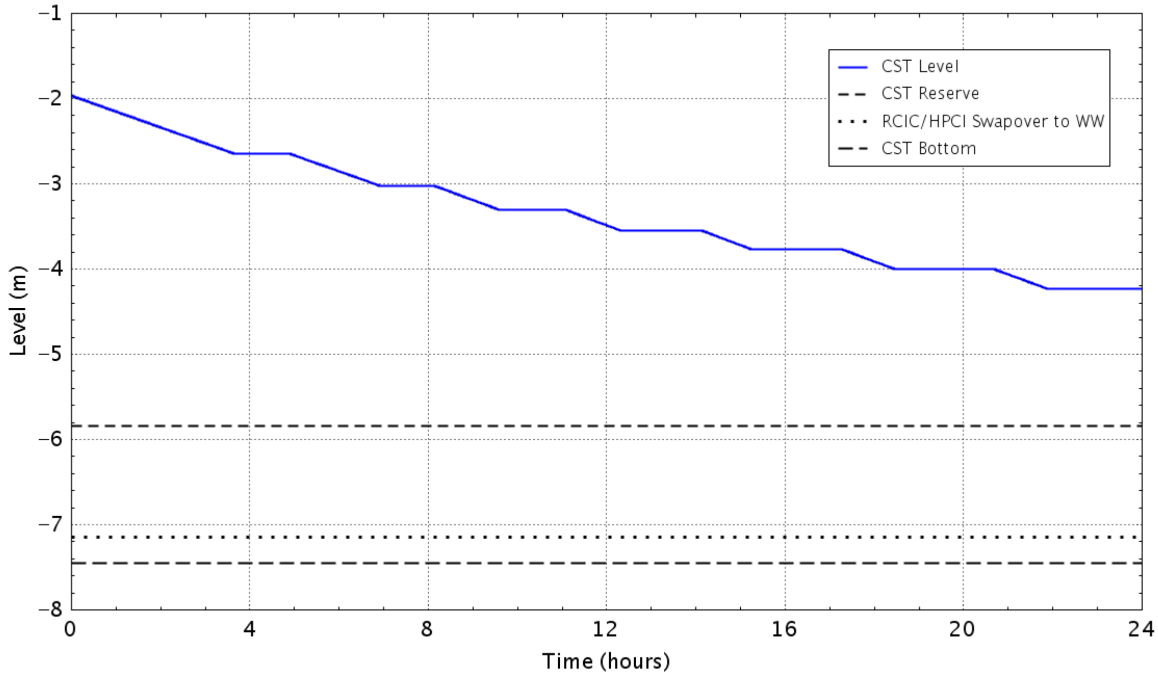

Figure C - 94 Water level in the CST

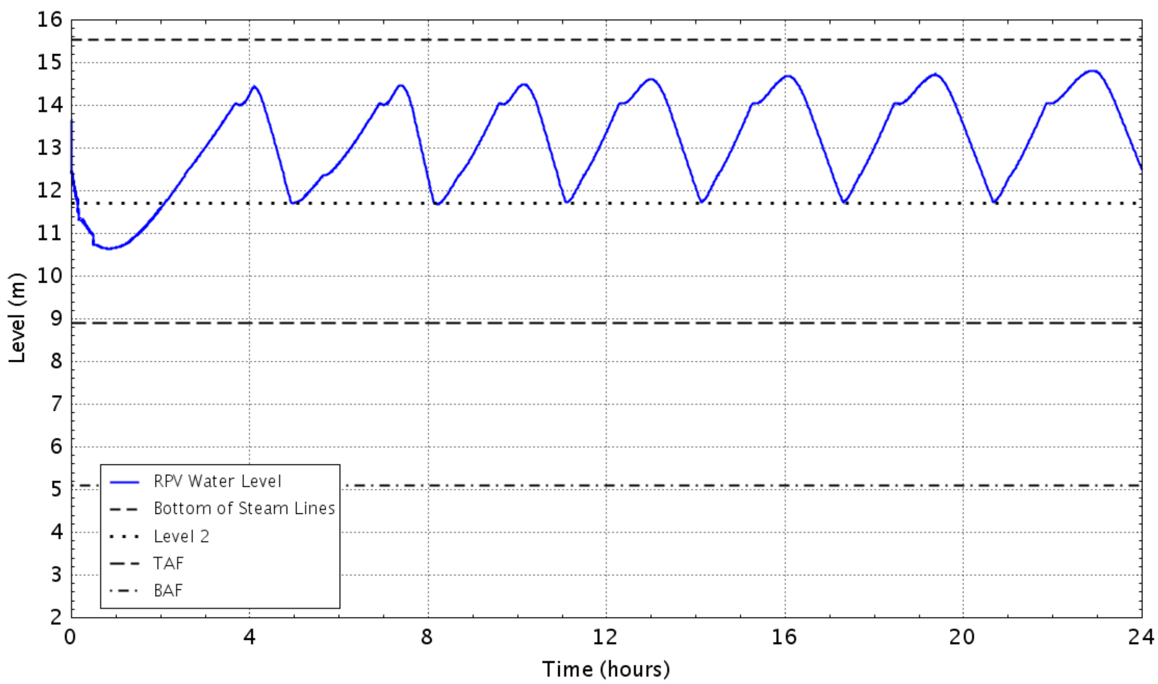

Figure C - 95 RPV Downcomer water level

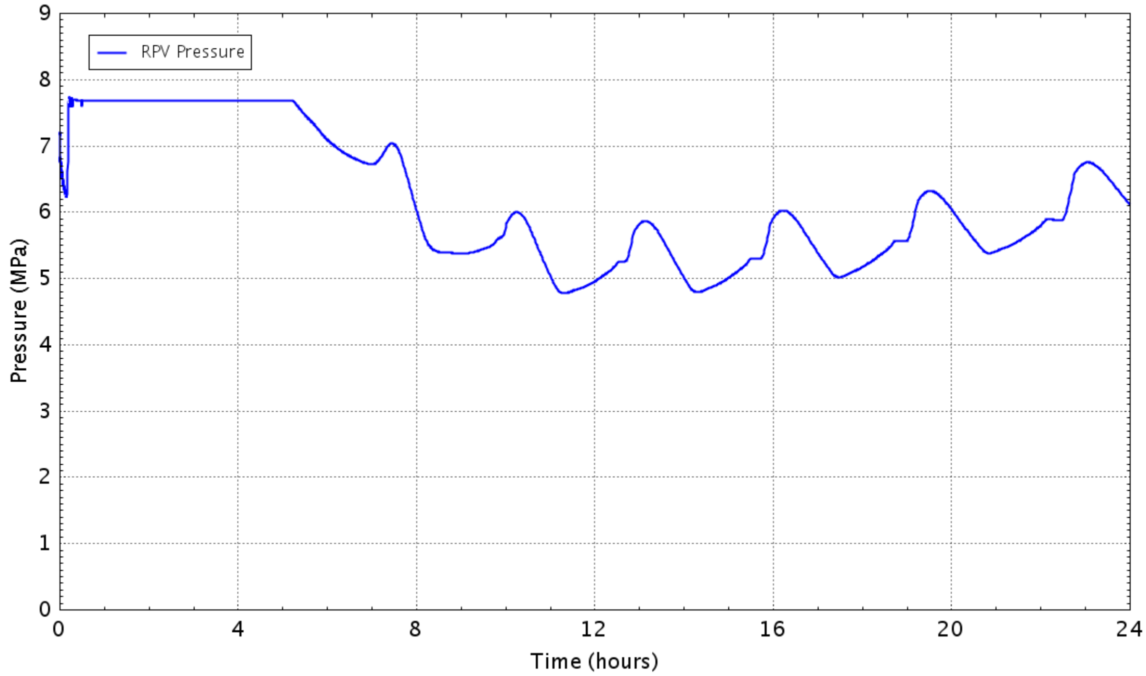

Figure C - 96 Pressure in the RPV

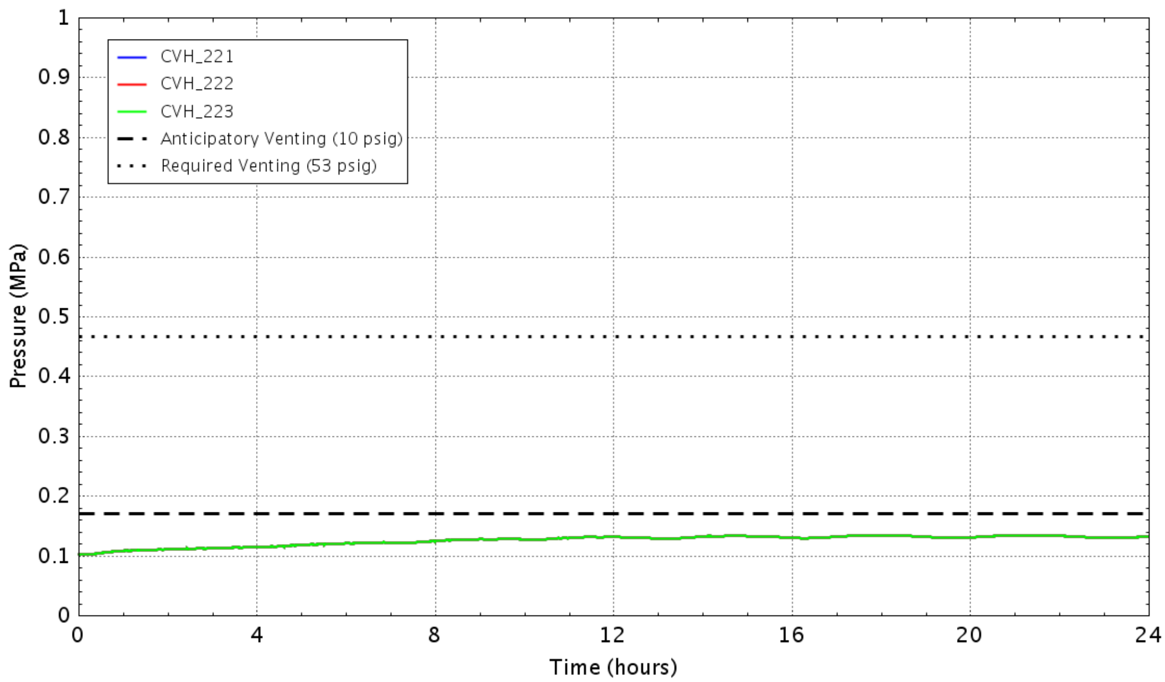

Figure C - 97 Pressure in the wetwell

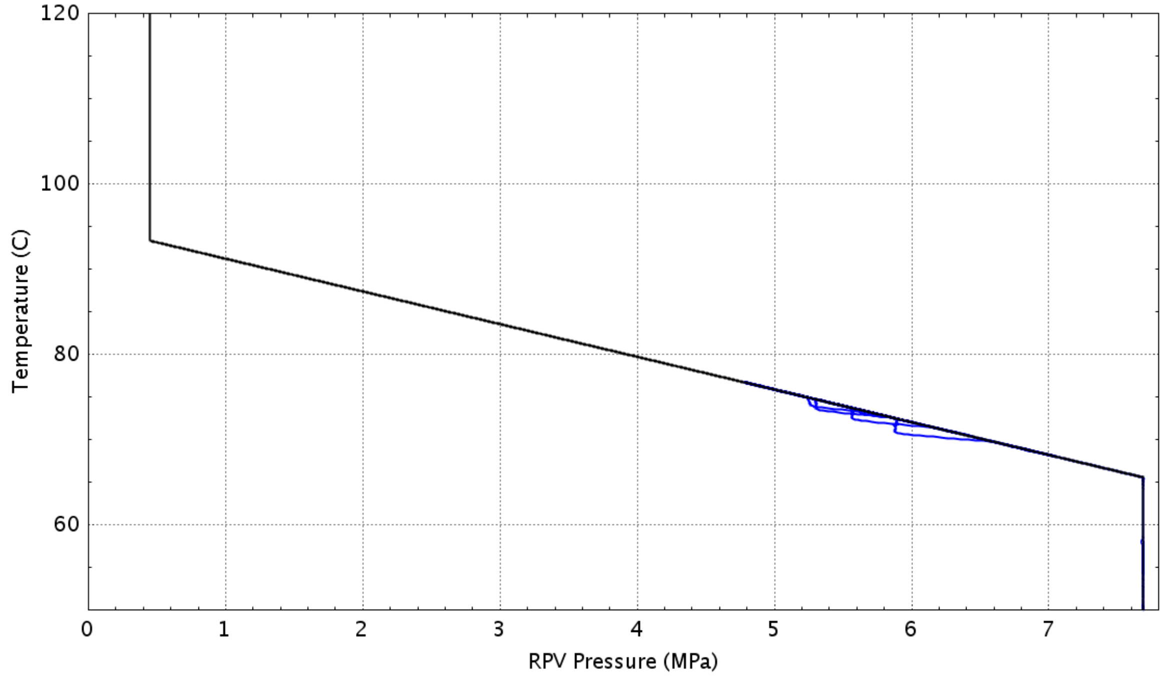

Figure C - 98   Plant status relative to the HCL curve (Graph 4 of the EOPs)

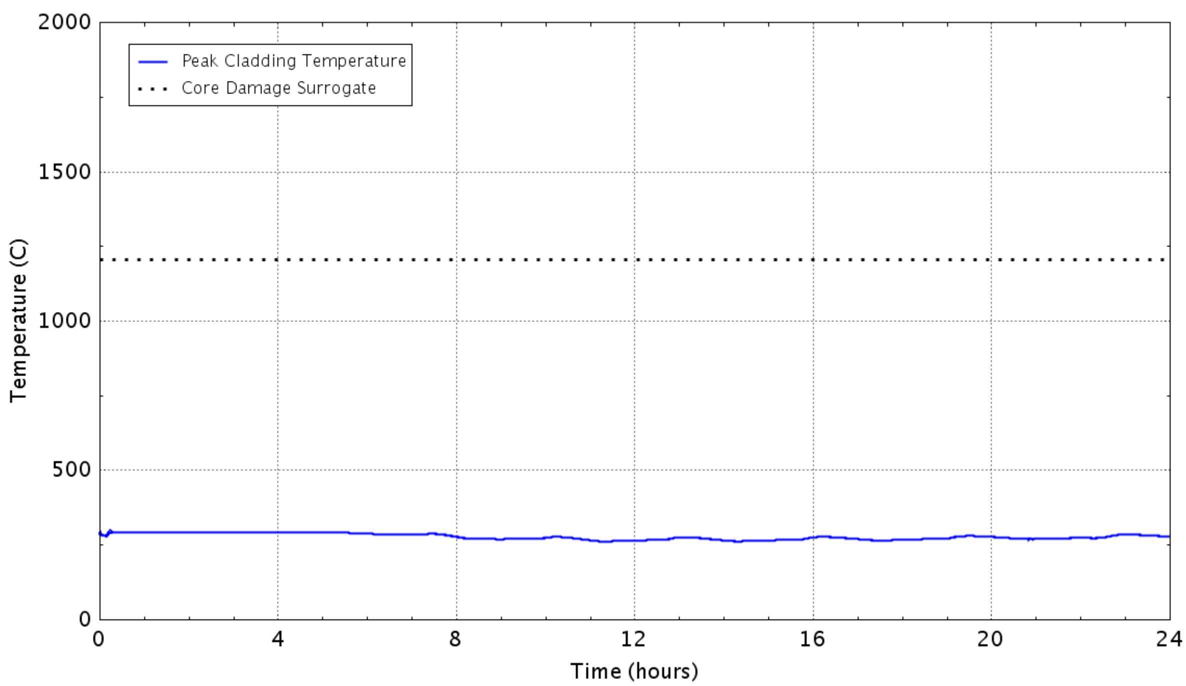

Figure C - 99 Peak temperature of the fuel cladding as a function of time

C.1.10 Case 10: TRANS-30, One Train of CRDHS, MSIV Closure at 10 min.,Emergency Depressurization at HCL Curve

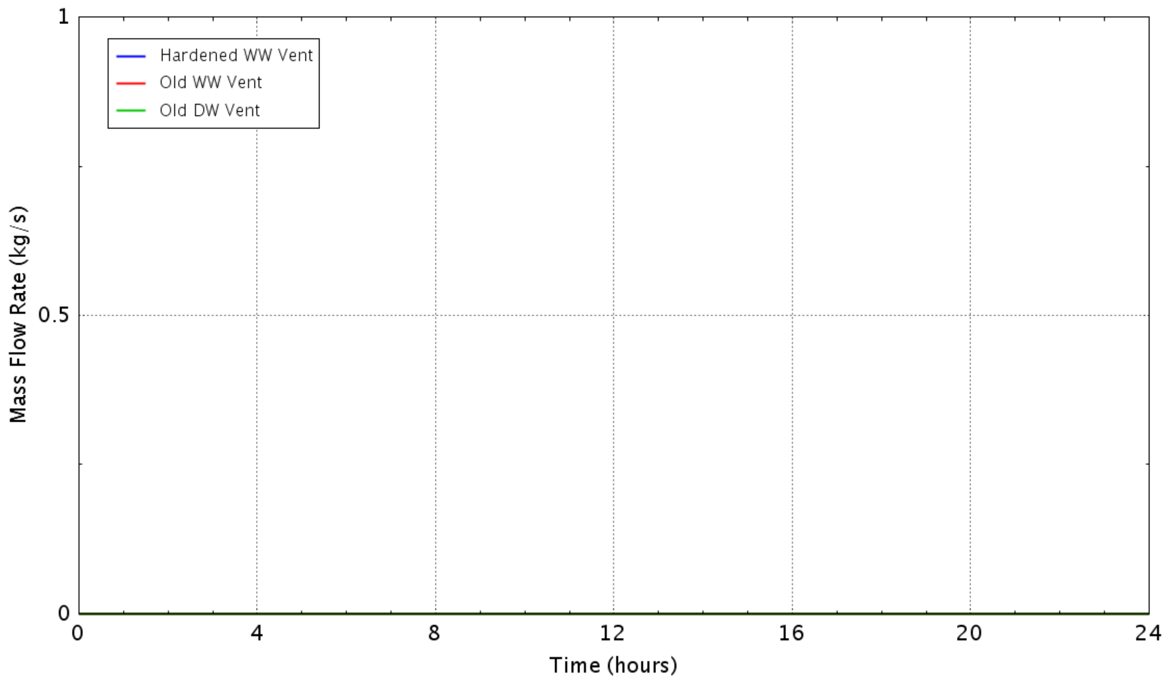

Figure C - 100 Flow rate of the containment vents

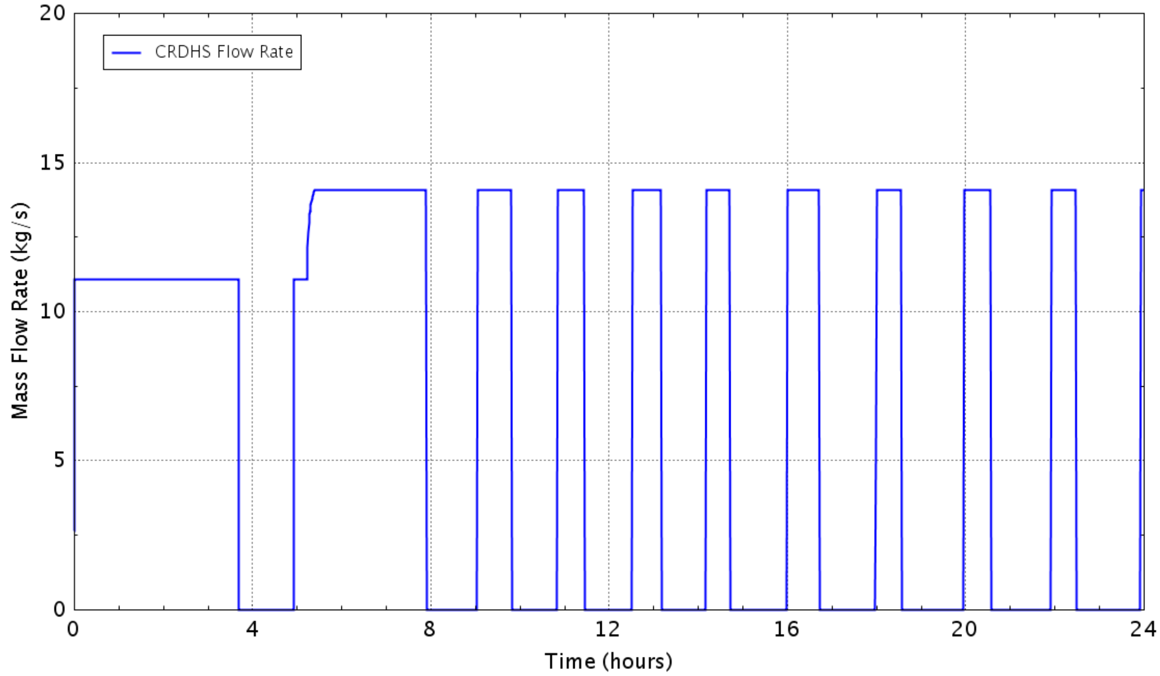

Figure C - 101 Flow rate of the control rod drive hydraulic system

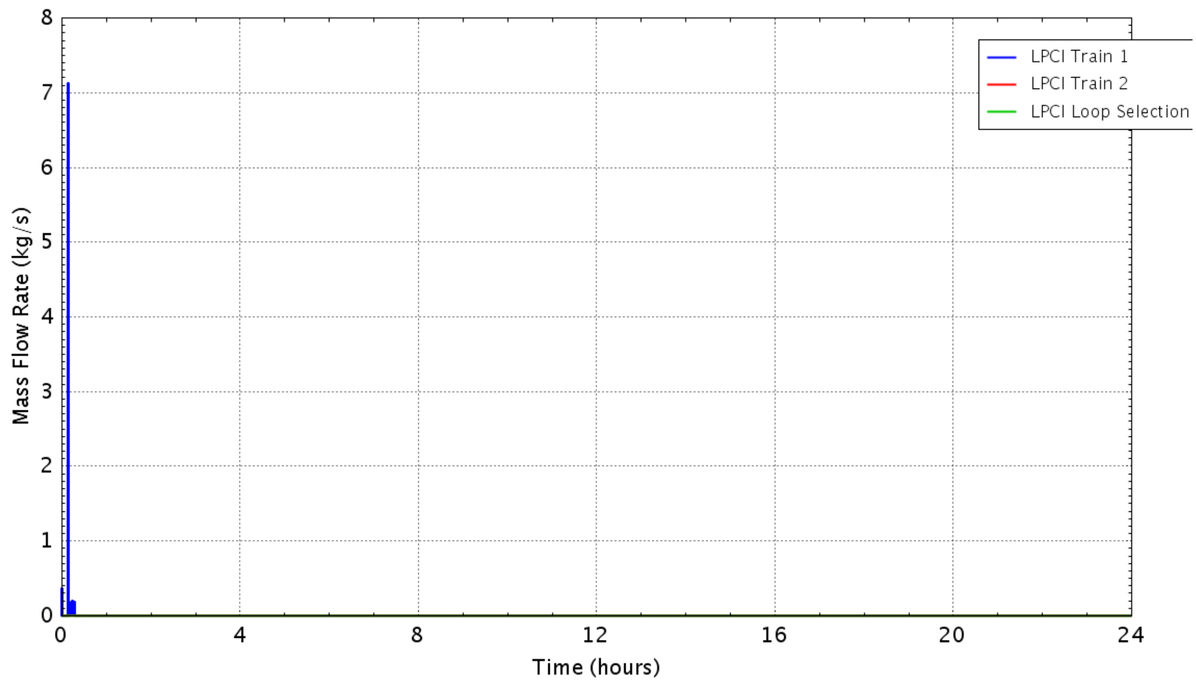

Figure C - 102 Flow rate of the LPCI pump

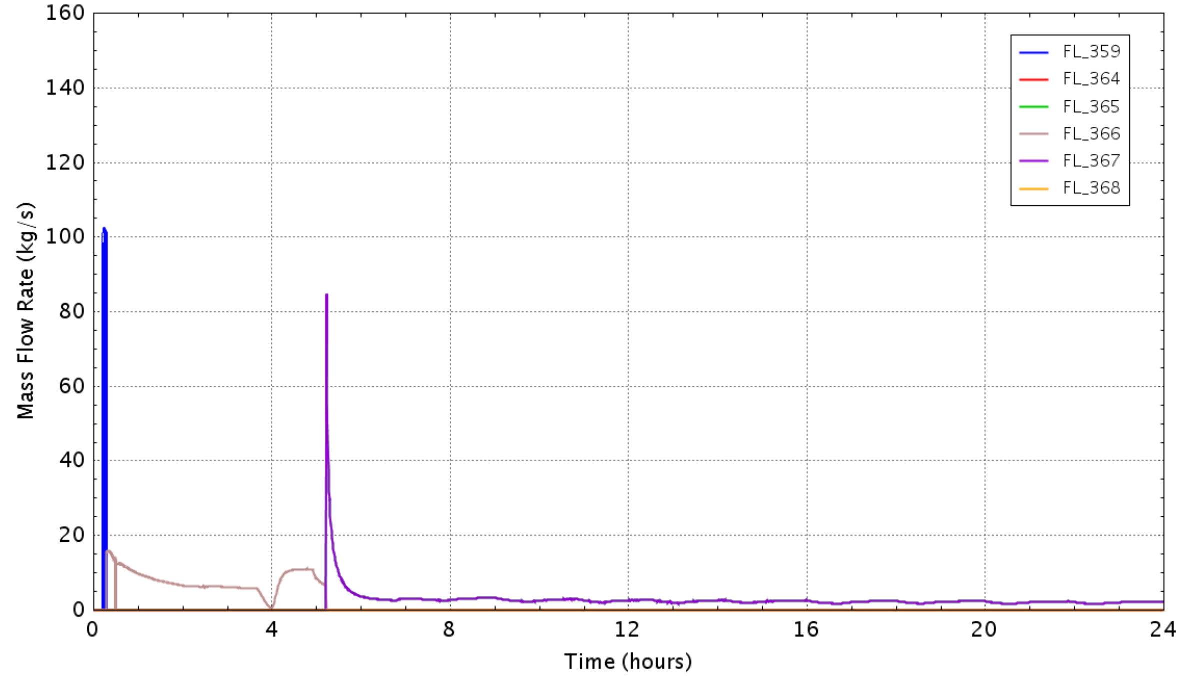

Figure C - 103 Flow rate of the SRVs

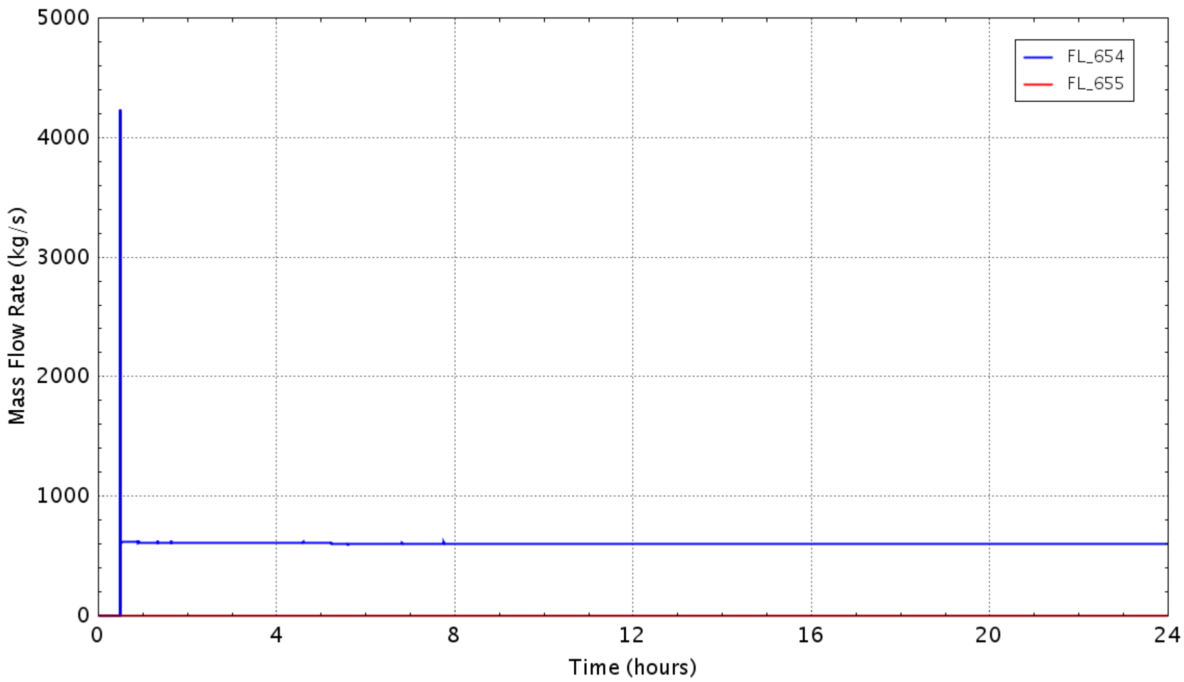

Figure C - 104 Flow rate of the wetwell cooling system

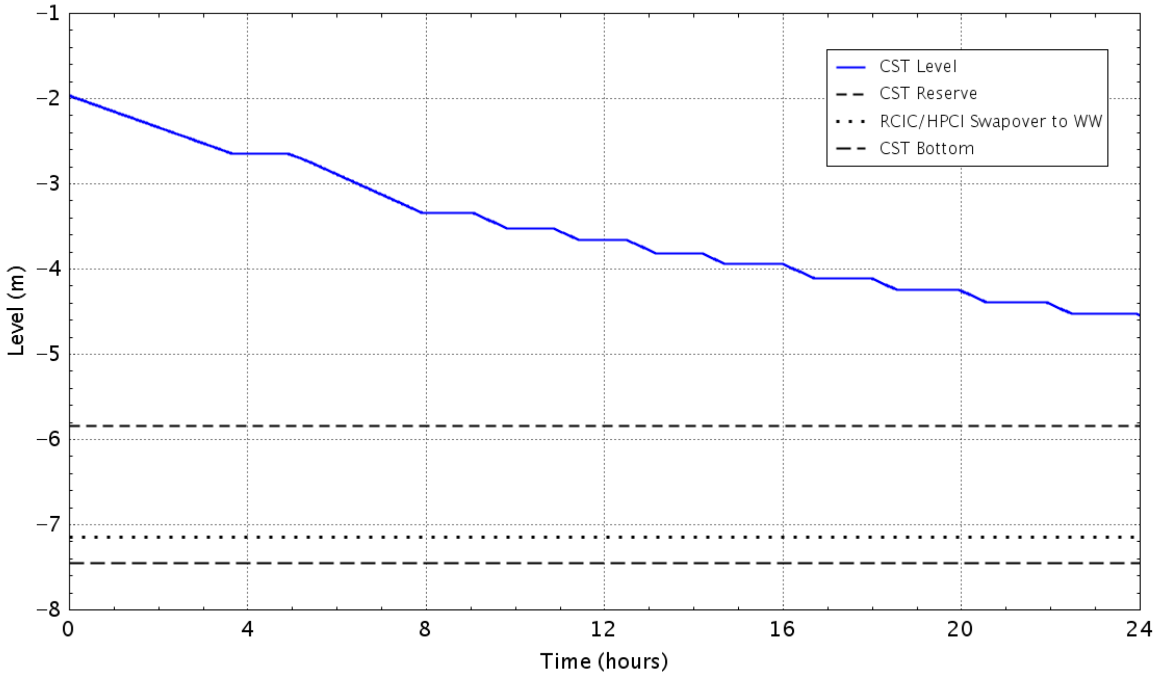

Figure C - 105 Water level in the CST

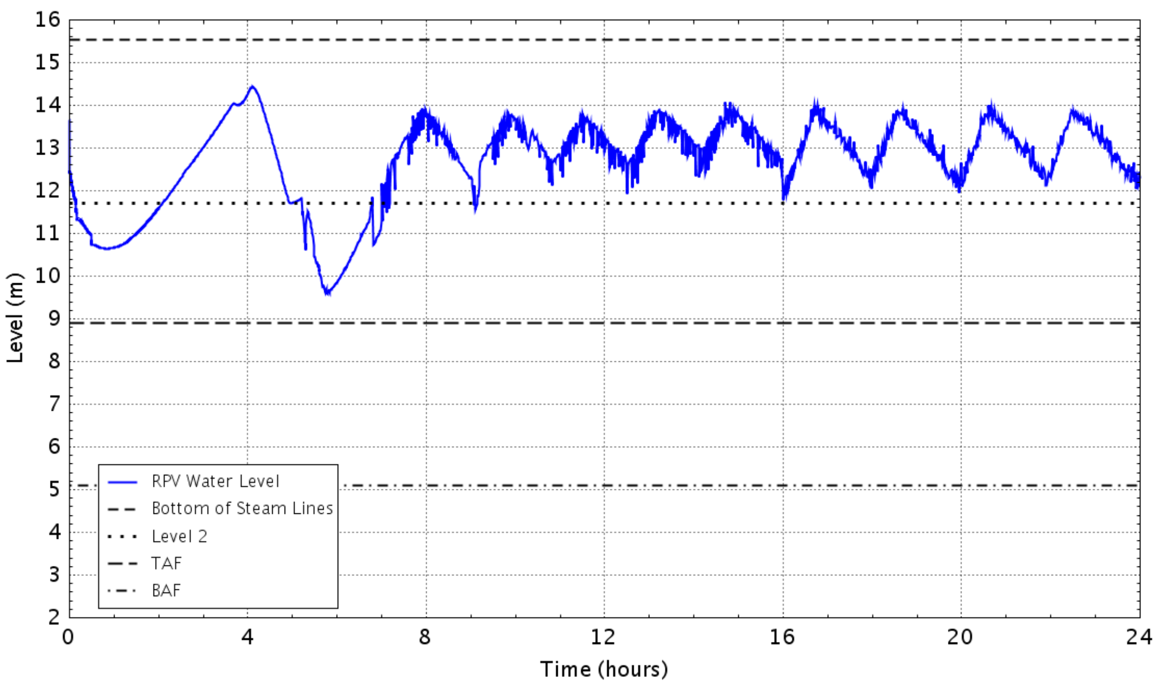

Figure C - 106 RPV Downcomer water level

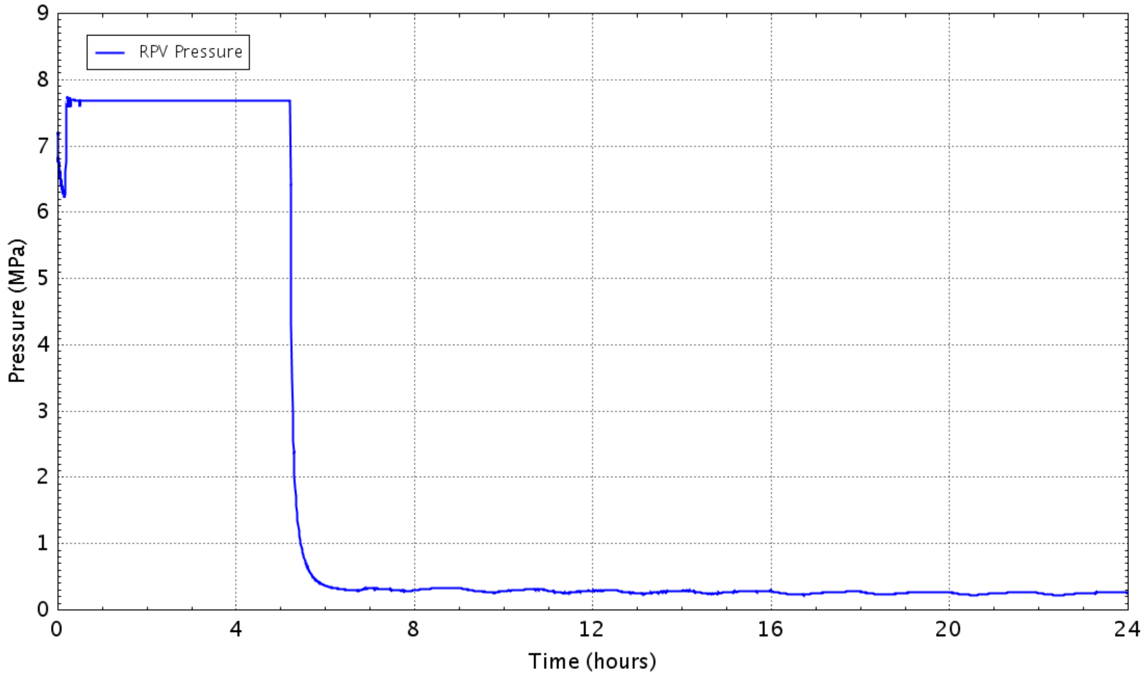

Figure C - 107 Pressure in the RPV

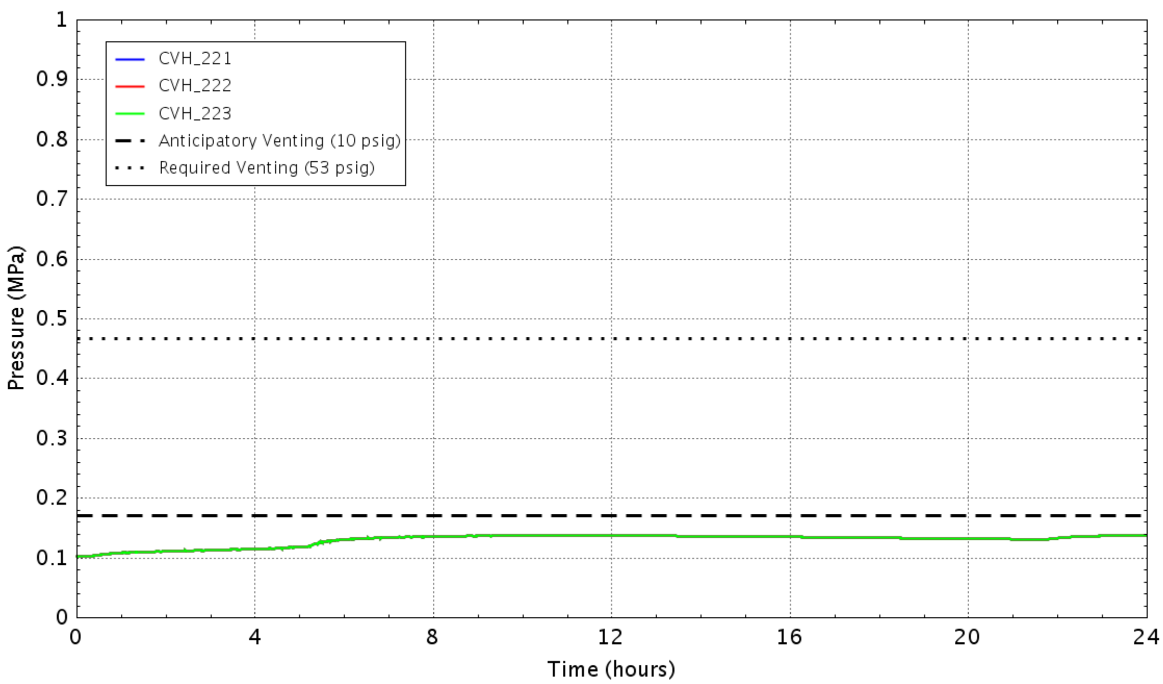

Figure C - 108 Pressure in the wetwell

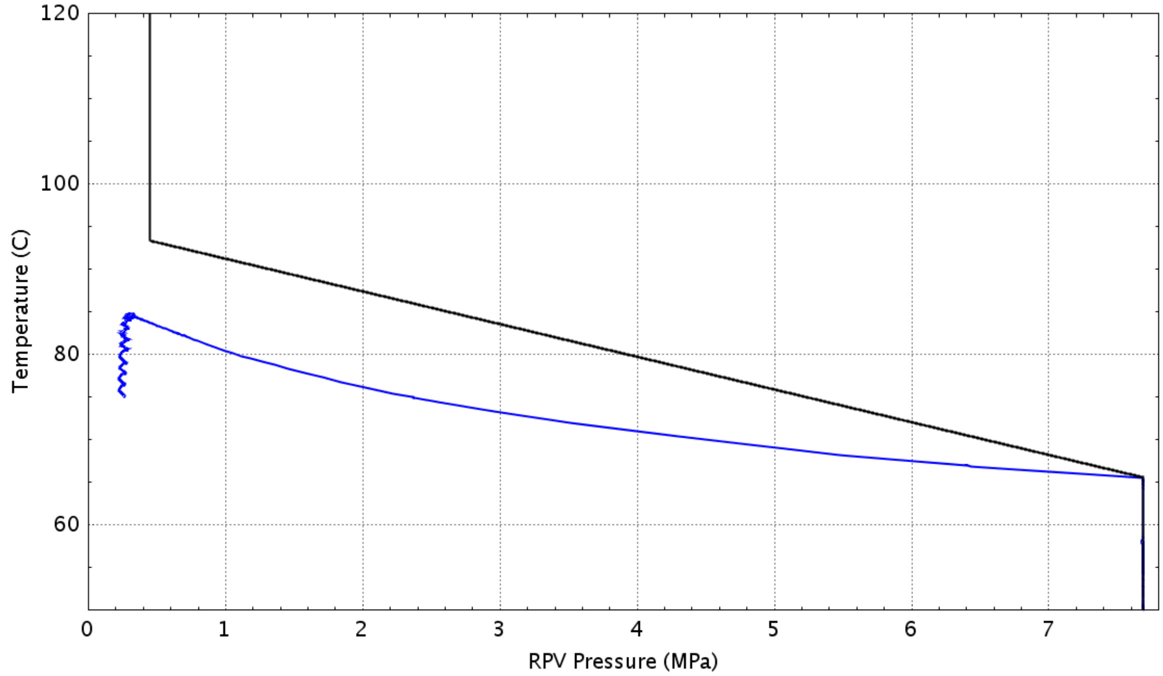

Figure C - 109 Plant status relative to the HCL curve (Graph 4 of the EOPs)

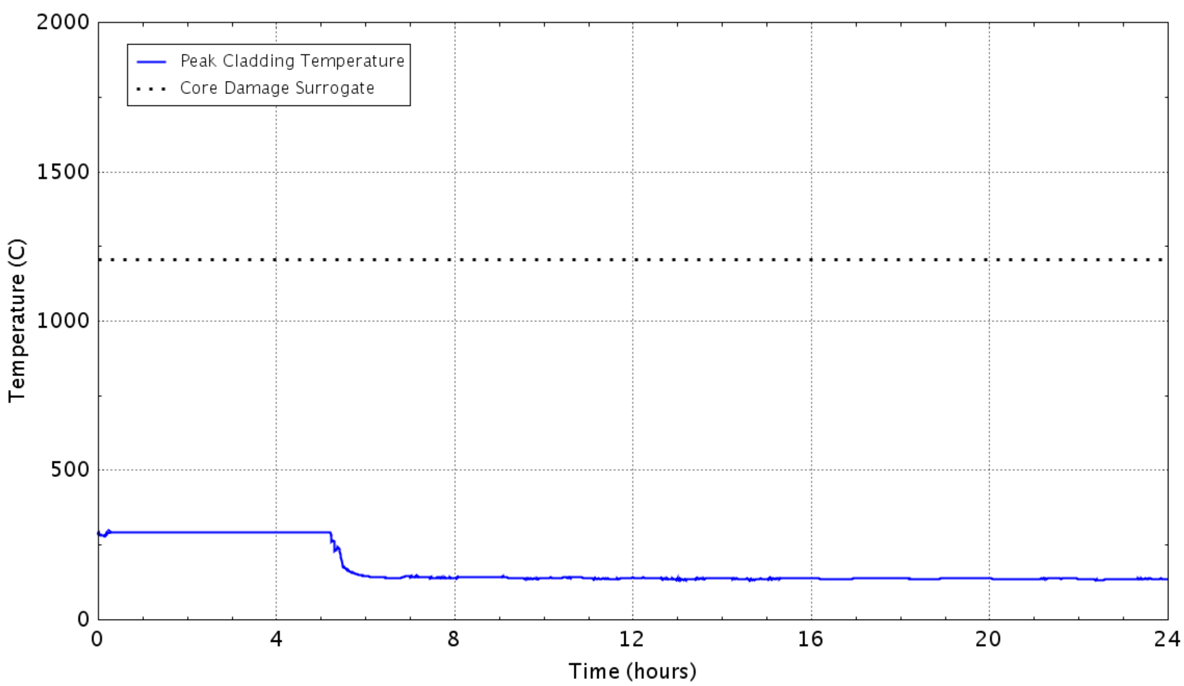

Figure C - 110   Peak temperature of the fuel cladding as a function of time

C.1.11 Case 11: TRANS-30, One Train of CRDHS, MSIV Closure at 20 min., RPV Pressure Follows HCL curve

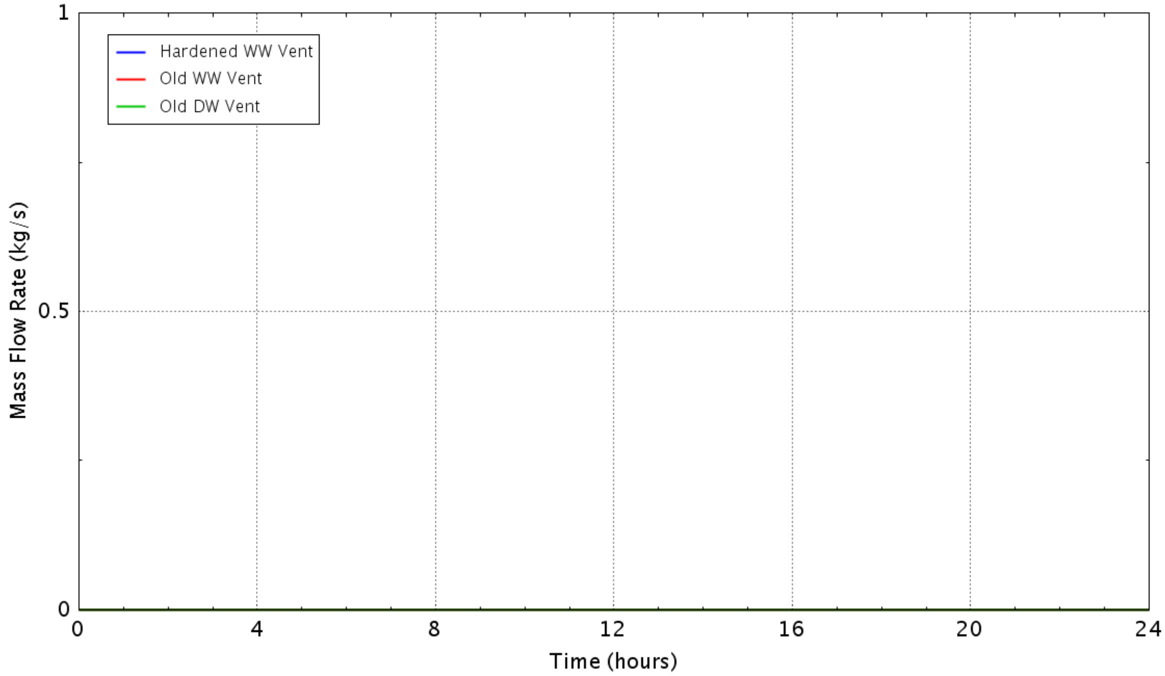

Figure C - 111 Flow rate of the containment vents

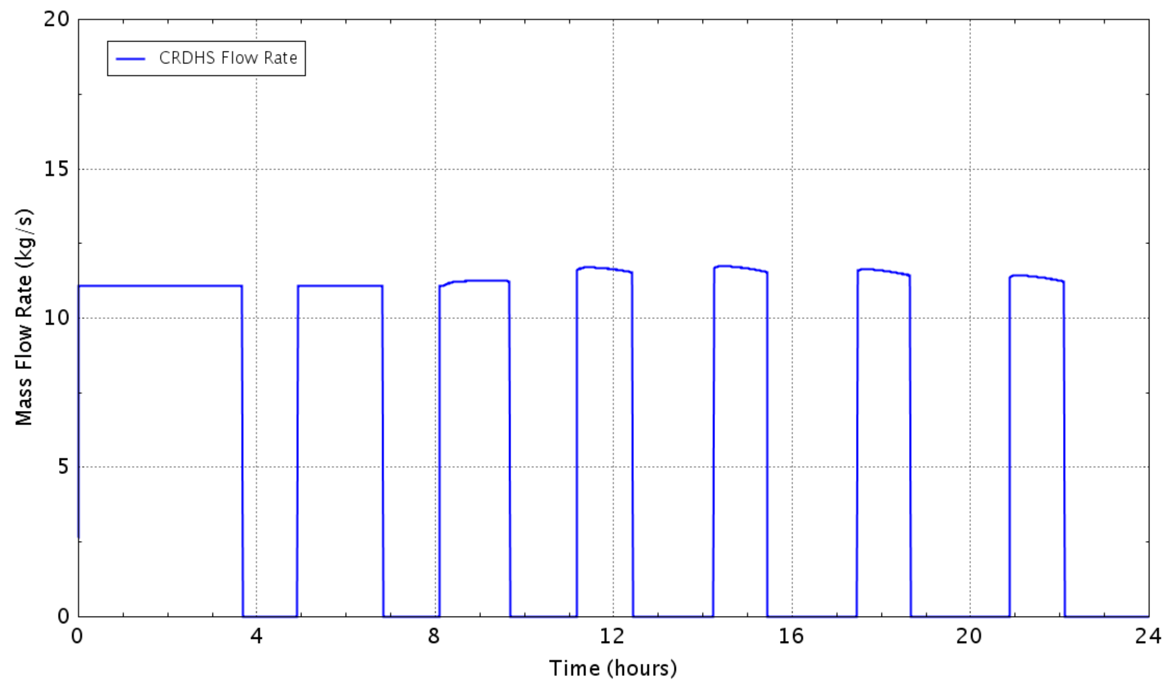

Figure C - 112 Flow rate of the control rod drive hydraulic system

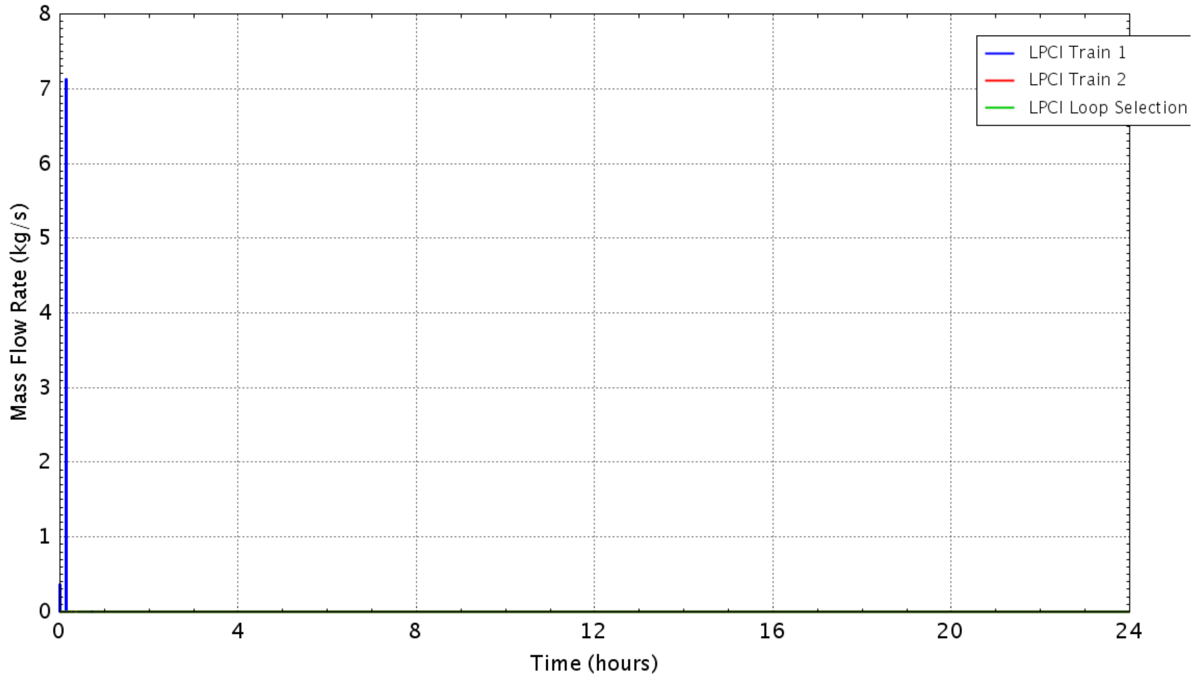

Figure C - 113 Flow rate of the LPCI pump

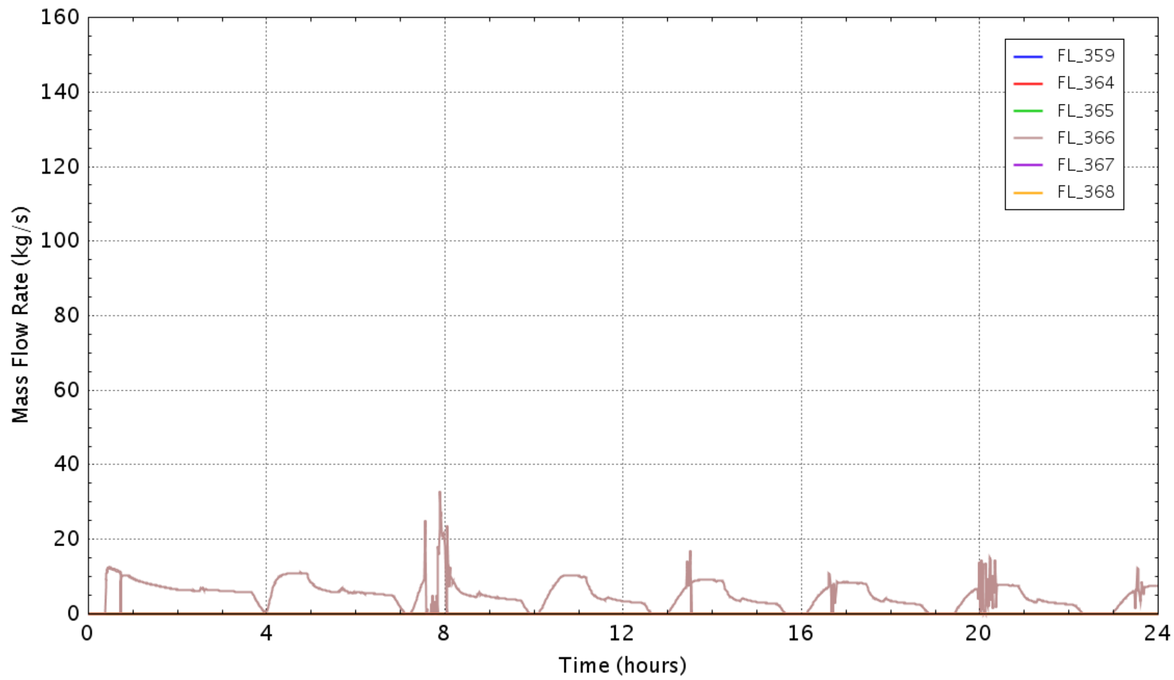

Figure C - 114 Flow rate of the SRVs

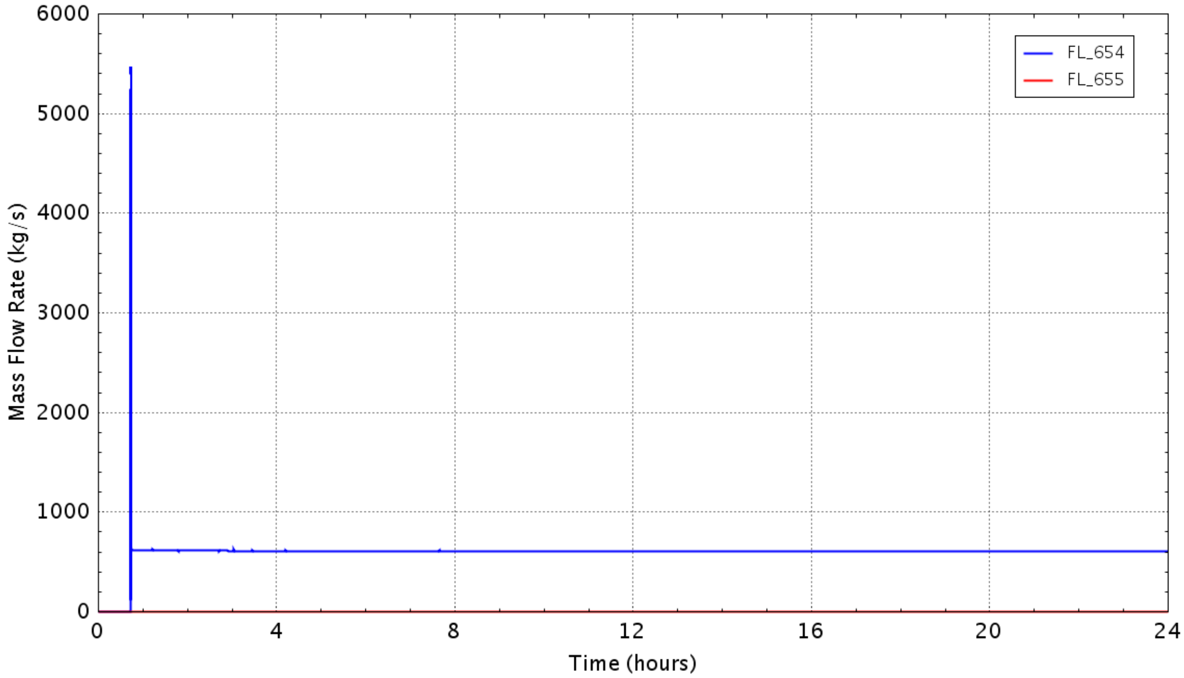

Figure C - 115 Flow rate of the wetwell cooling system

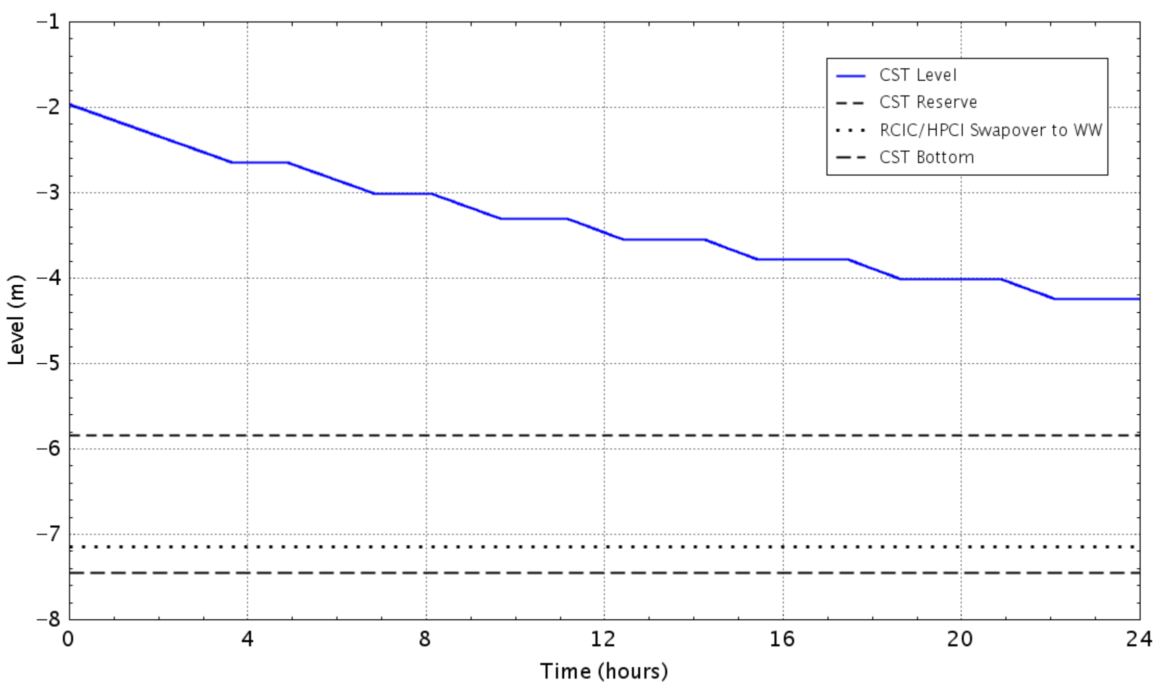

Figure C - 116 Water level in the CST

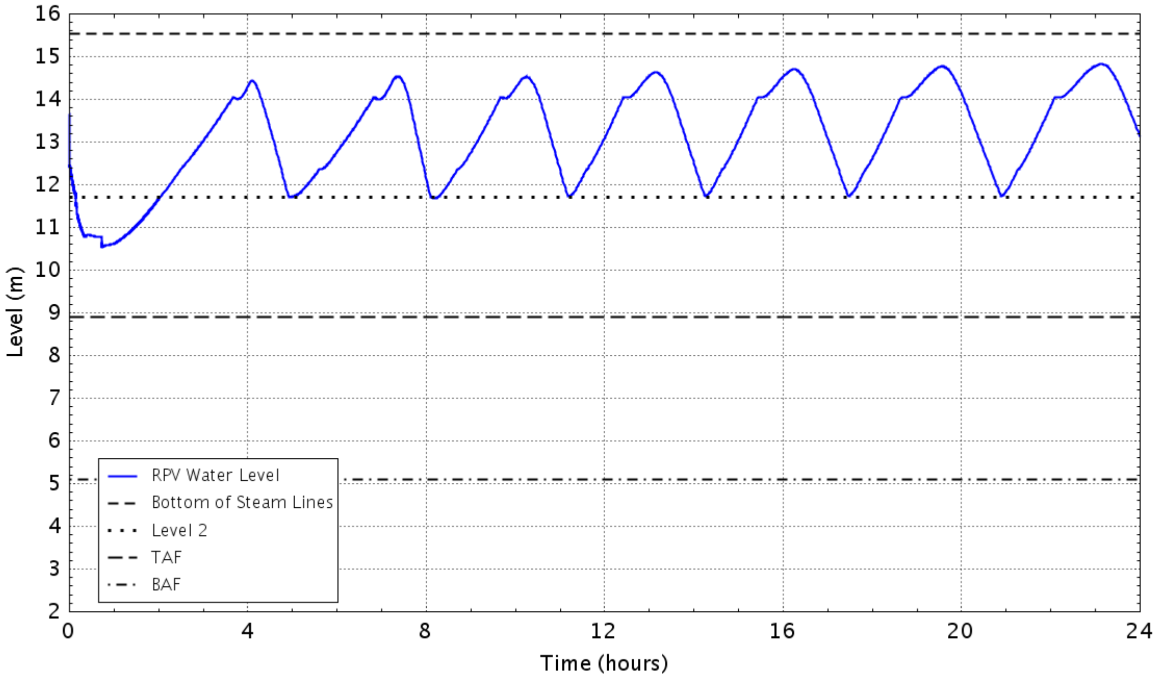

Figure C - 117 RPV Downcomer water level

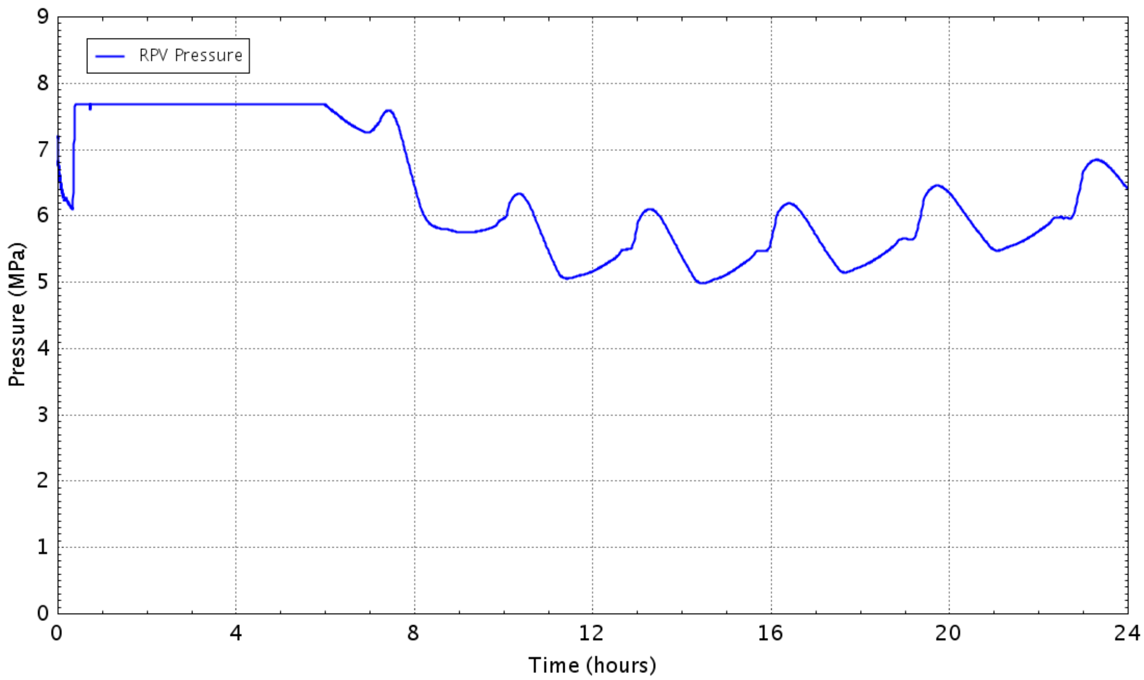

Figure C - 118 Pressure in the RPV

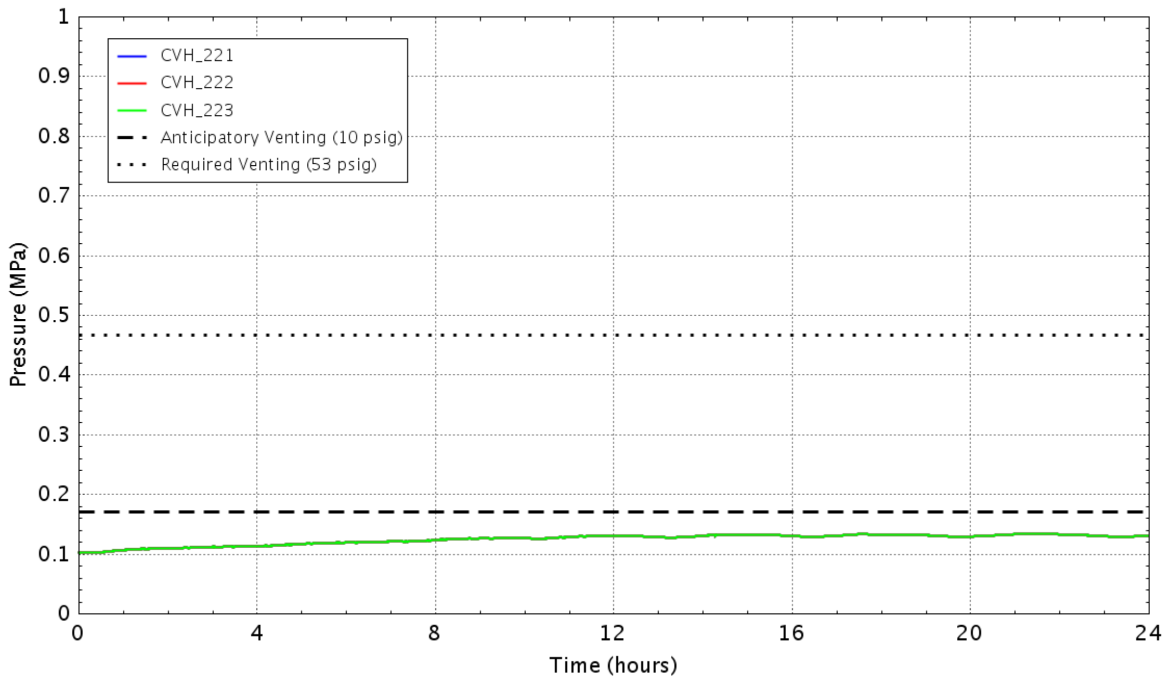

Figure C - 119 Pressure in the wetwell

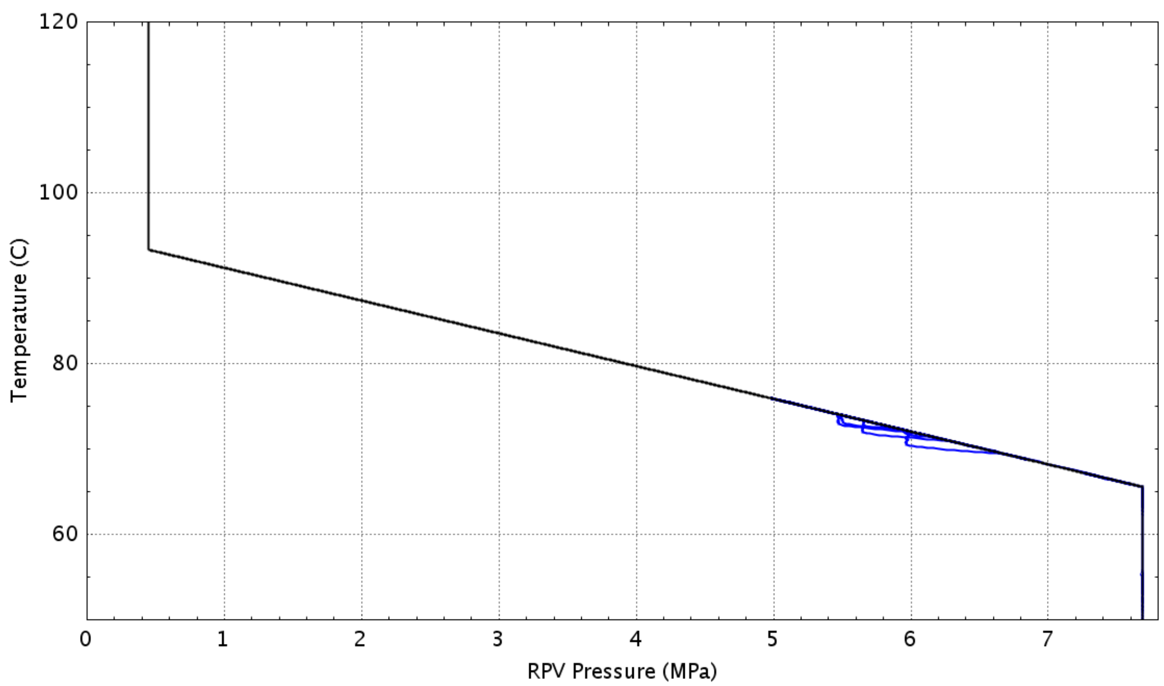

Figure C - 120 Plant status relative to the HCL curve (Graph 4 of the EOPs)

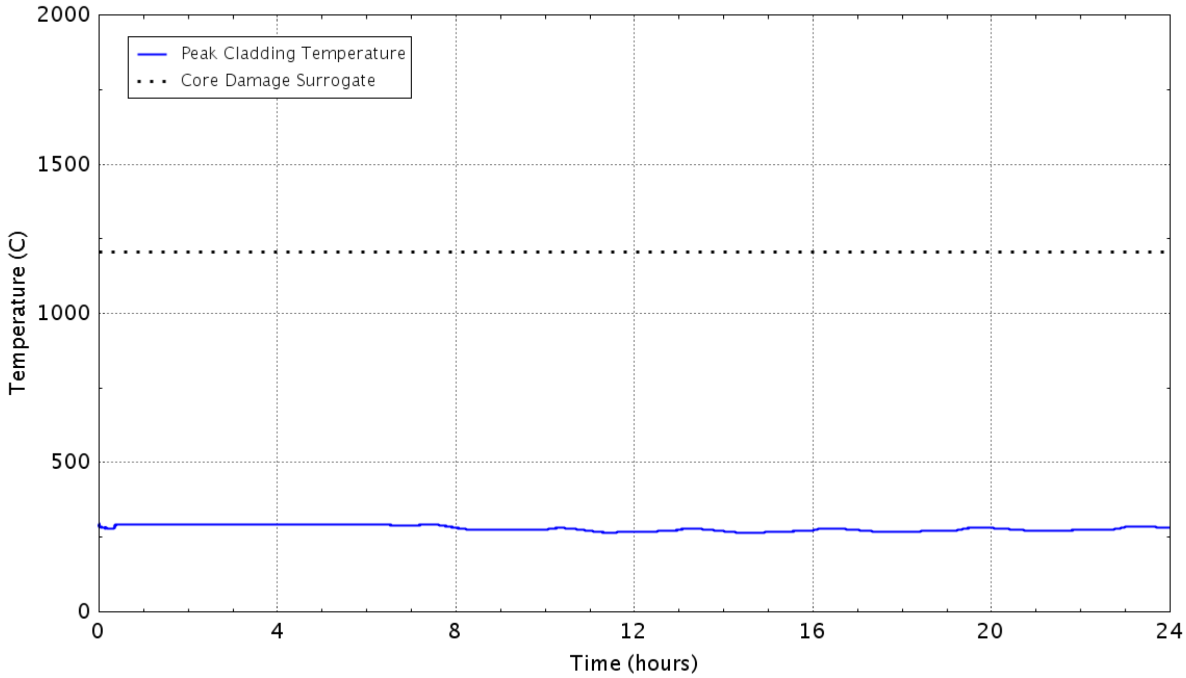

Figure C - 121 Peak temperature of the fuel cladding as a function of time

C.1.12 Case 12: TRANS-30, One Train of CRDHS, MSIV Closure at 20 min., Emergency Depressurization at HCL Curve

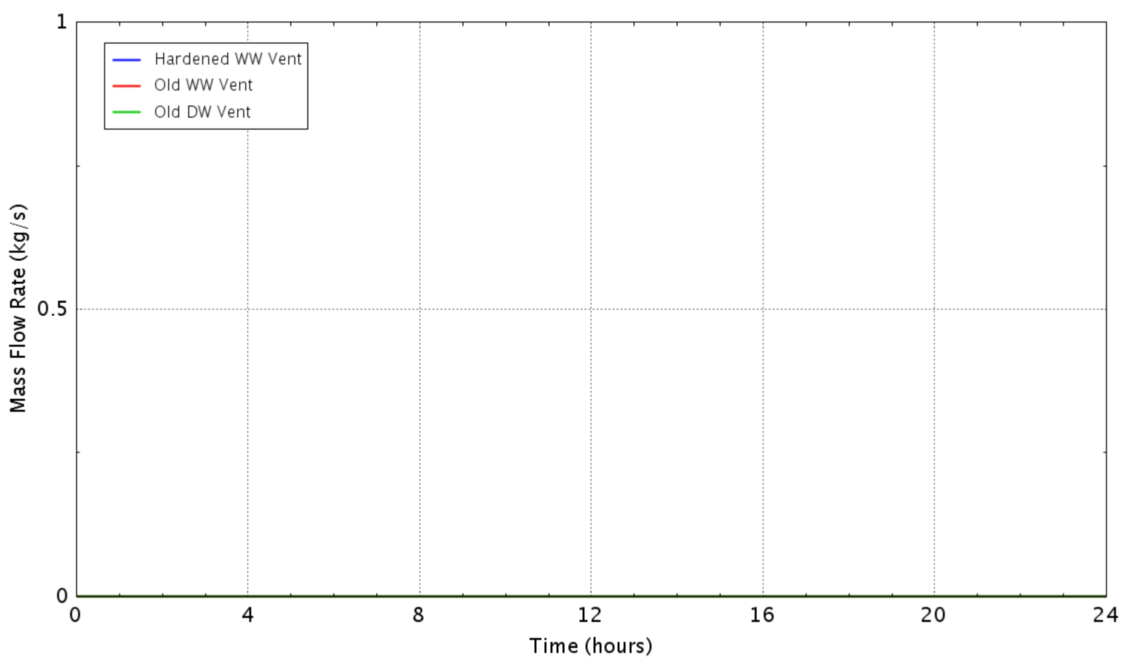

Figure C - 122 Flow rate of the containment vents

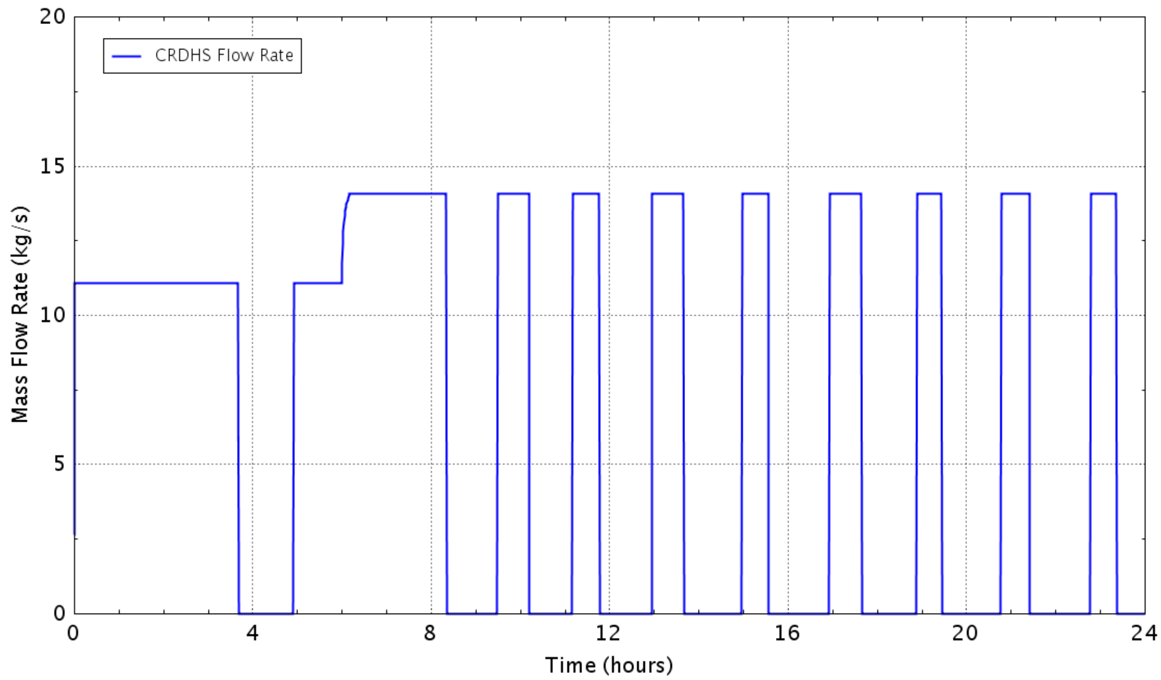

Figure C - 123 Flow rate of the control rod drive hydraulic system

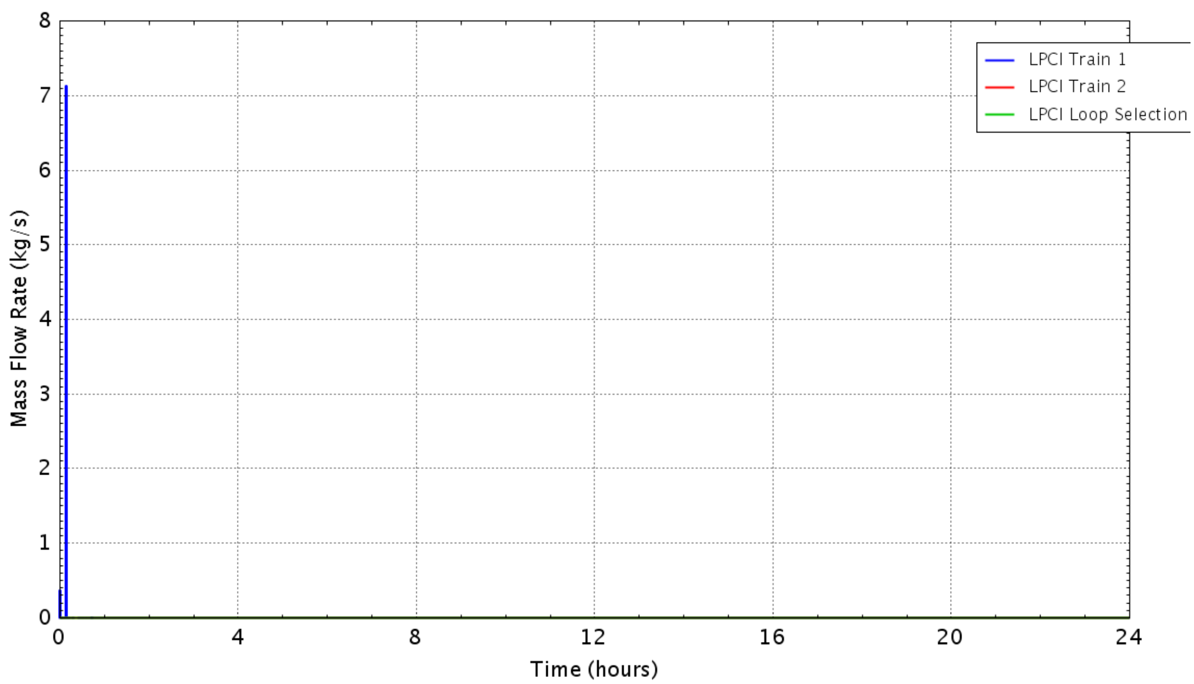

Figure C - 124 Flow rate of the LPCI pump

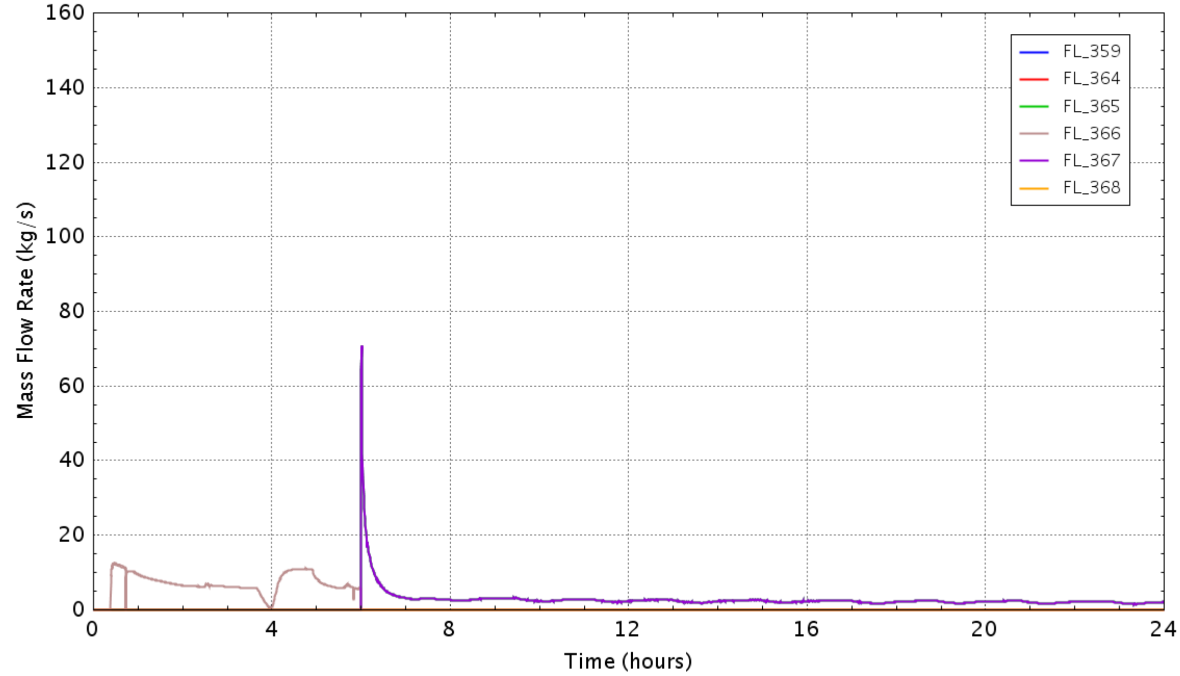

Figure C - 125 Flow rate of the SRVs

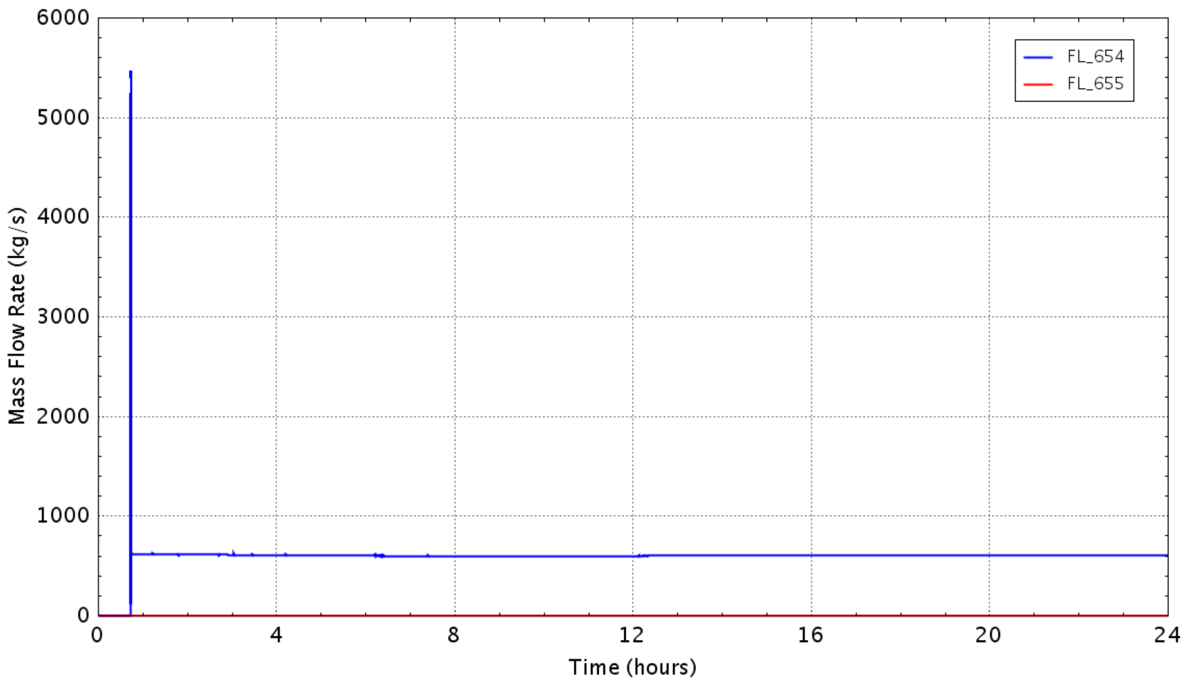

Figure C - 126 Flow rate of the wetwell cooling system

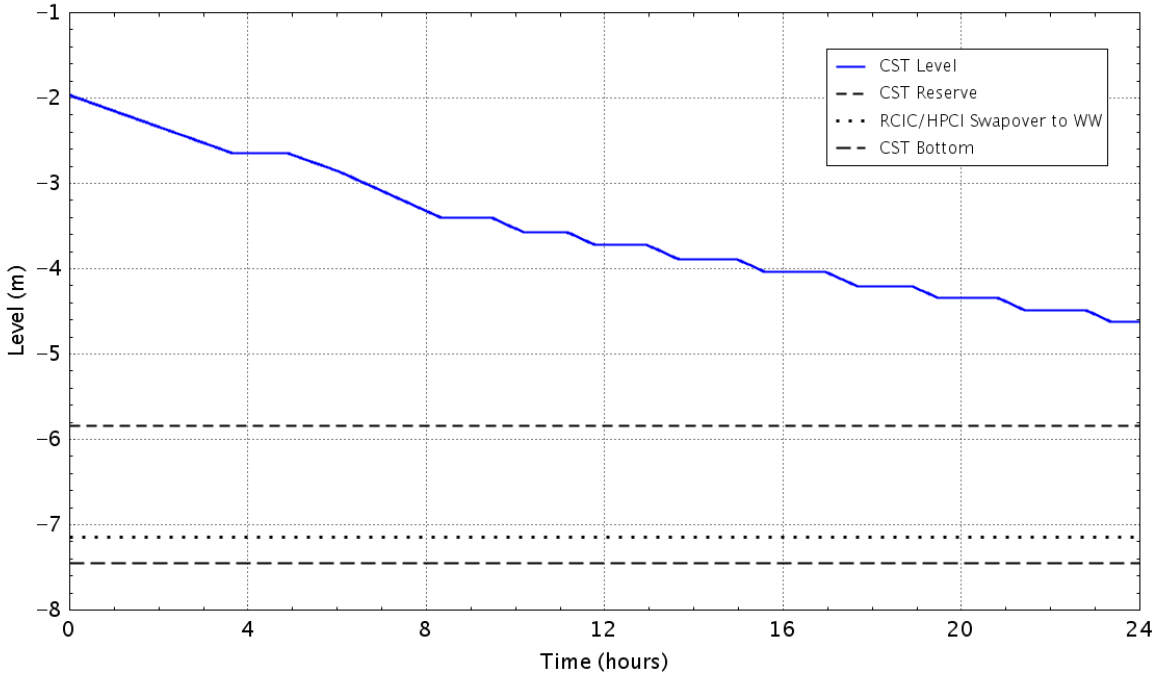

Figure C - 127 Water level in the CST

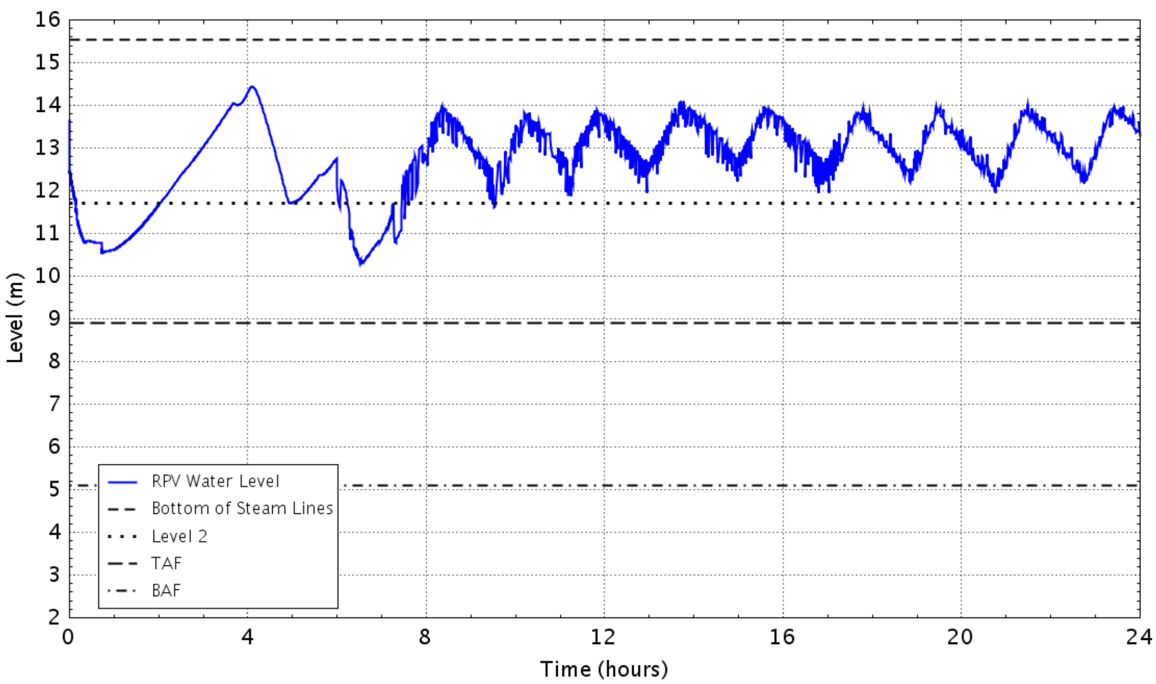

Figure C - 128 RPV Downcomer water level

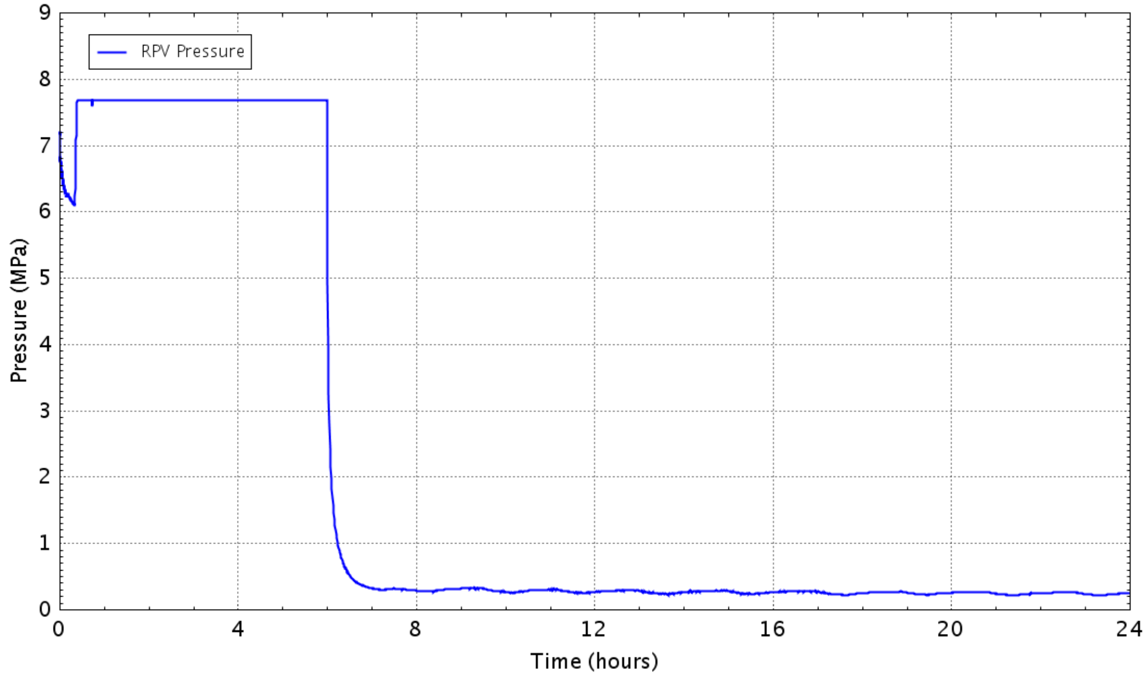

Figure C - 129 Pressure in the RPV

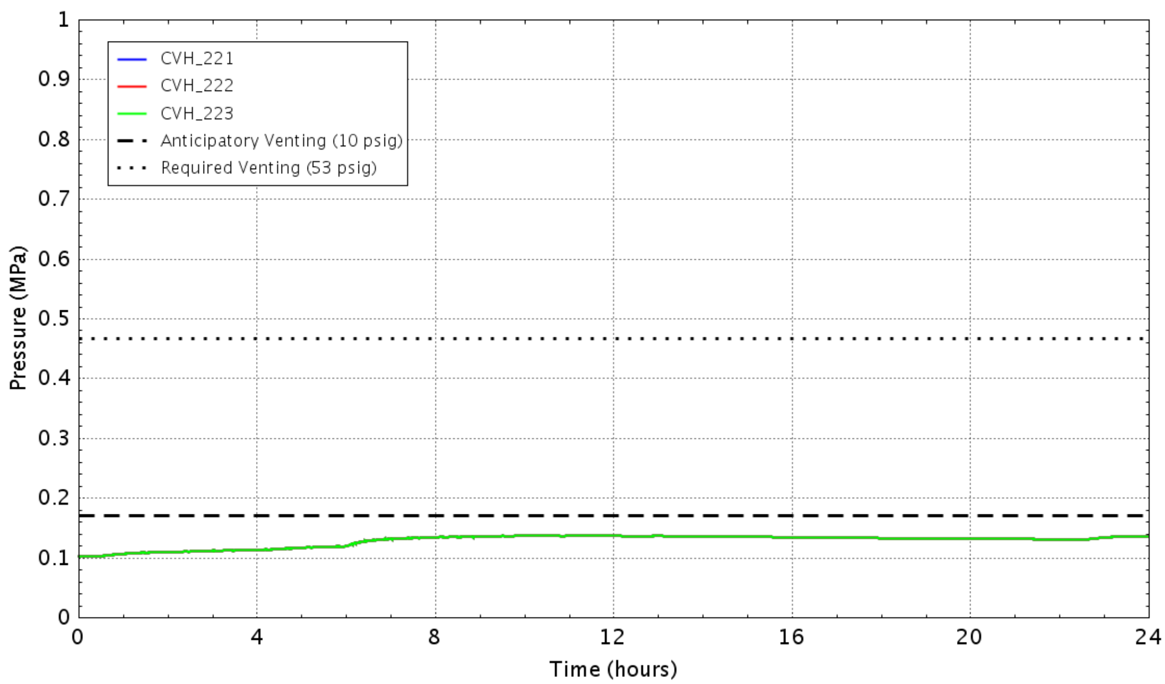

Figure C - 130 Pressure in the wetwell

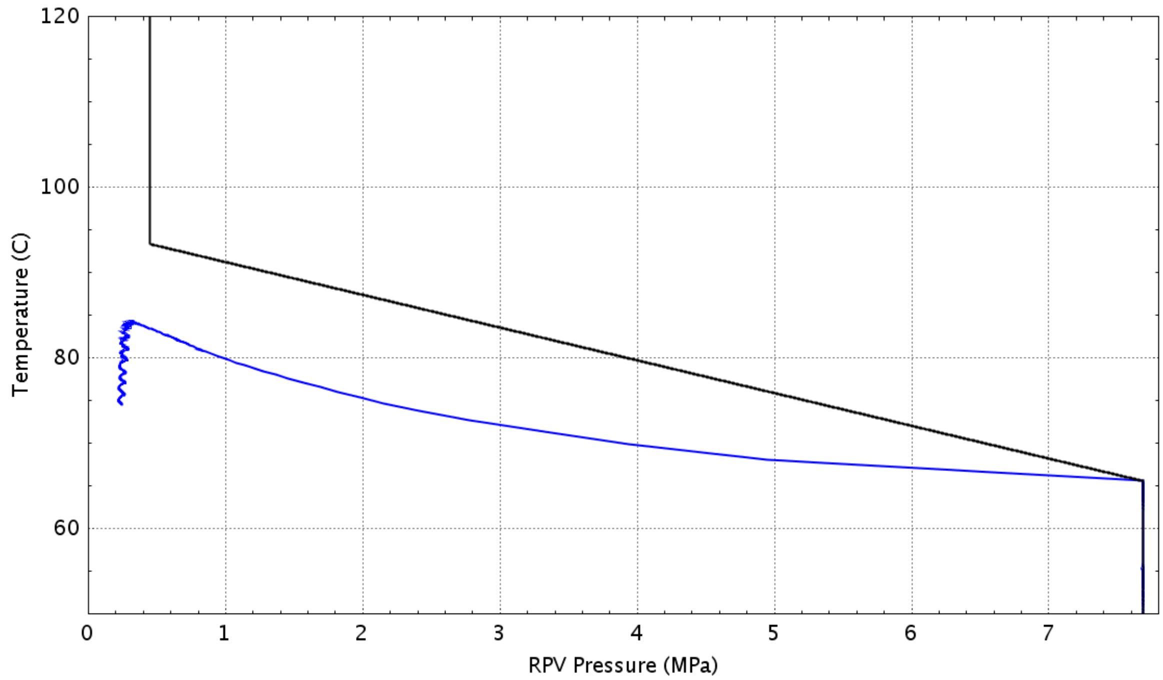

Figure C - 131 Plant status relative to the HCL curve (Graph 4 of the EOPs)

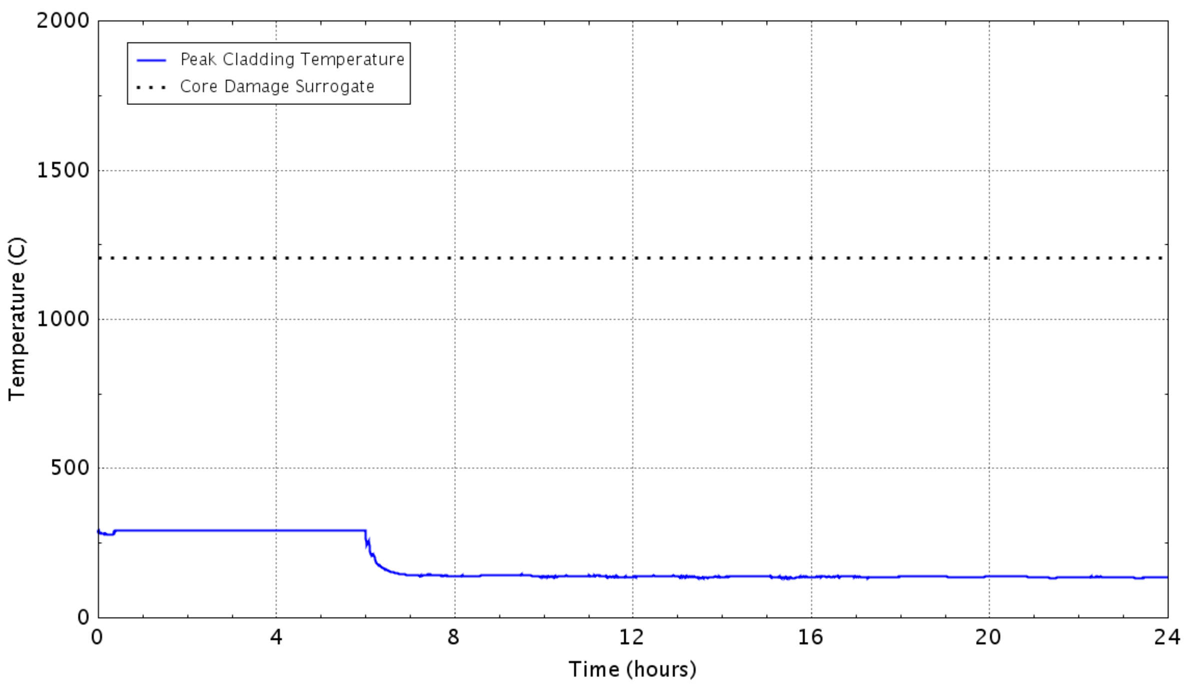

Figure C - 132 Peak temperature of the fuel cladding as a function of time

C.1.13 Case 13: TRANS-30, One Train of CRDHS, Automatic MSIV Closure, RPV Pressure Follows HCL Curve

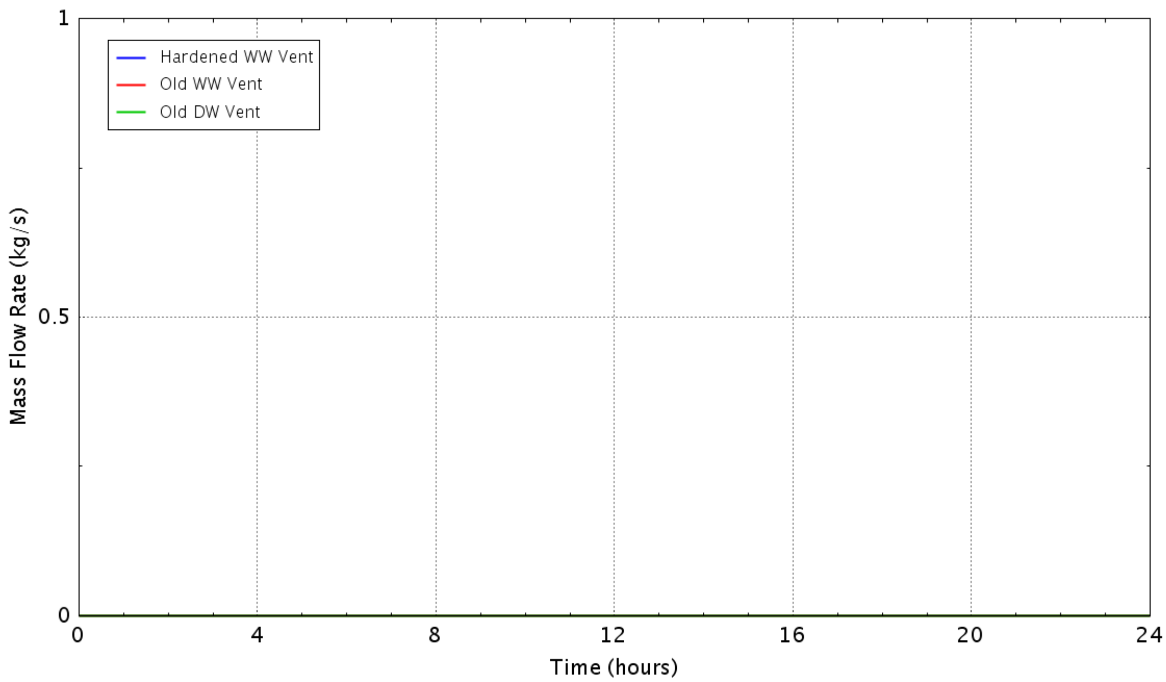

Figure C - 133 Flow rate of the containment vents

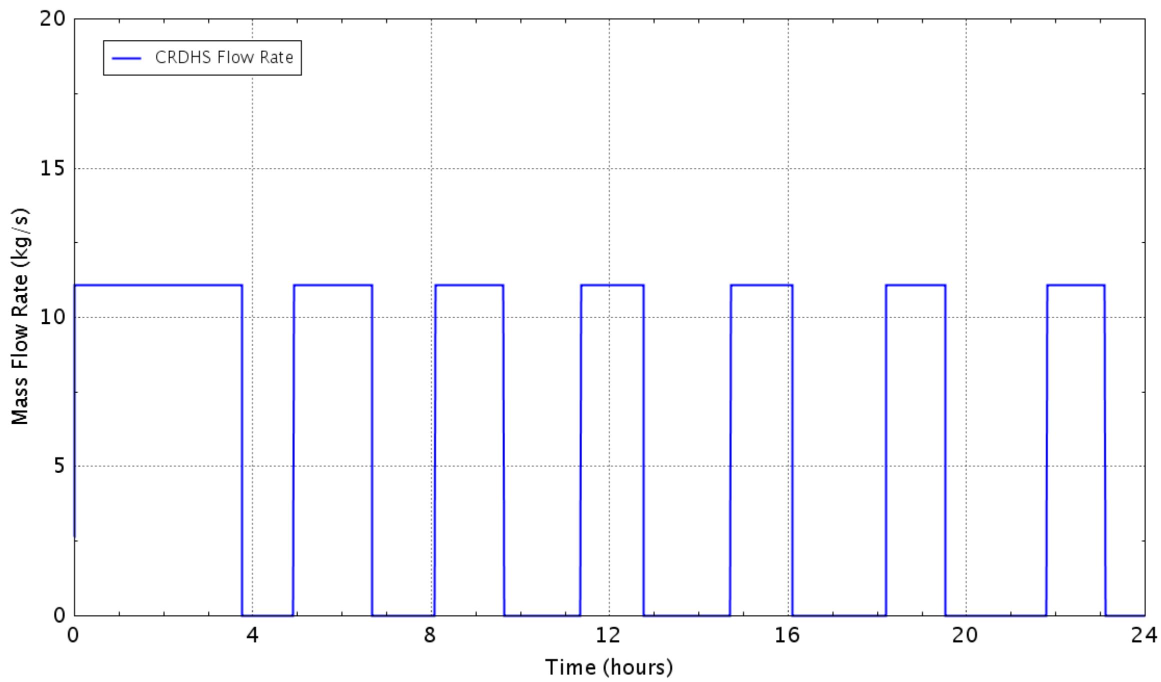

Figure C - 134 Flow rate of the control rod drive hydraulic system

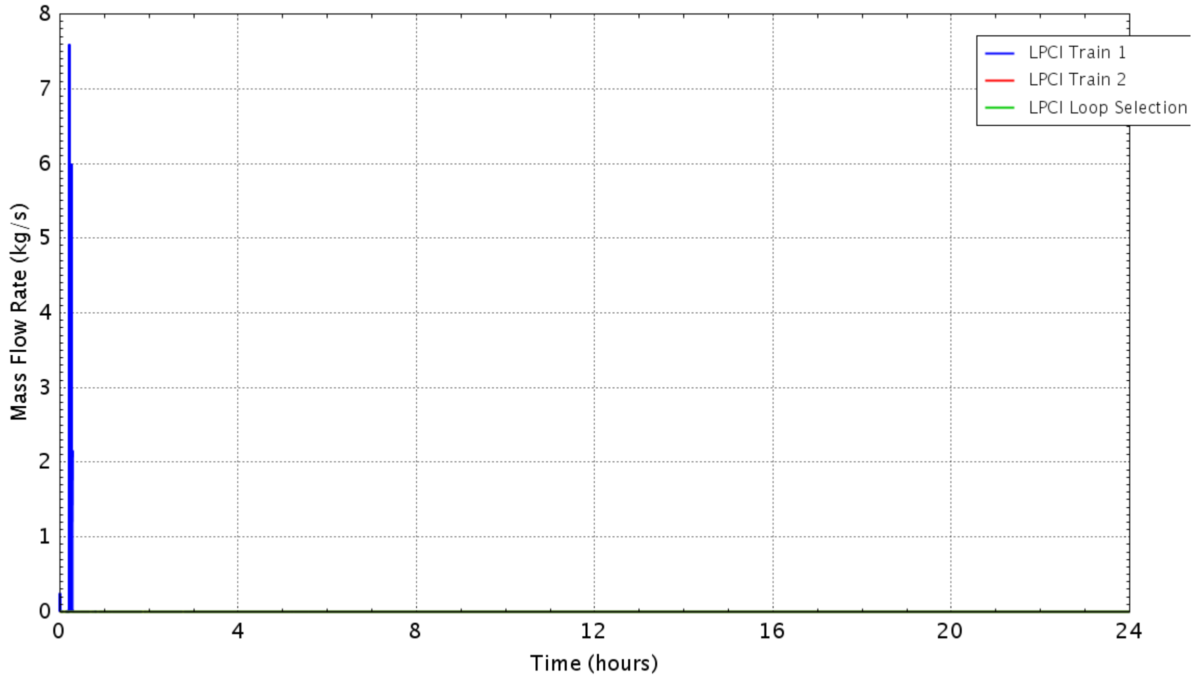

Figure C - 135 Flow rate of the LPCI pump

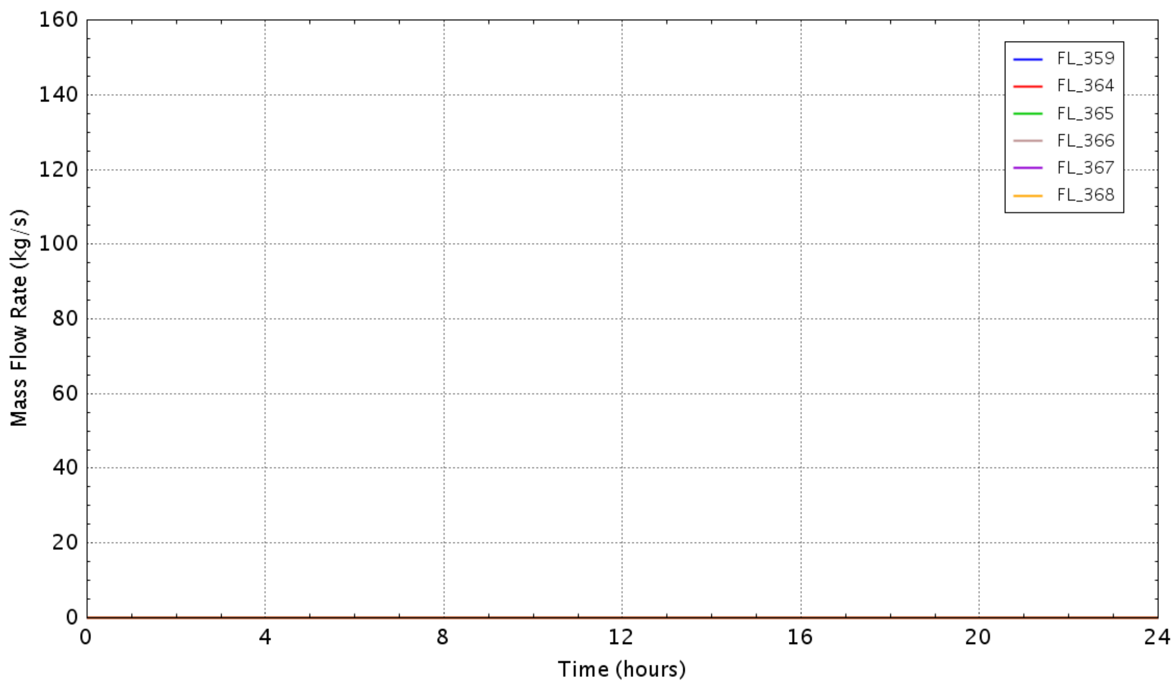

Figure C - 136 Flow rate of the SRVs

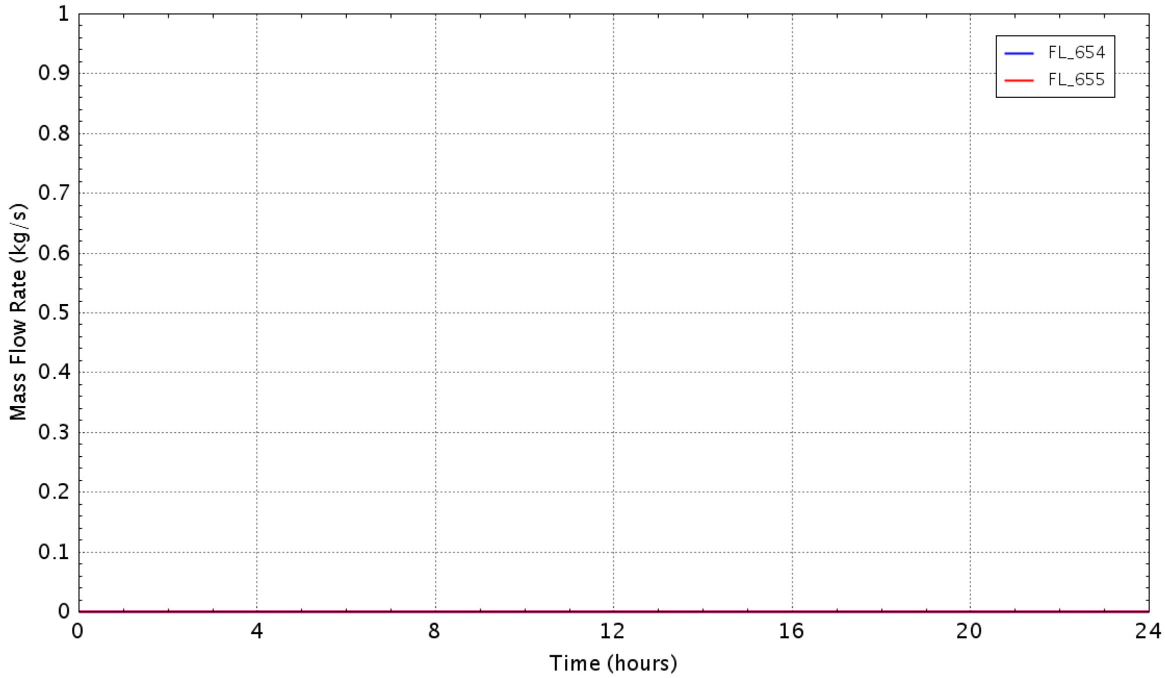

Figure C - 137 Flow rate of the wetwell cooling system

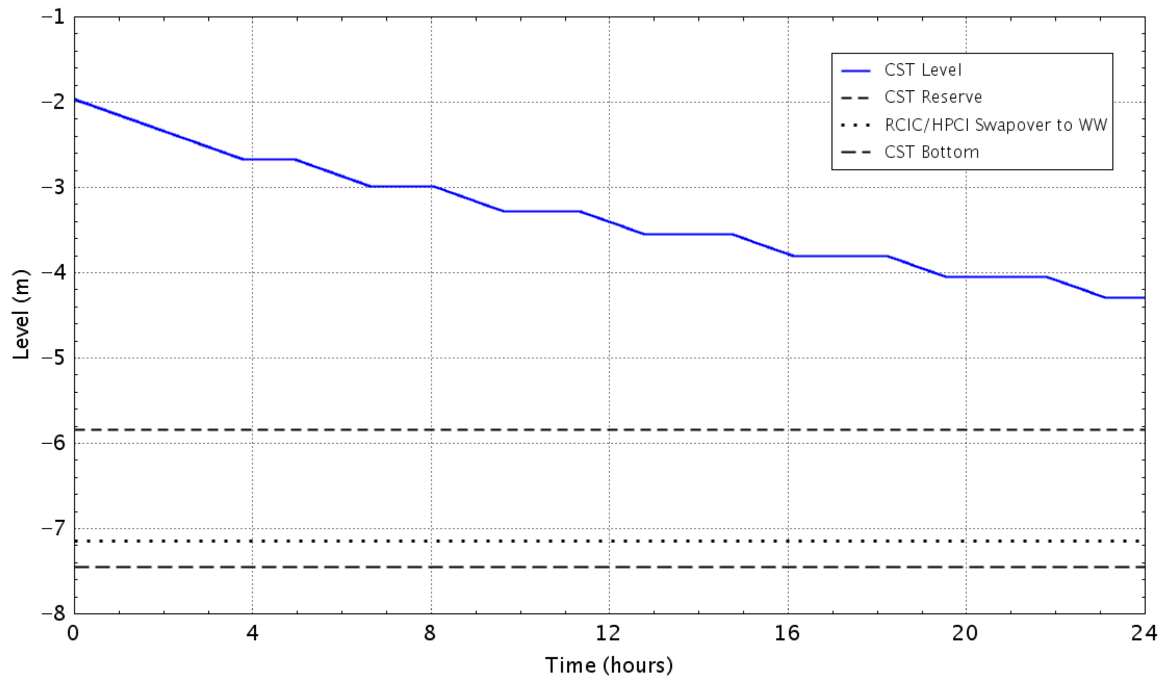

Figure C - 138 Water level in the CST

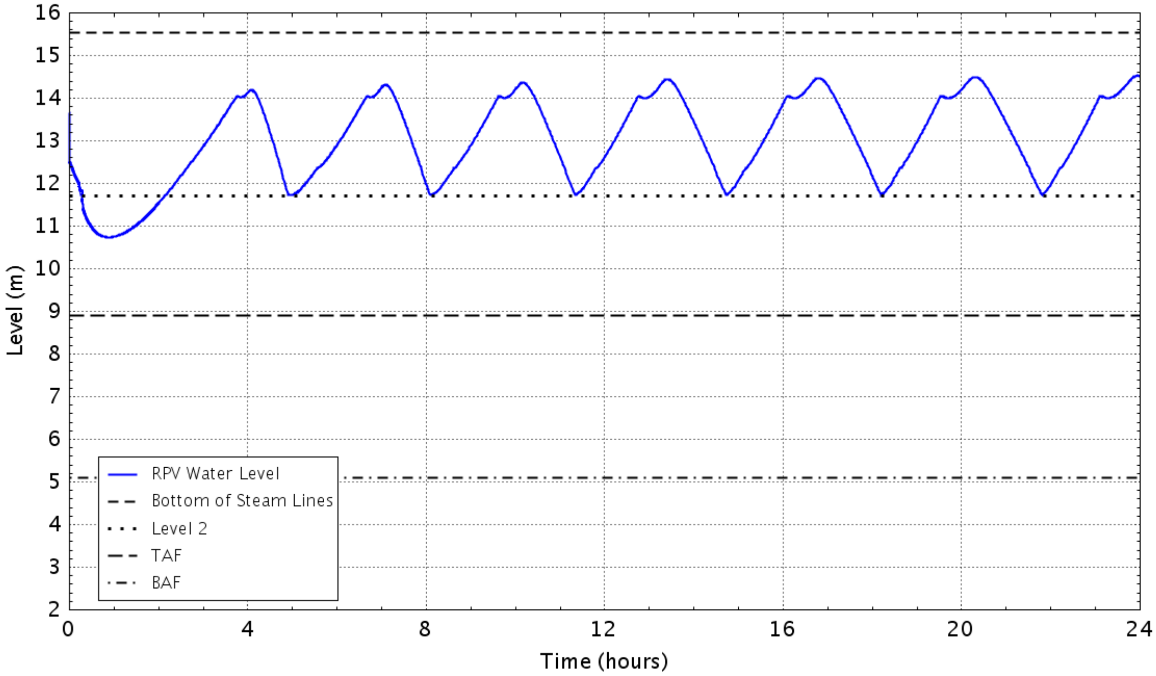

Figure C - 139 RPV Downcomer water level

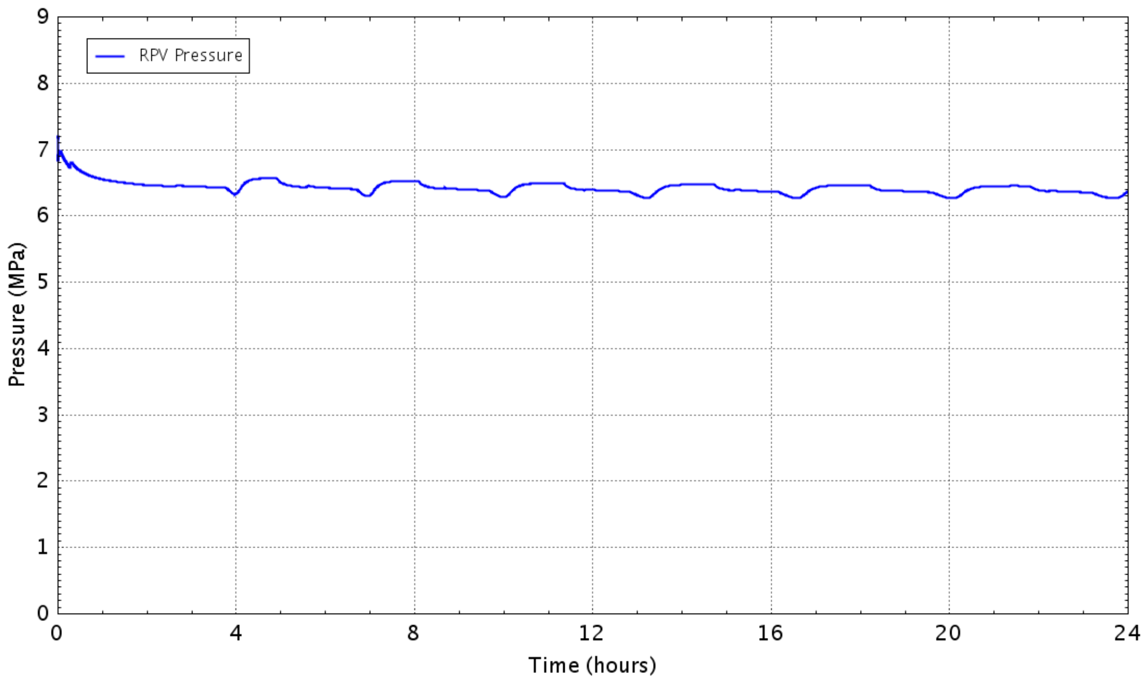

Figure C - 140 Pressure in the RPV

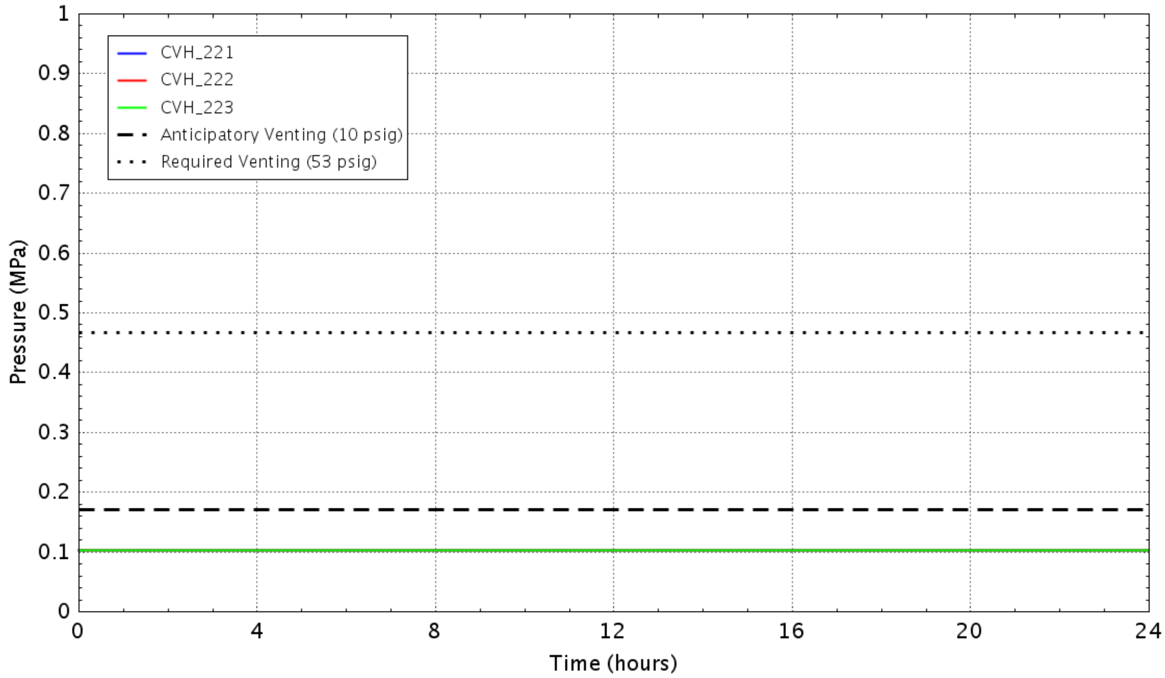

Figure C - 141 Pressure in the wetwell

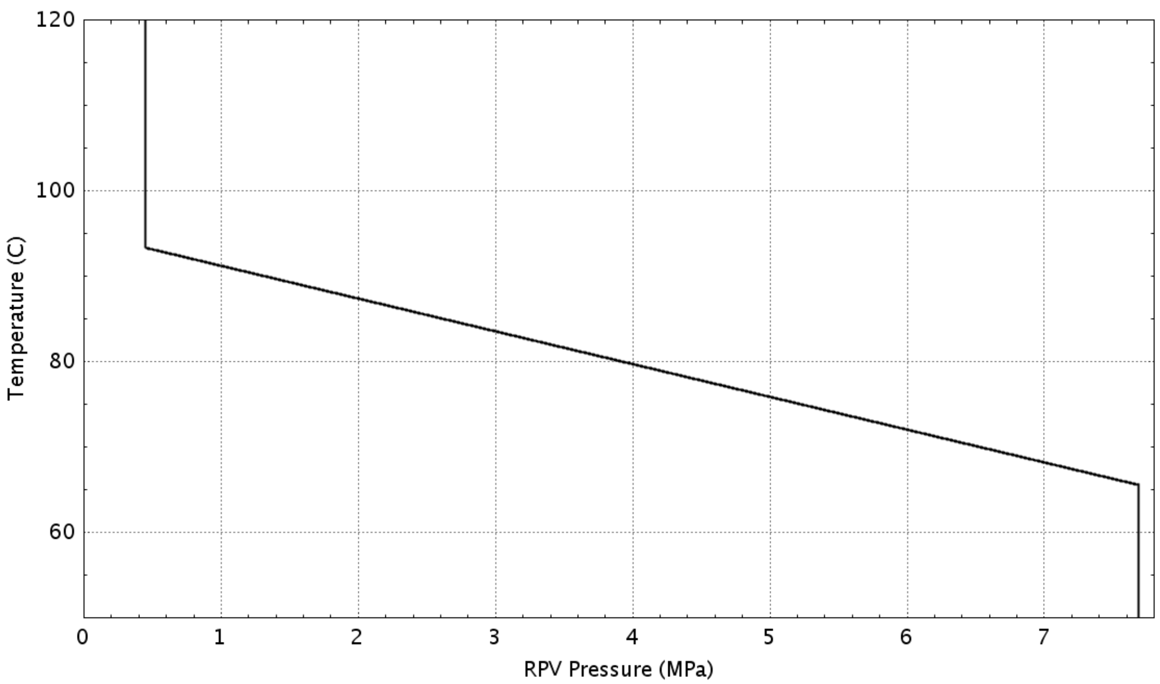

Figure C - 142 Plant status relative to the HCL curve (Graph 4 of the EOPs)

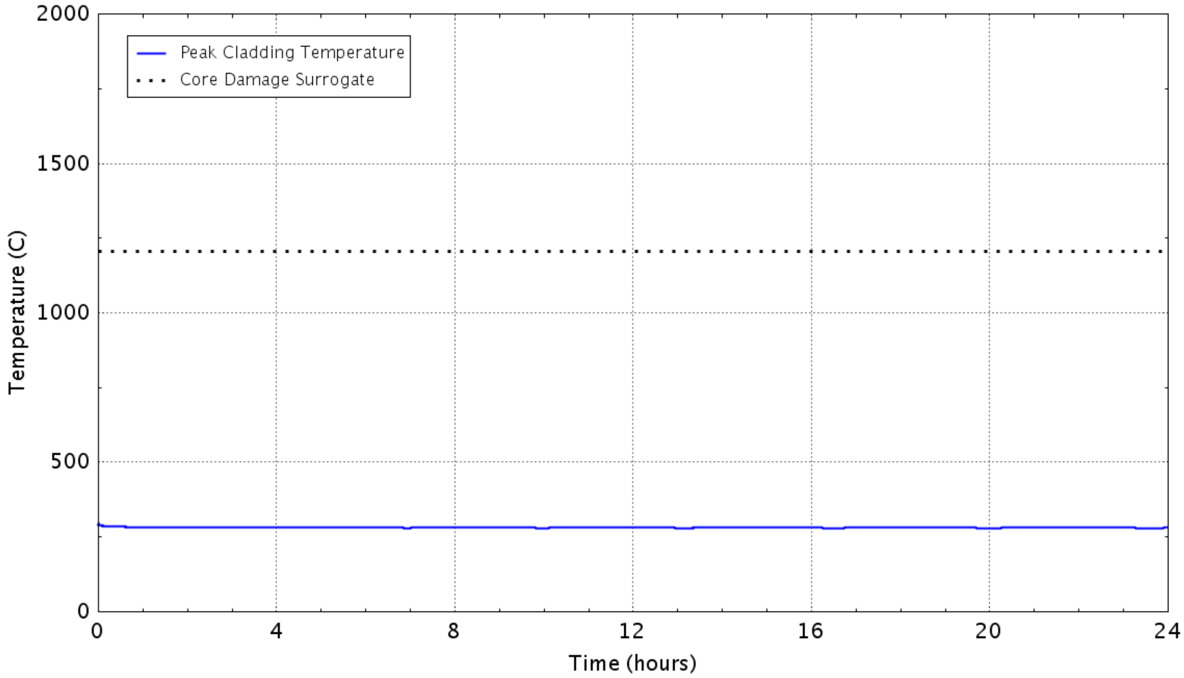

Figure C - 143 Peak temperature of the fuel cladding as a function of time

C.1.14 Case 14: TRANS-30, Two Trains of CRDHS, MSIV Closure at 10 min.

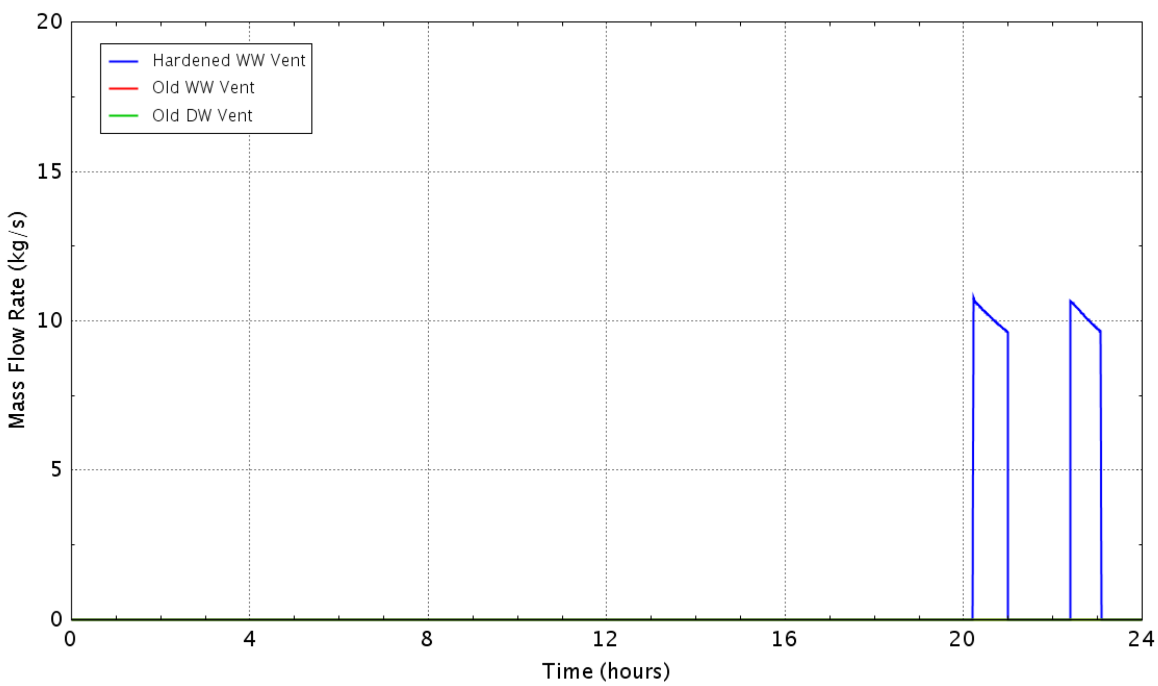

Figure C - 144 Flow rate of the containment vents

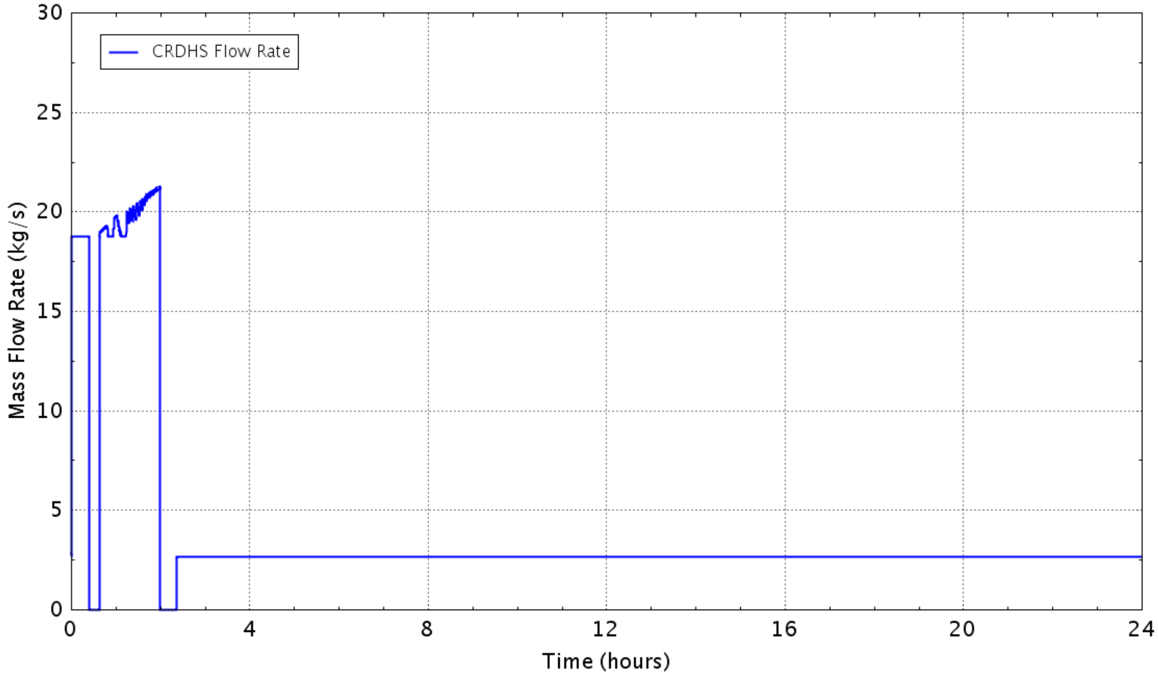

Figure C - 145 Flow rate of the control rod drive hydraulic system

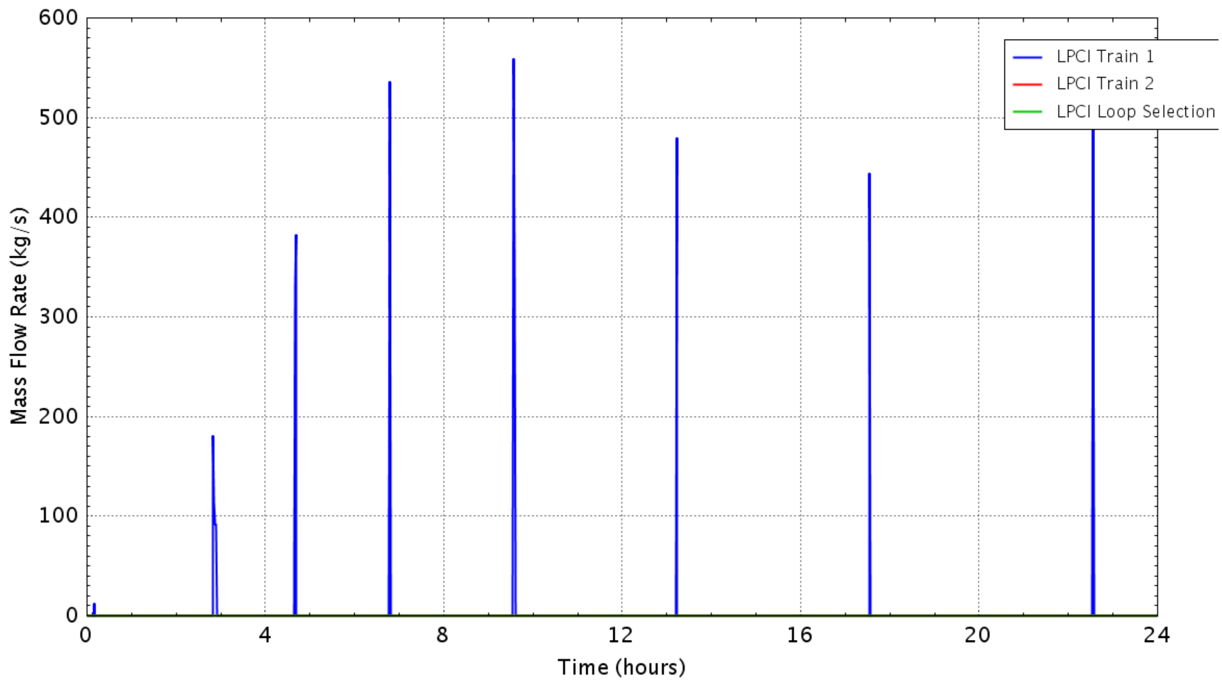

Figure C - 146 Flow rate of the LPCI pump

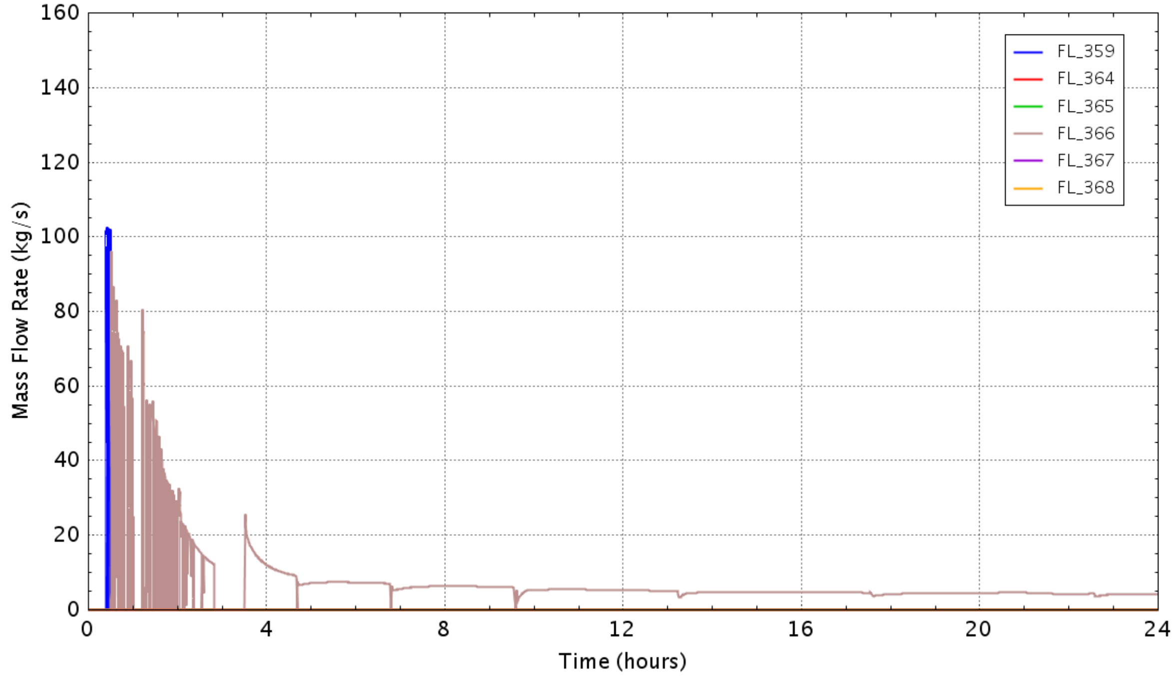

Figure C - 147   Flow rate of the SRVs

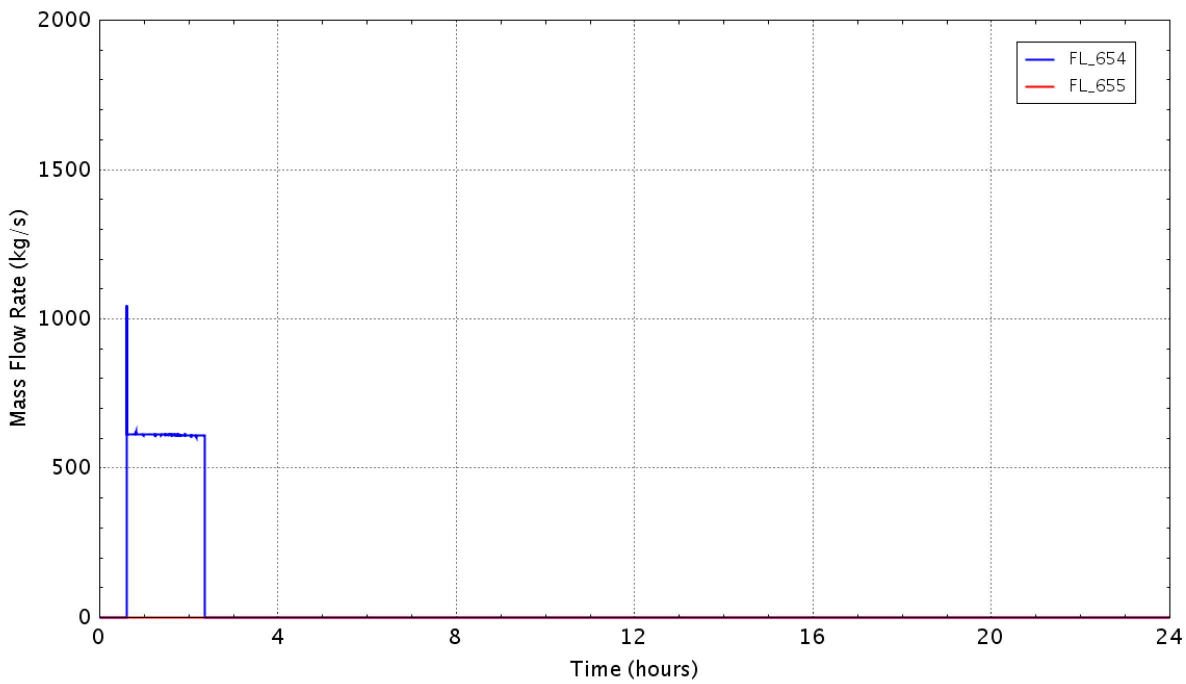

Figure C - 148   Flow rate of the wetwell cooling system

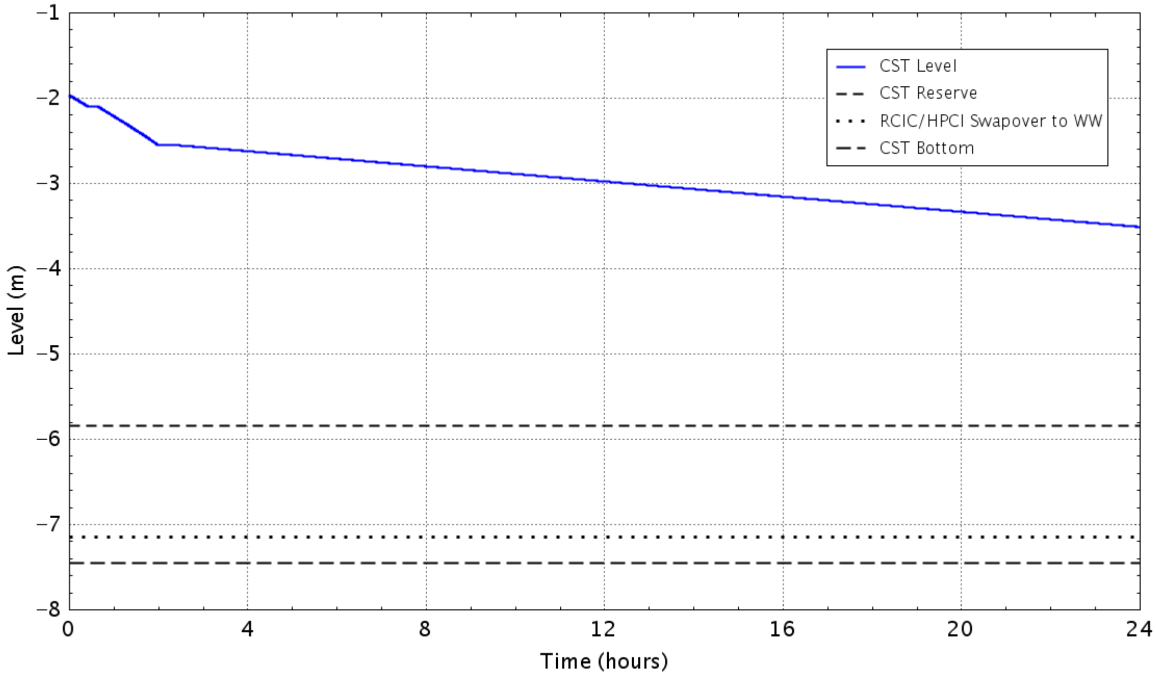

Figure C - 149 Water level in the CST

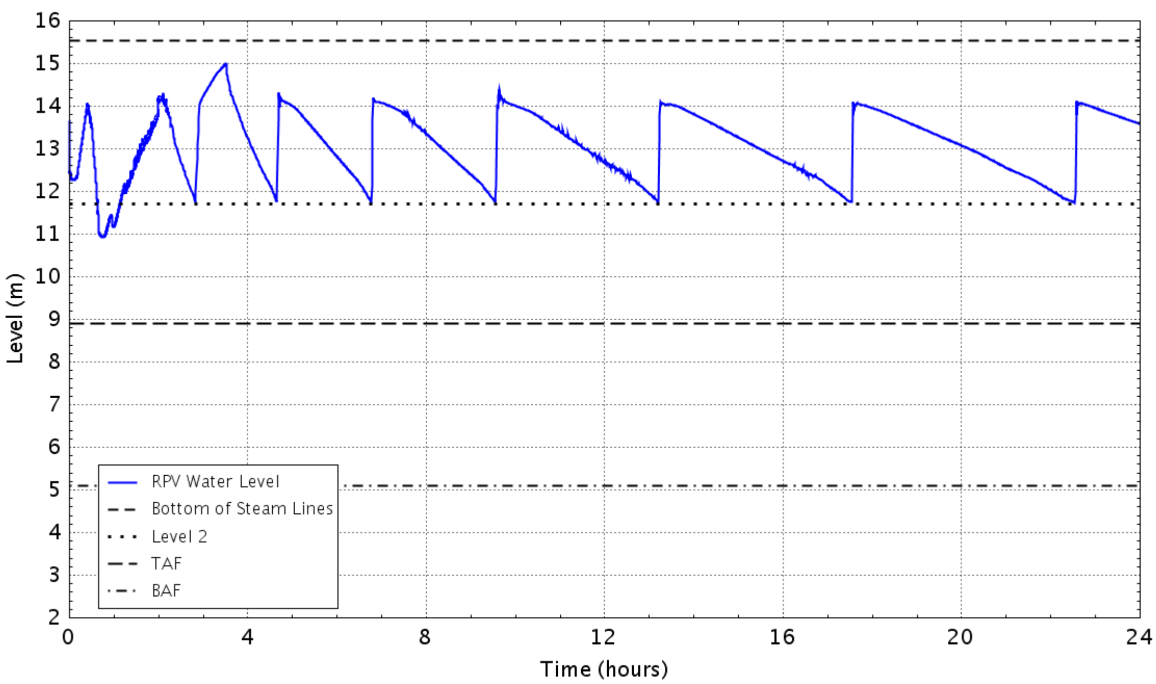

Figure C - 150 RPV Downcomer water level

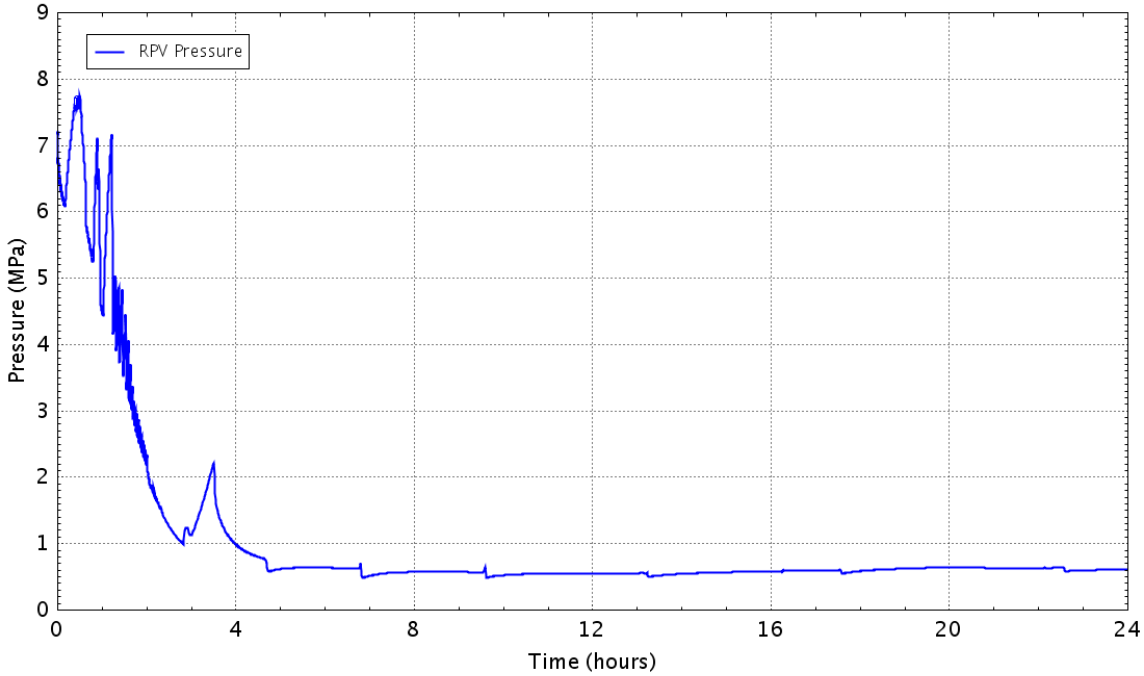

Figure C - 151 Pressure in the RPV

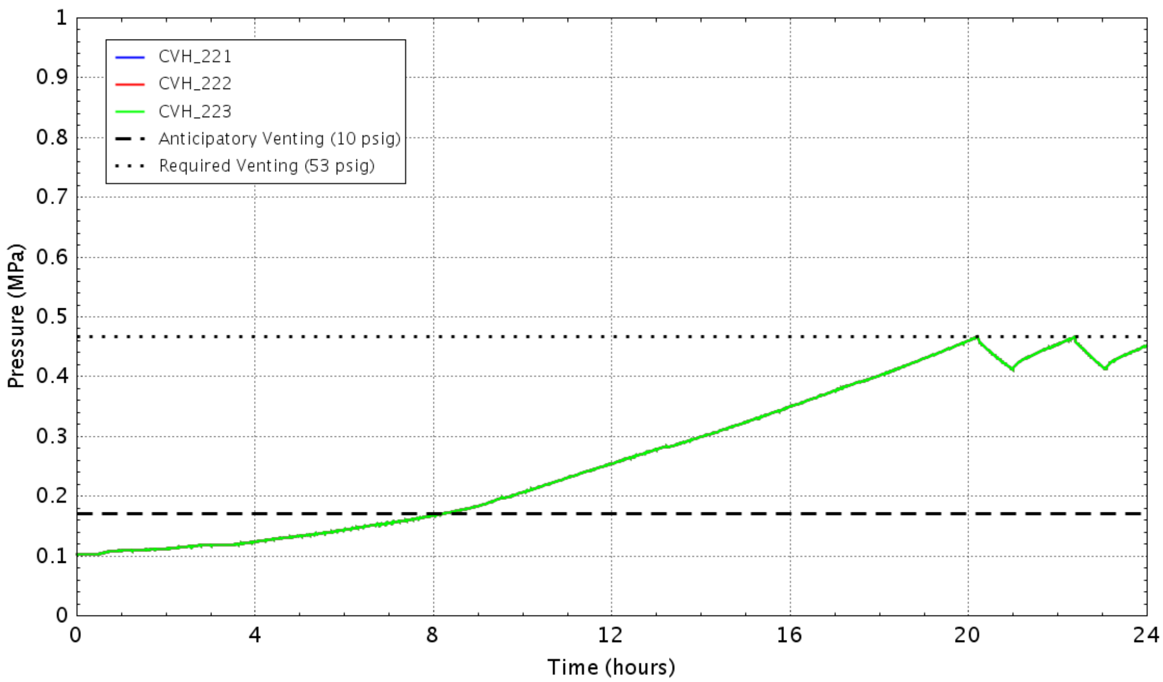

Figure C - 152   Pressure in the wetwell

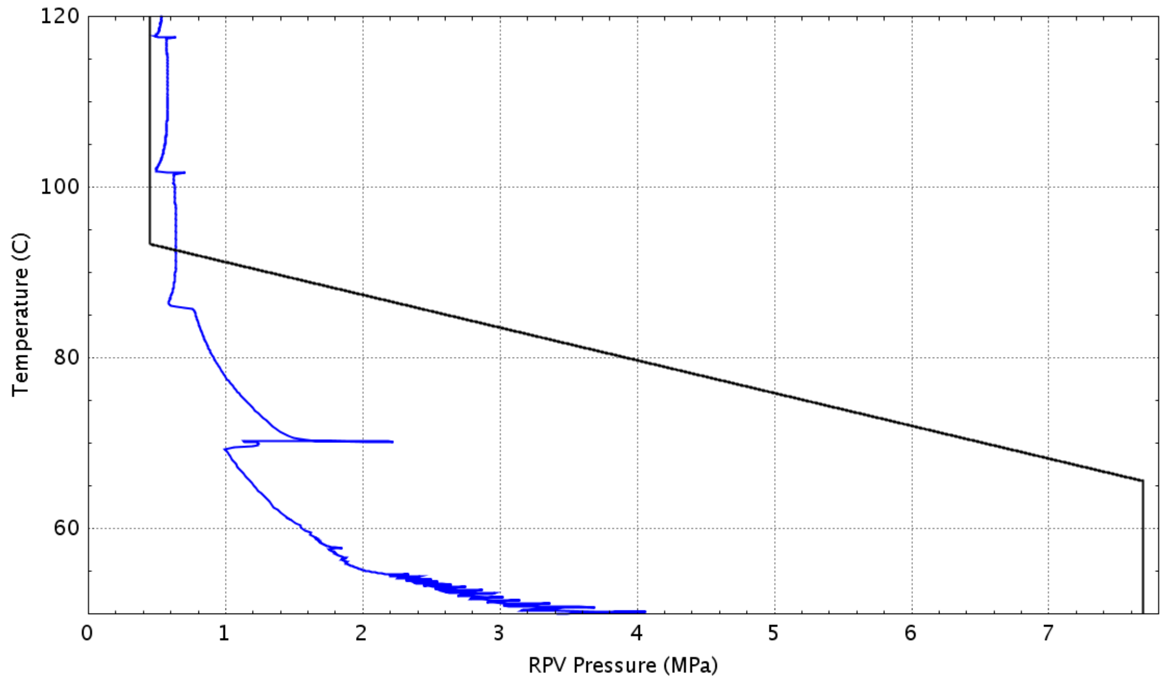

Figure C - 153 Plant status relative to the HCL curve (Graph 4 of the EOPs)

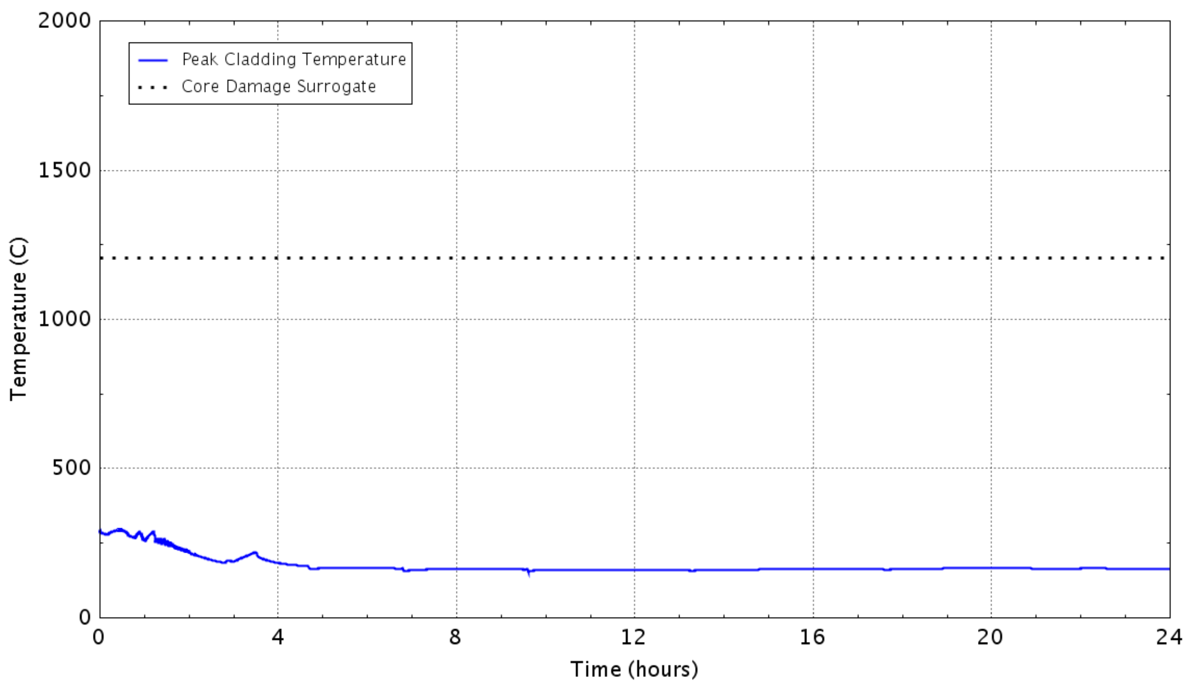

Figure C - 154 Peak temperature of the fuel cladding as a function of time

C.1.15 Case 15: TRANS-30, Two Trains of CRDHS, MSIV Closure at 20 min.

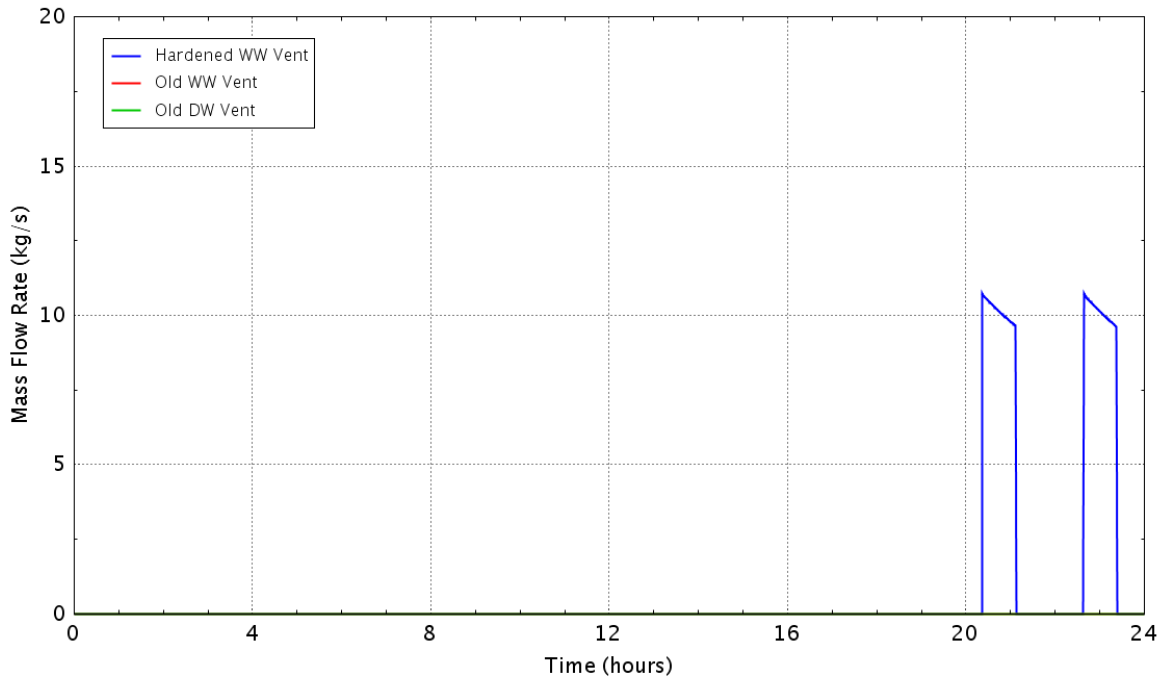

Figure C - 155 Flow rate of the containment vents

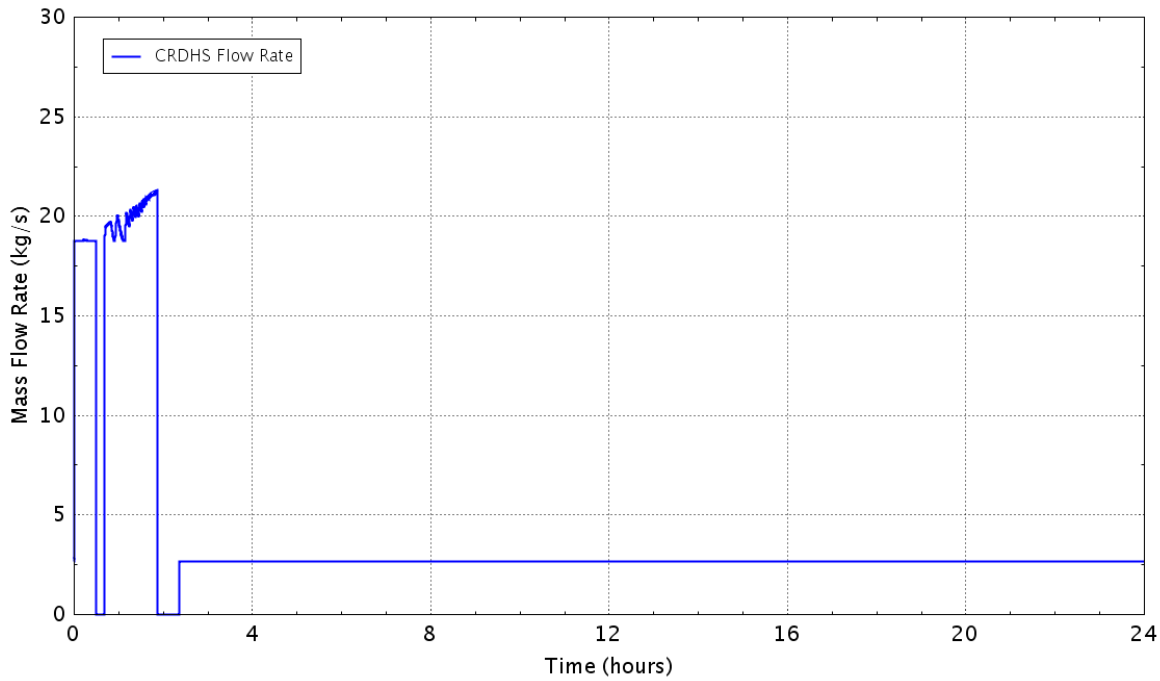

Figure C - 156 Flow rate of the control rod drive hydraulic system

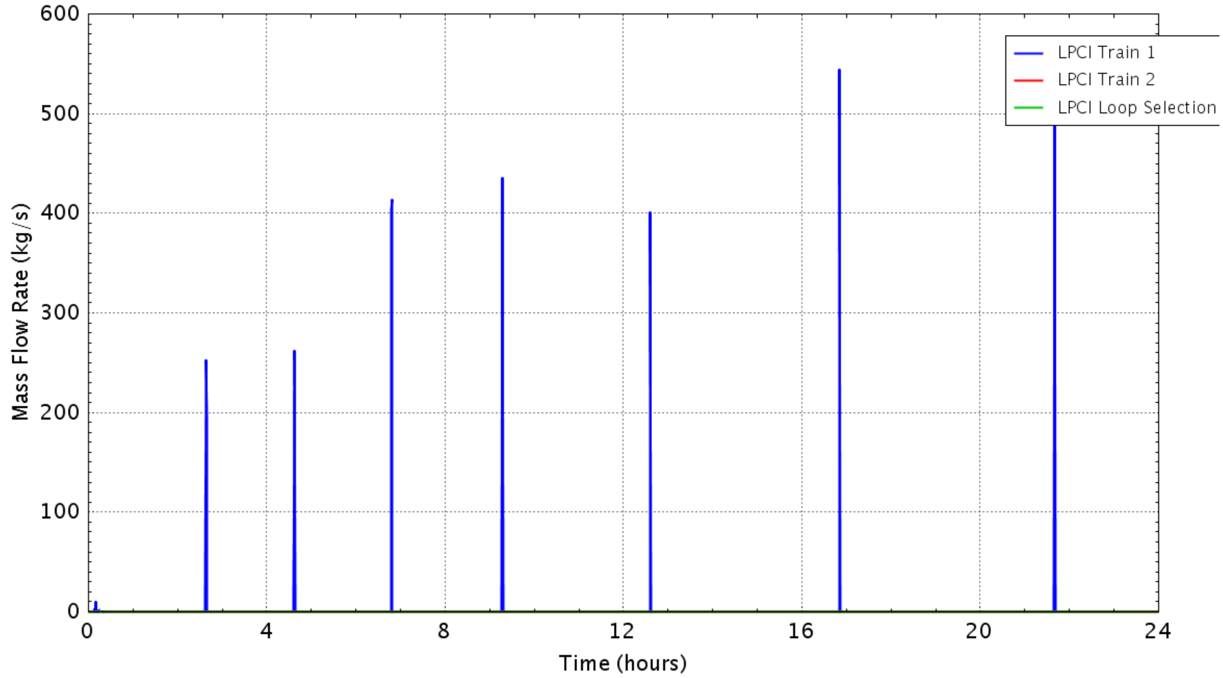

Figure C - 157   Flow rate of the LPCI pump

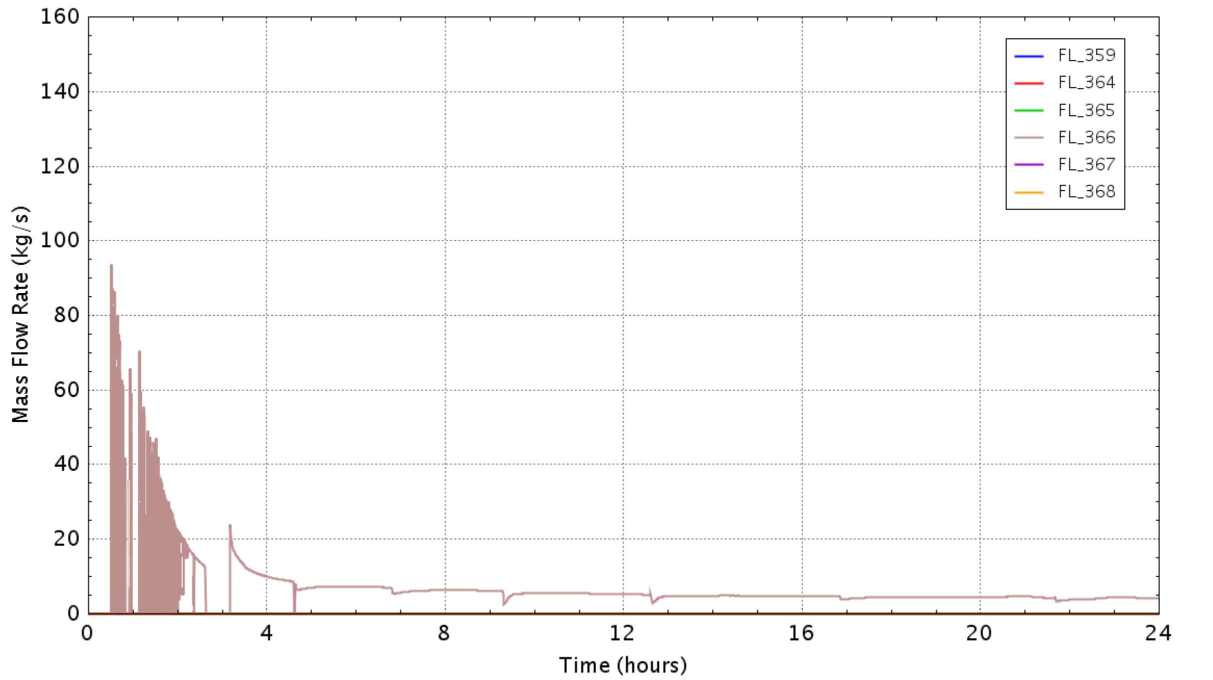

Figure C - 158   Flow rate of the SRVs

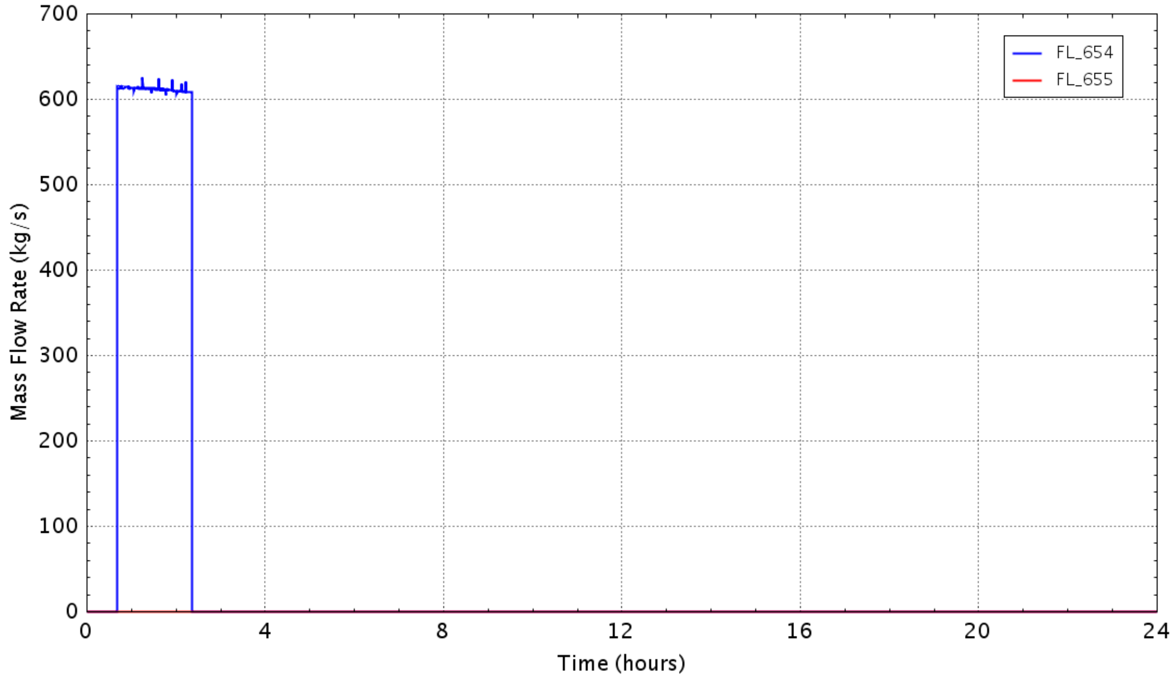

Figure C - 159 Flow rate of the wetwell cooling system

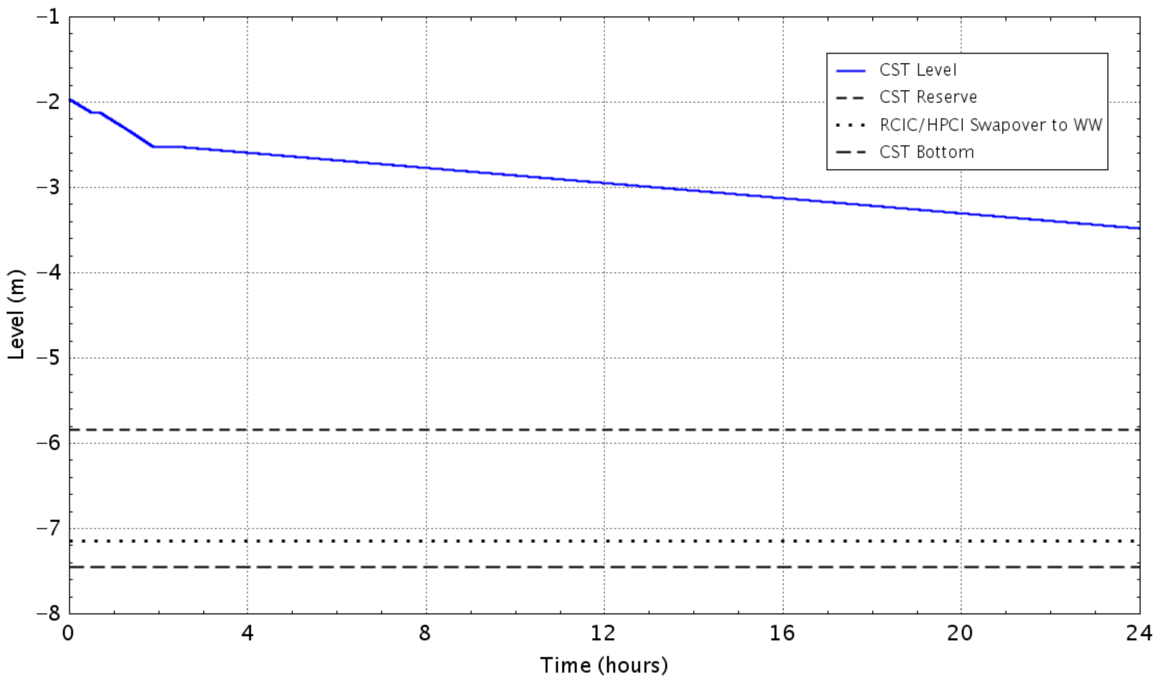

Figure C - 160 Water level in the CST

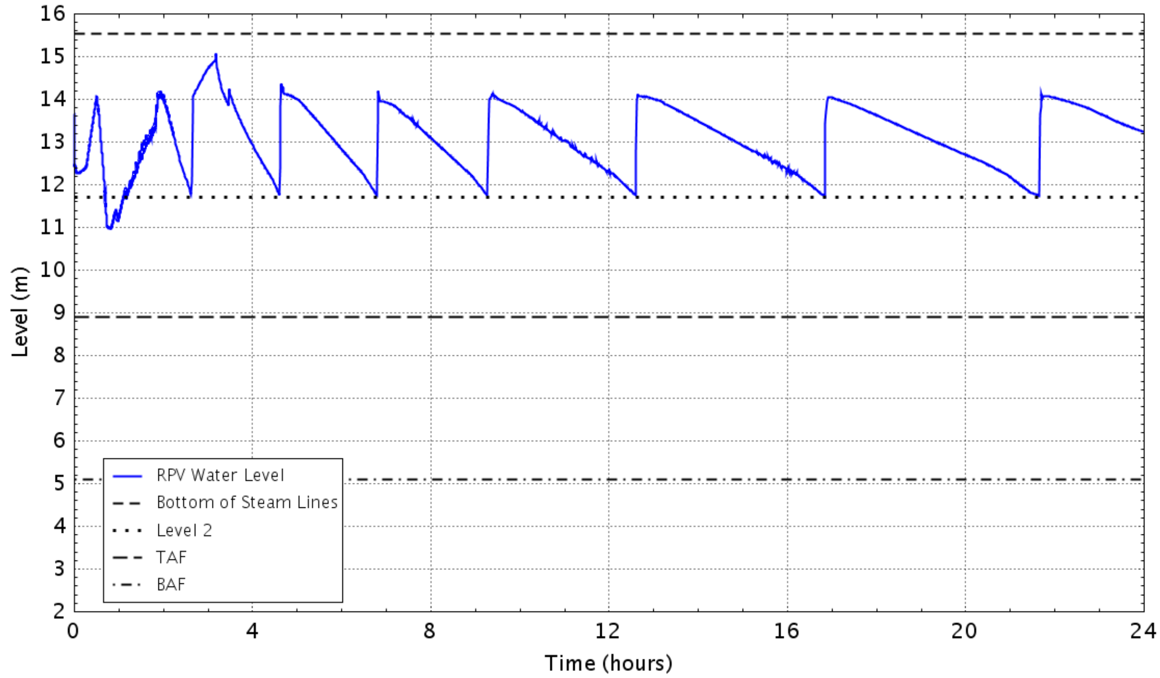

Figure C - 161 RPV Downcomer water level

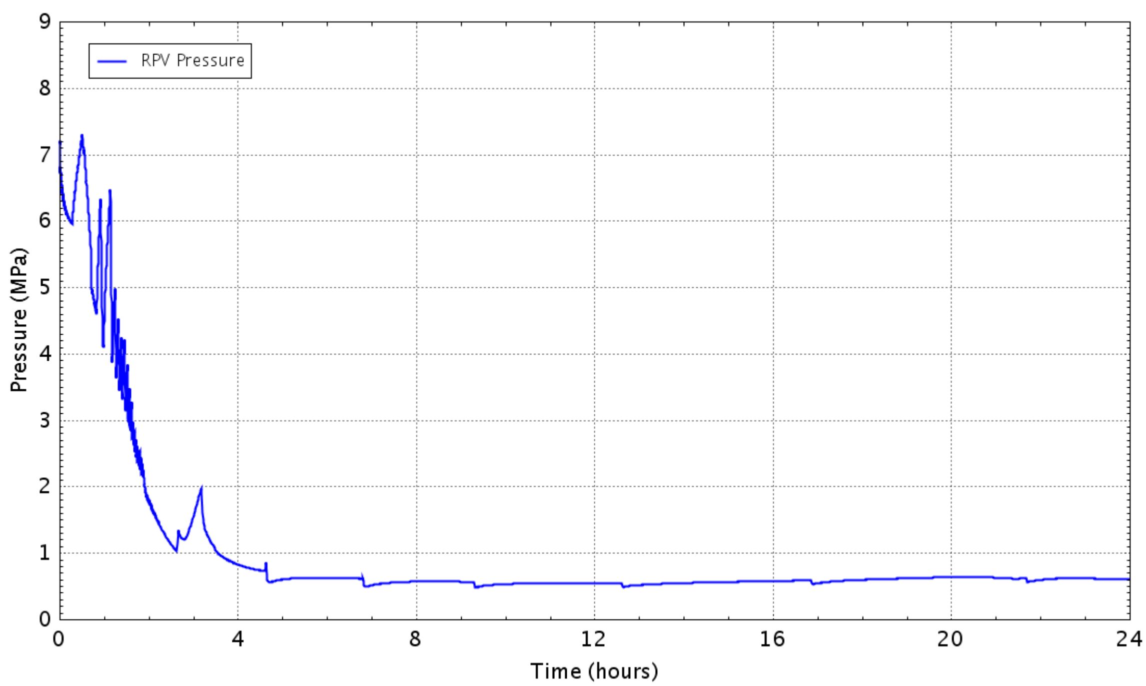

Figure C - 162 Pressure in the RPV

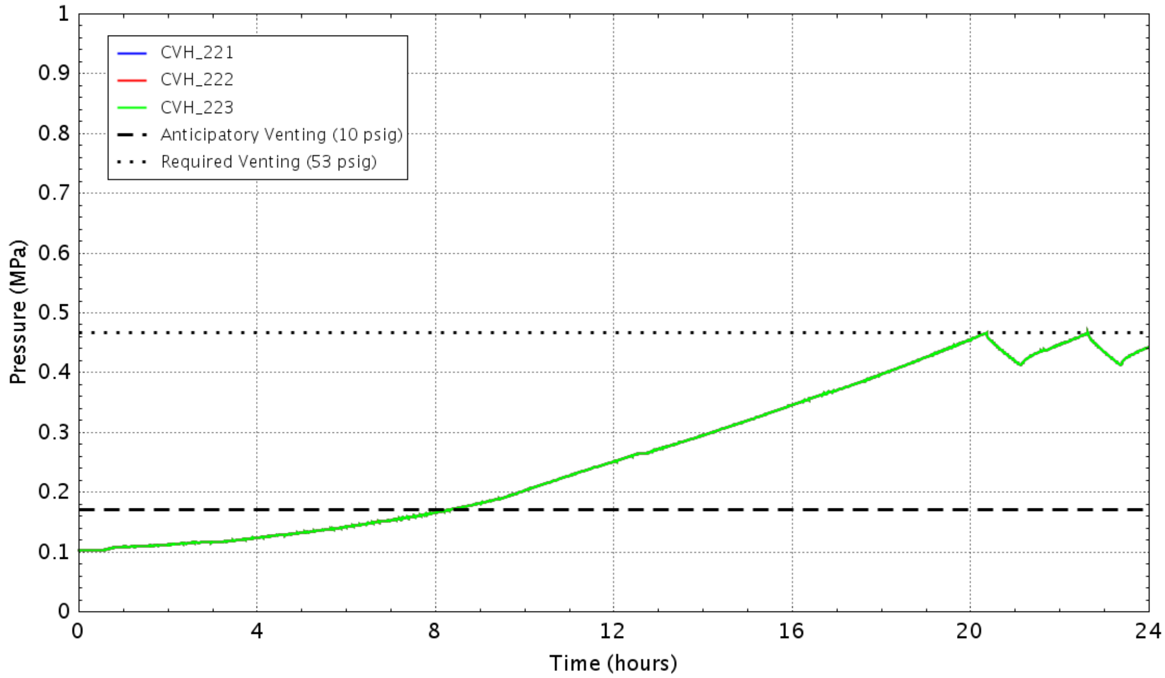

Figure C - 163   Pressure in the wetwell

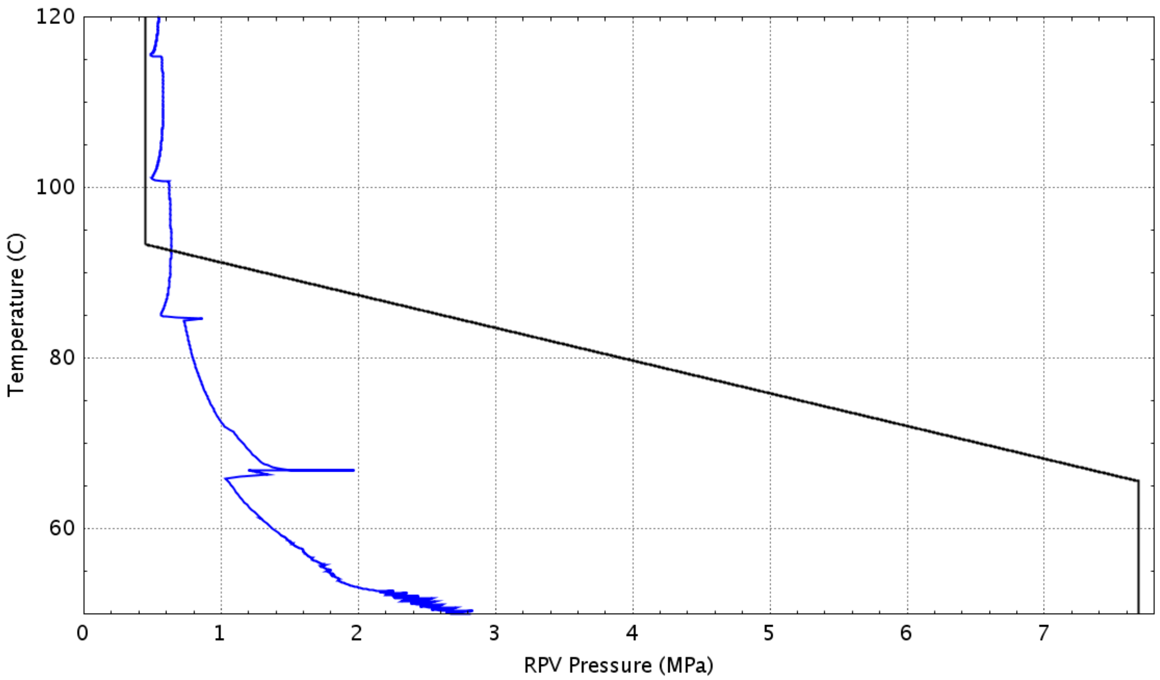

Figure C - 164   Plant status relative to the HCL curve (Graph 4 of the EOPs)

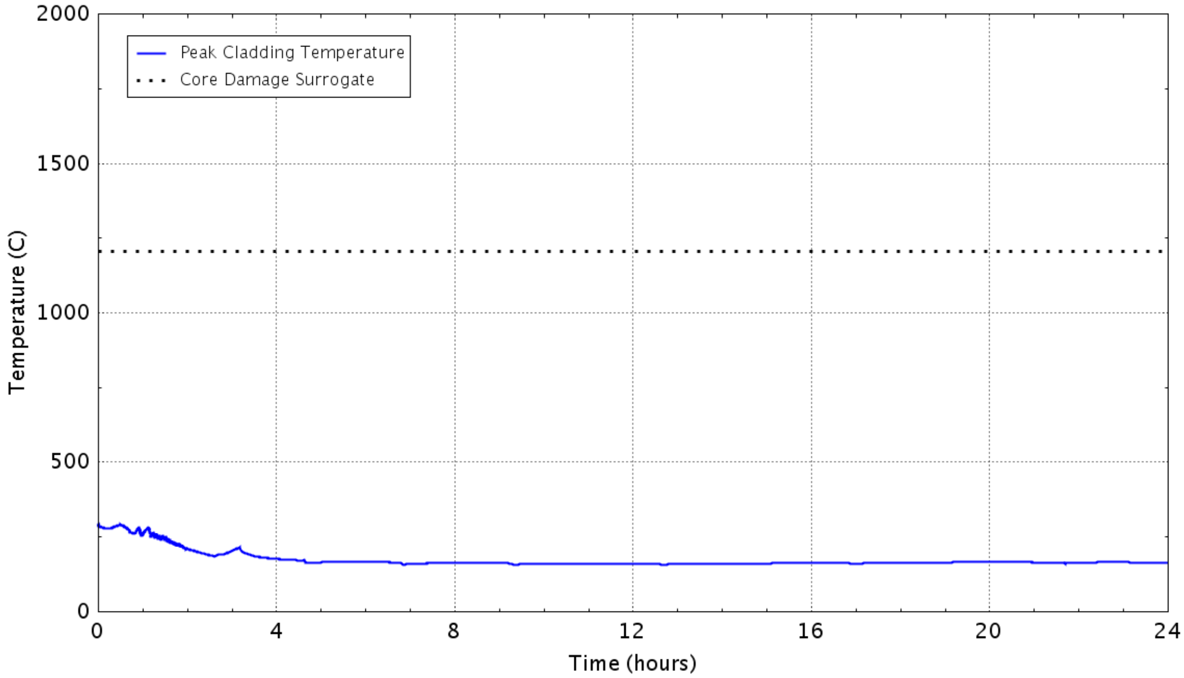

Figure C - 165 Peak temperature of the fuel cladding as a function of time

C.1.16 Case 16: TRANS-30, Two Trains of CRDHS, Automatic MSIV Closure

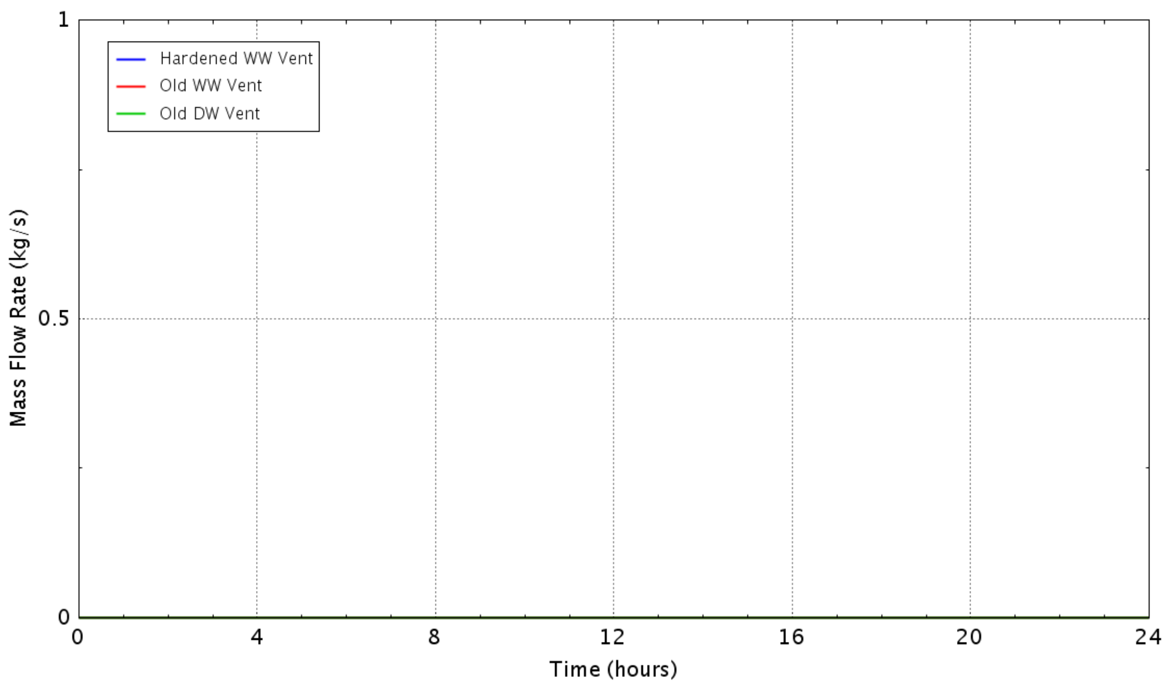

Figure C - 166 Flow rate of the containment vents

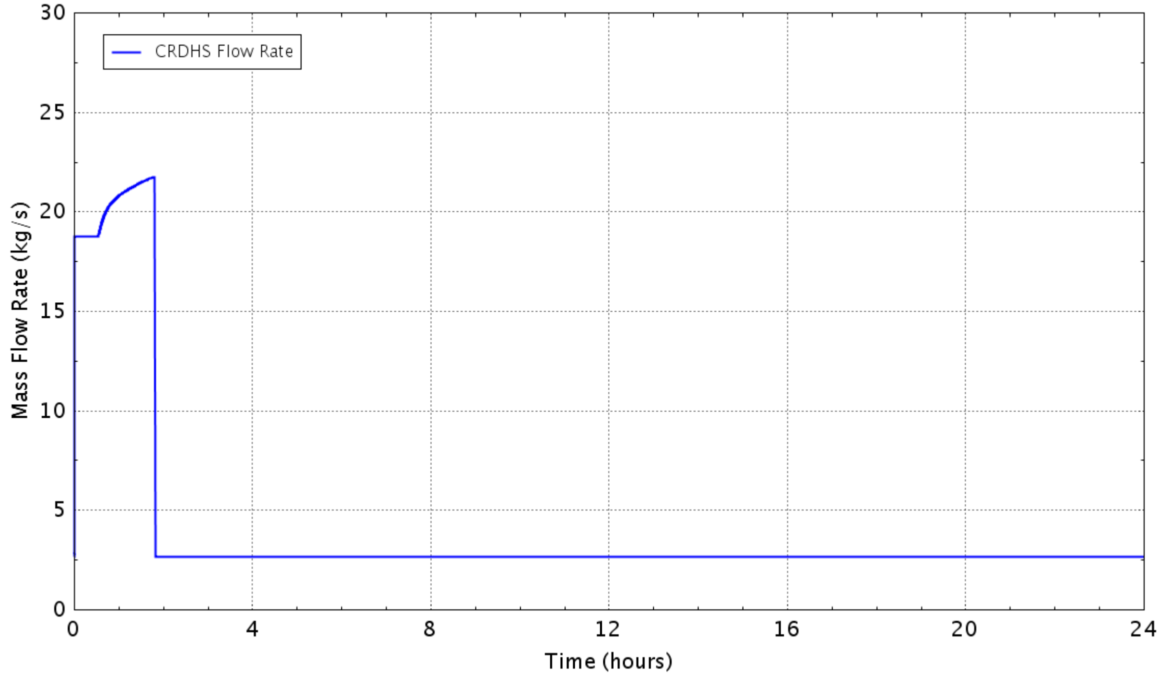

Figure C - 167 Flow rate of the control rod drive hydraulic system

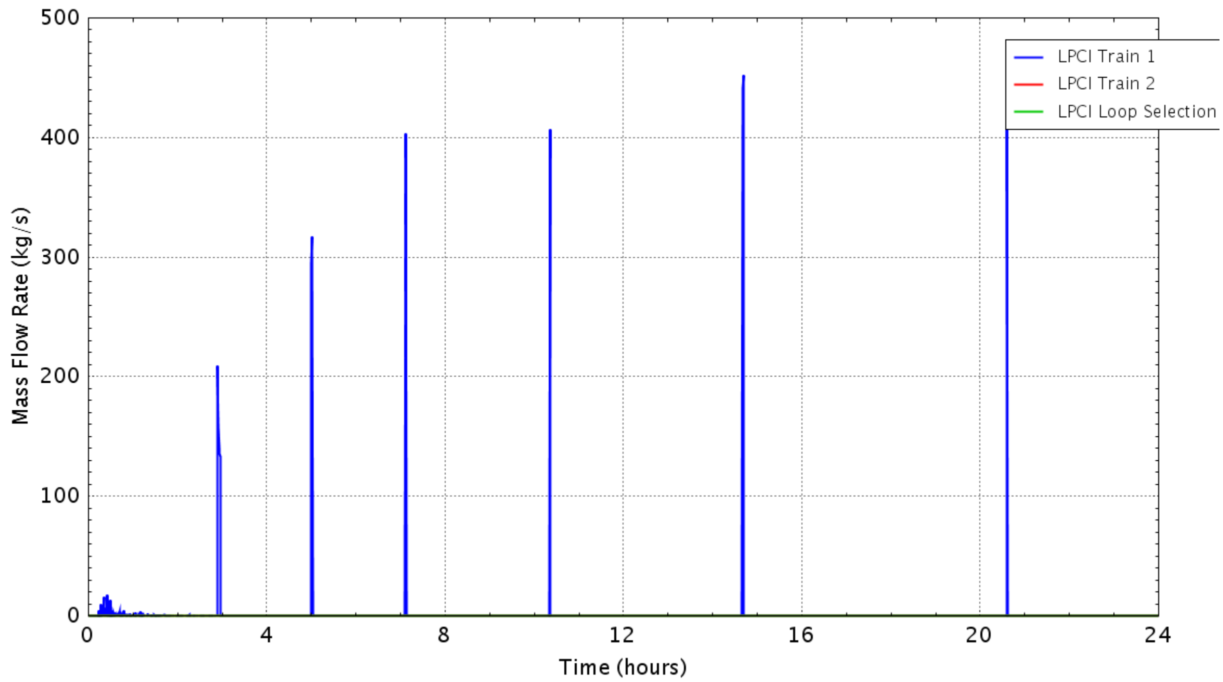

Figure C - 168 Flow rate of the LPCI pump

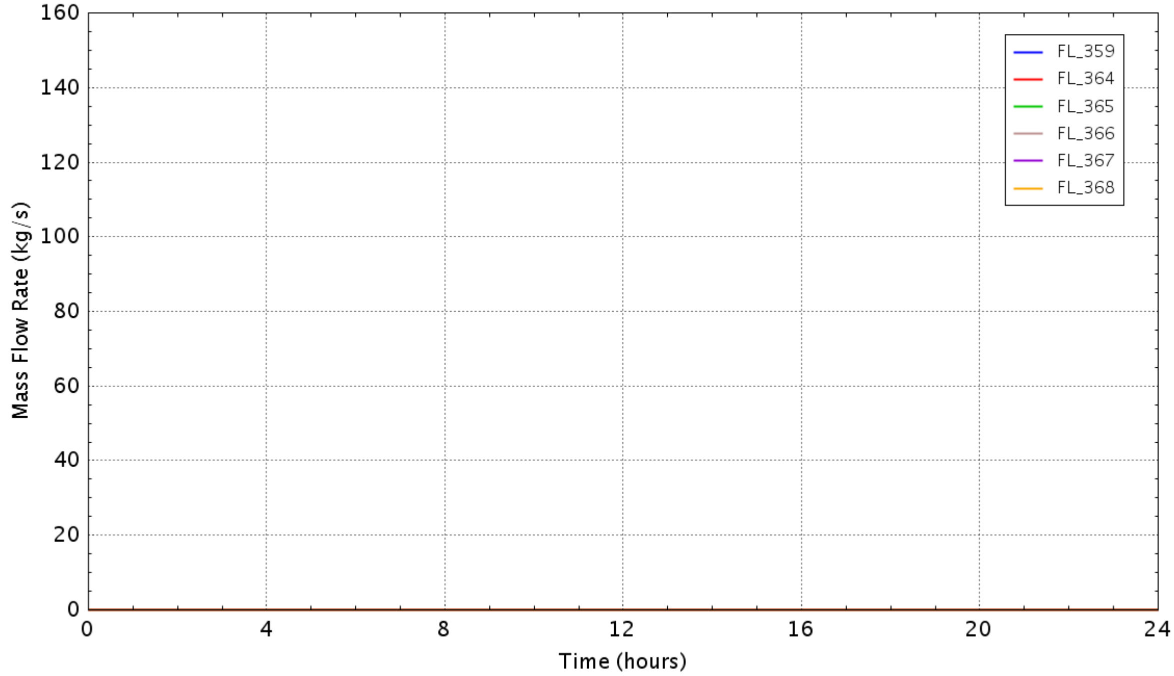

Figure C - 169 Flow rate of the SRVs

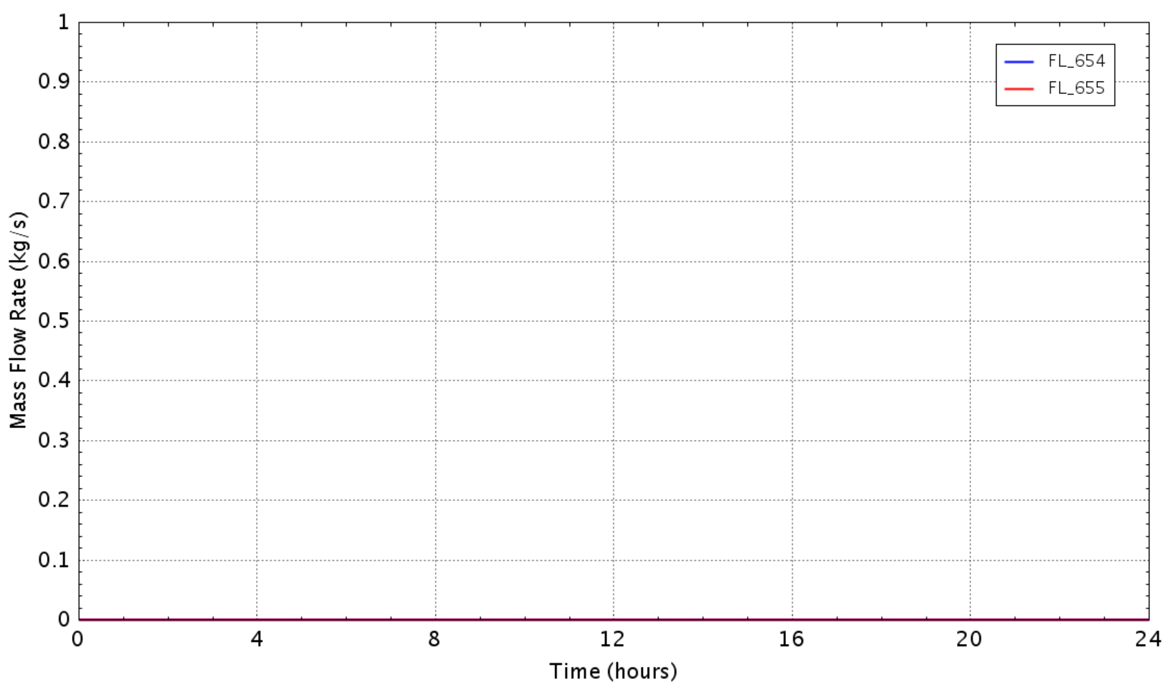

Figure C - 170 Flow rate of the wetwell cooling system

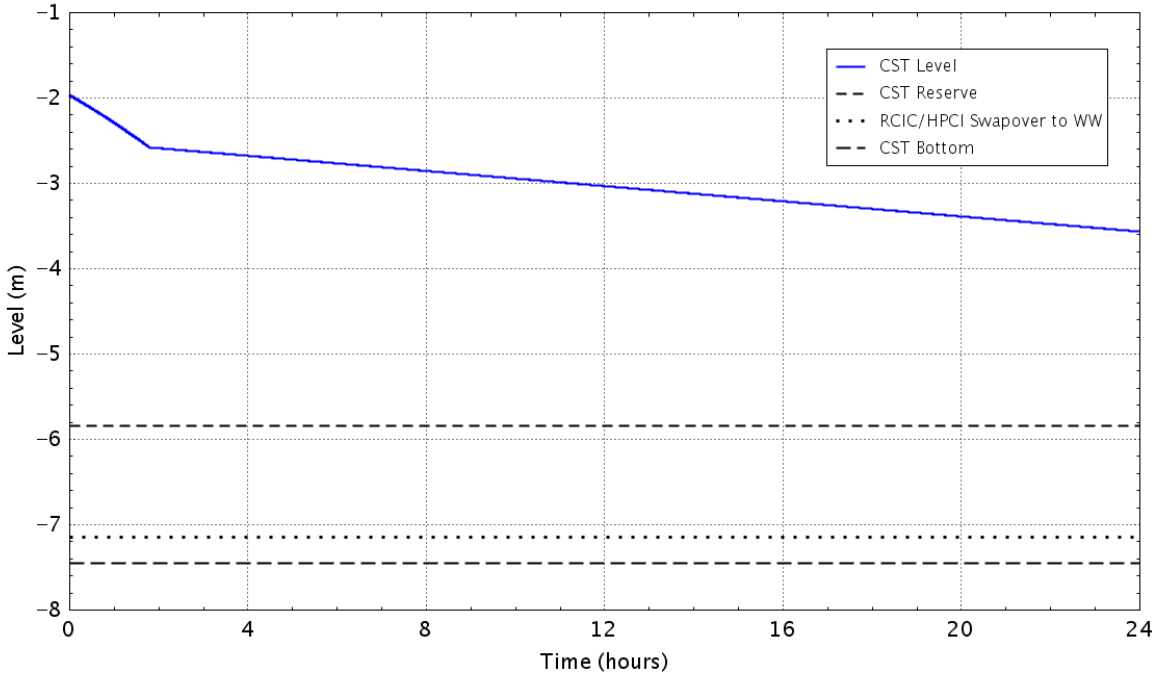

Figure C - 171 Water level in the CST

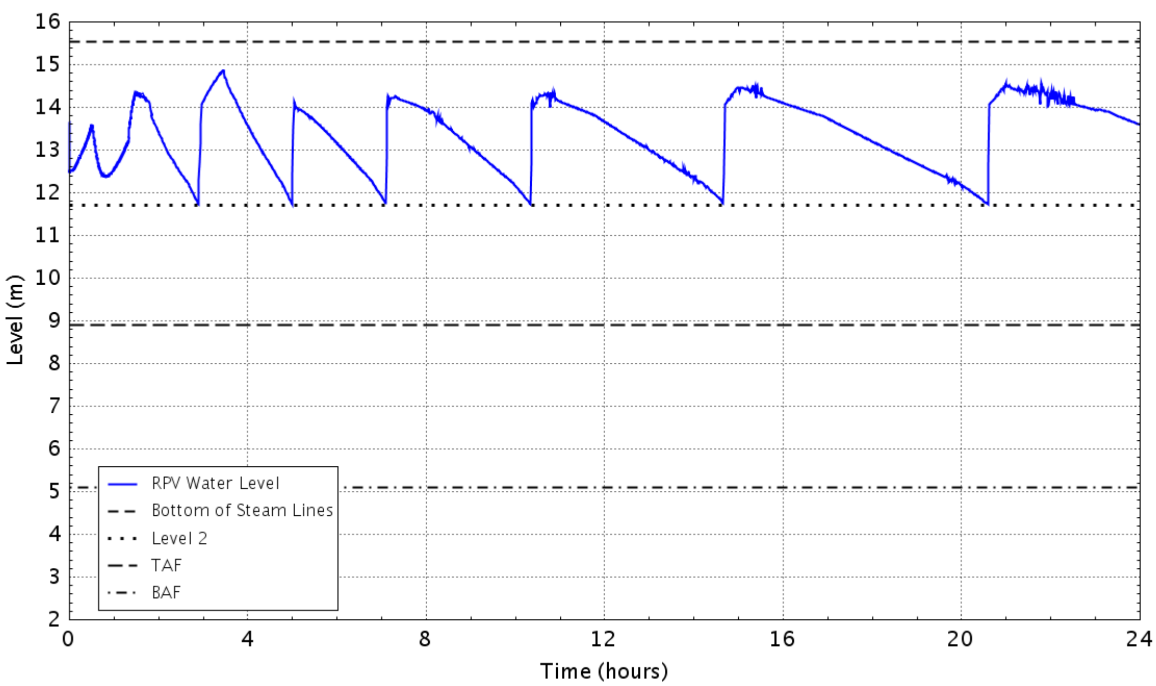

Figure C - 172 RPV Downcomer water level

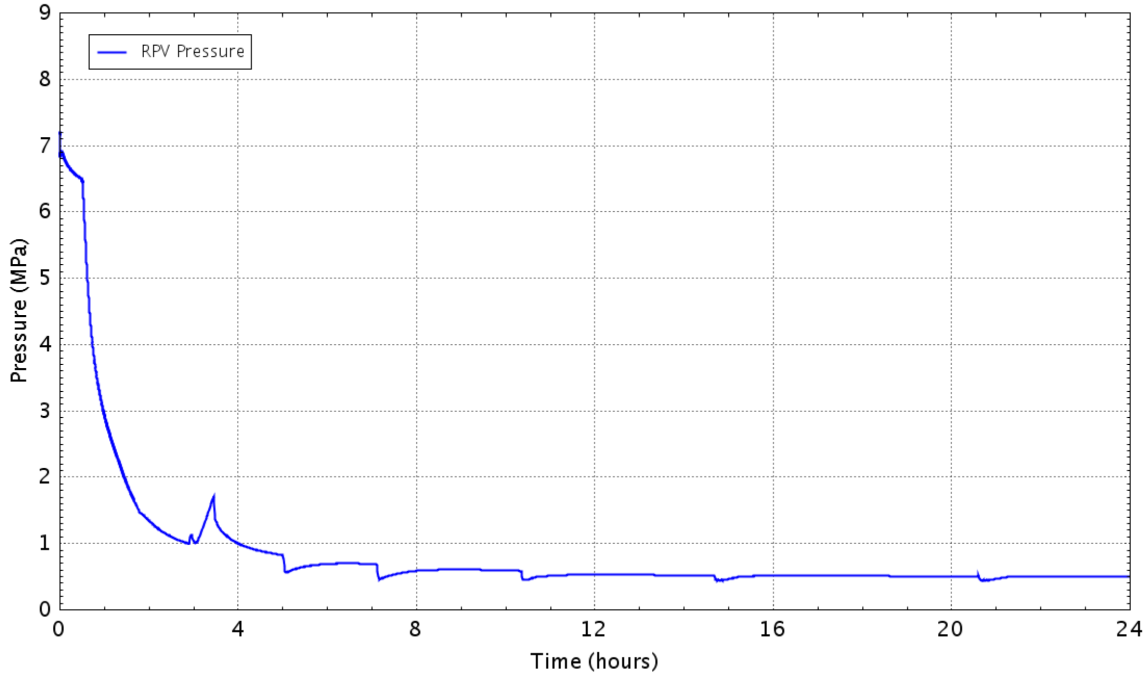

Figure C - 173 Pressure in the RPV

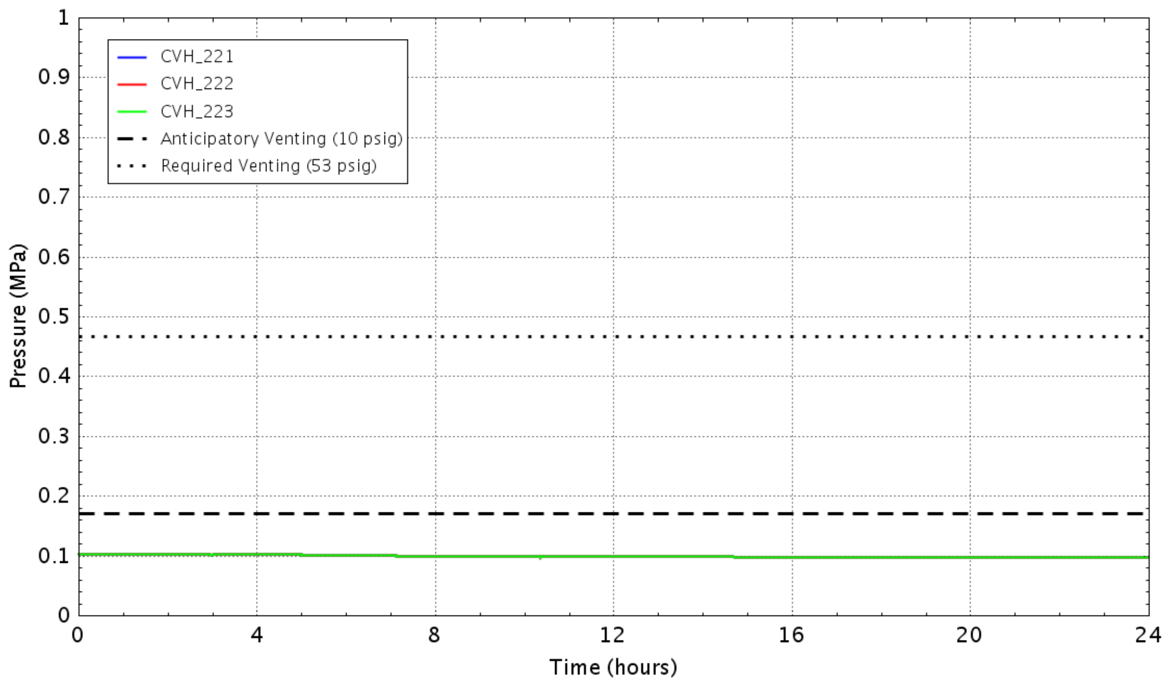

Figure C - 174   Pressure in the wetwell

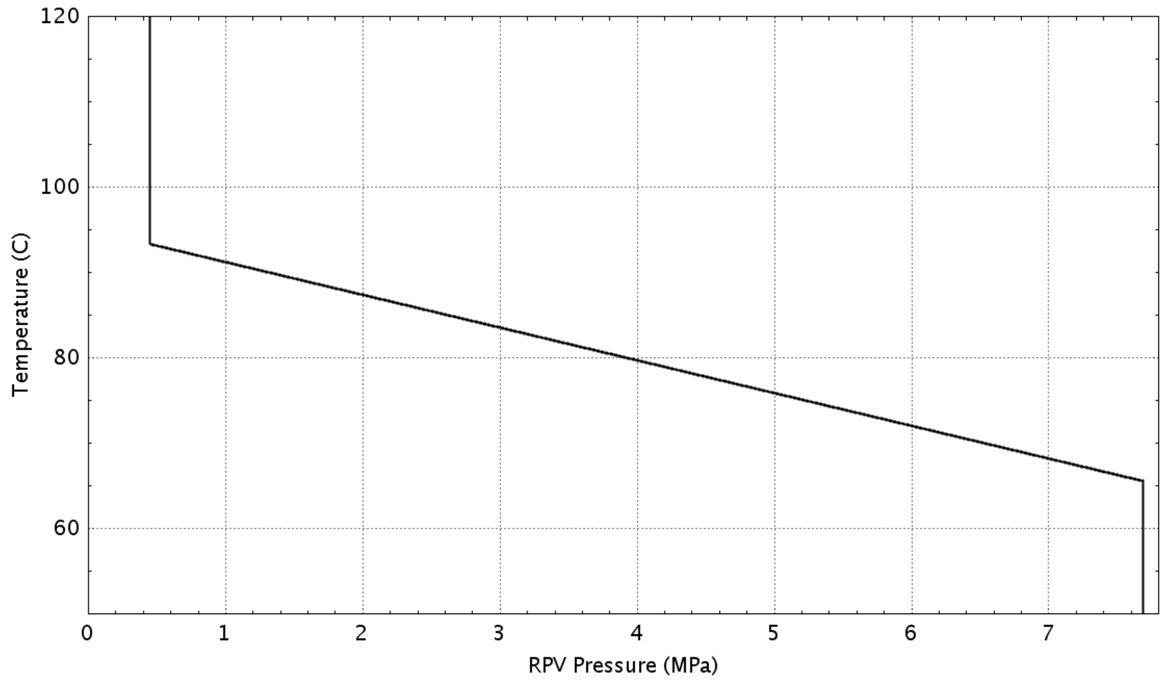

Figure C - 175   Plant status relative to the HCL curve (Graph 4 of the EOPs)

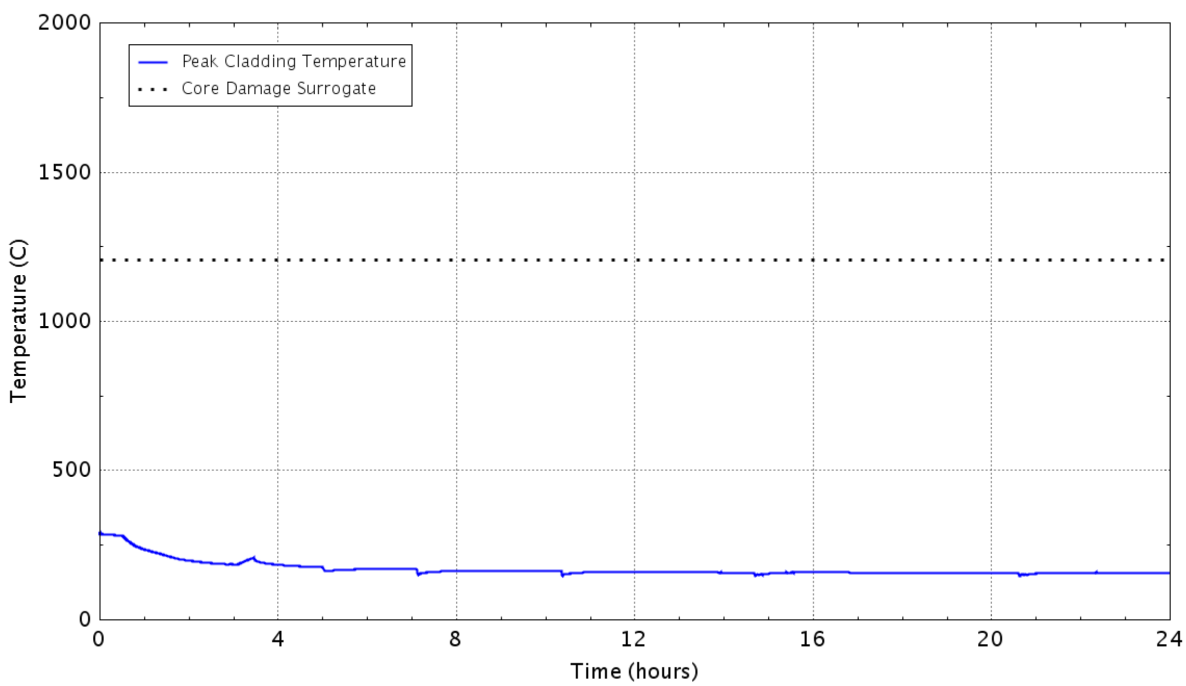

Figure C - 176   Peak temperature of the fuel cladding as a function of time

C.1.17 Case 17: TRANS-49, One Train of CRDHS, MSIV Closure at 10 min.

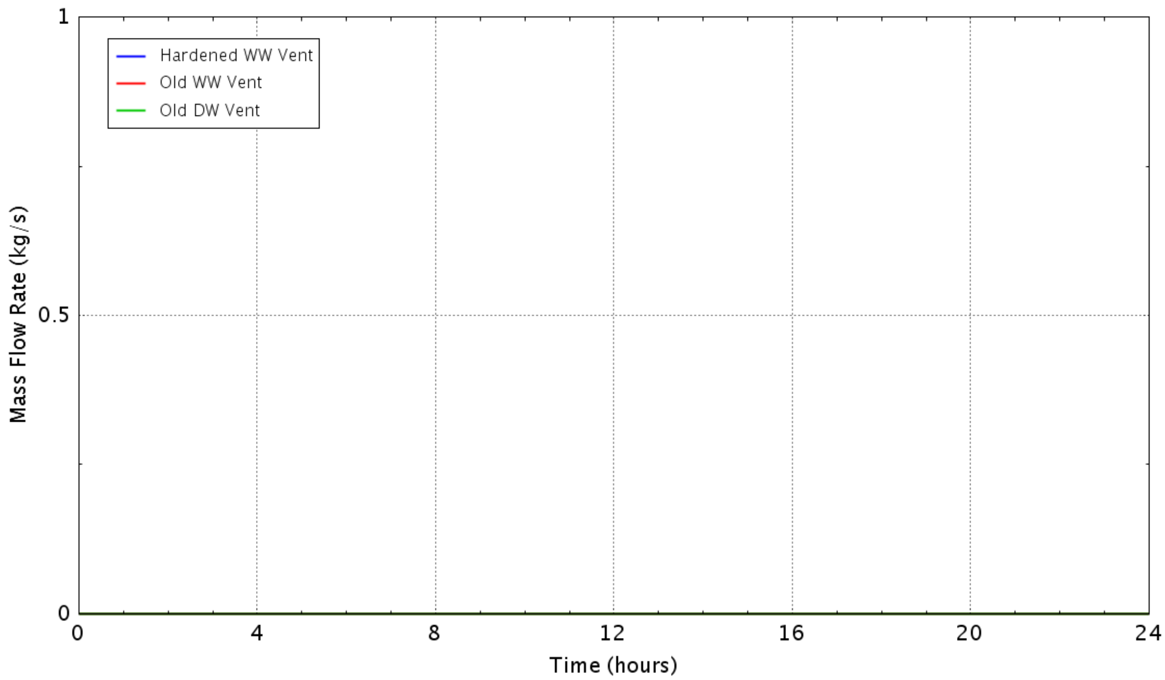

Figure C - 177 Flow rate of the containment vents

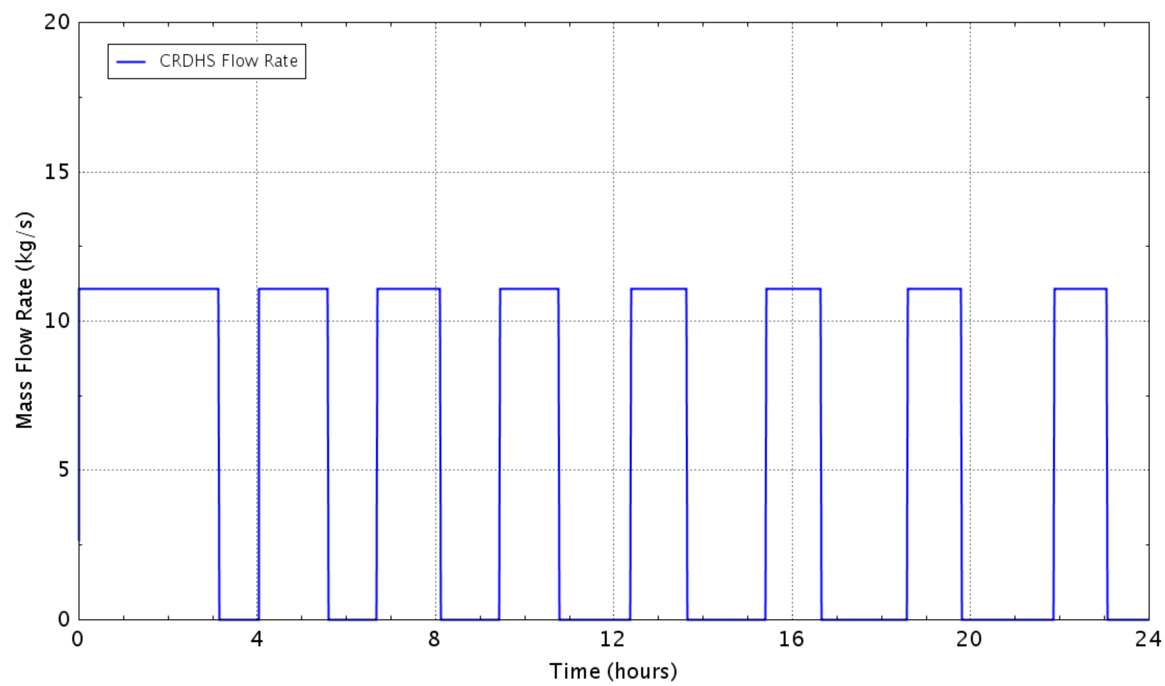

Figure C - 178 Flow rate of the control rod drive hydraulic system

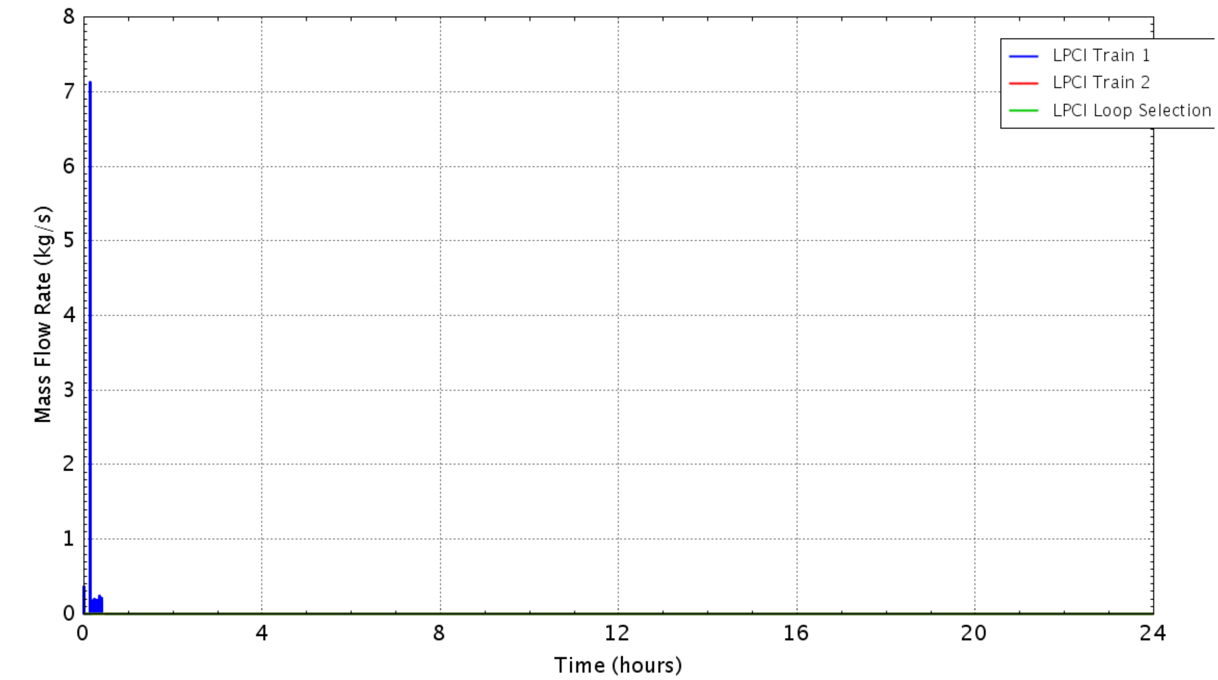

Figure C - 179 Flow rate of the LPCI pump

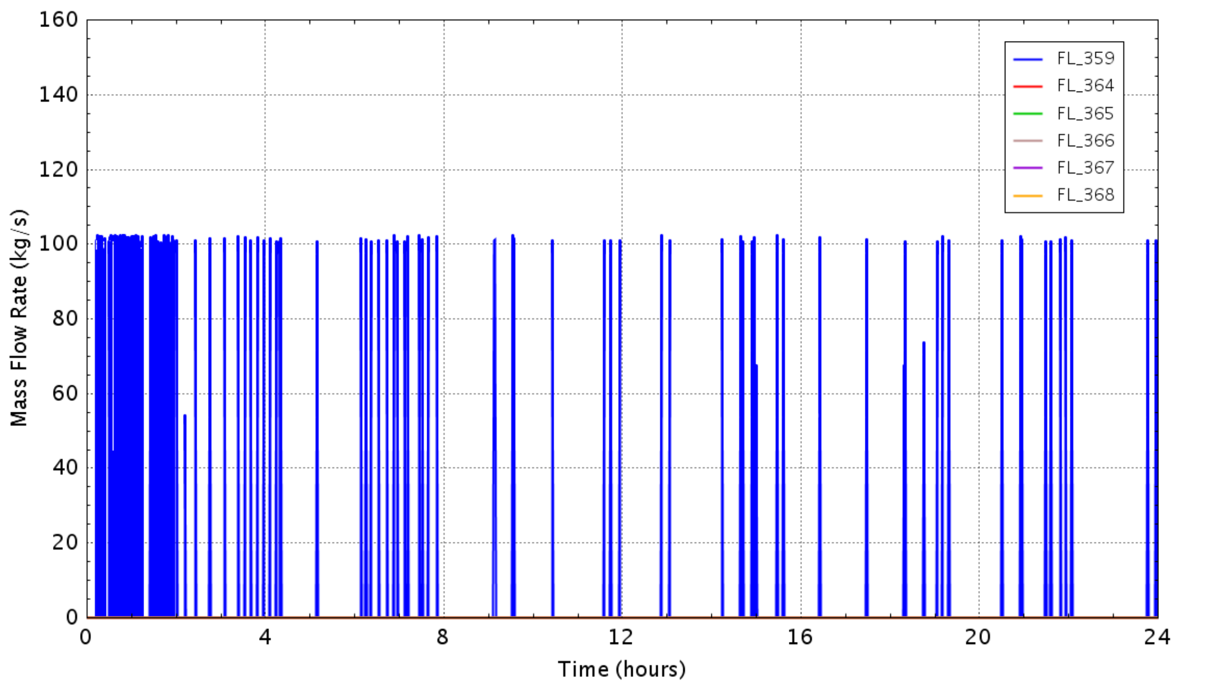

Figure C - 180 Flow rate of the SRVs

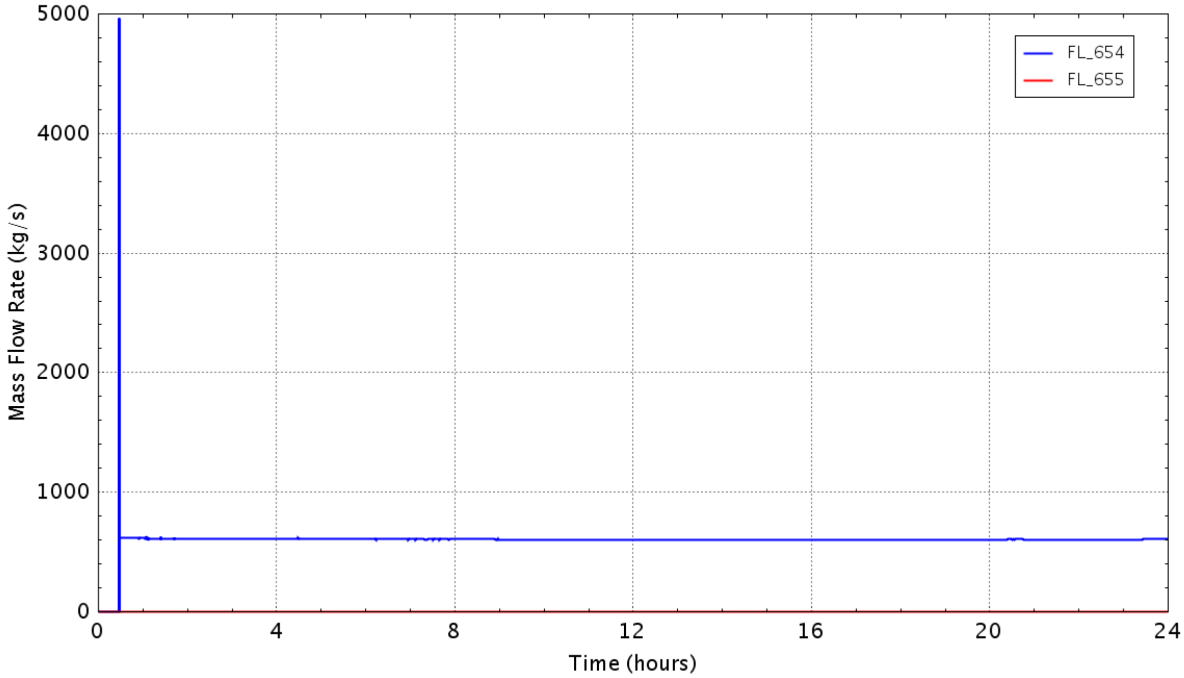

Figure C - 181 Flow rate of the wetwell cooling system

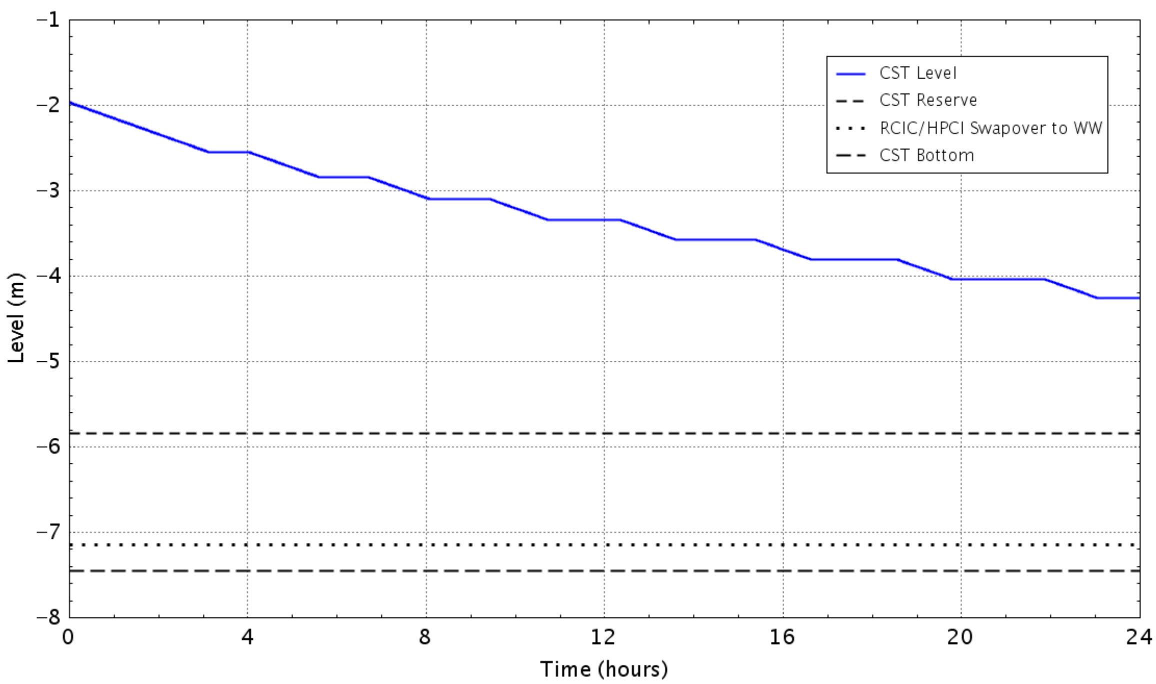

Figure C - 182 Water level in the CST

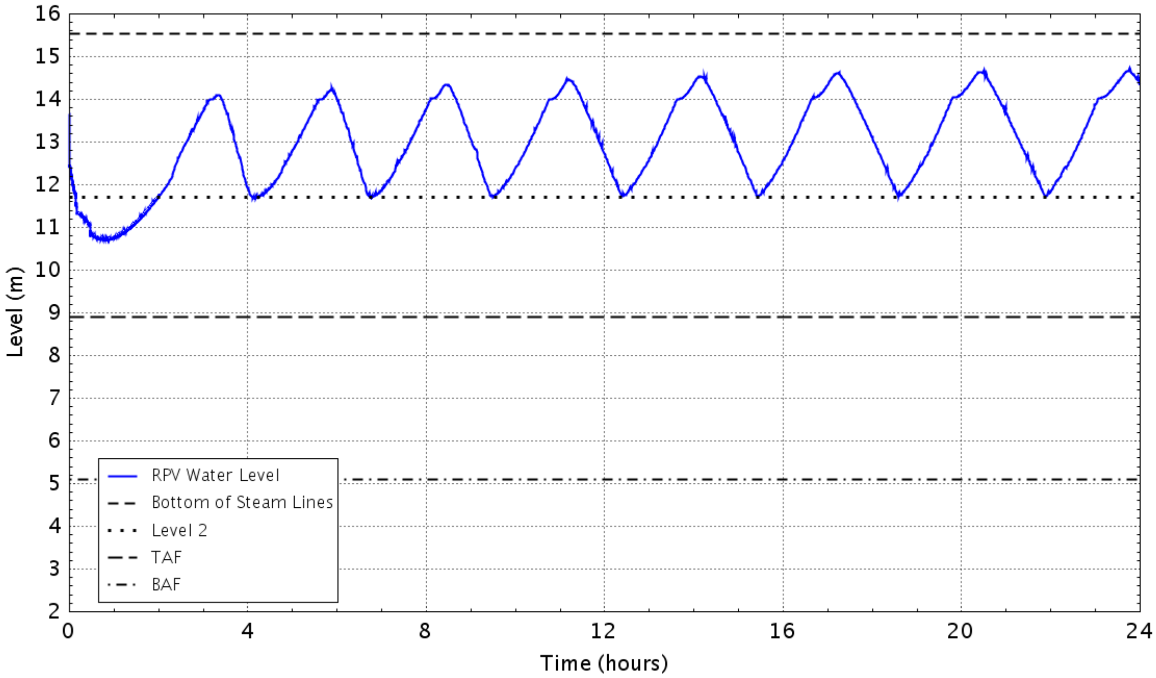

Figure C - 183 RPV Downcomer water level

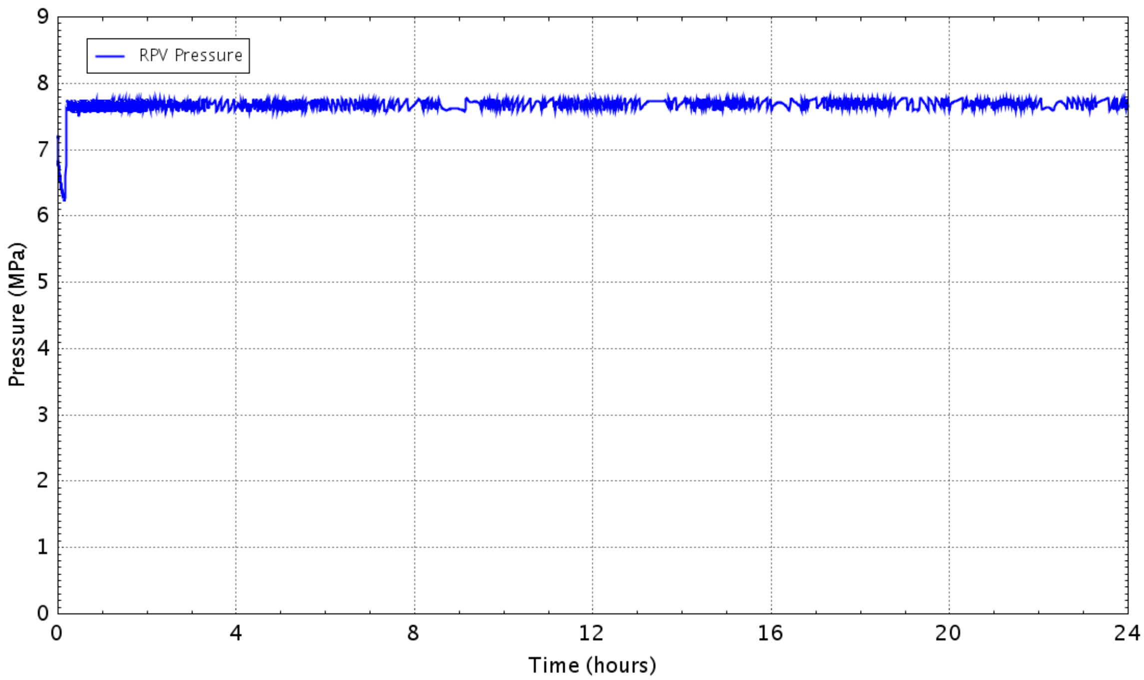

Figure C - 184 Pressure in the RPV

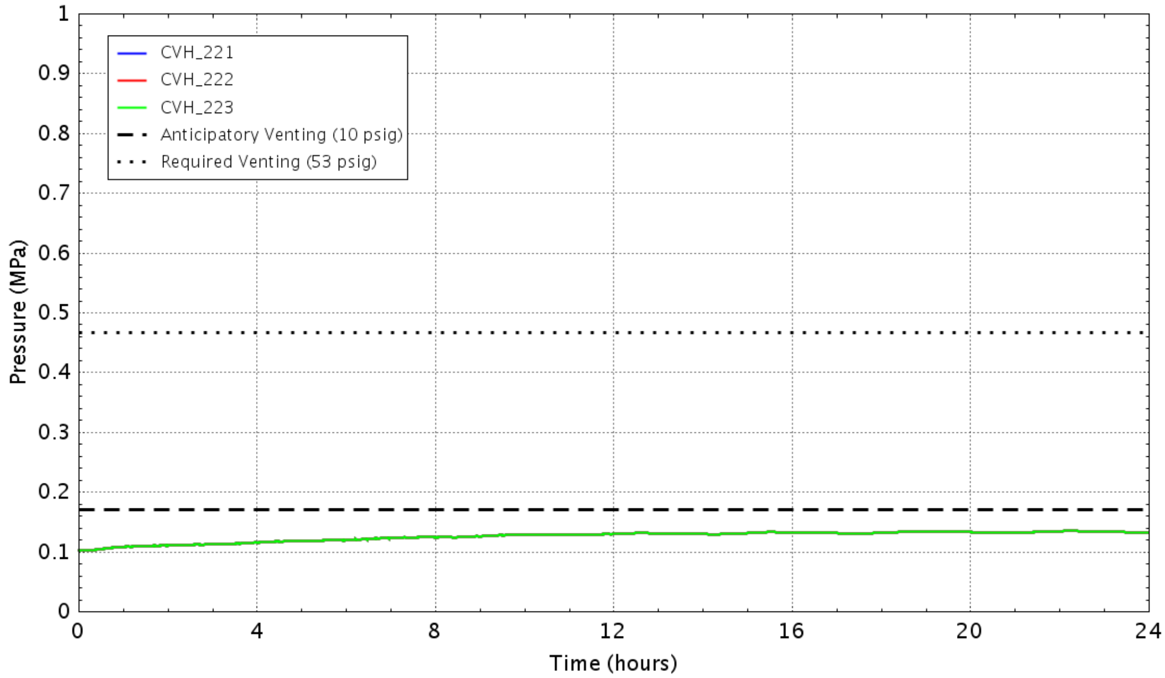

Figure C - 185   Pressure in the wetwell

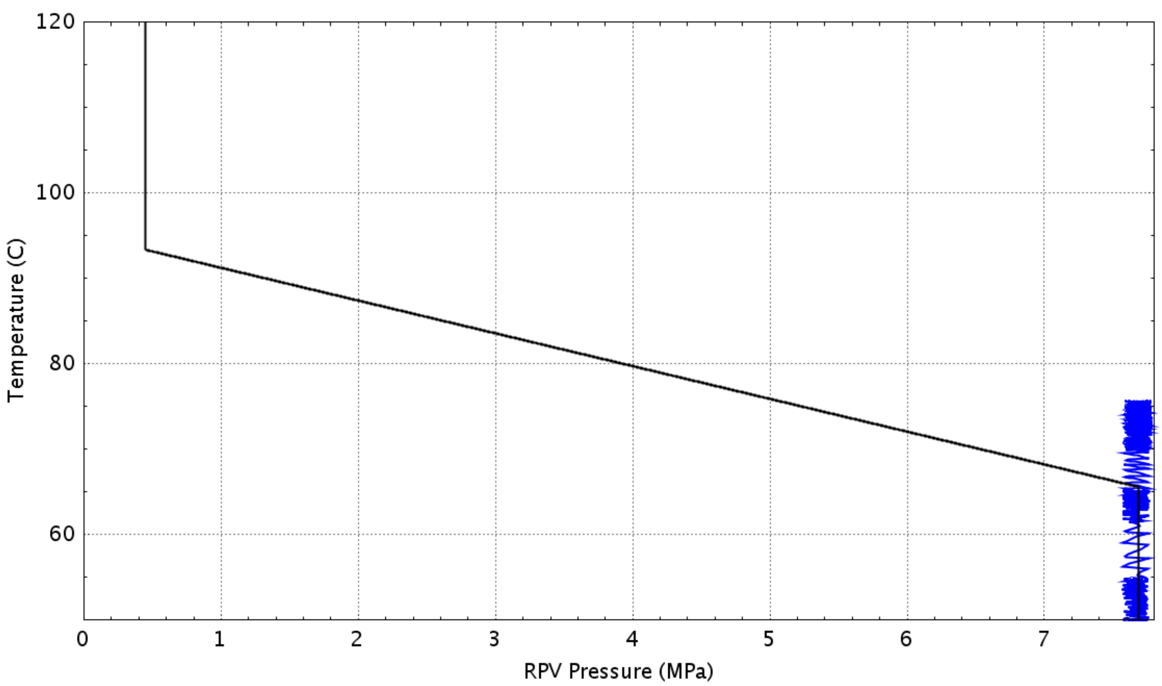

Figure C - 186   Plant status relative to the HCL curve (Graph 4 of the EOPs)

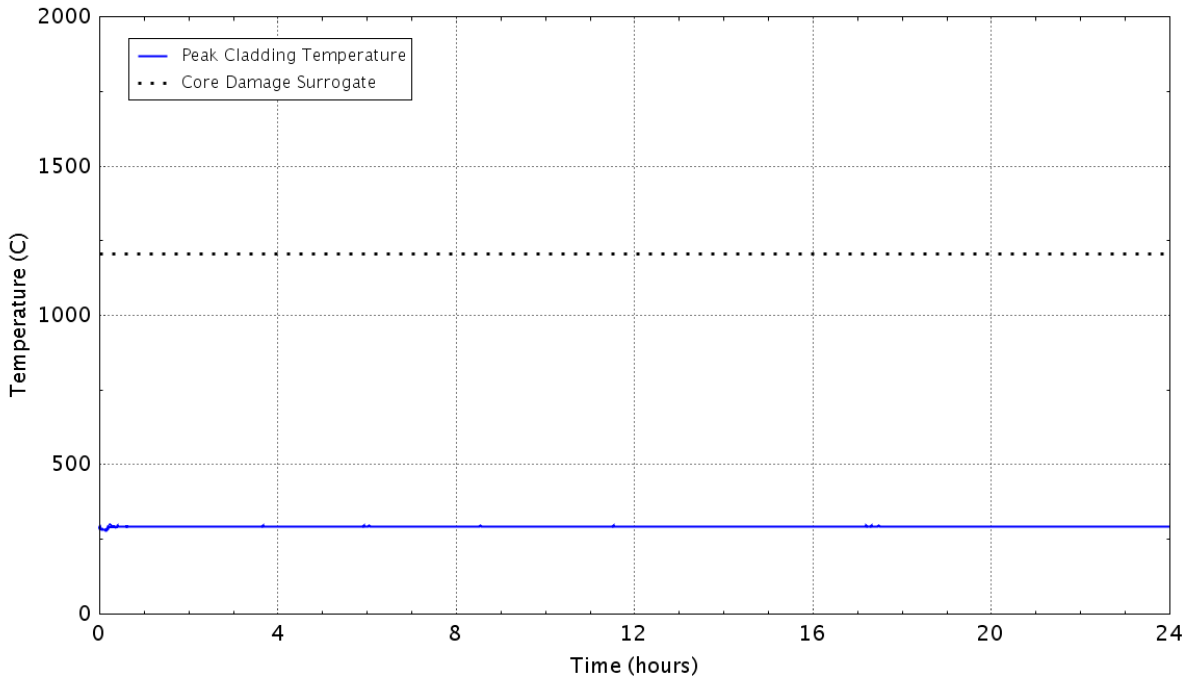

Figure C - 187 Peak temperature of the fuel cladding as a function of time

C.1.18 Case 18: TRANS-49, Two Trains of CRDHS, Automatic MSIV Closure

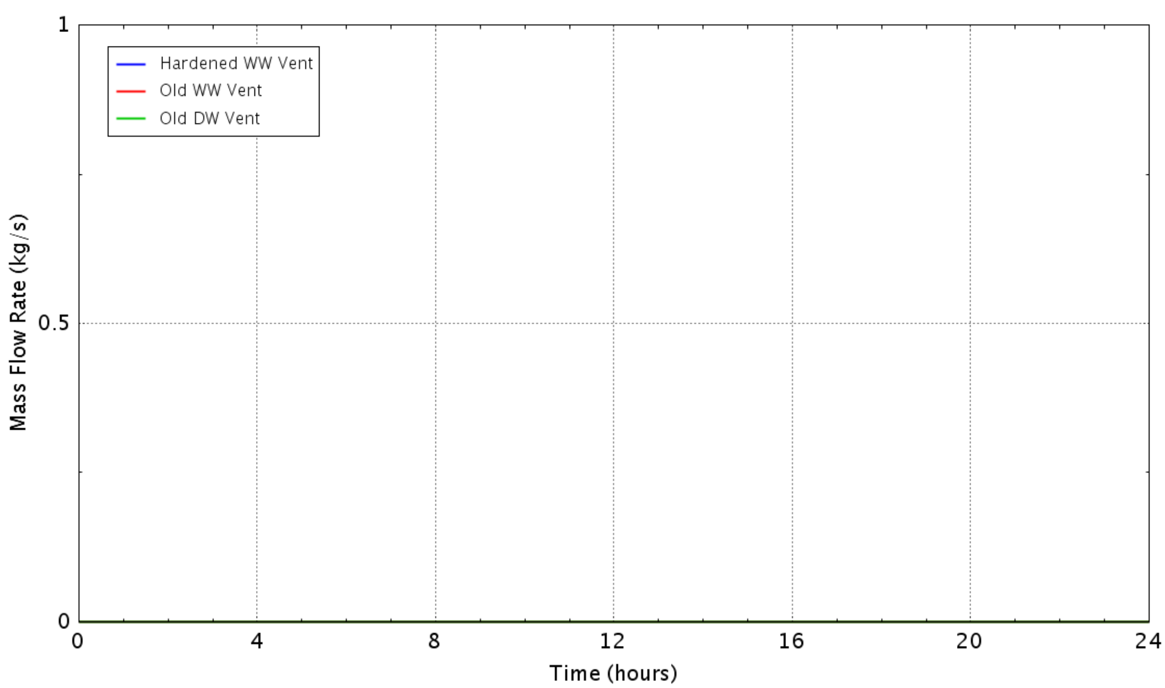

Figure C - 188 Flow rate of the containment vents

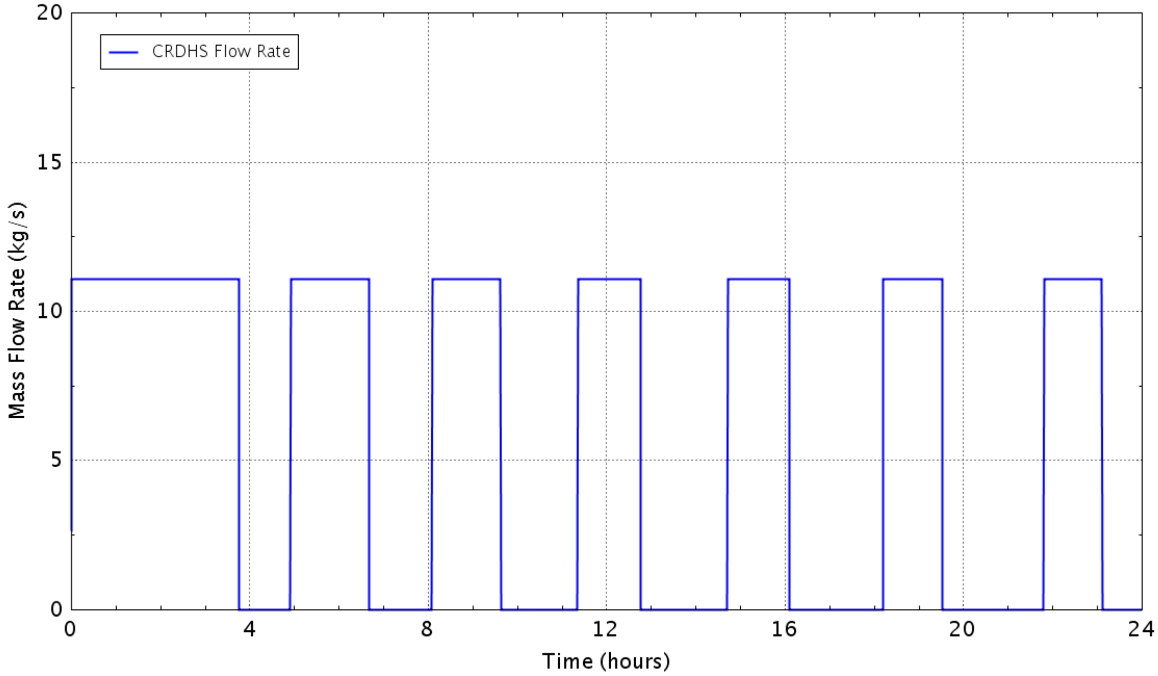

Figure C - 189 Flow rate of the control rod drive hydraulic system

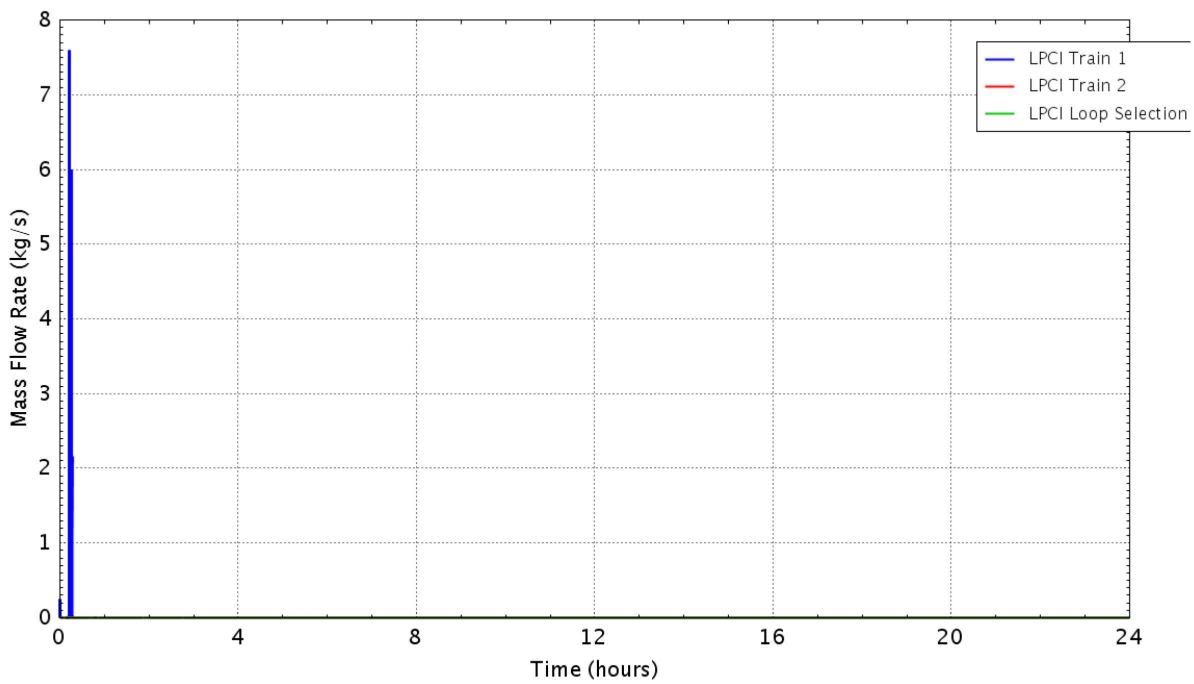

Figure C - 190 Flow rate of the LPCI pump

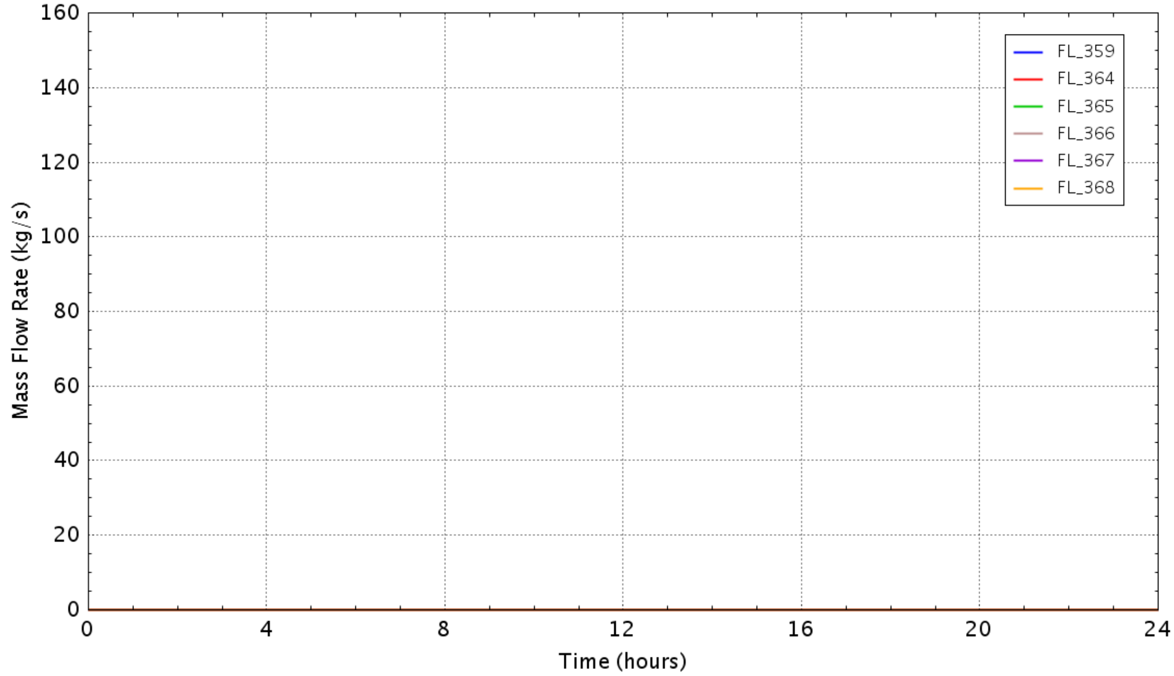

Figure C - 191 Flow rate of the SRVs

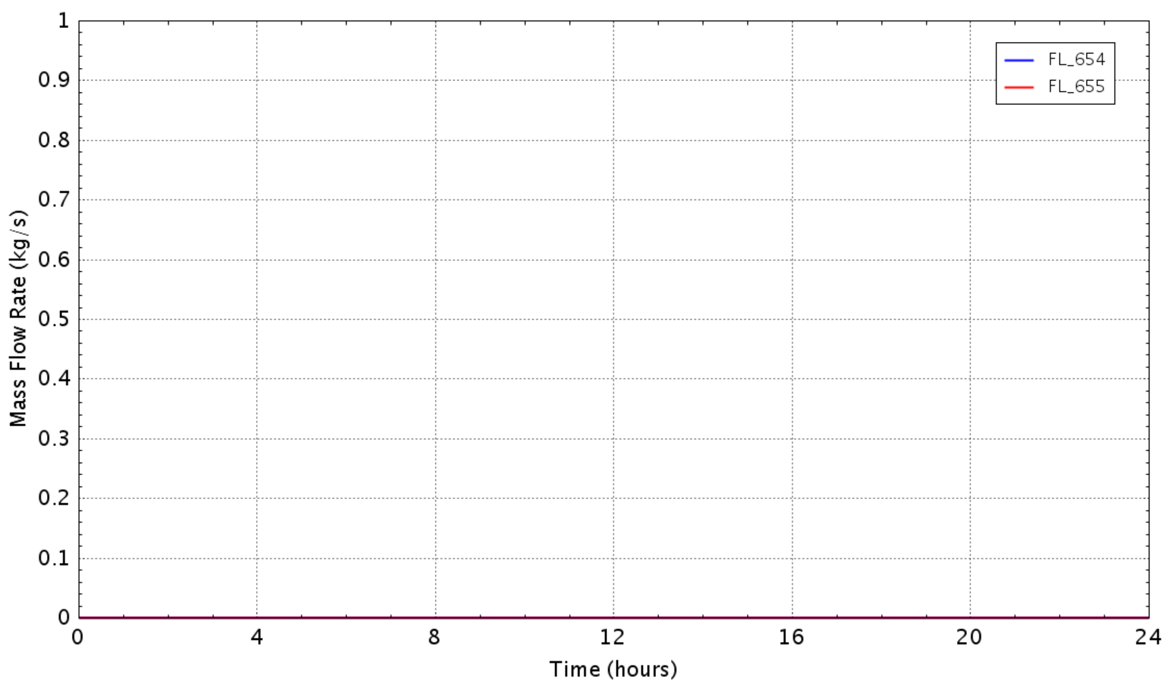

Figure C - 192 Flow rate of the wetwell cooling system

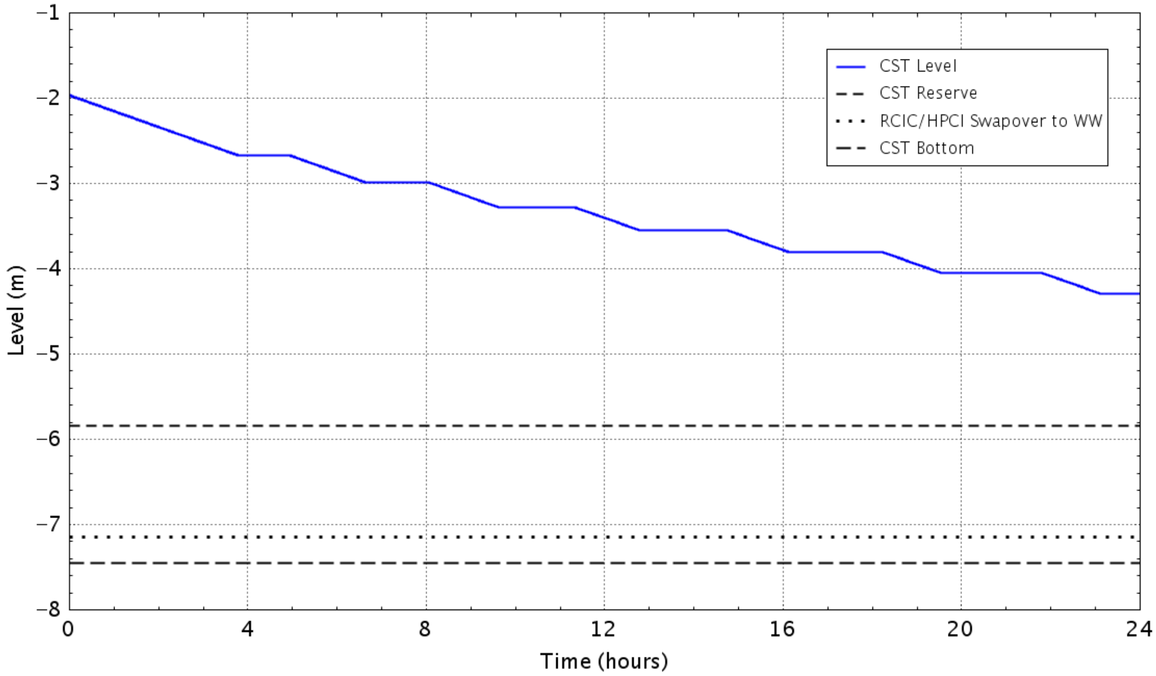

Figure C - 193 Water level in the CST

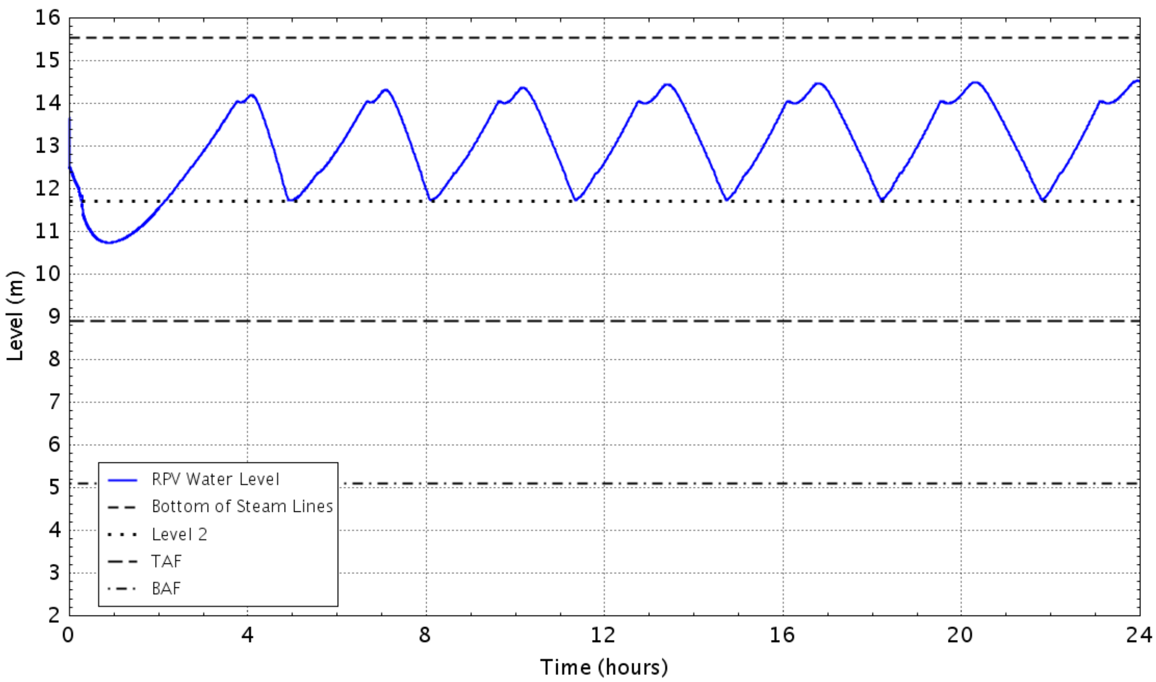

Figure C - 194 RPV Downcomer water level

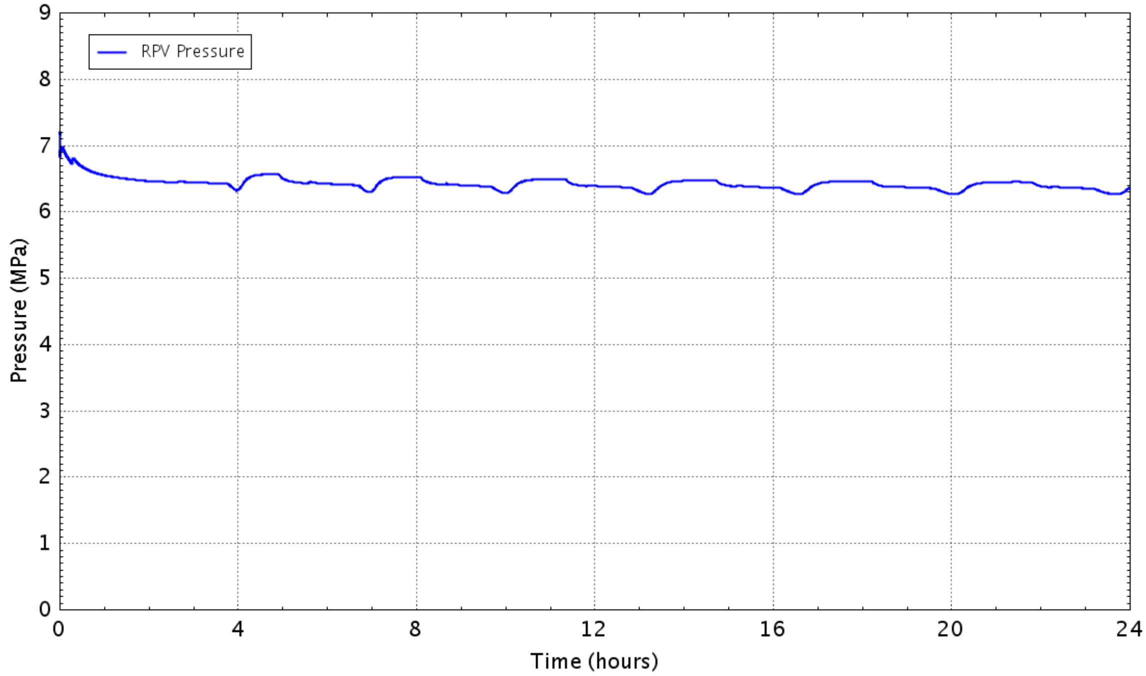

Figure C - 195 Pressure in the RPV

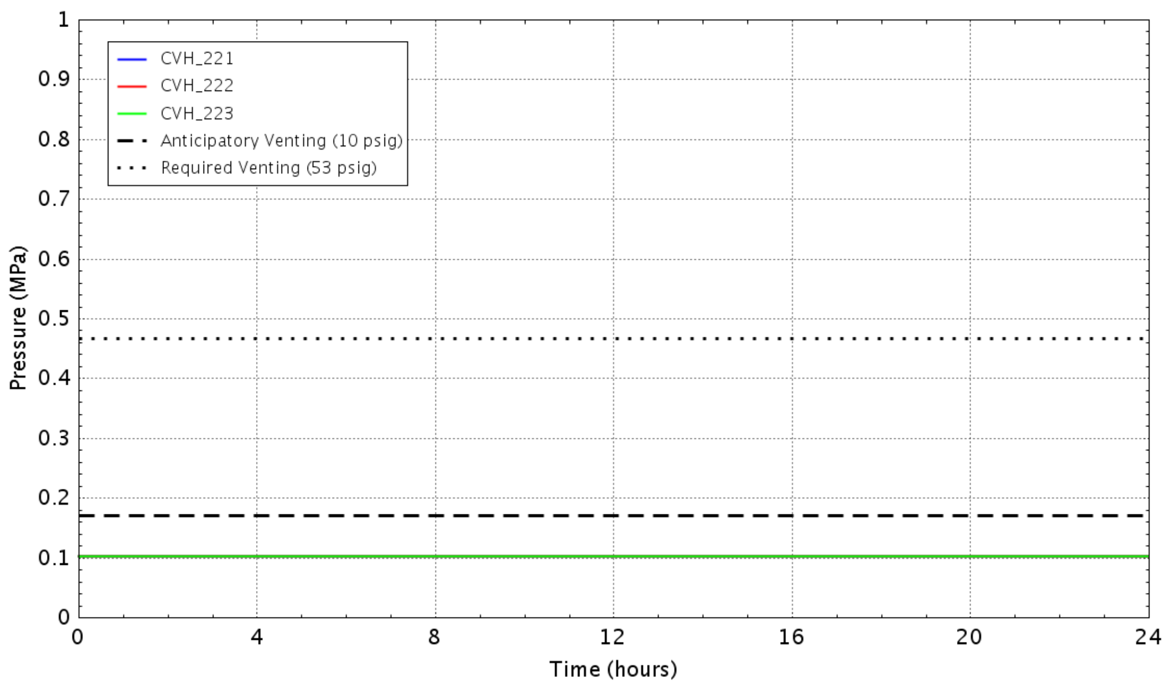

Figure C - 196   Pressure in the wetwell

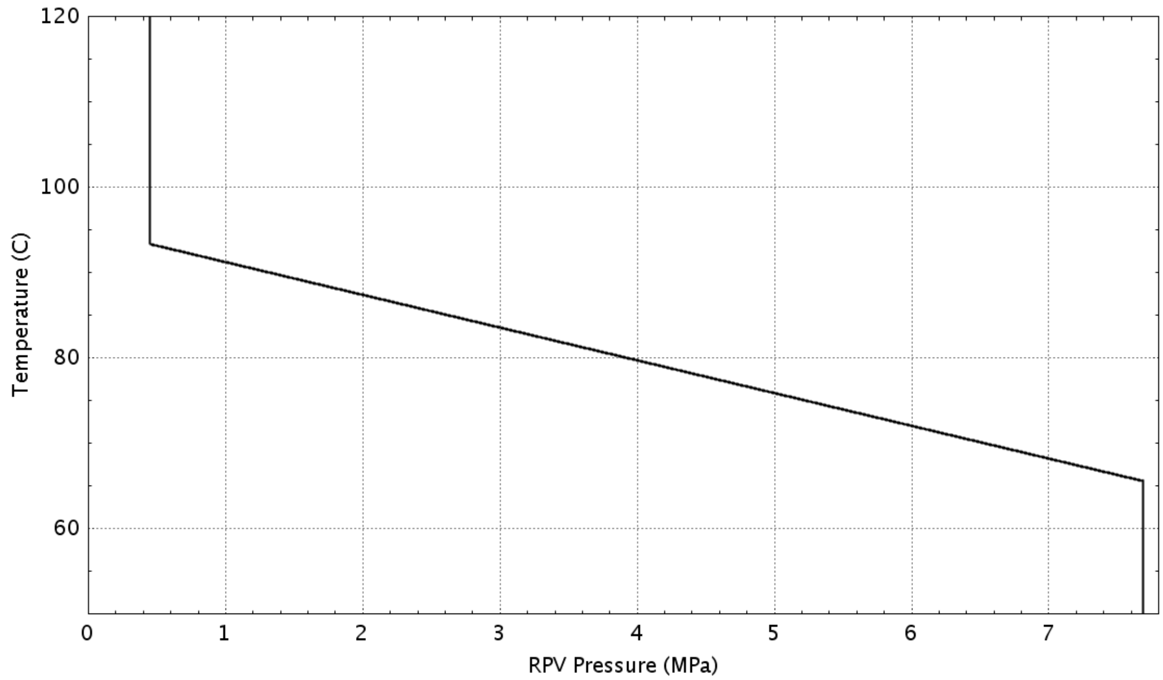

Figure C - 197   Plant status relative to the HCL curve (Graph 4 of the EOPs)

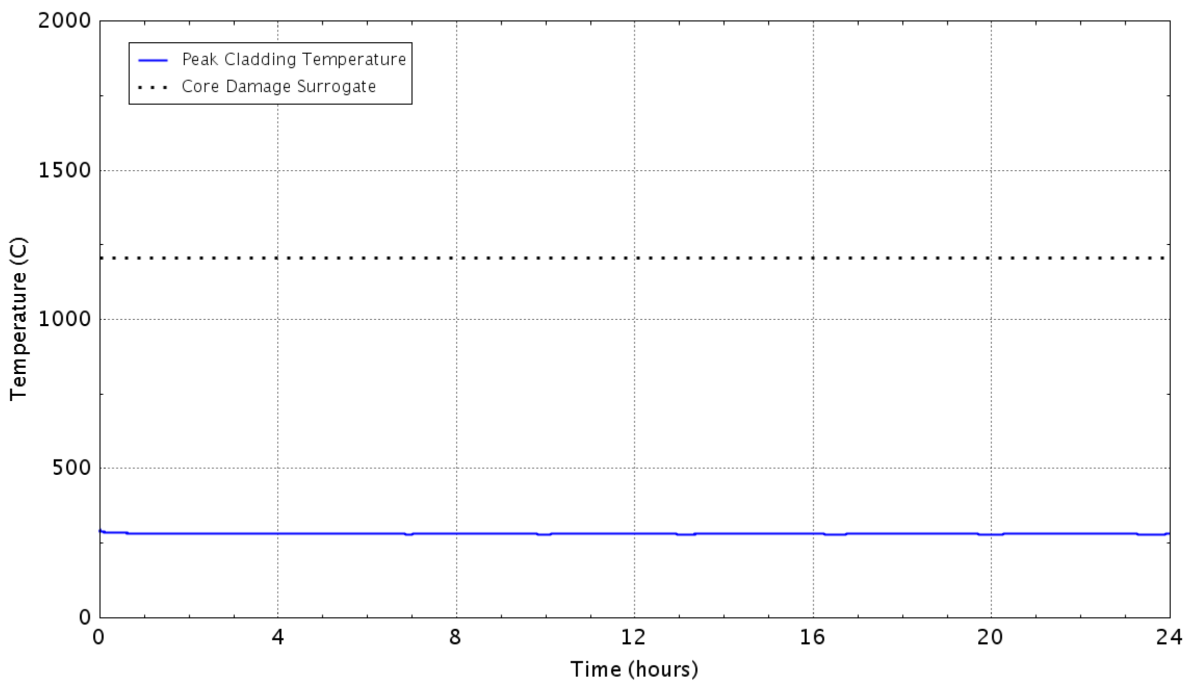

Figure C - 198   Peak temperature of the fuel cladding as a function of time

C.1.19 Case 19: TRANS-49, Two Trains of CRDHS, MSIV Closure at 10 min.

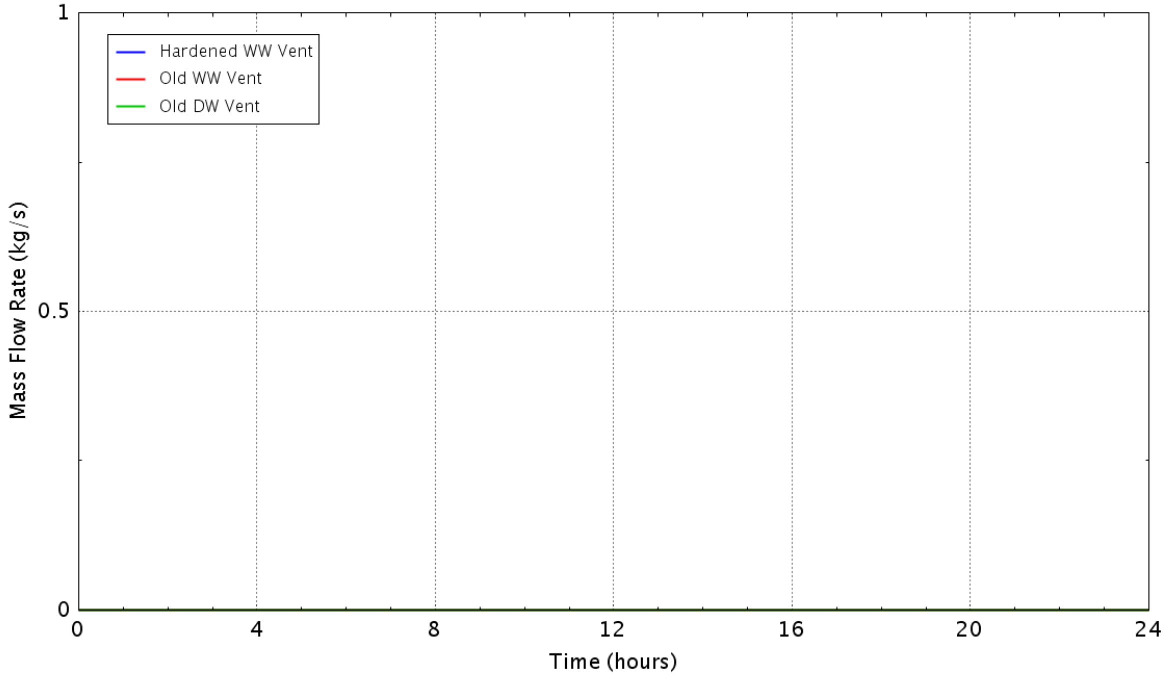

Figure C - 199 Flow rate of the containment vents

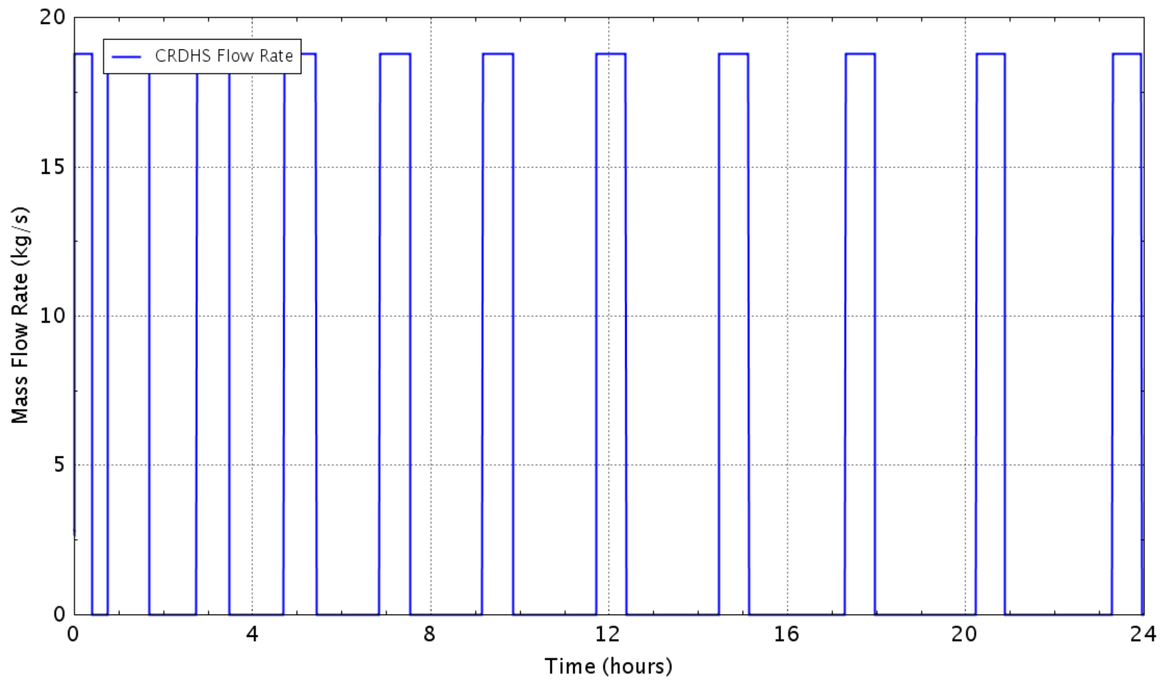

Figure C - 200 Flow rate of the control rod drive hydraulic system

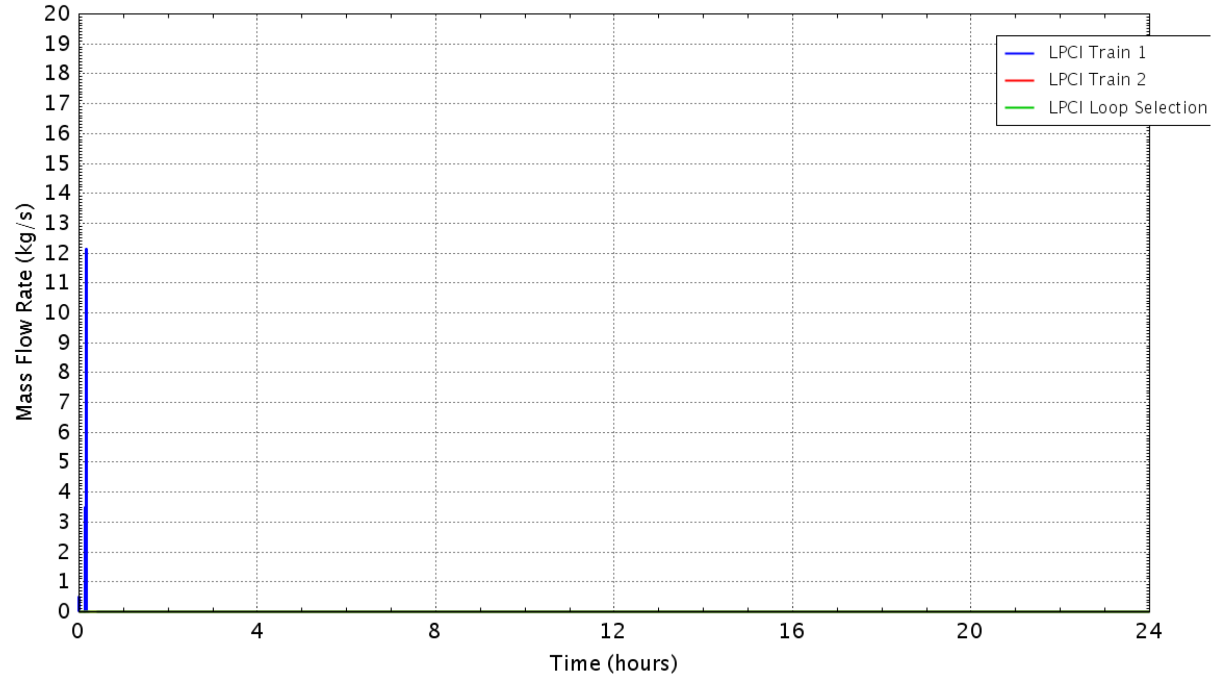

Figure C - 201 Flow rate of the LPCI pump

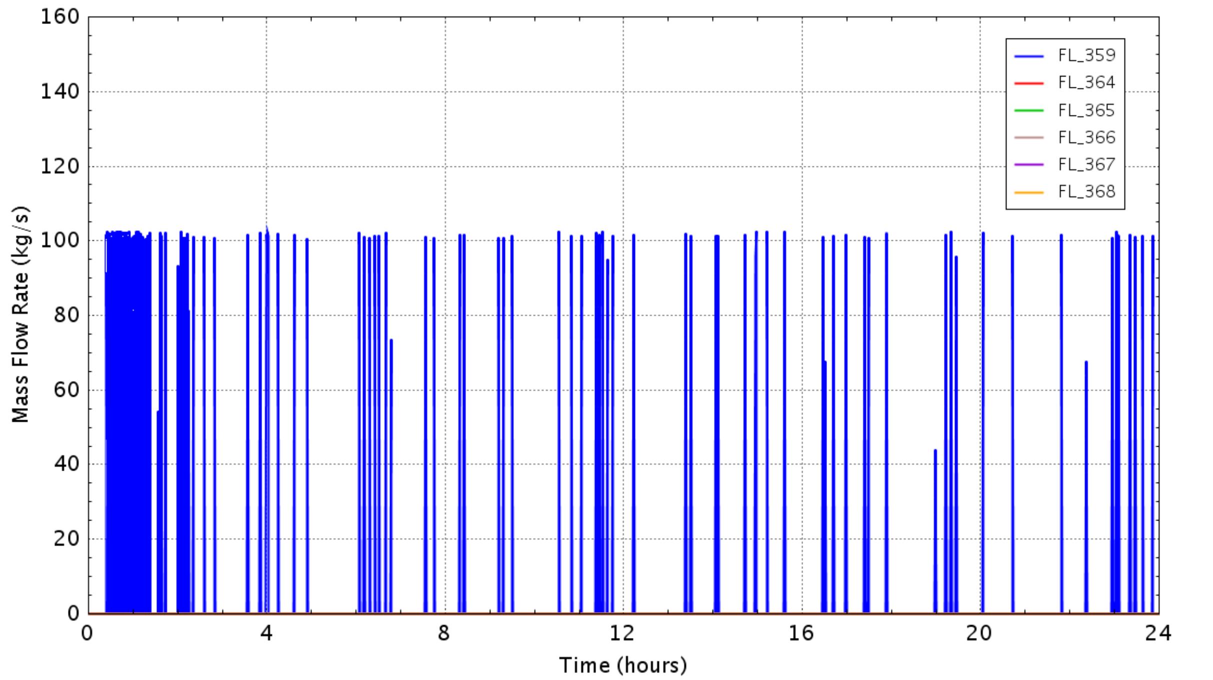

Figure C - 202 Flow rate of the SRVs

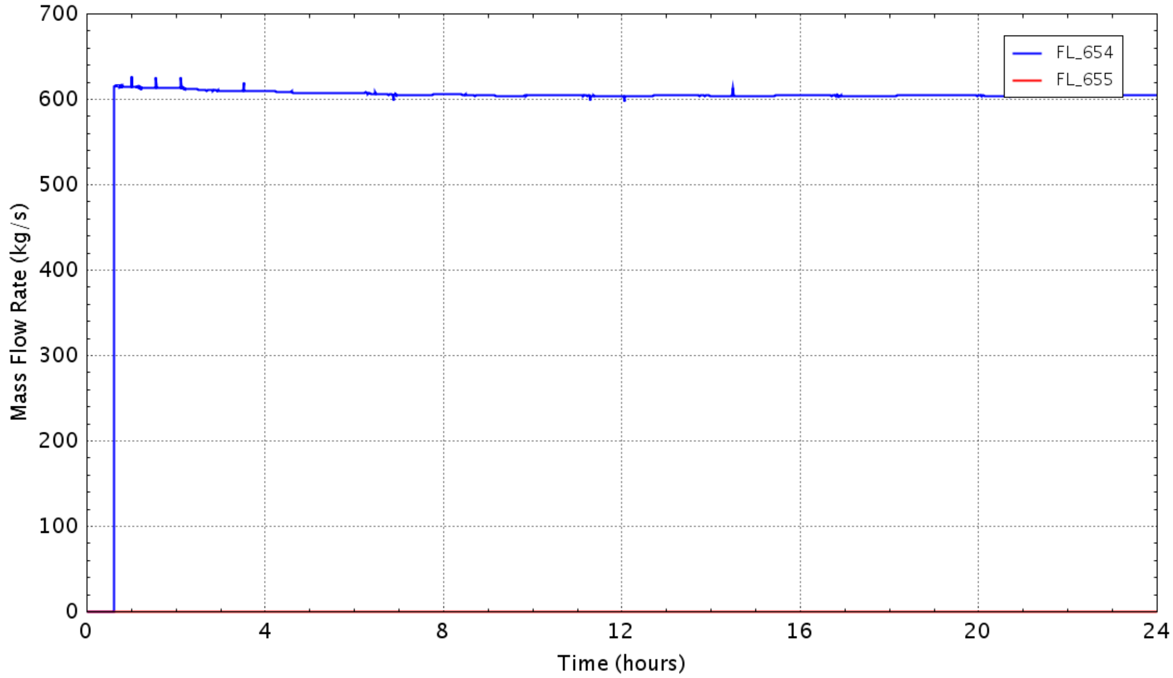

Figure C - 203 Flow rate of the wetwell cooling system

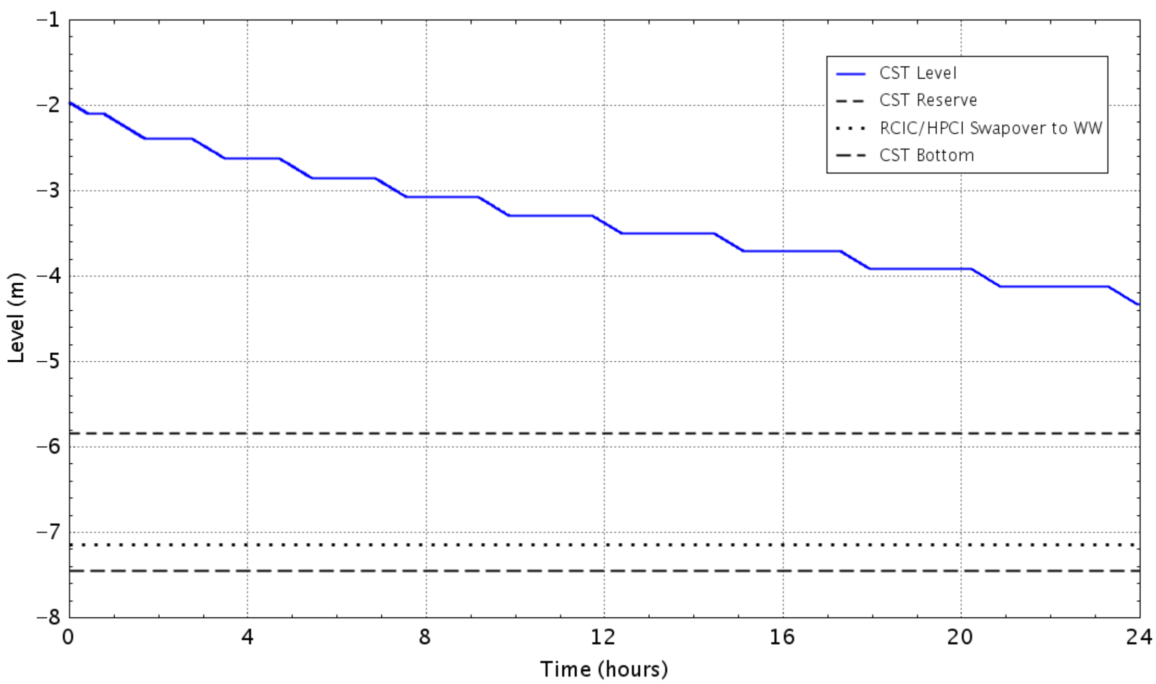

Figure C - 204 Water level in the CST

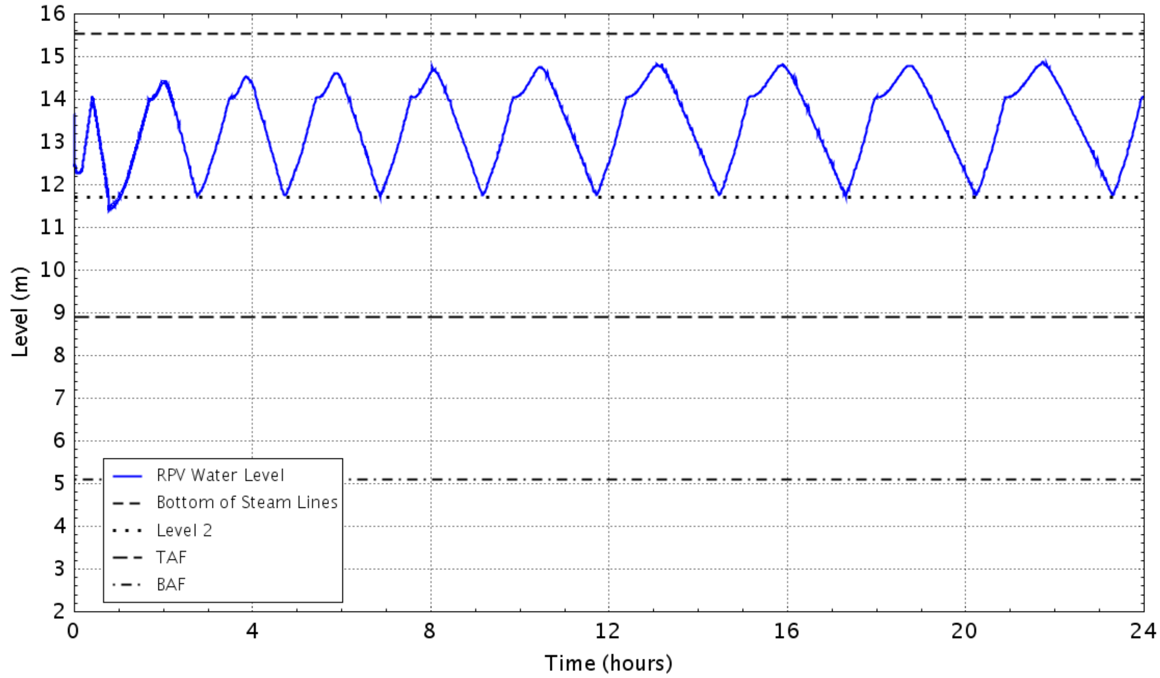

Figure C - 205 RPV Downcomer water level

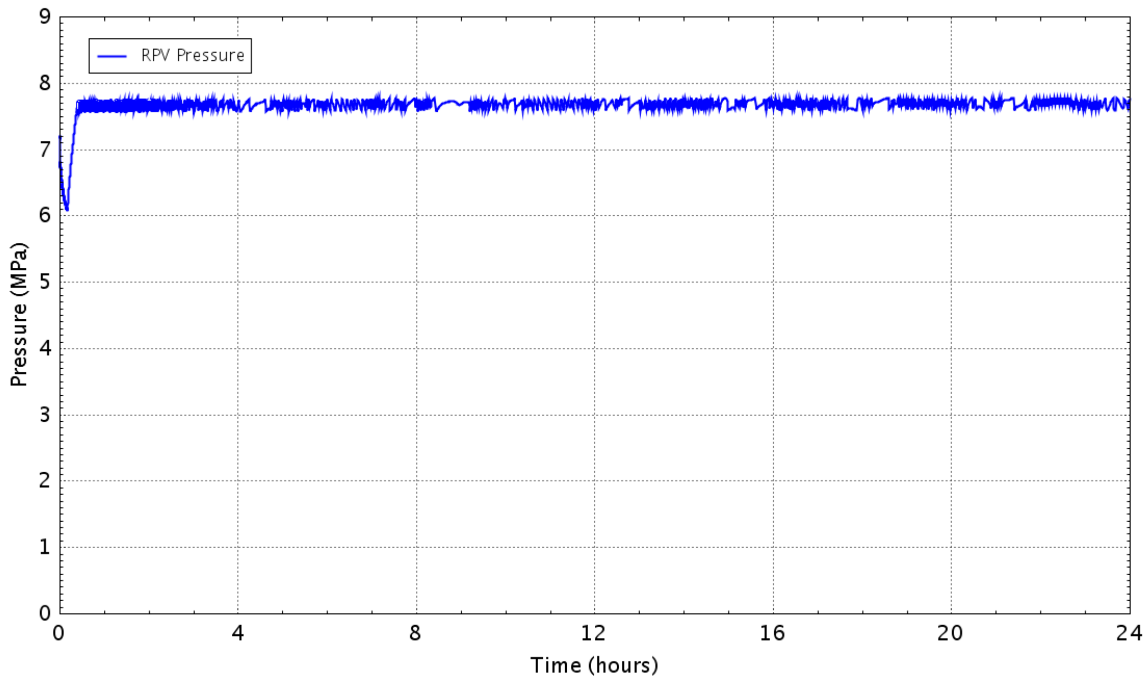

Figure C - 206 Pressure in the RPV

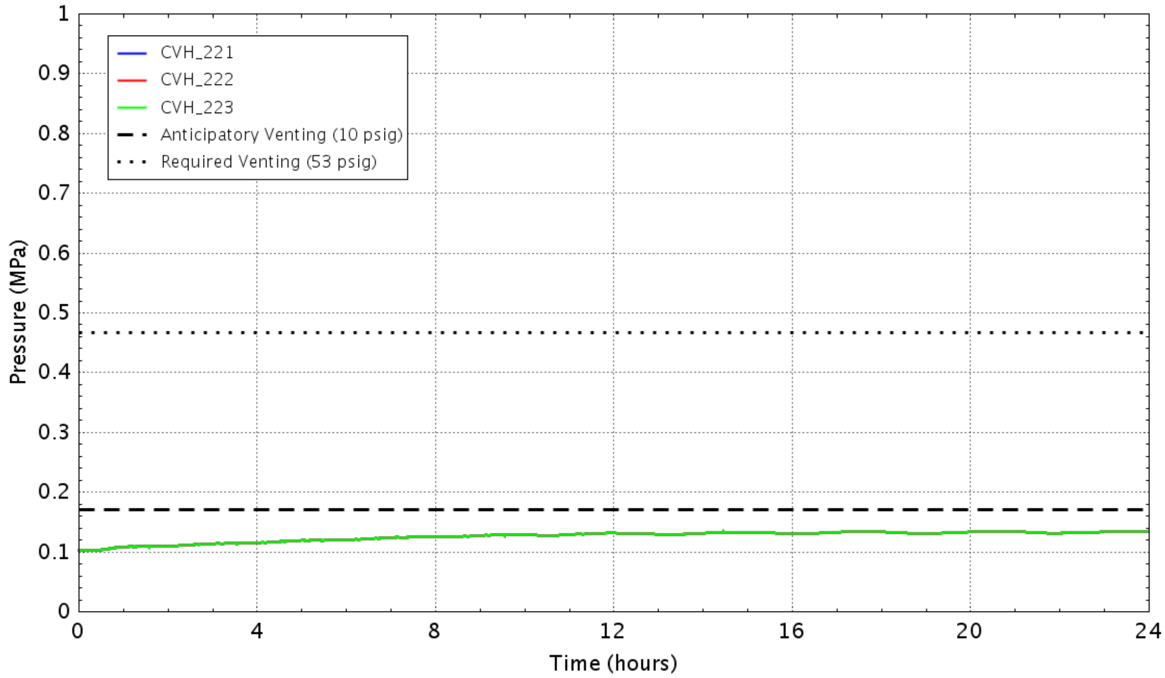

Figure C - 207   Pressure in the wetwell

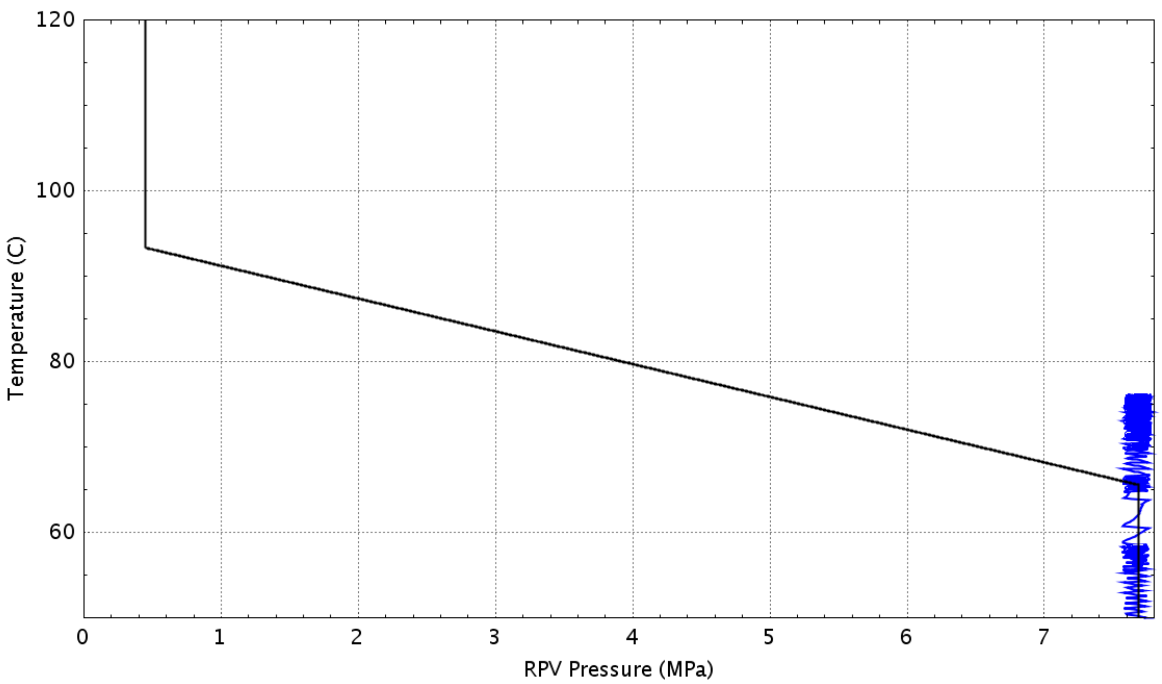

Figure C - 208   Plant status relative to the HCL curve (Graph 4 of the EOPs)

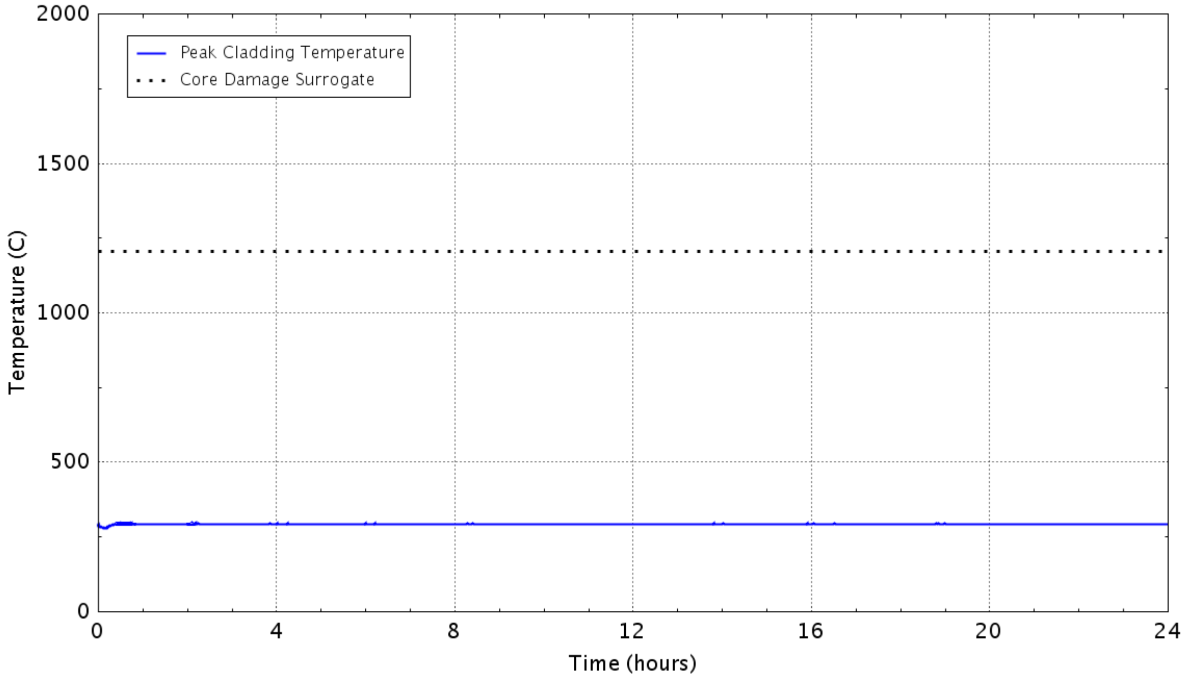

Figure C - 209 Peak temperature of the fuel cladding as a function of time

C.1.20 Case 20: TRANS-49, Two Trains of CRDHS, Automatic MSIV Closure

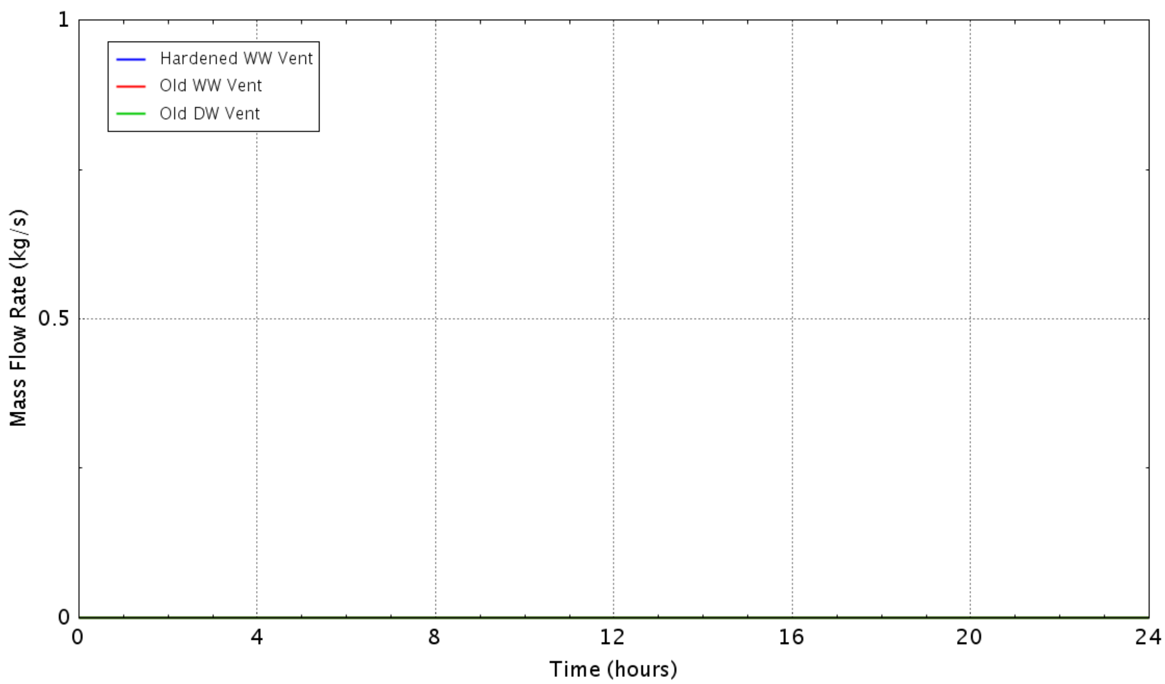

Figure C - 210 Flow rate of the containment vents

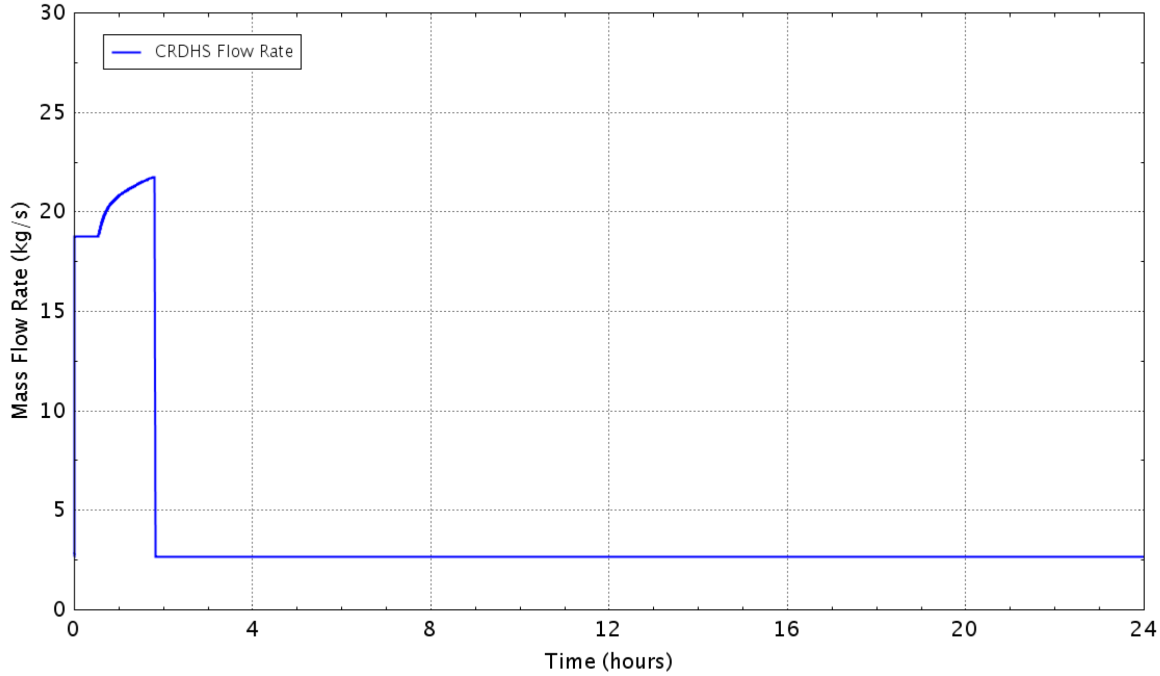

Figure C - 211 Flow rate of the control rod drive hydraulic system

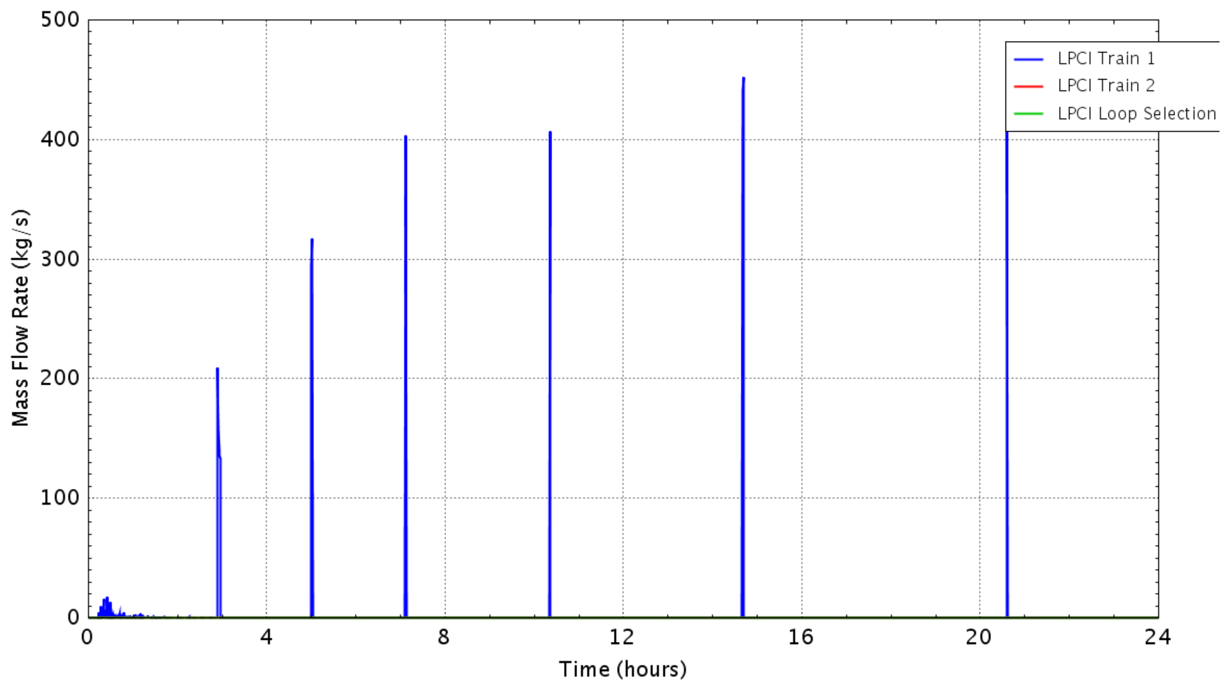

Figure C - 212 Flow rate of the LPCI pump

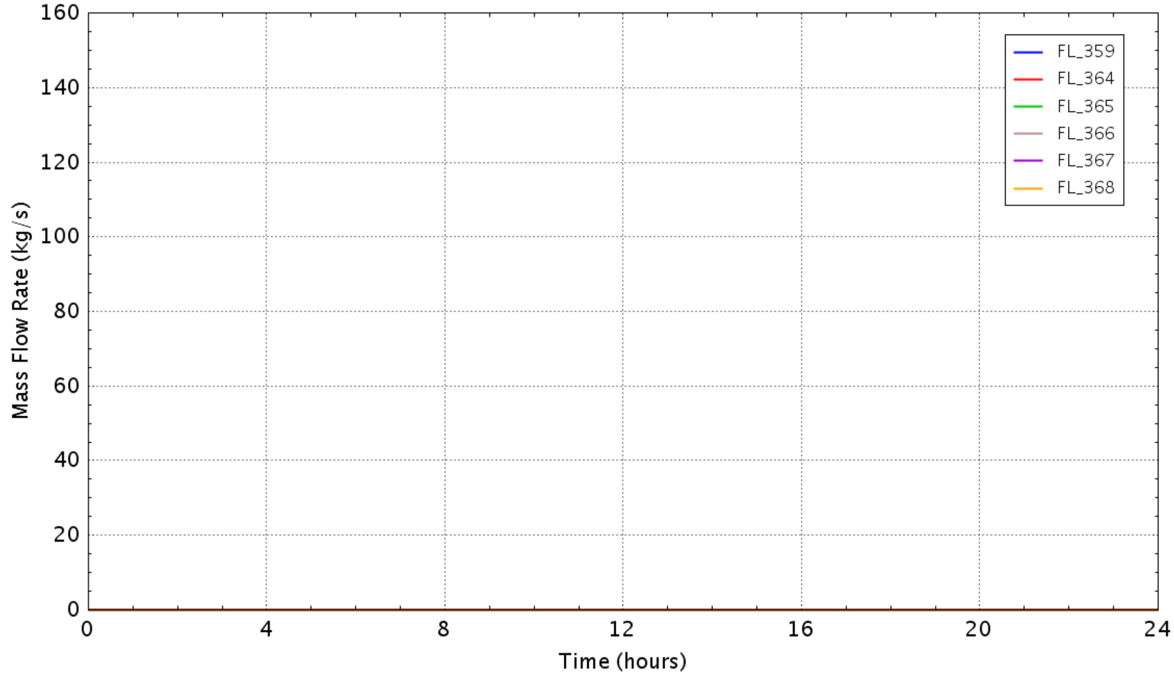

Figure C - 213 Flow rate of the SRVs

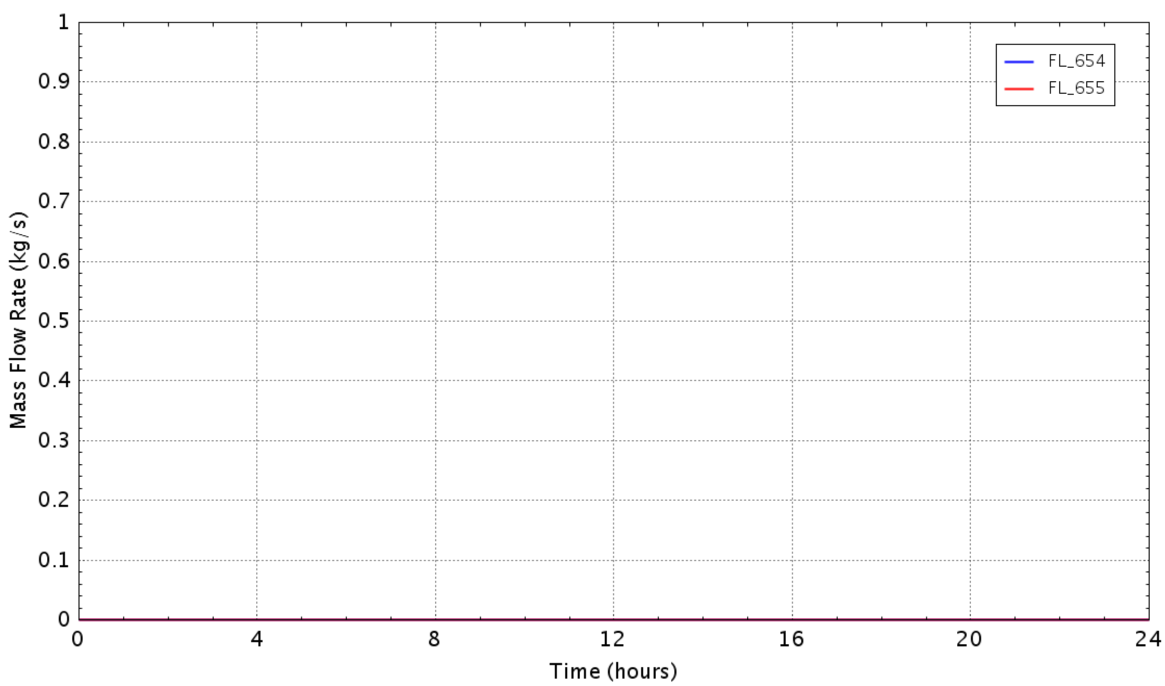

Figure C - 214 Flow rate of the wetwell cooling system

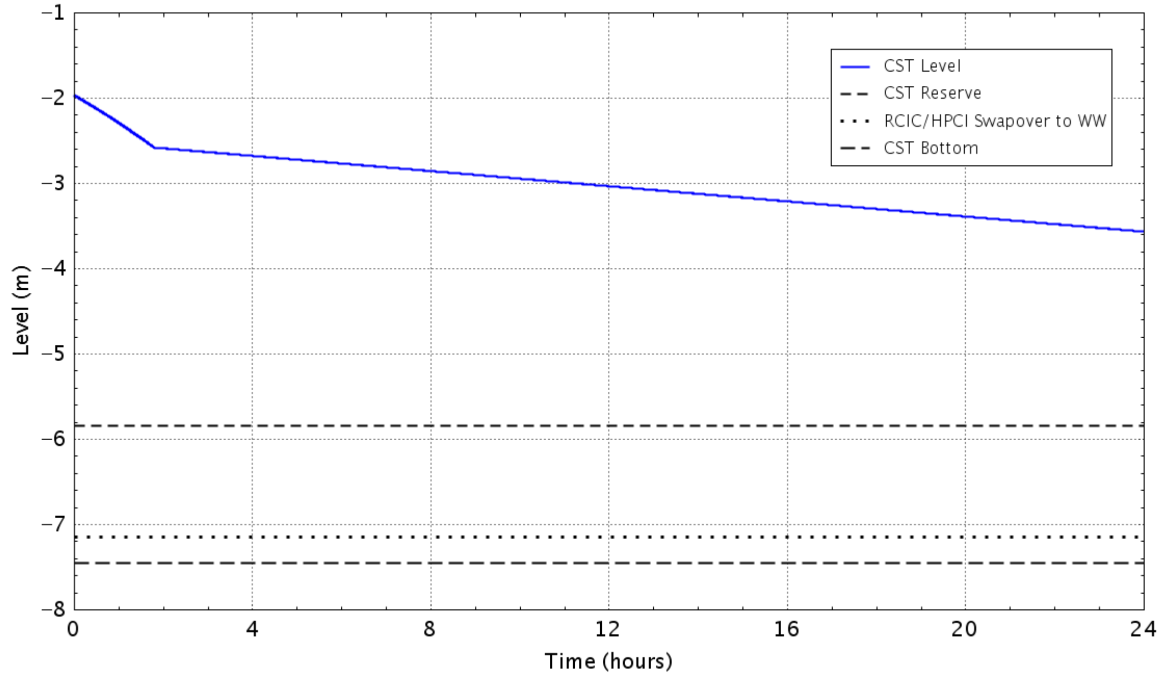

Figure C - 215   Water level in the CST

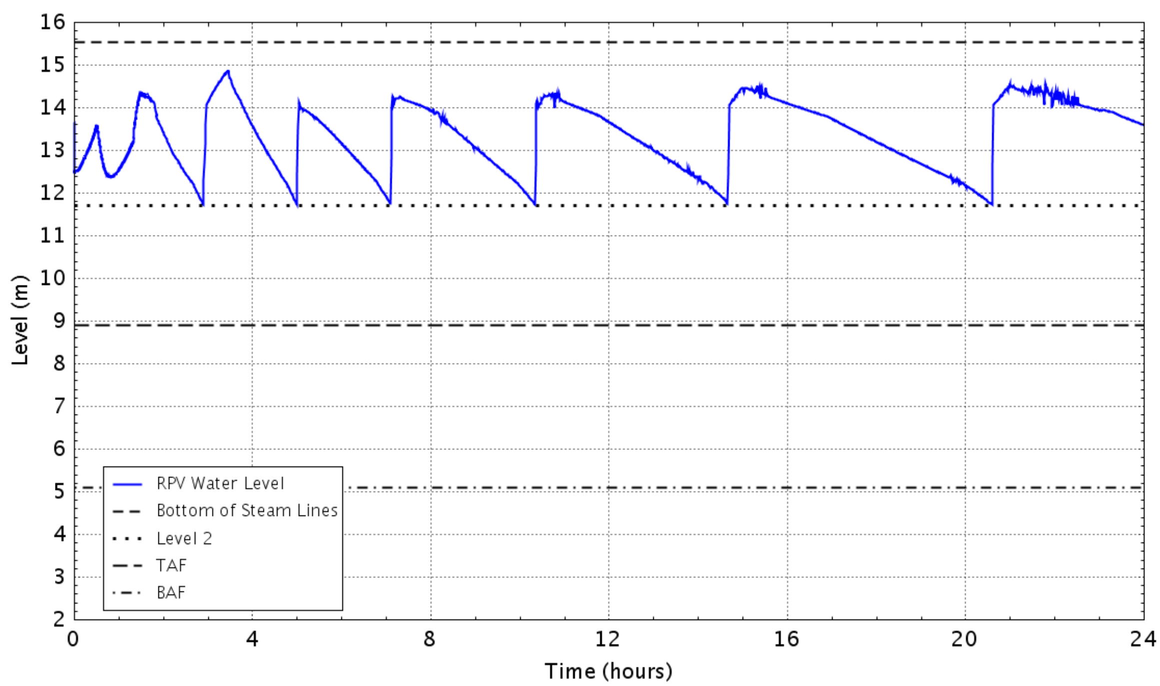

Figure C - 216   RPV Downcomer water level

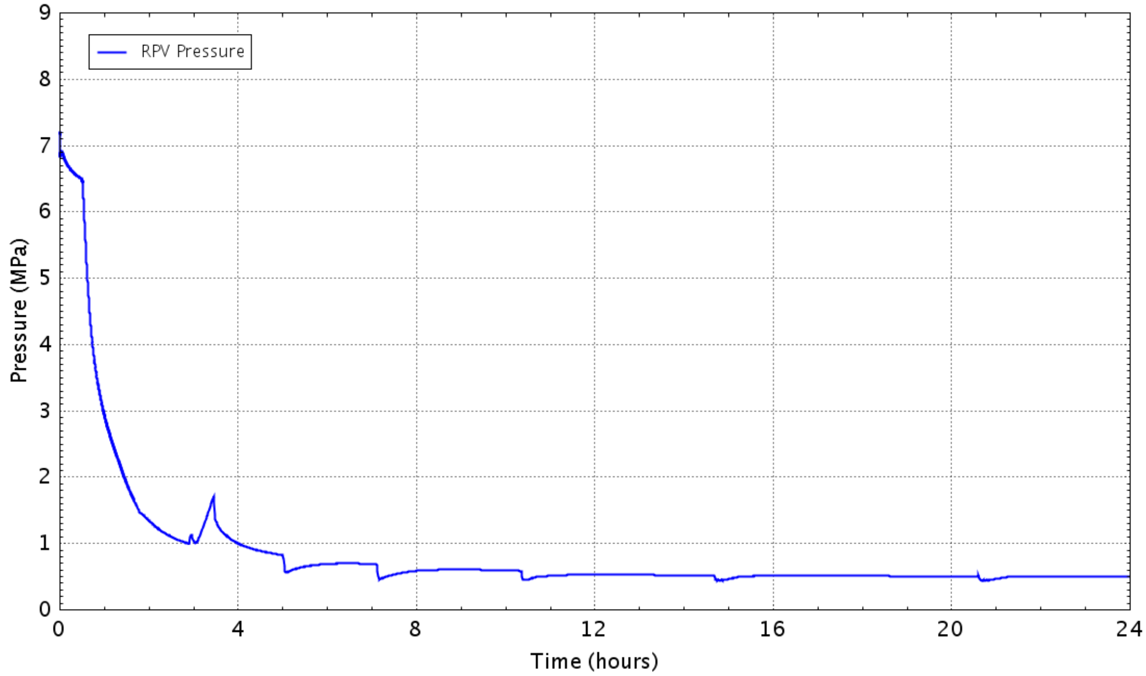

Figure C - 217 Pressure in the RPV

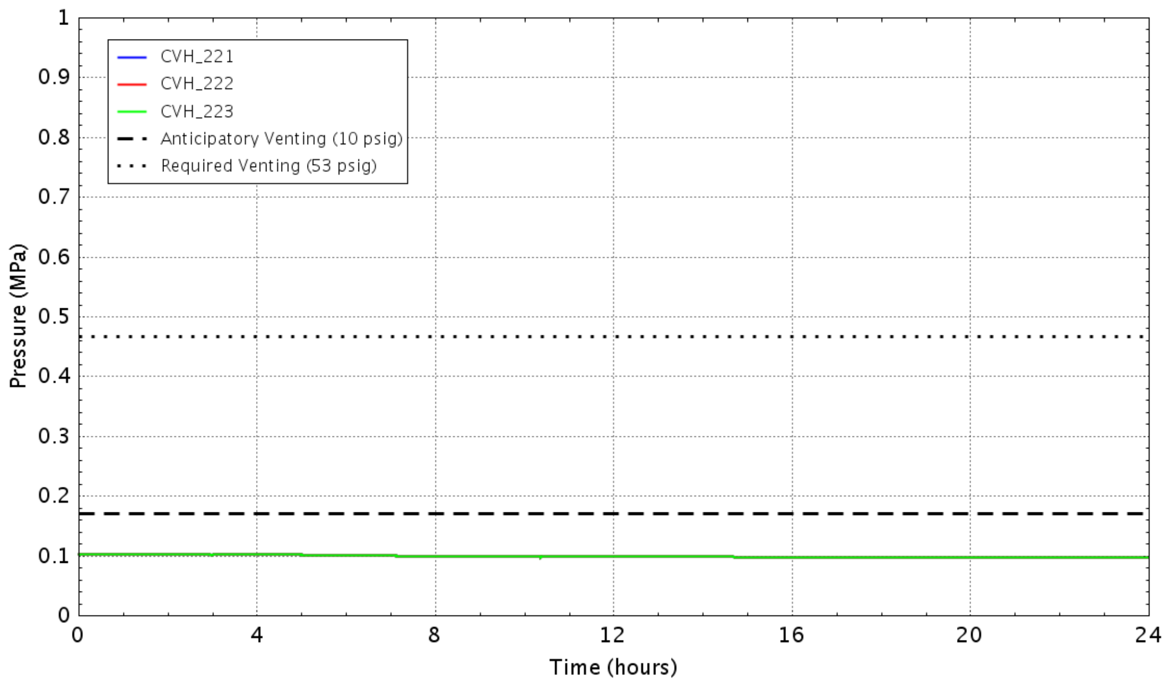

Figure C - 218 Pressure in the wetwell

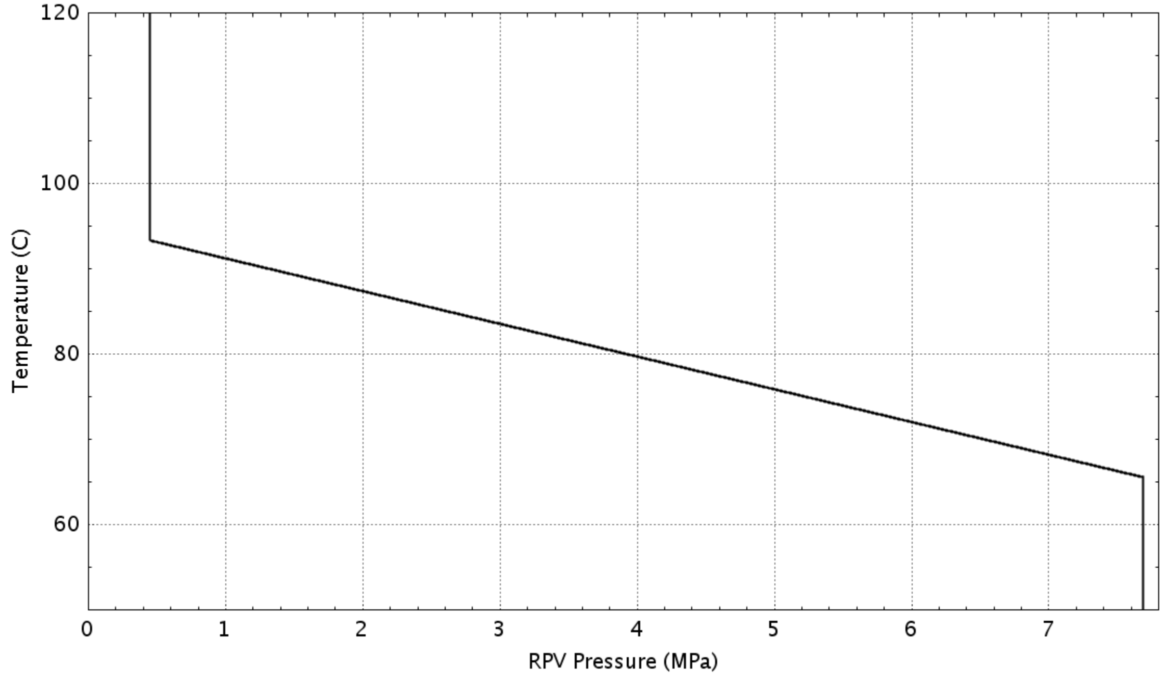

Figure C - 219 Plant status relative to the HCL curve (Graph 4 of the EOPs)

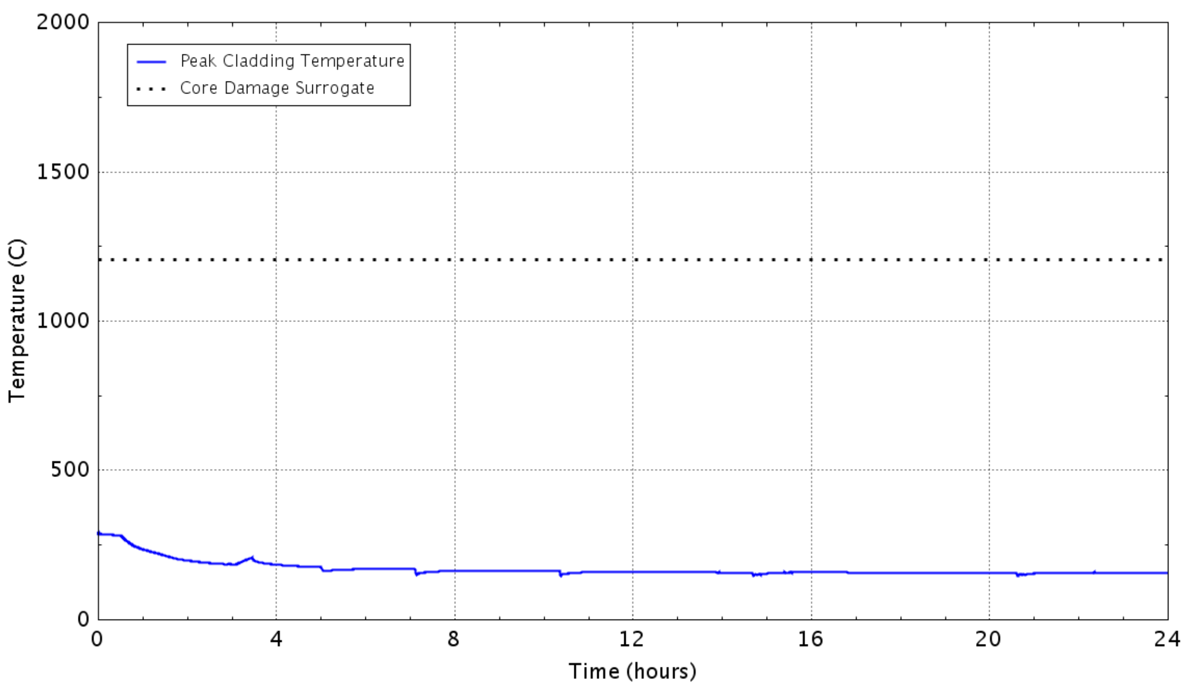

Figure C - 220 Peak temperature of the fuel cladding as a function of time

C.2 SLOCA Scenarios

C.2.1 Case 21: SLOCA-25, 1-in. Equivalent Steamline Break, One Train of CRDHS

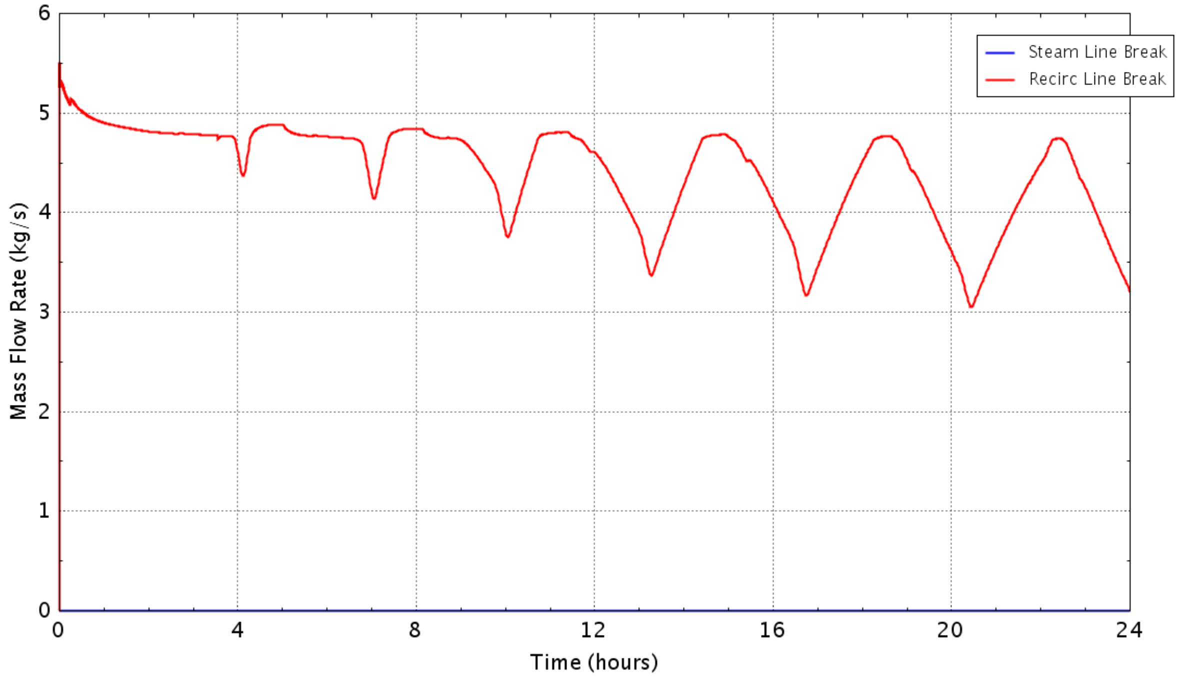

Figure C - 221 Flow rate of the break in the steamline/recirculation line

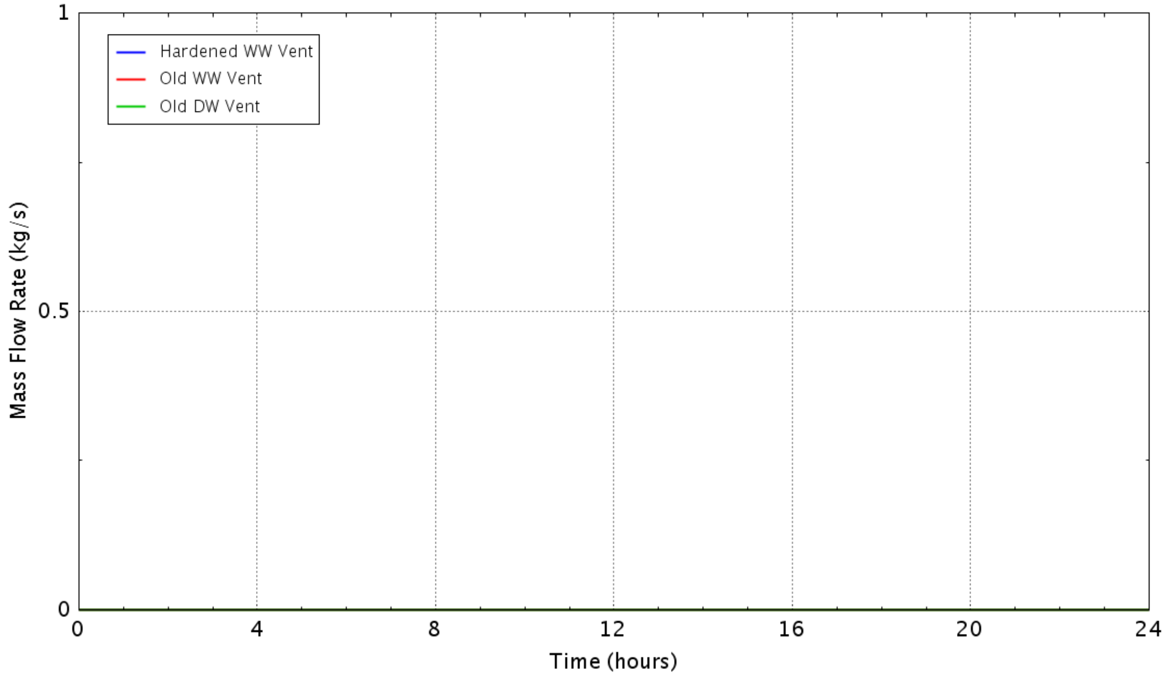

Figure C - 222 Flow rate of the containment vents

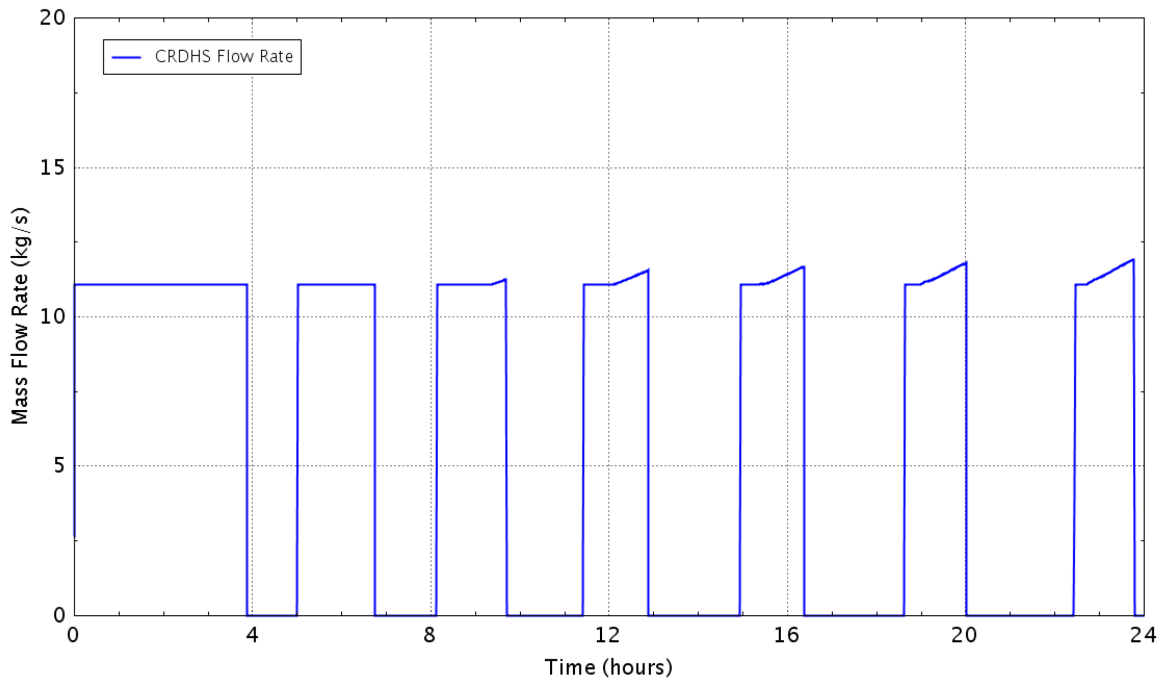

Figure C - 223 Flow rate of the control rod drive hydraulic system

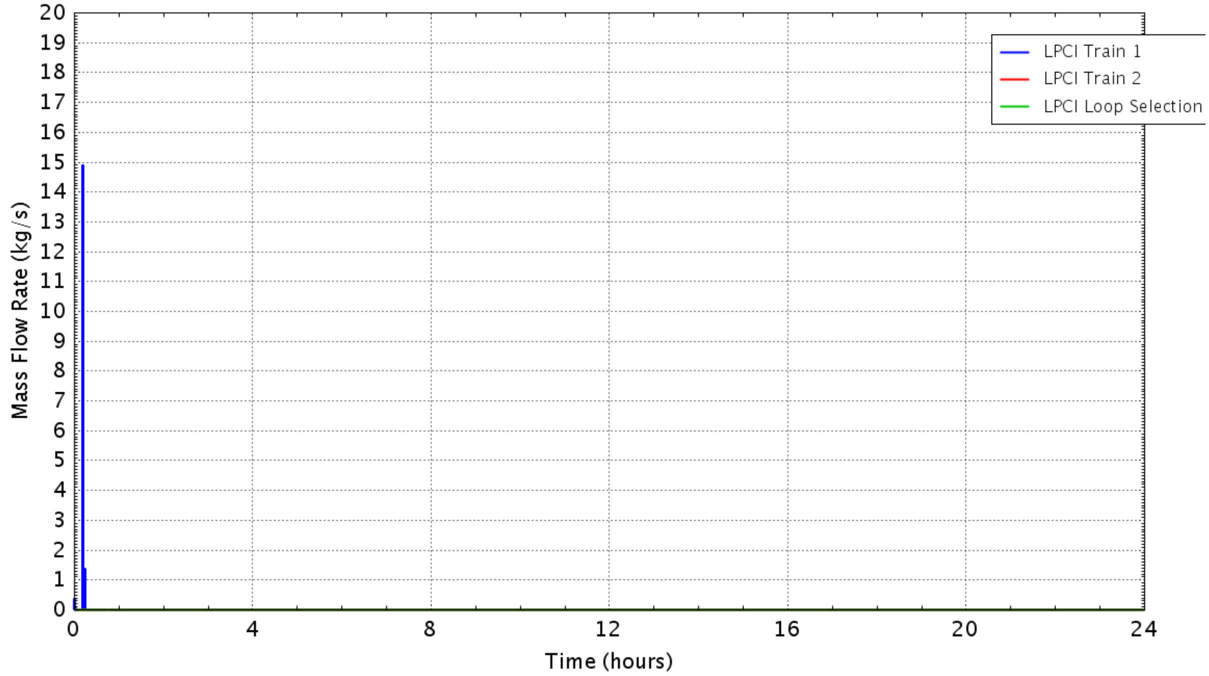

Figure C - 224 Flow rate of the LPCI pump

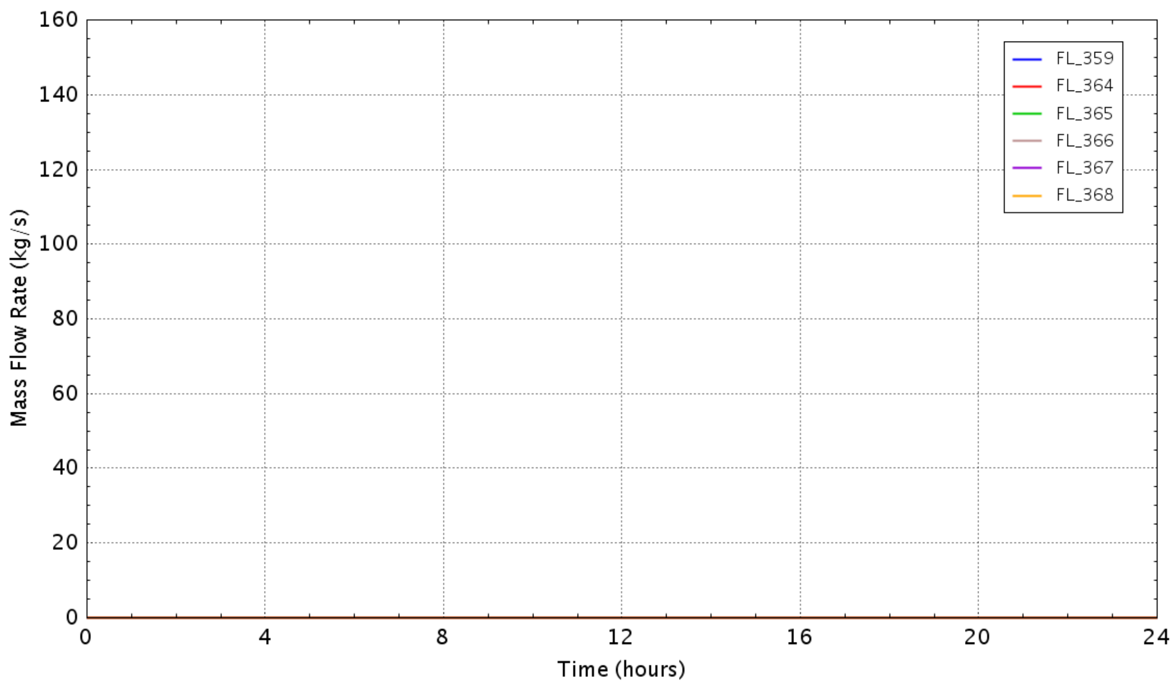

Figure C - 225 Flow rate of the SRVs

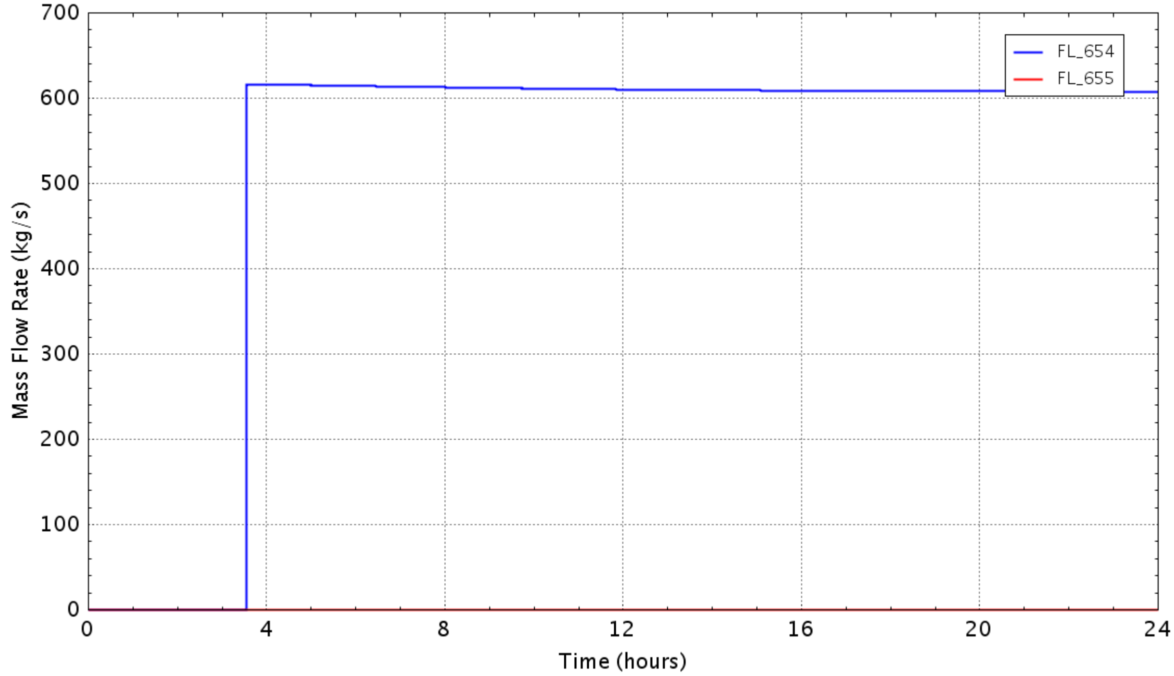

Figure C - 226 Flow rate of the wetwell cooling system

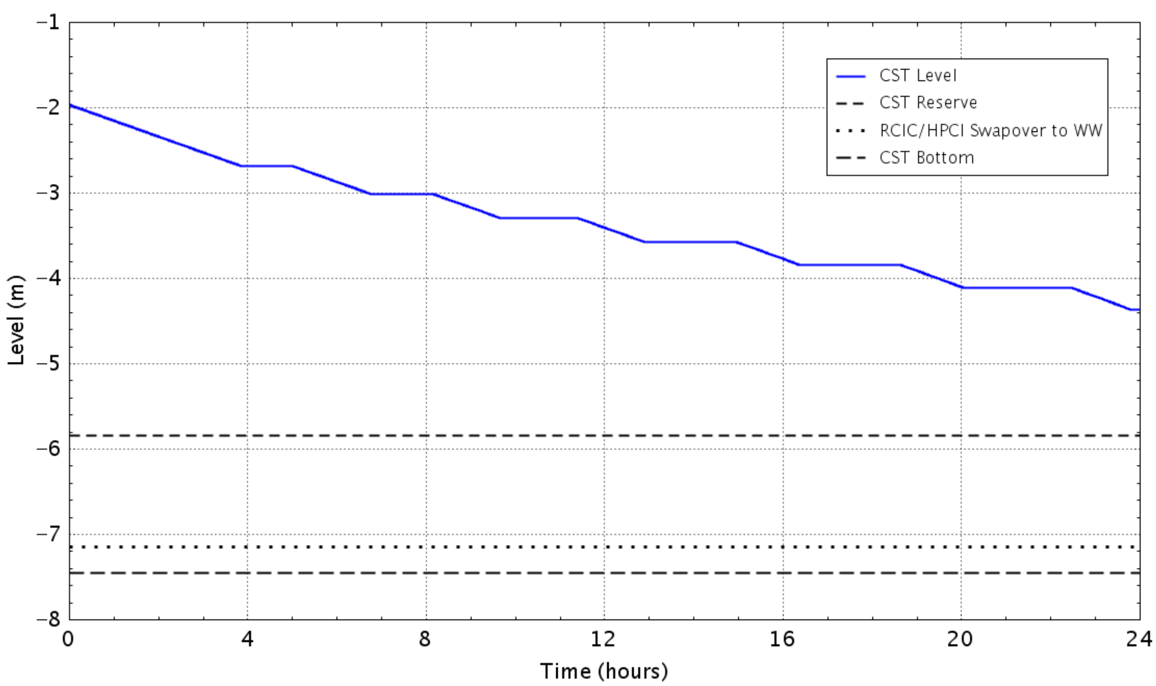

Figure C - 227 Water level in the CST

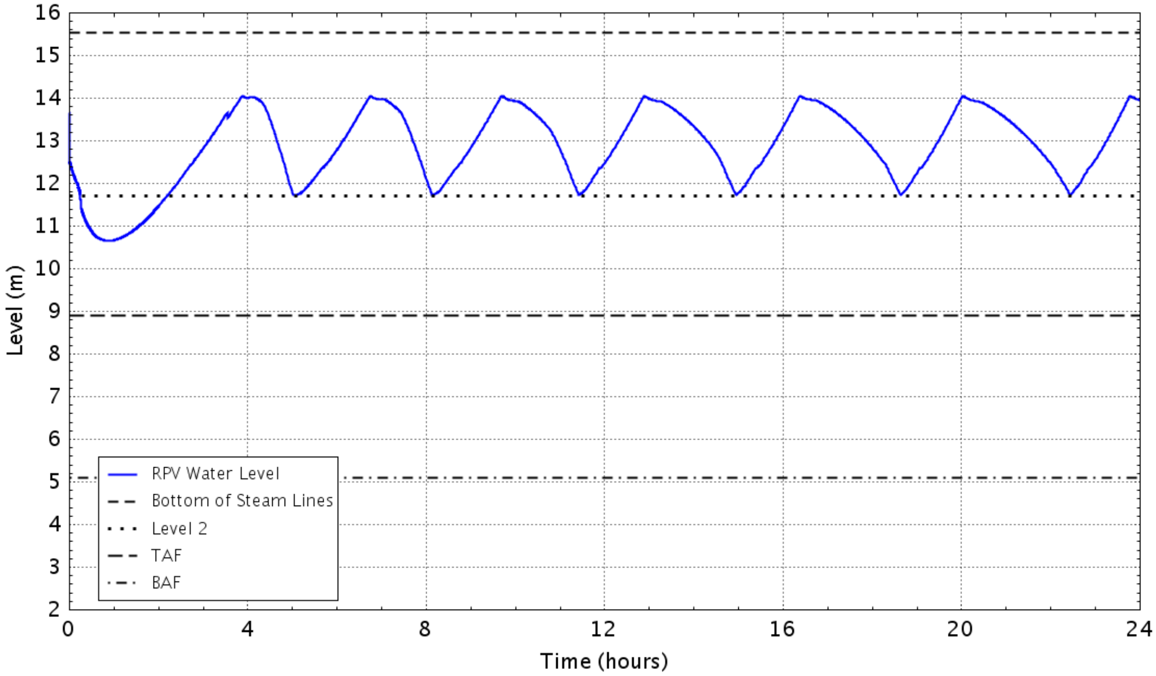

Figure C - 228   RPV Downcomer water level

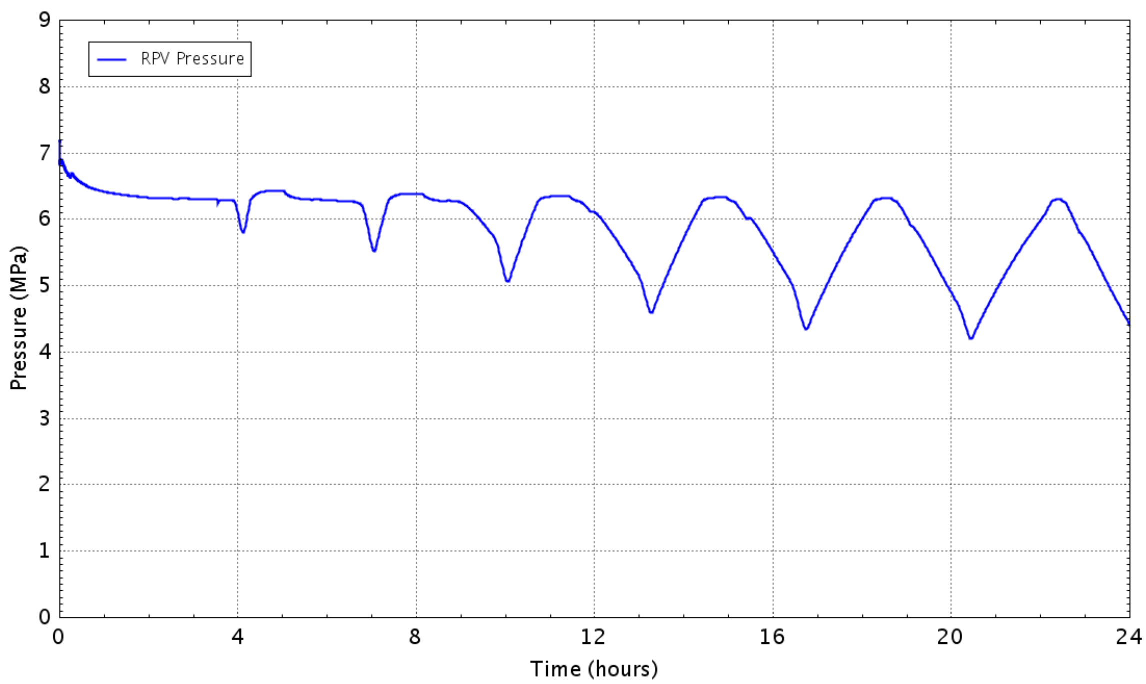

Figure C - 229 Pressure in the RPV

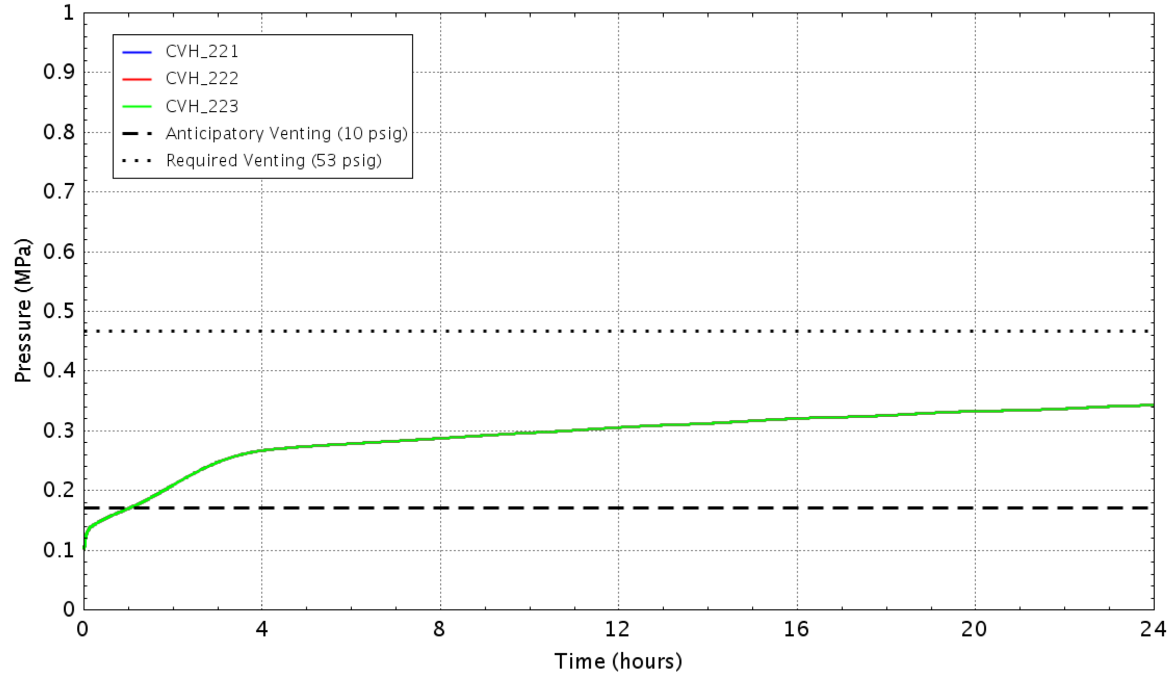

Figure C - 230   Pressure in the wetwell

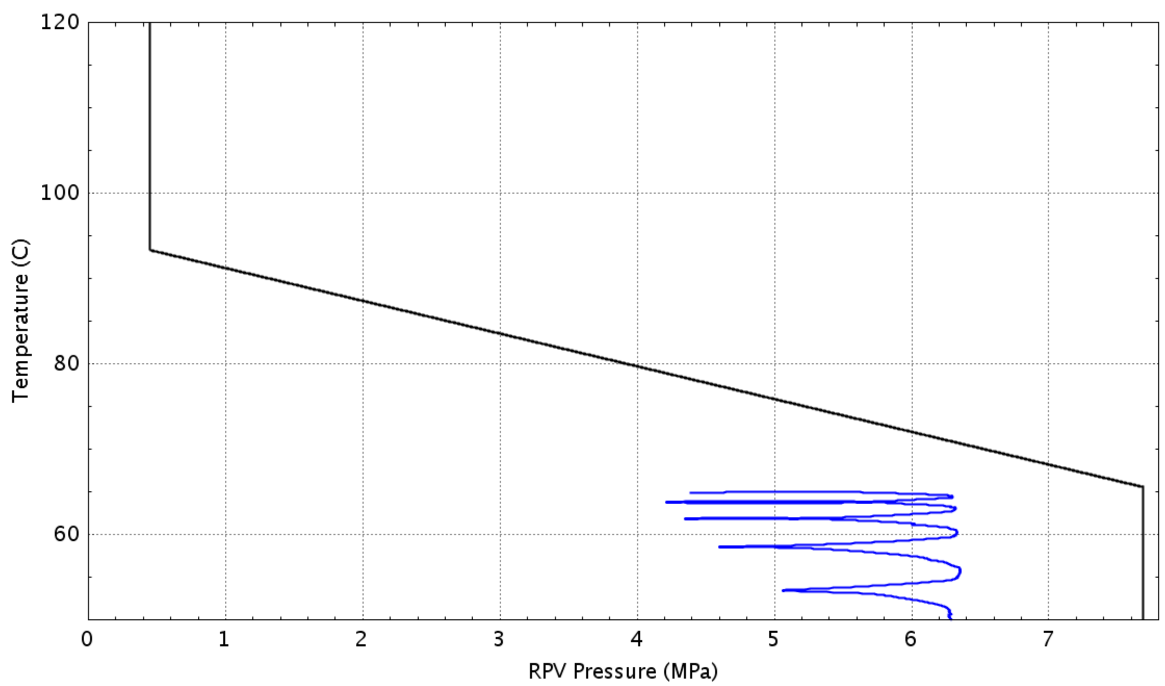

Figure C - 231   Plant status relative to the HCL curve (Graph 4 of the EOPs)

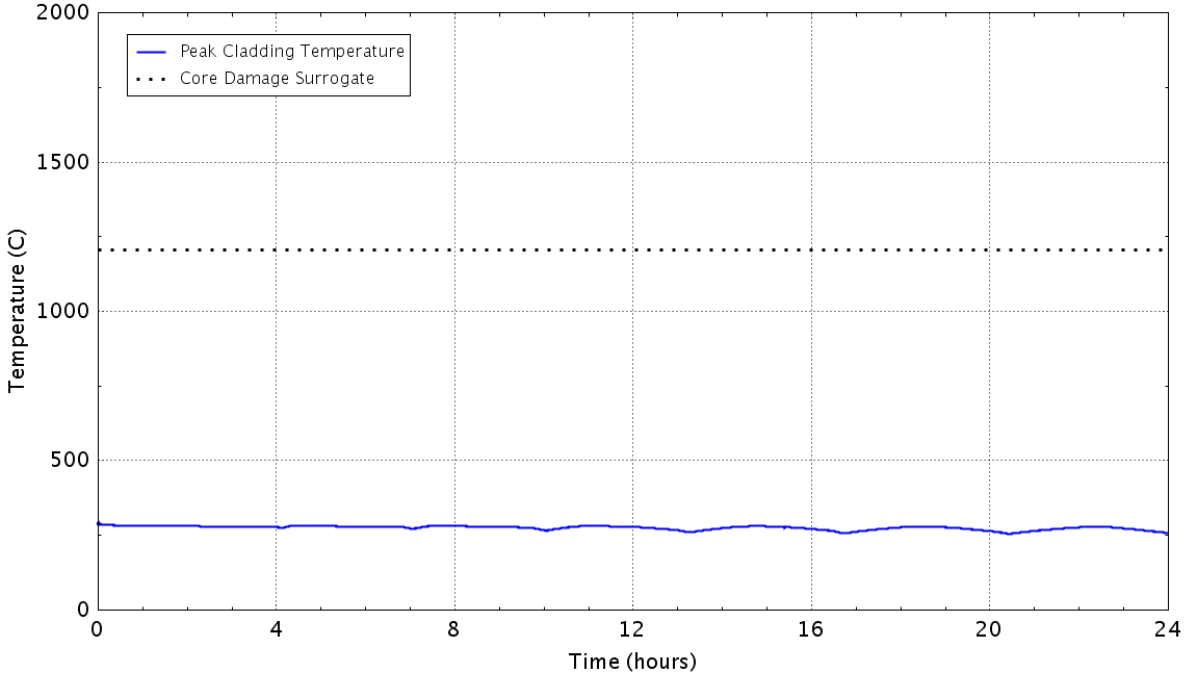

Figure C - 232 Peak temperature of the fuel cladding as a function of time

C.2.2 Case 22: SLOCA-25, 1-in. Equivalent Steamline Break, TwoTrains ofCRDHS

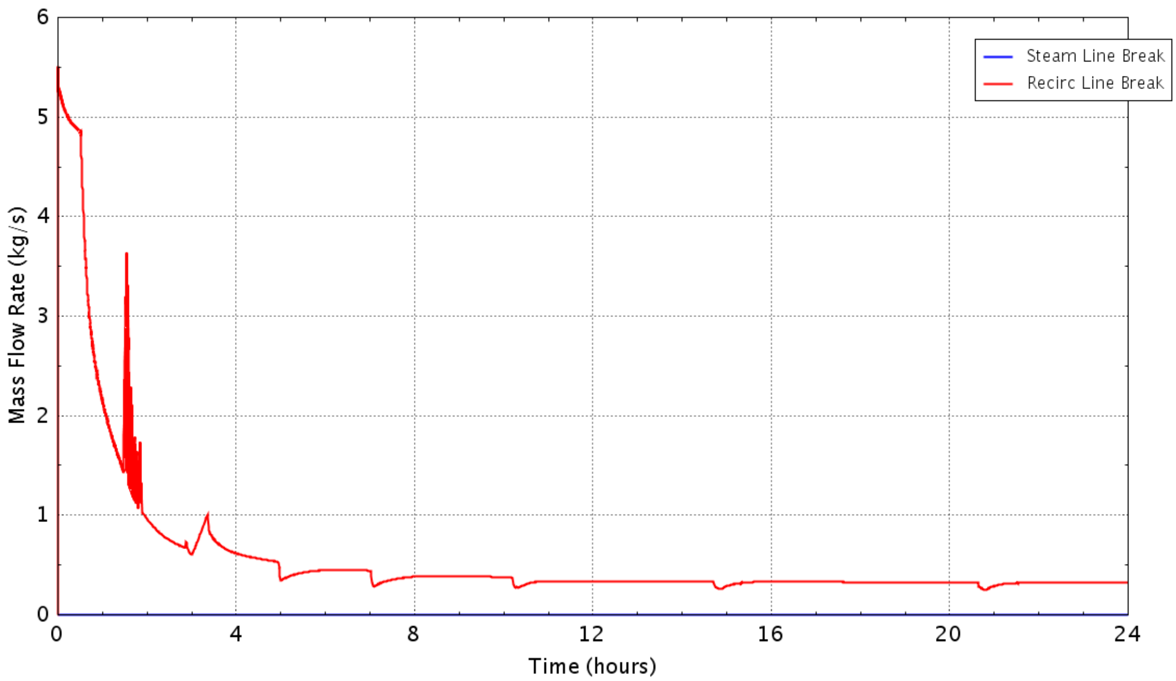

Figure C - 233 Flow rate of the break in the steamline/recirculation line

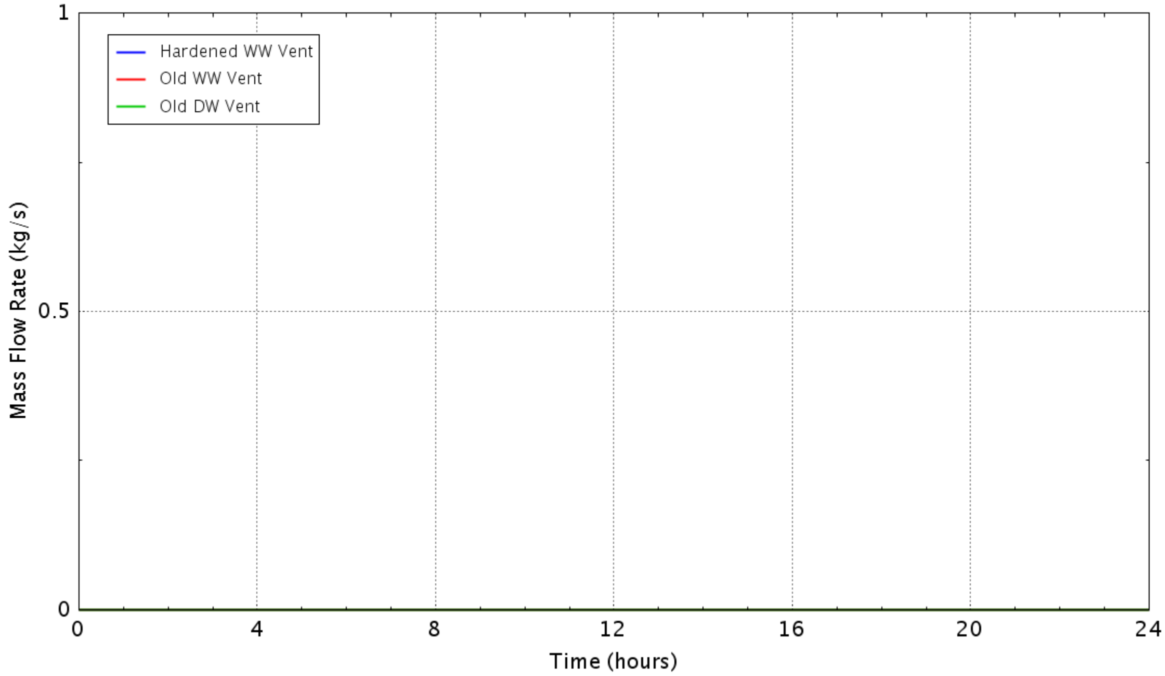

Figure C - 234 Flow rate of the containment vents

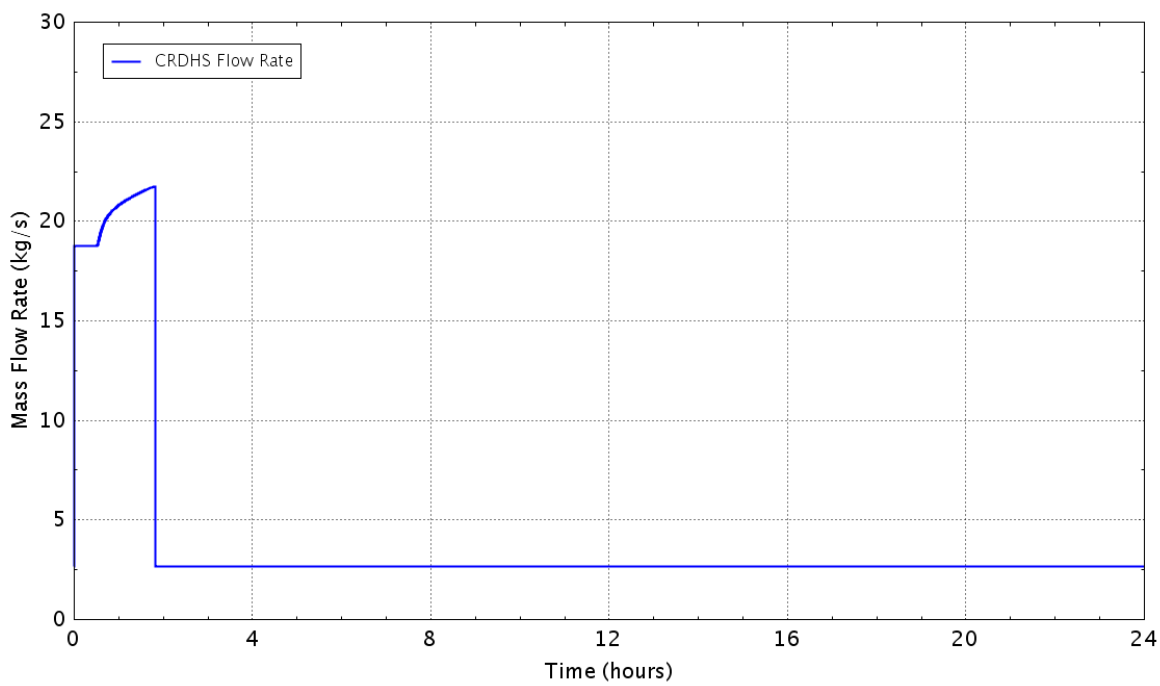

Figure C - 235 Flow rate of the control rod drive hydraulic system

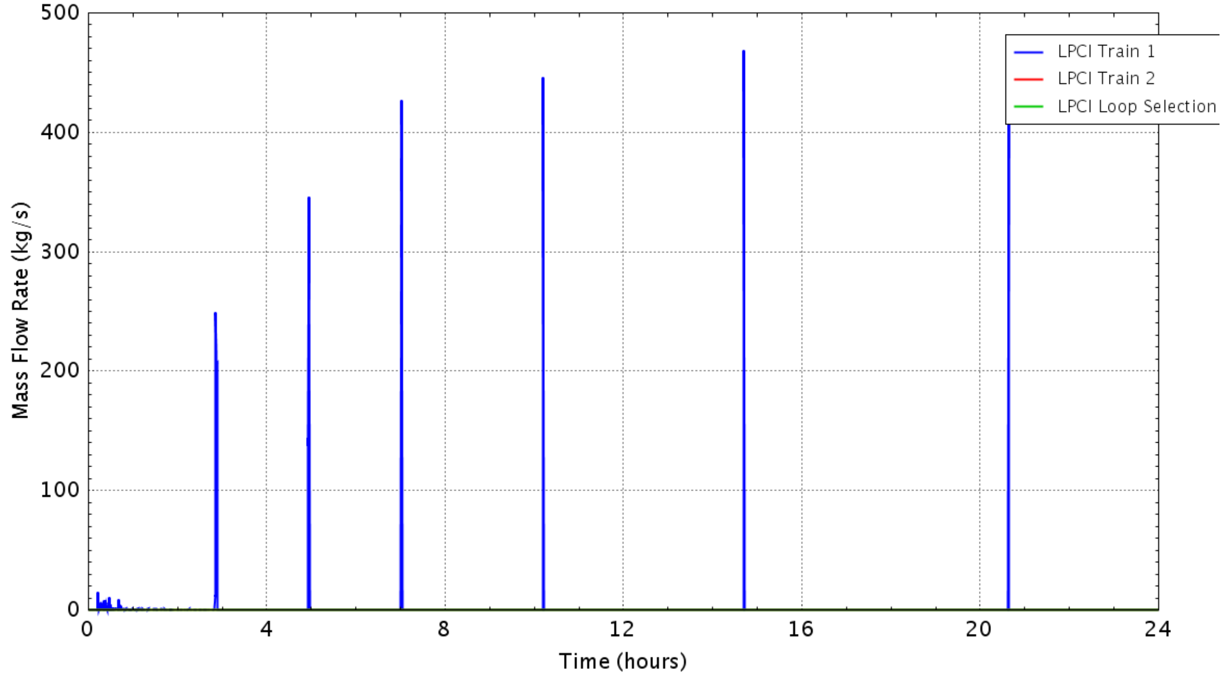

Figure C - 236 Flow rate of the LPCI pump

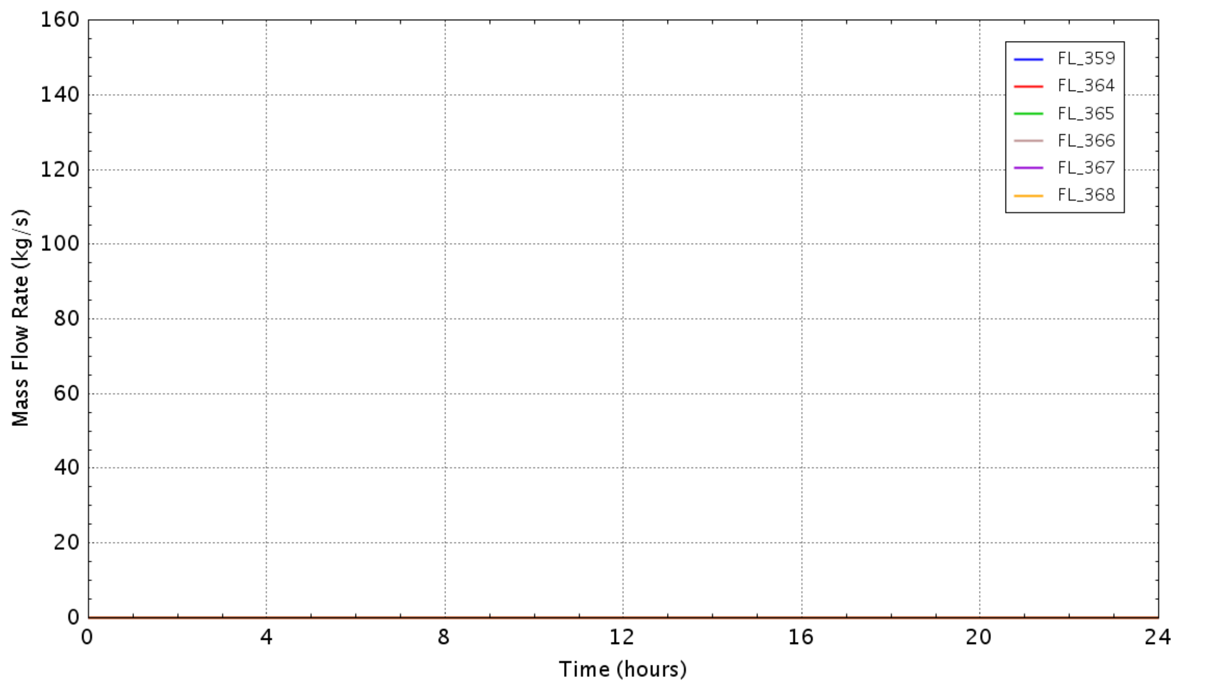

Figure C - 237 Flow rate of the SRVs

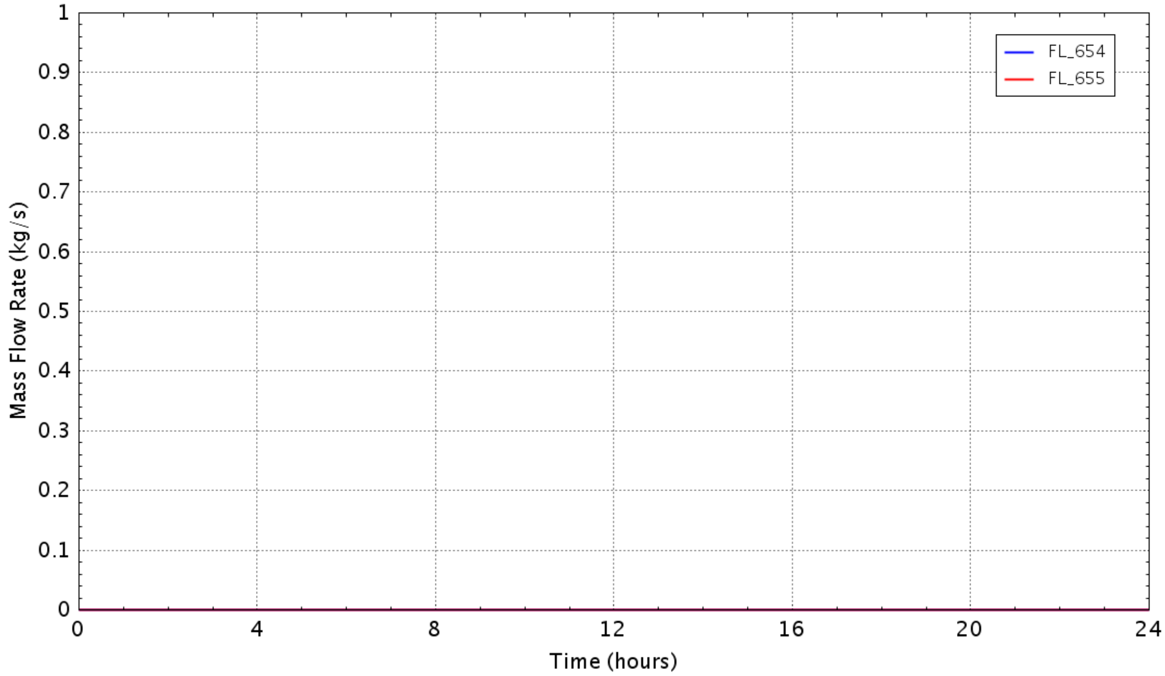

Figure C - 238 Flow rate of the wetwell cooling system

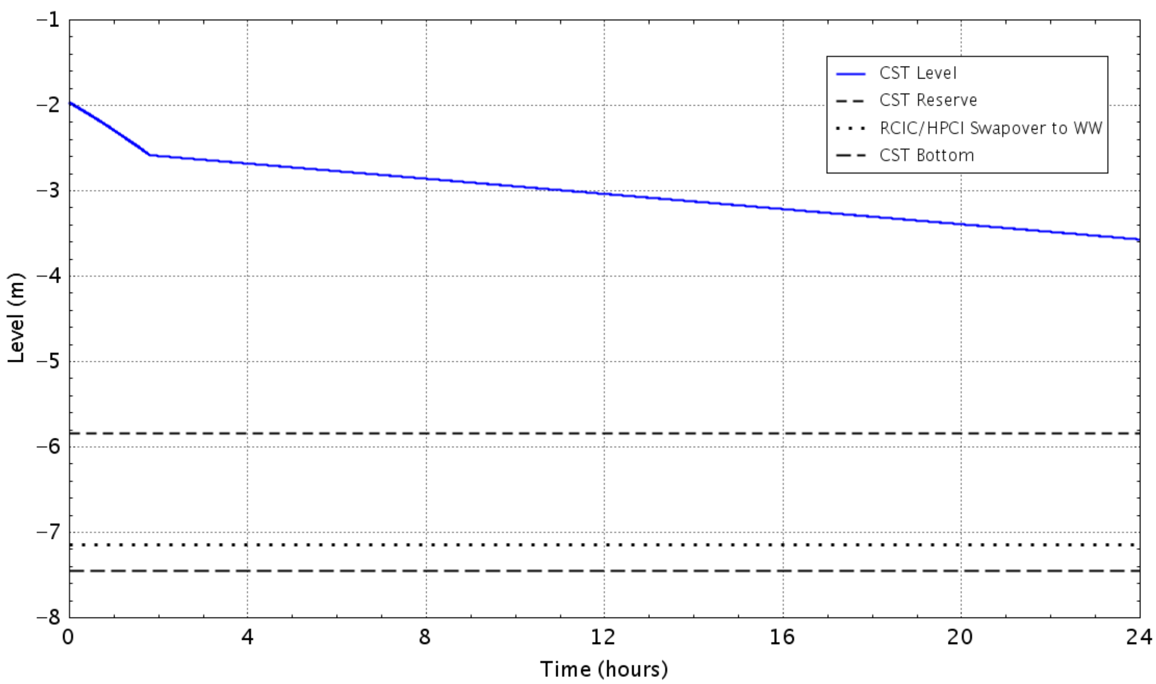

Figure C - 239 Water level in the CST

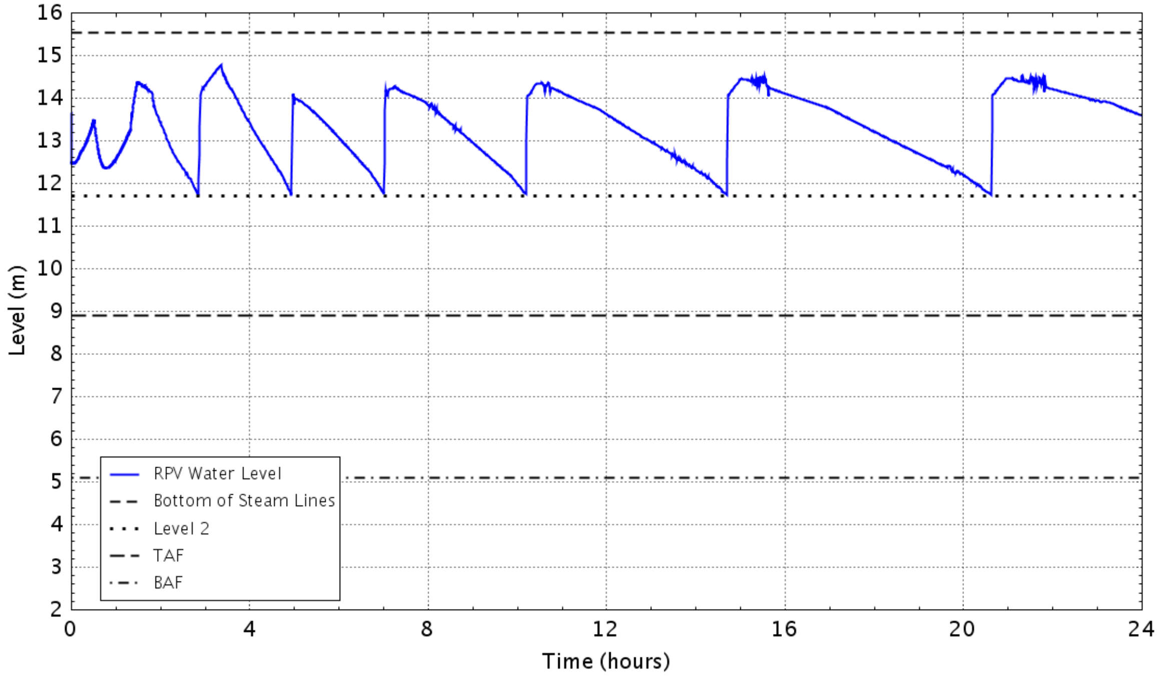

Figure C - 240 RPV Downcomer water level

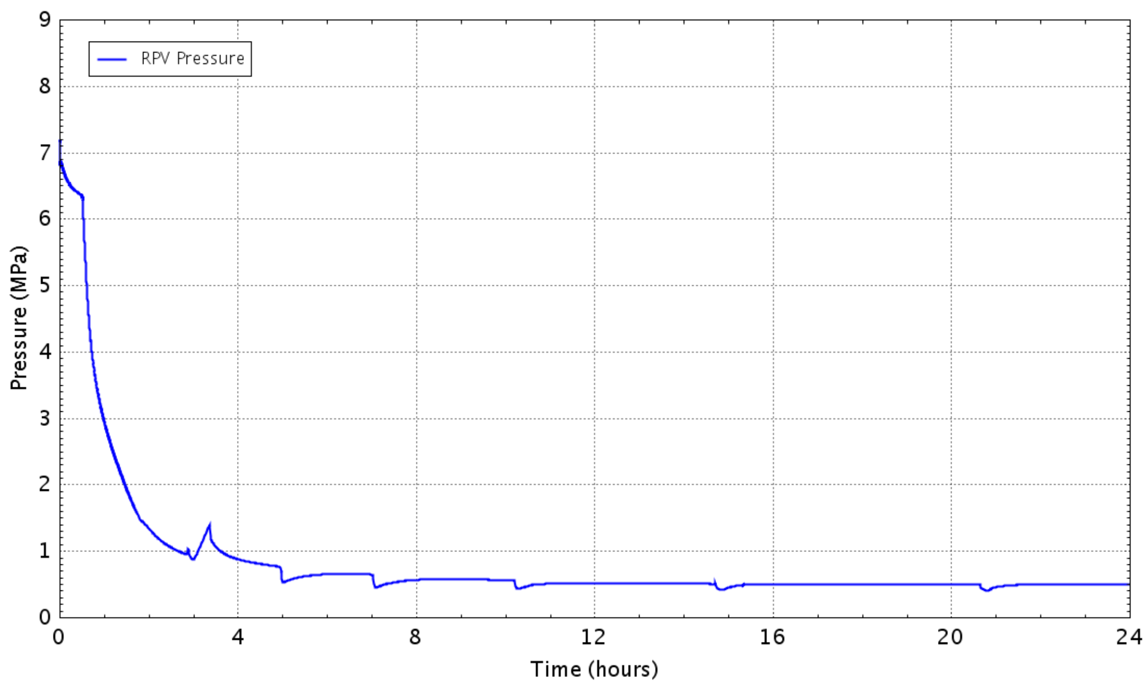

Figure C - 241 Pressure in the RPV

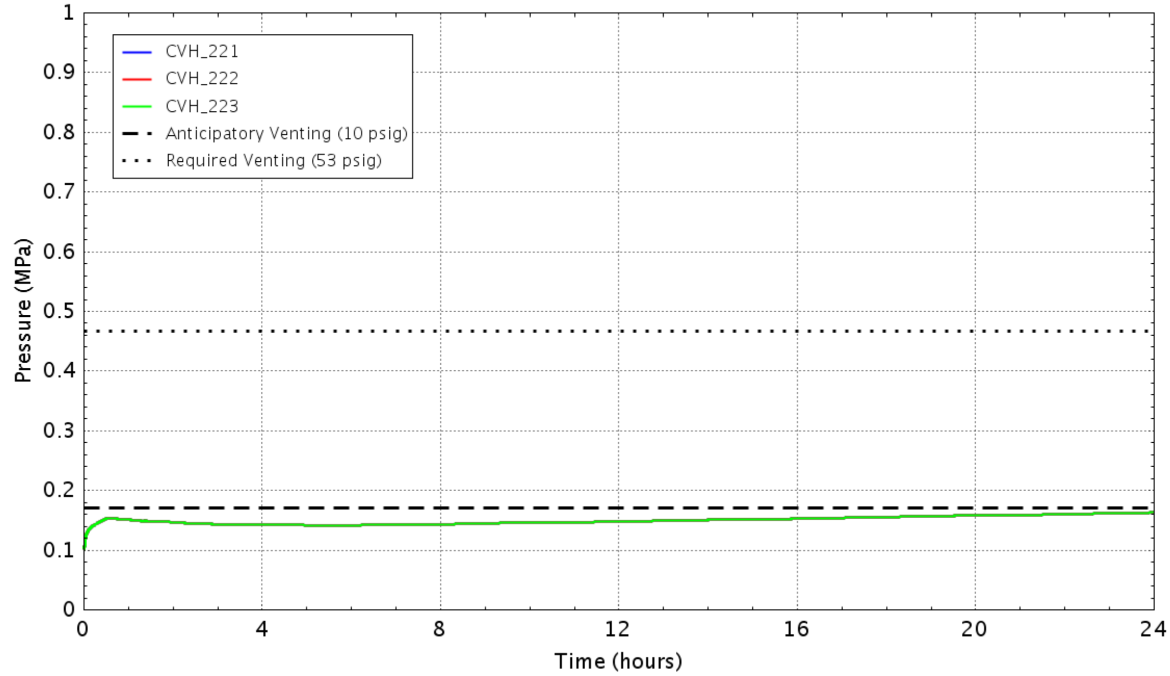

Figure C - 242 Pressure in the wetwell

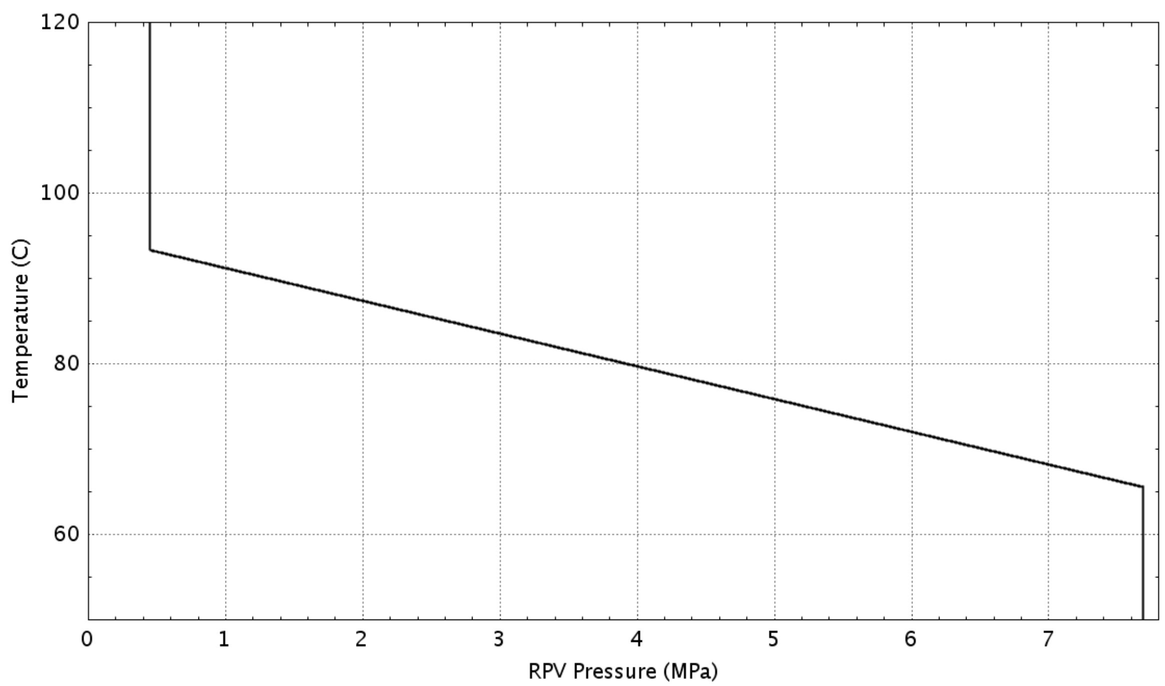

Figure C - 243 Plant status relative to the HCL curve (Graph 4 of the EOPs)

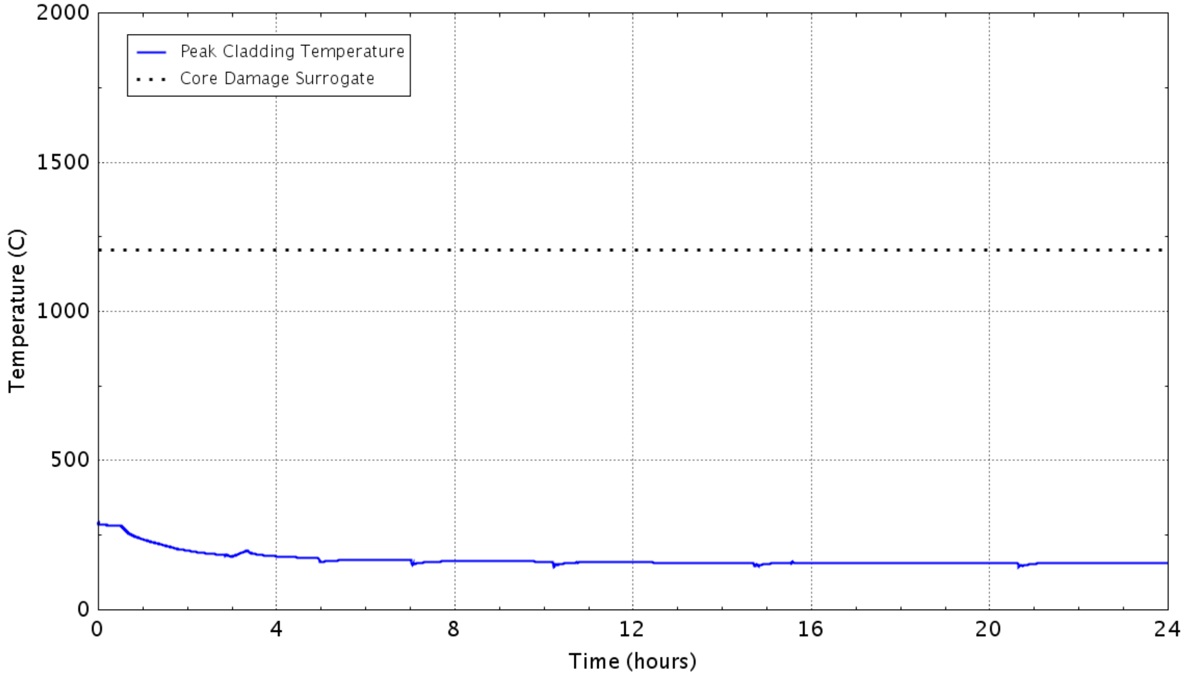

Figure C - 244 Peak temperature of the fuel cladding as a function of time

C.2.3 Case 23: SLOCA-25, 1.8-in. Equivalent Liquid Break, One Trainof CRDHS,ADS at +15 in., One SRV

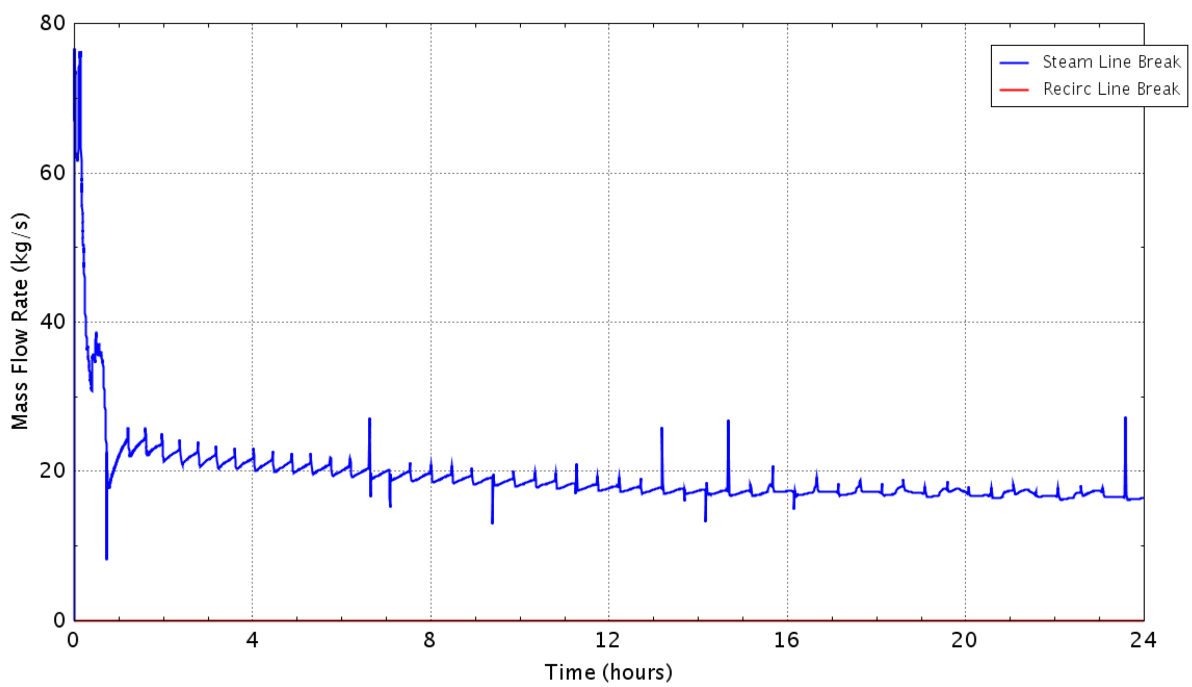

Figure C - 245 Flow rate of the break in the steamline/recirculation line

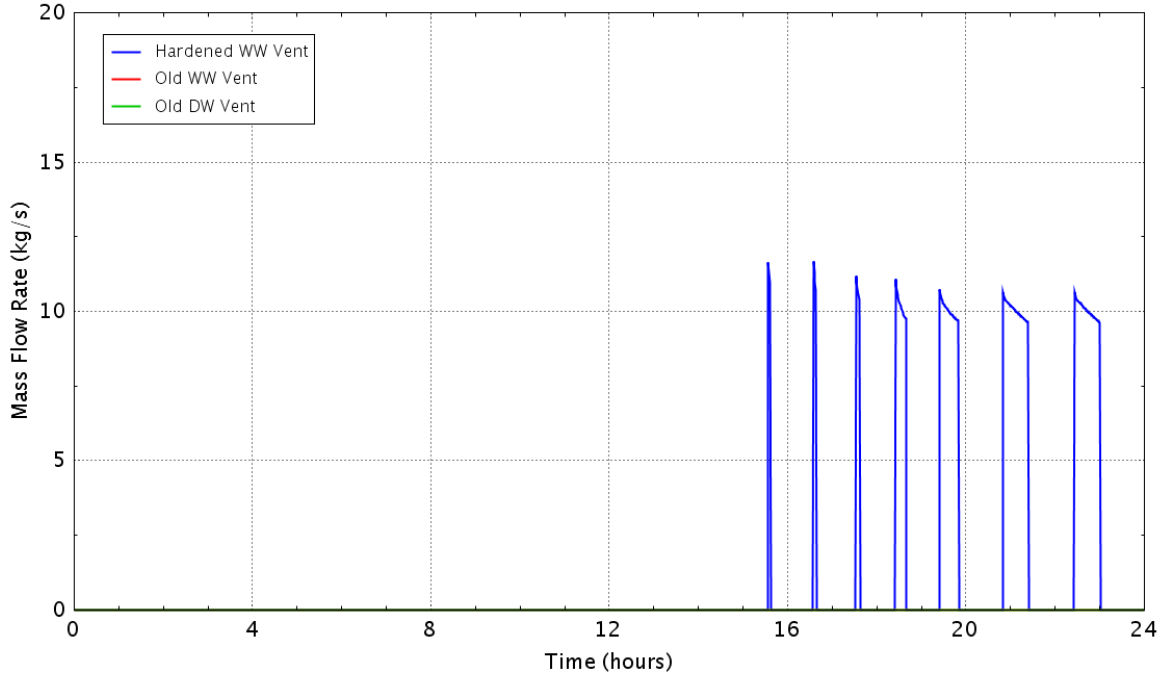

Figure C - 246 Flow rate of the containment vents

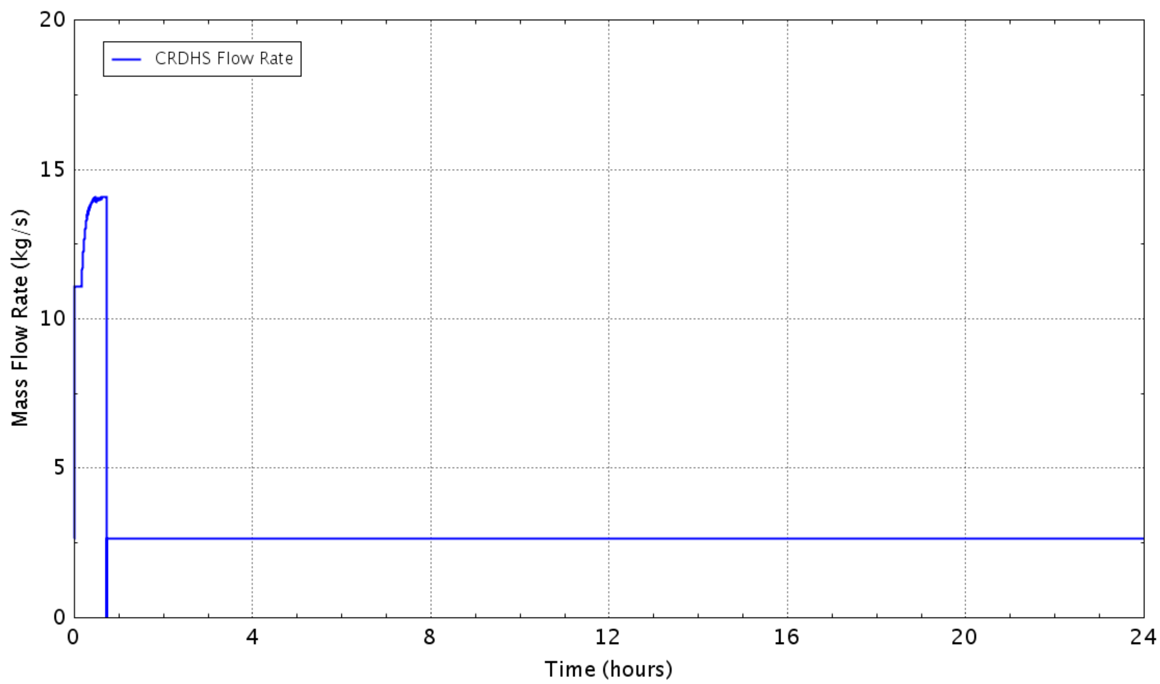

Figure C - 247 Flow rate of the control rod drive hydraulic system

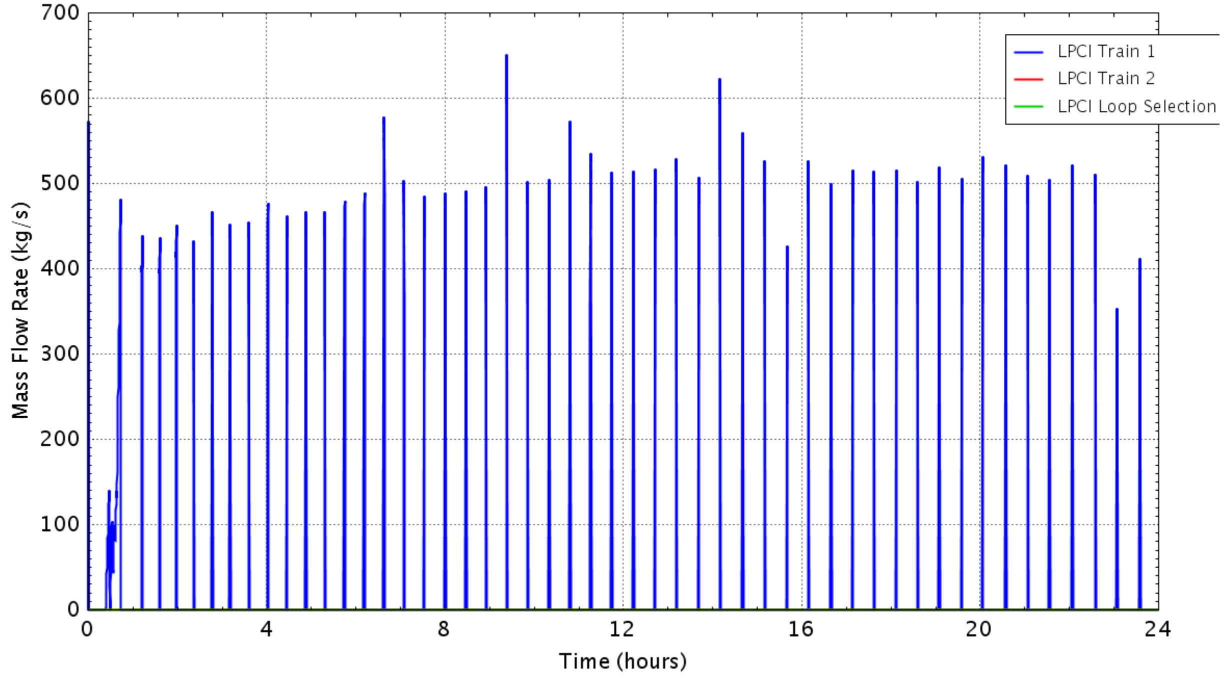

Figure C - 248 Flow rate of the LPCI pump

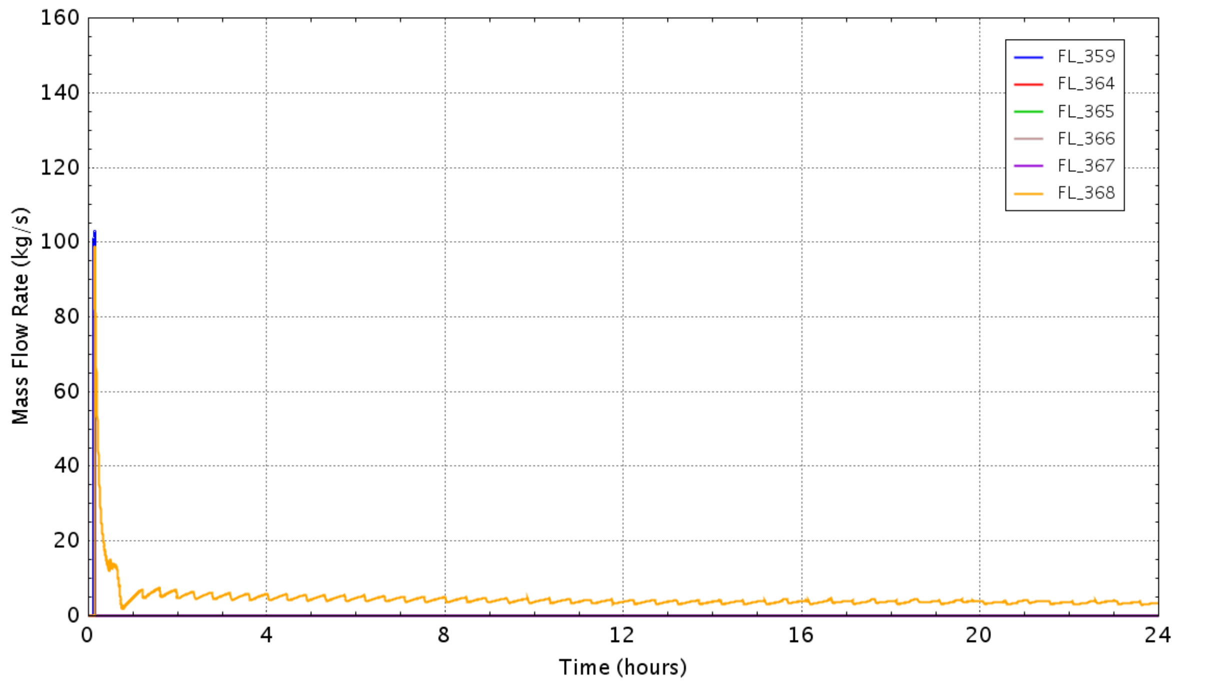

Figure C - 249 Flow rate of the SRVs

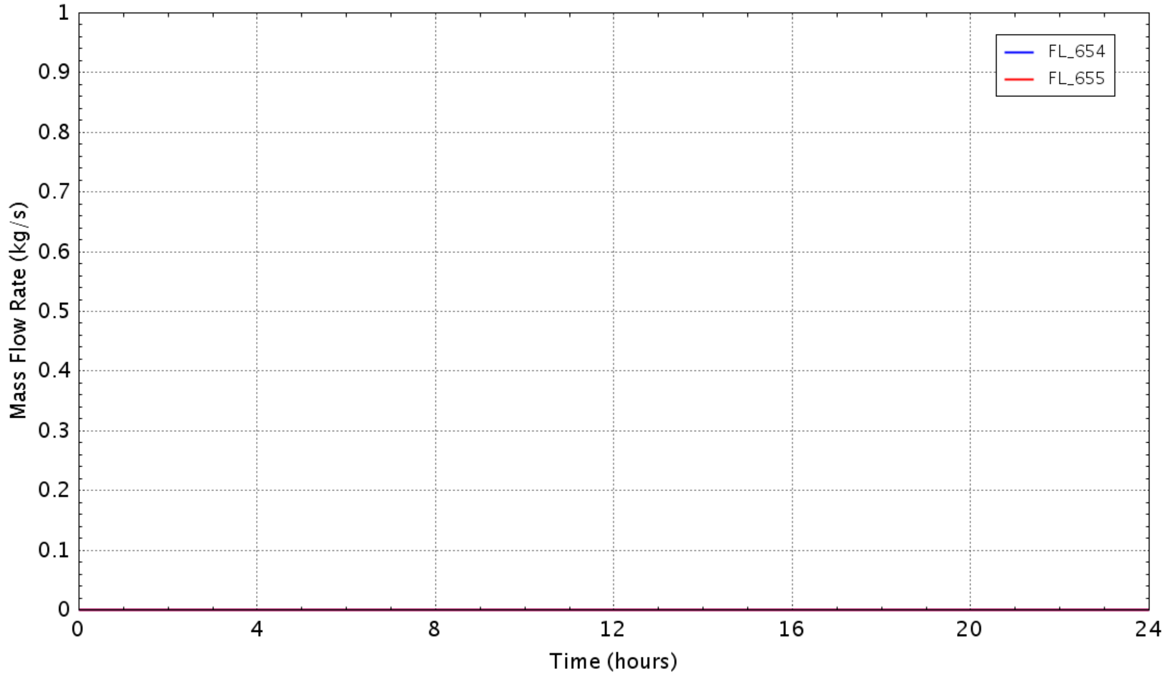

Figure C - 250 Flow rate of the wetwell cooling system

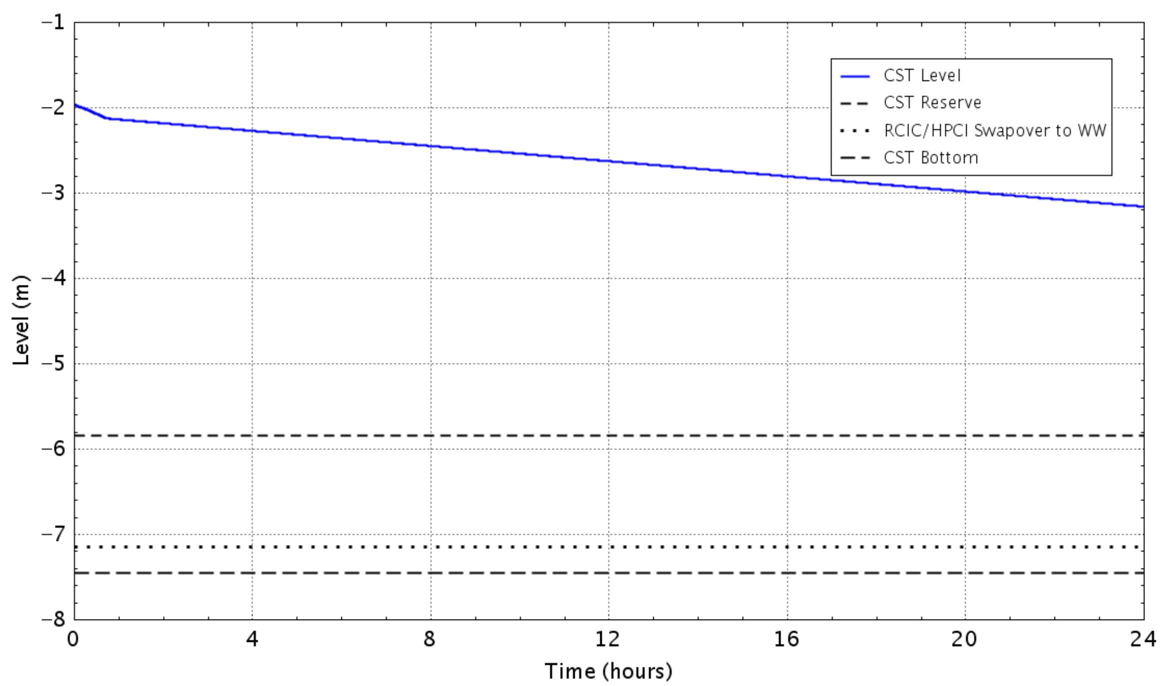

Figure C - 251 Water level in the CST

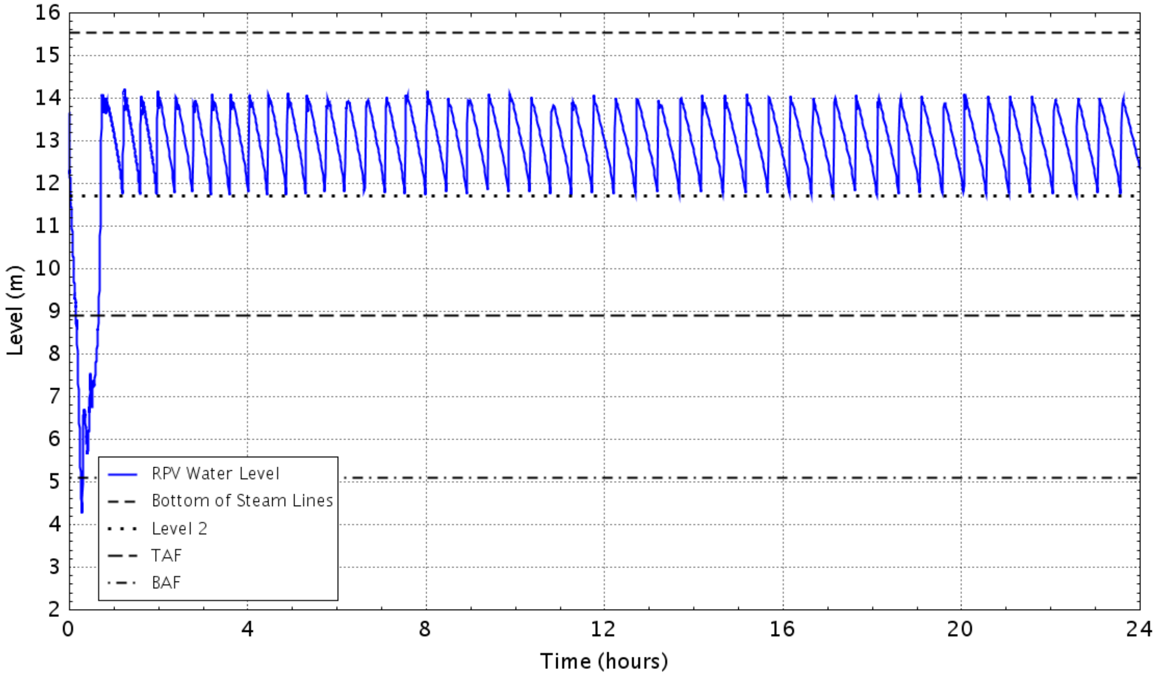

Figure C - 252 RPV Downcomer water level

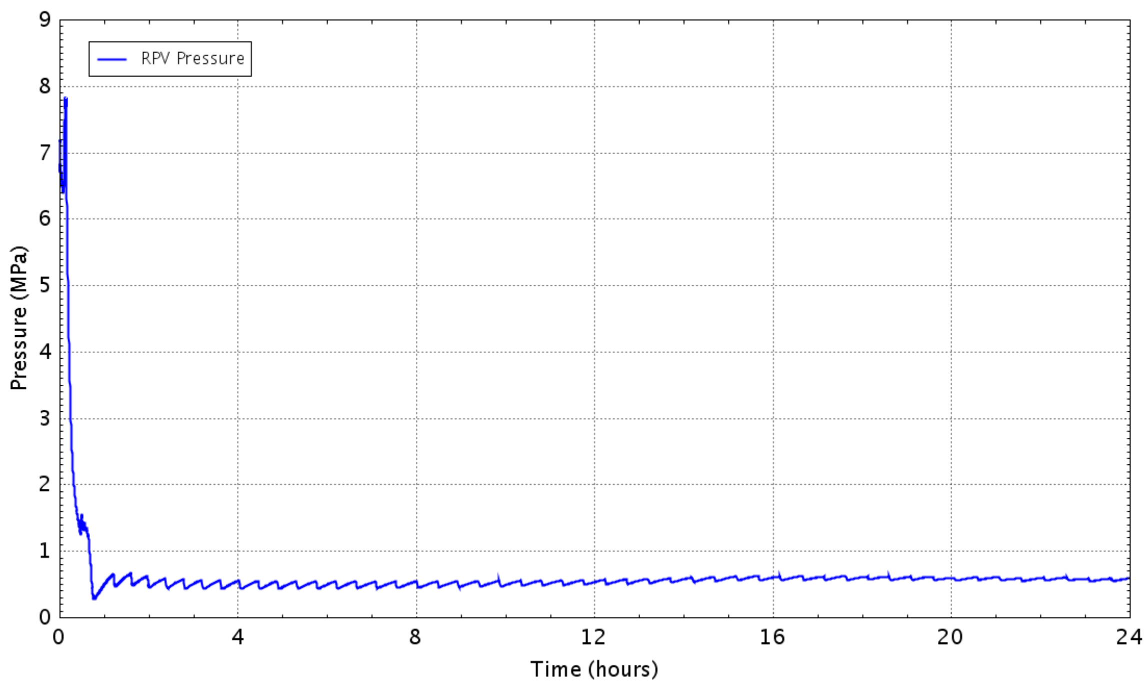

Figure C - 253 Pressure in the RPV

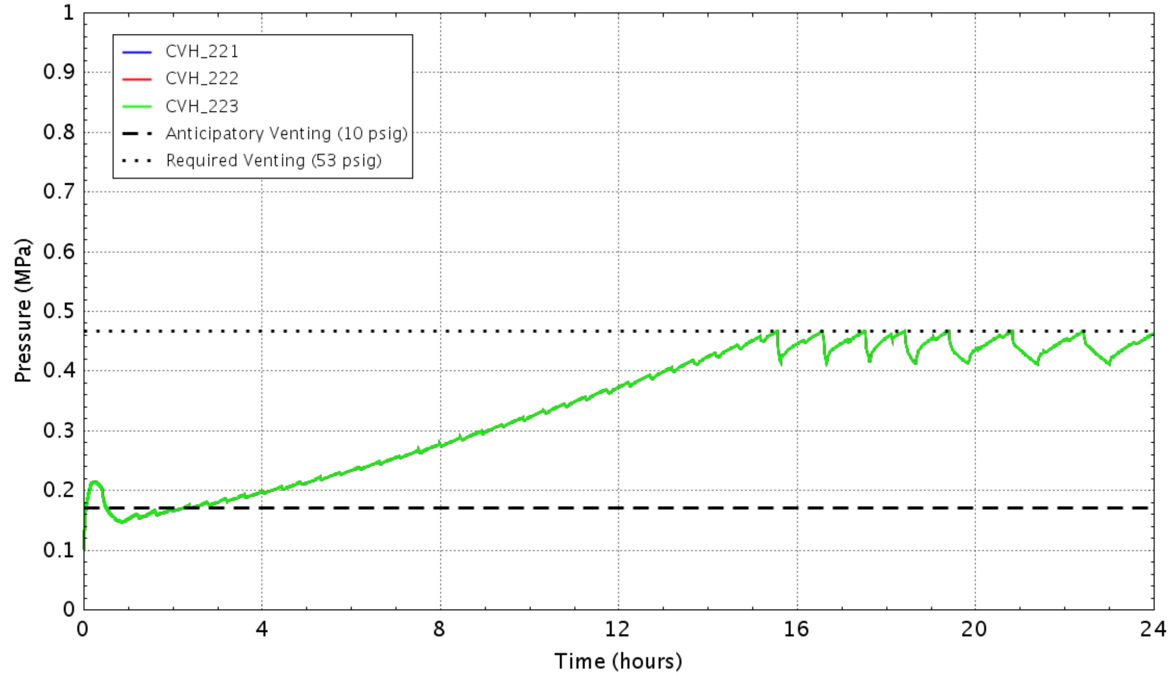

Figure C - 254 Pressure in the wetwell

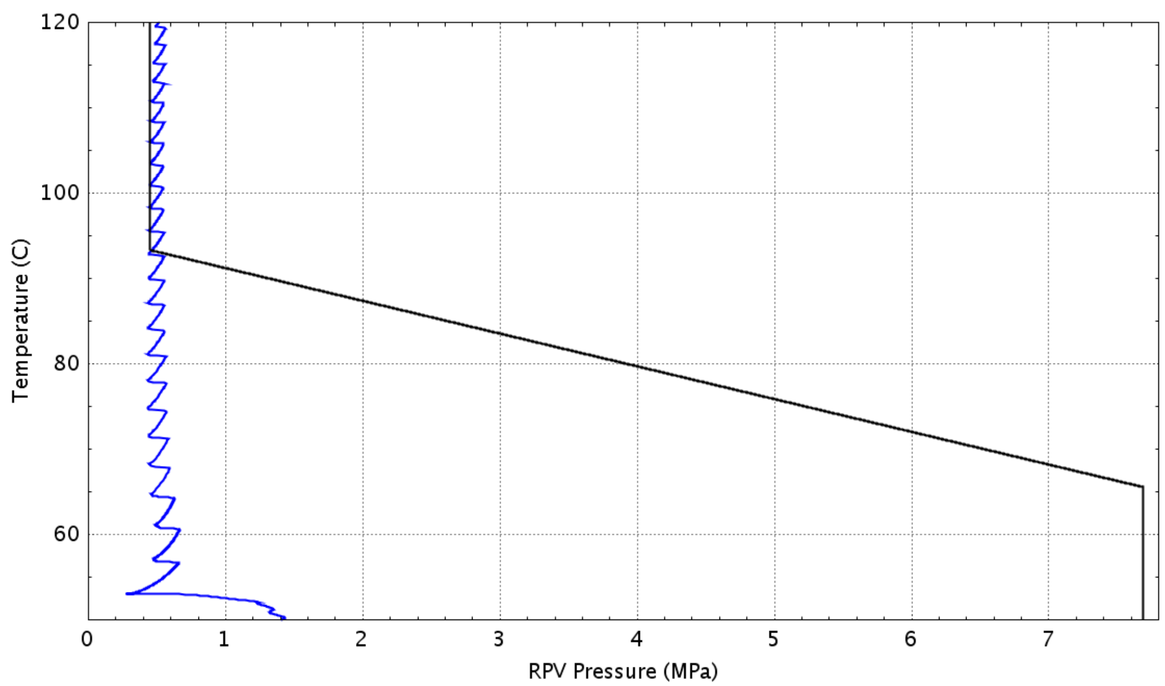

Figure C - 255 Plant status relative to the HCL curve (Graph 4 of the EOPs)

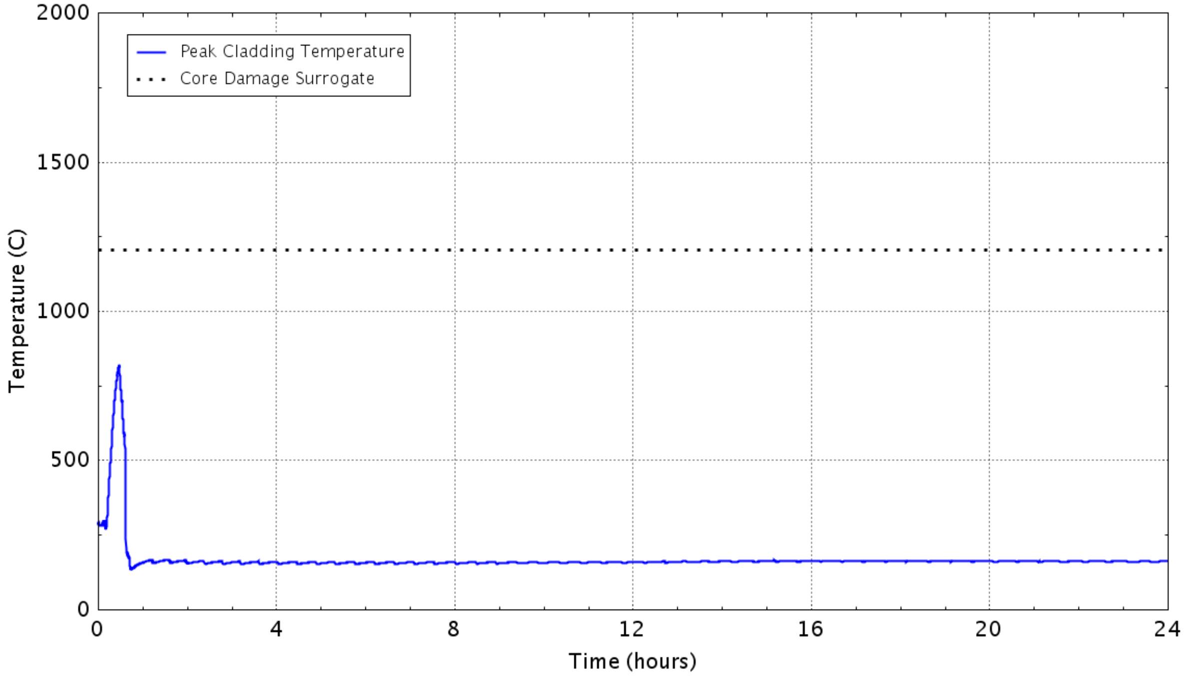

Figure C - 256 Peak temperature of the fuel cladding as a function of time

C.2.4 Case 24: SLOCA-25, 1.8-in. Equivalent Liquid Break, One Trainof CRDHS,ADS at +15 in., Two SRVs

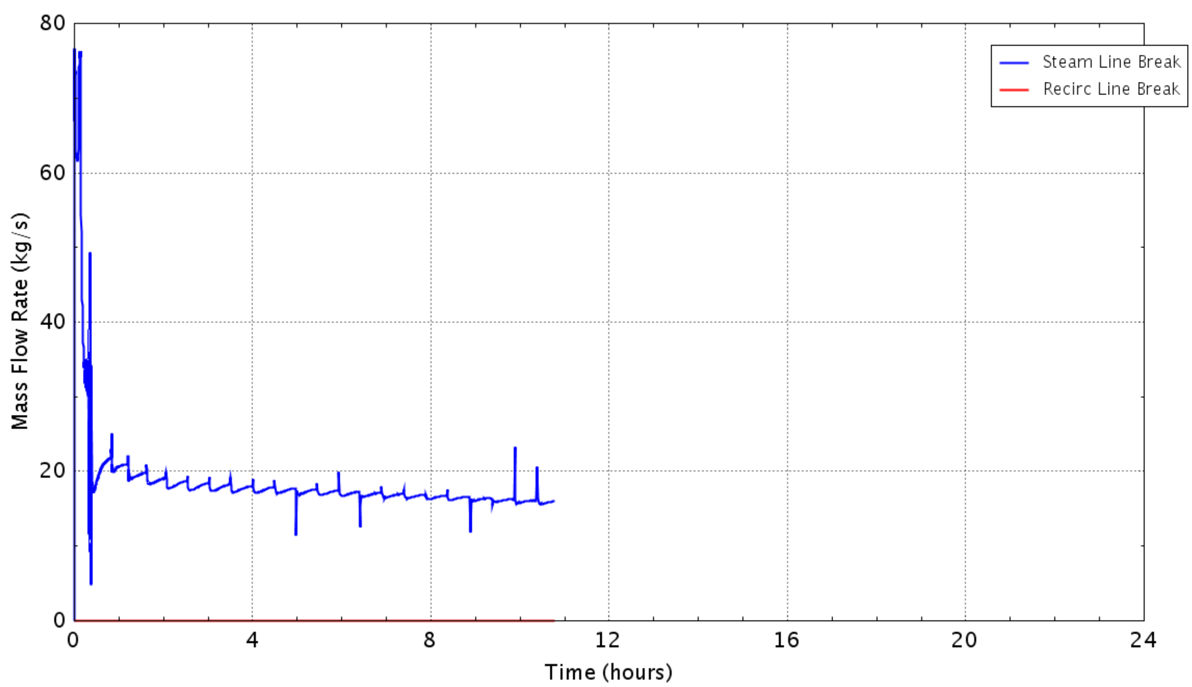

Figure C - 257 Flow rate of the break in the steamline/recirculation line

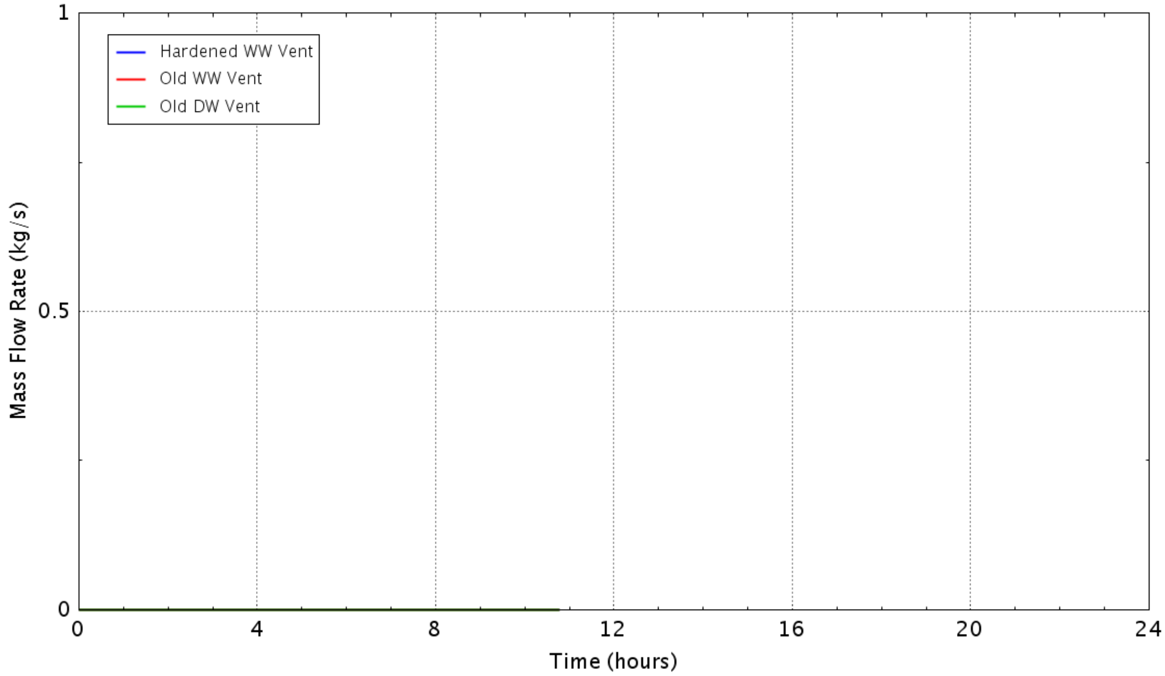

Figure C - 258 Flow rate of the containment vents

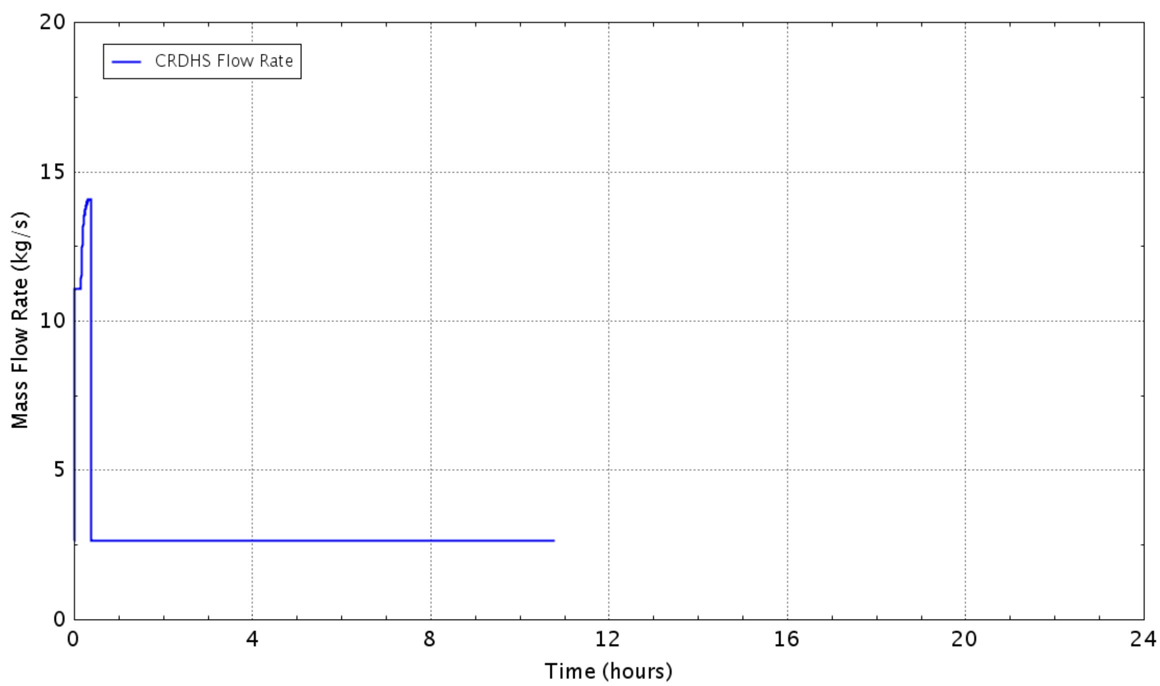

Figure C - 259 Flow rate of the control rod drive hydraulic system

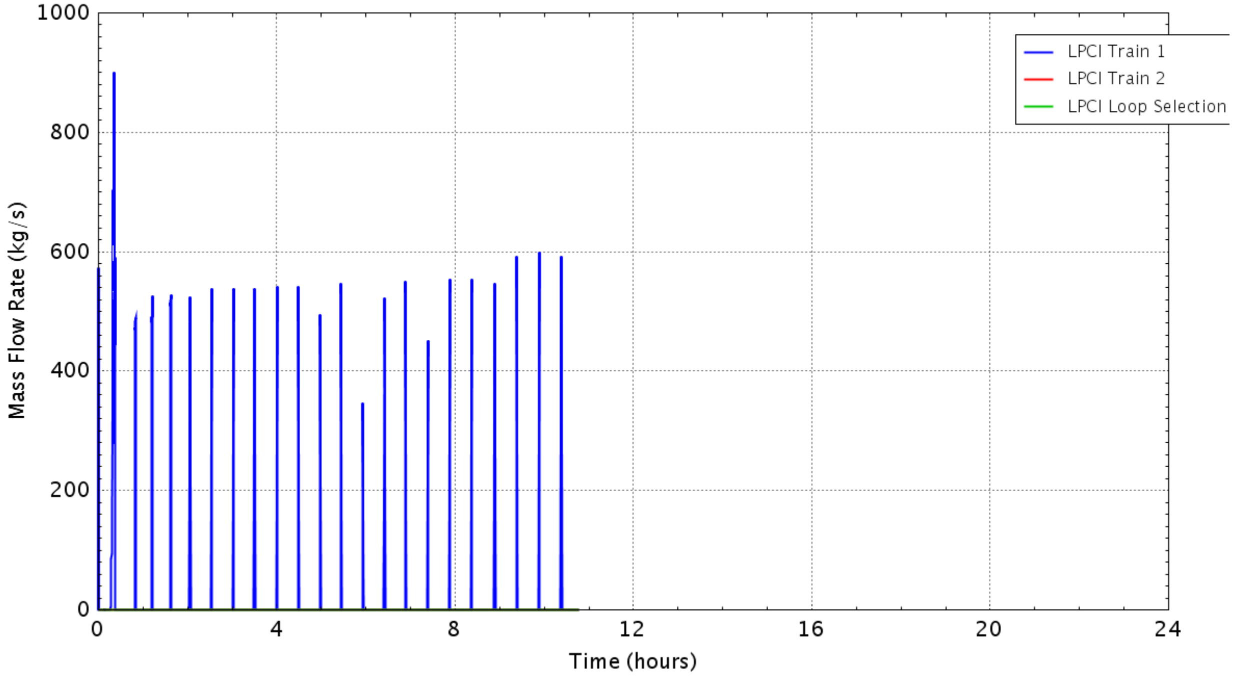

Figure C - 260 Flow rate of the LPCI pump

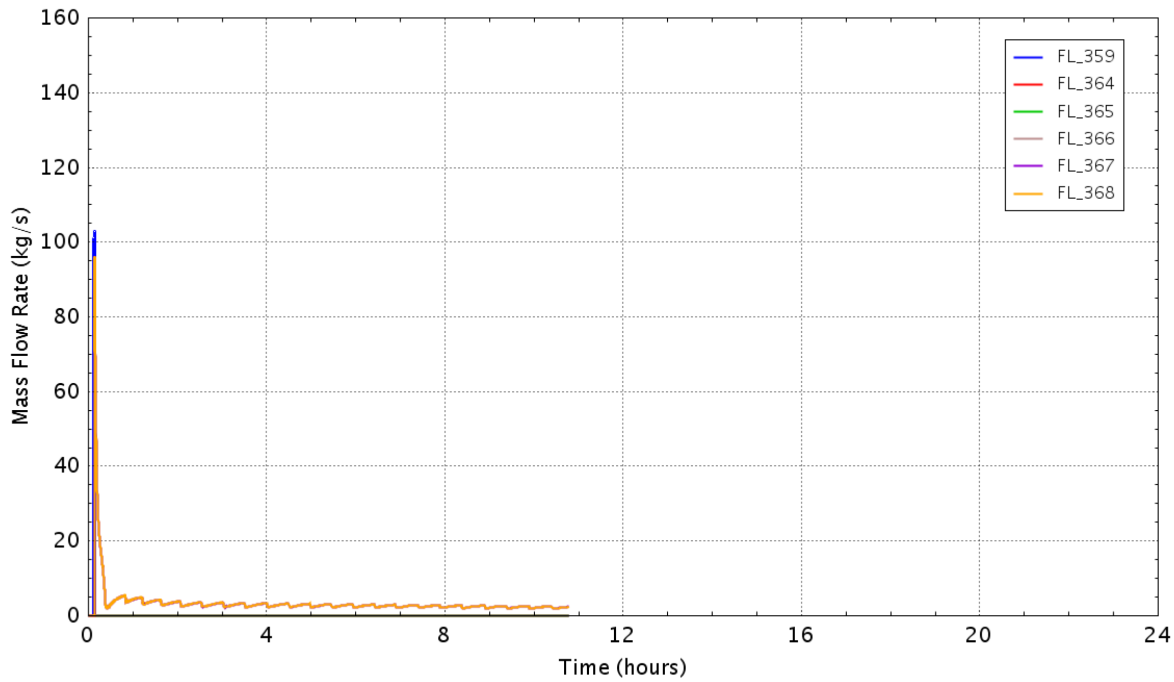

Figure C - 261 Flow rate of the SRVs

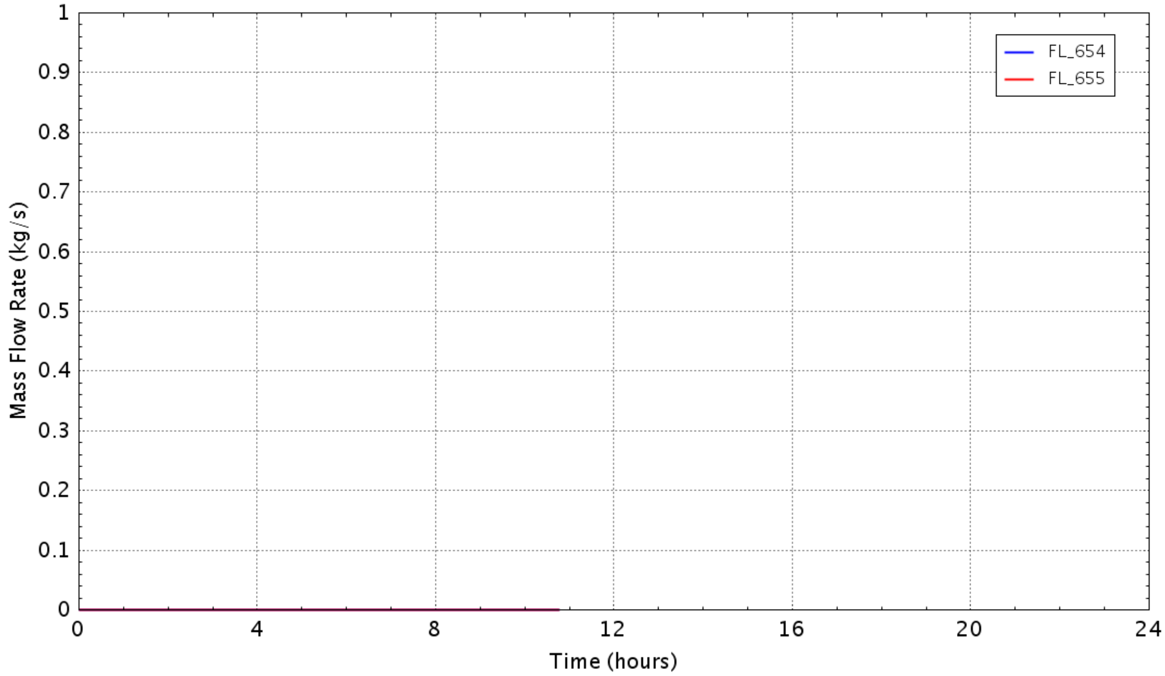

Figure C - 262 Flow rate of the wetwell cooling system

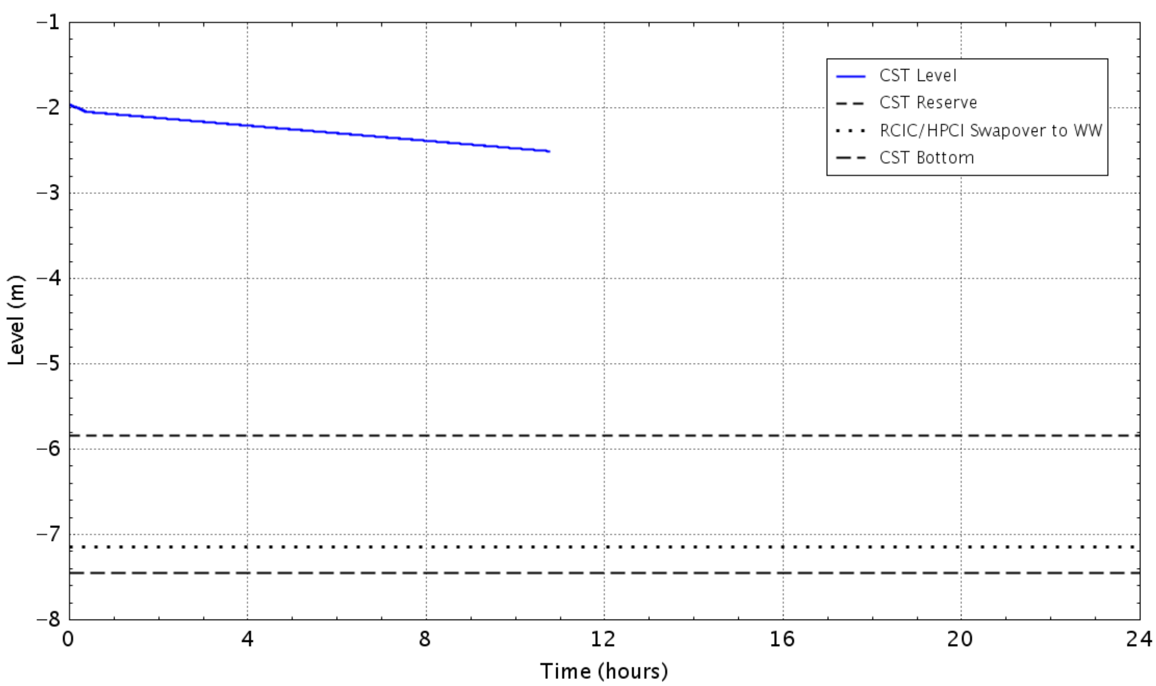

Figure C - 263 Water level in the CST

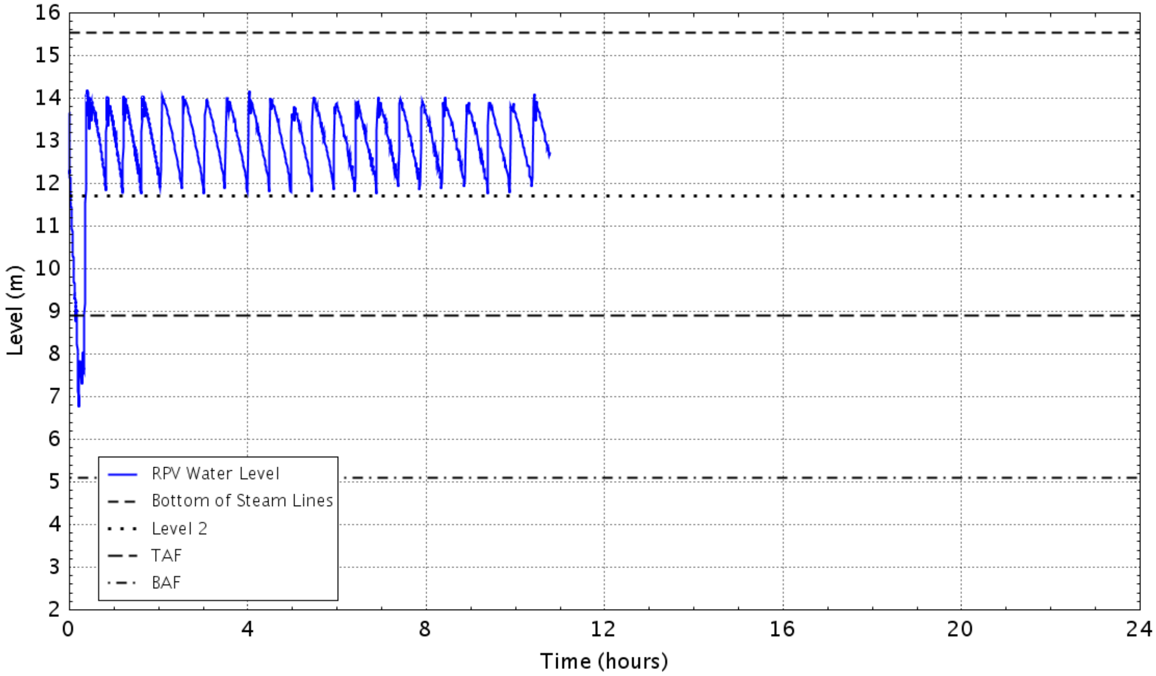

Figure C - 264 RPV Downcomer water level

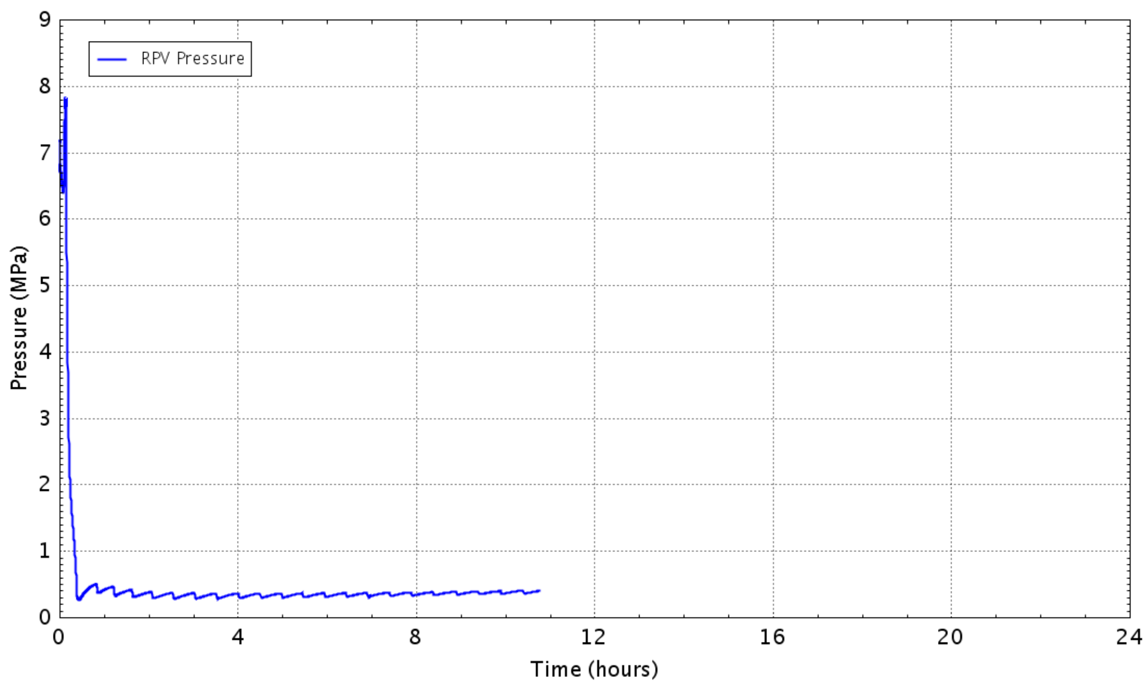

Figure C - 265 Pressure in the RPV

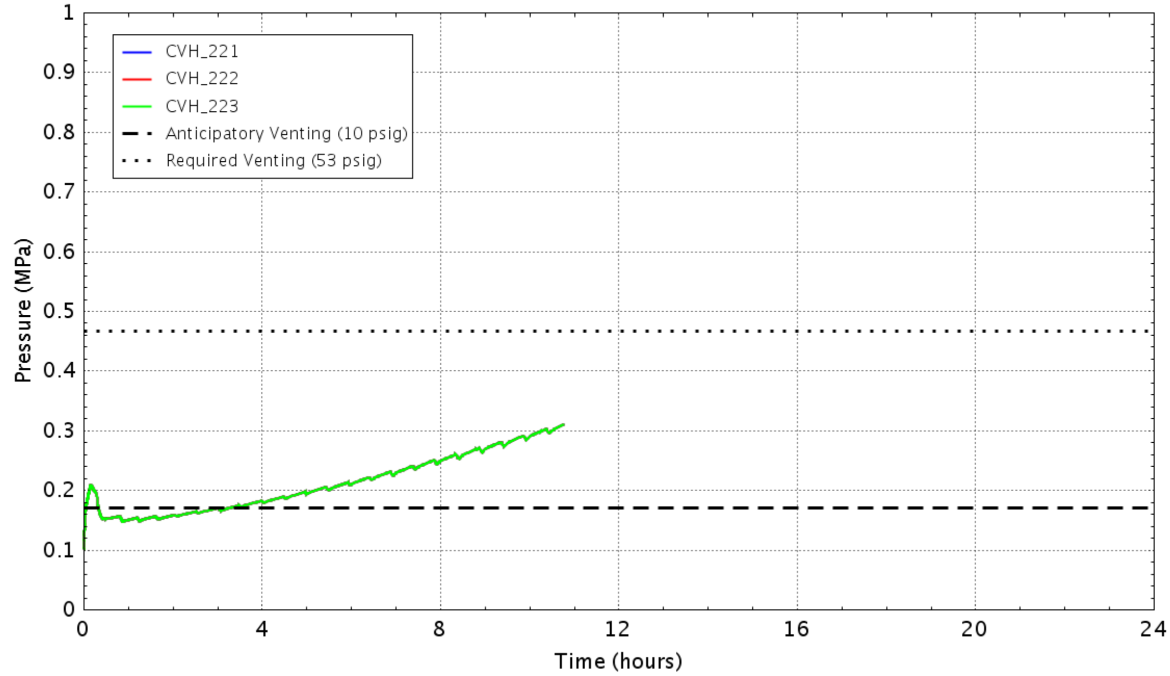

Figure C - 266   Pressure in the wetwell

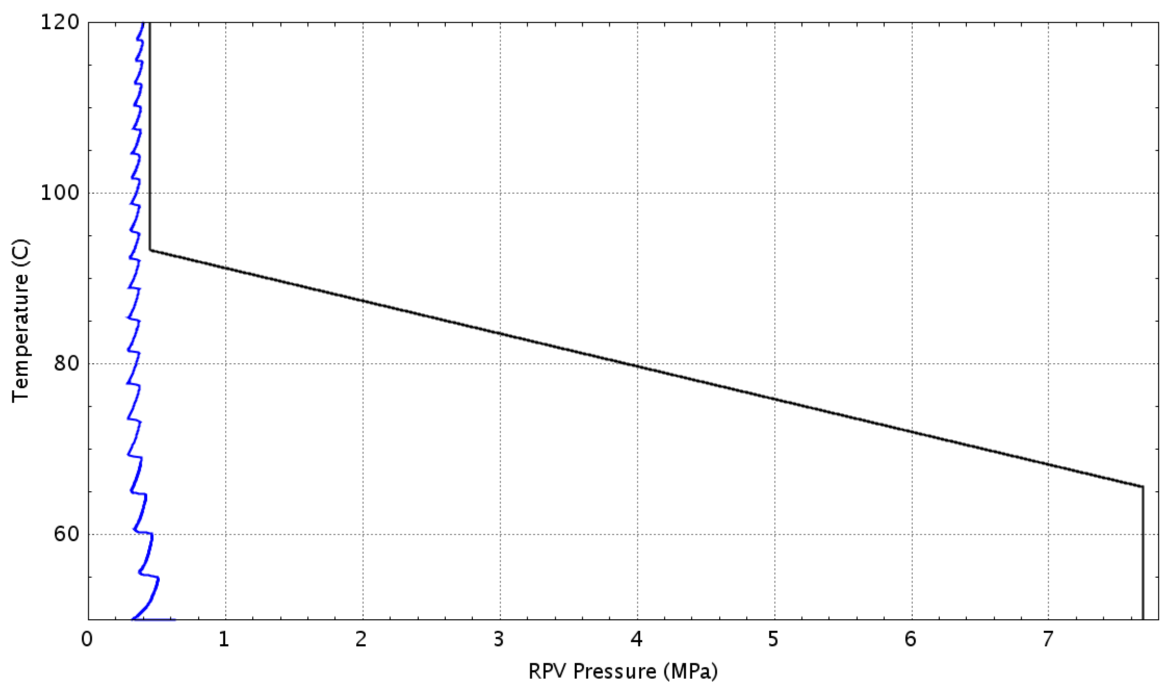

Figure C - 267   Plant status relative to the HCL curve (Graph 4 of the EOPs)

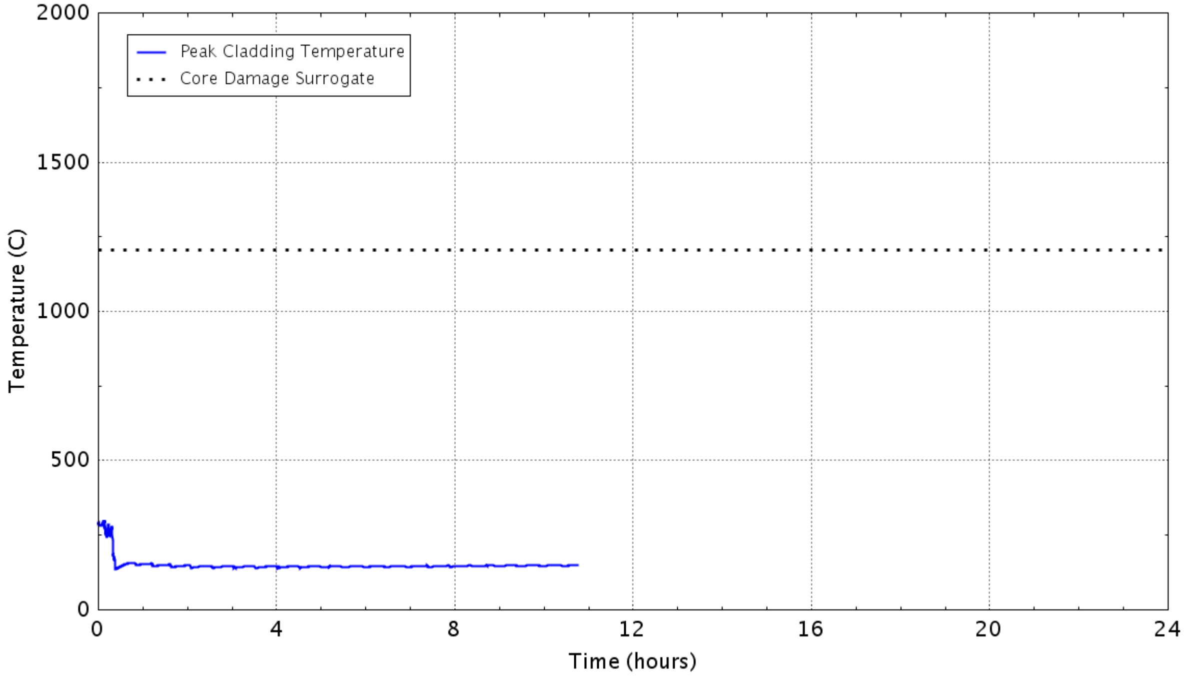

Figure C - 268 Peak temperature of the fuel cladding as a function of time

C.2.5 Case 25: SLOCA-25, 1.8-in. Equivalent Liquid Break, One Trainof CRDHS,ADS at -25 in., One SRV

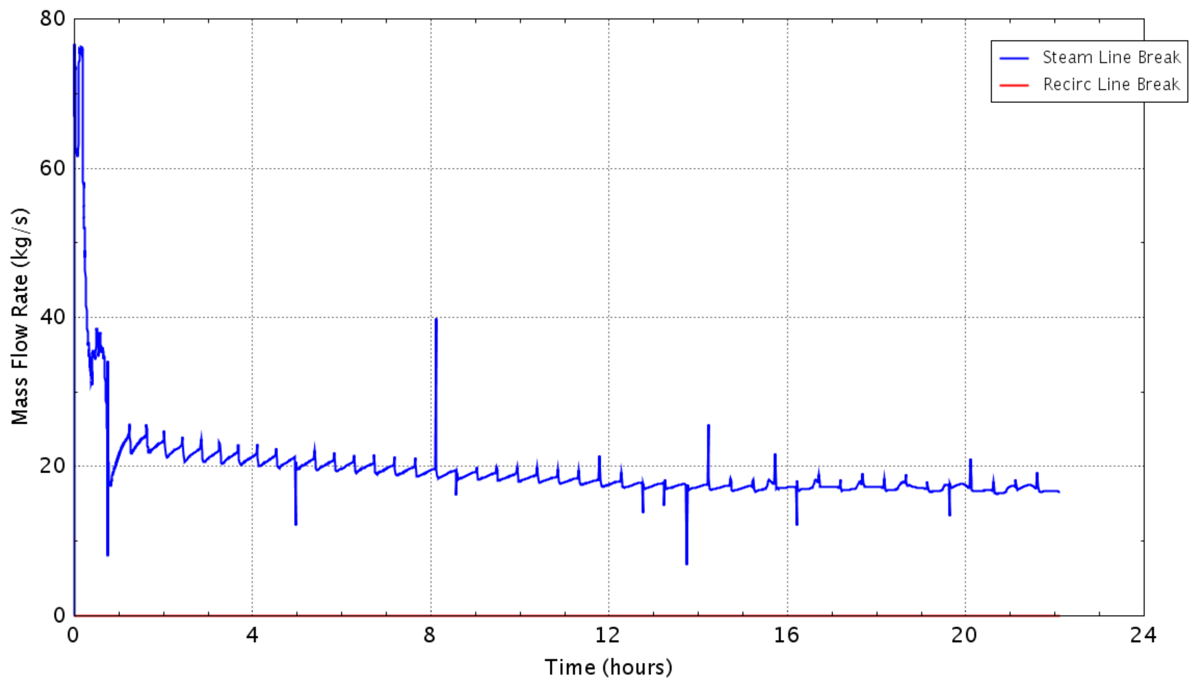

Figure C - 269 Flow rate of the break in the steamline/recirculation line

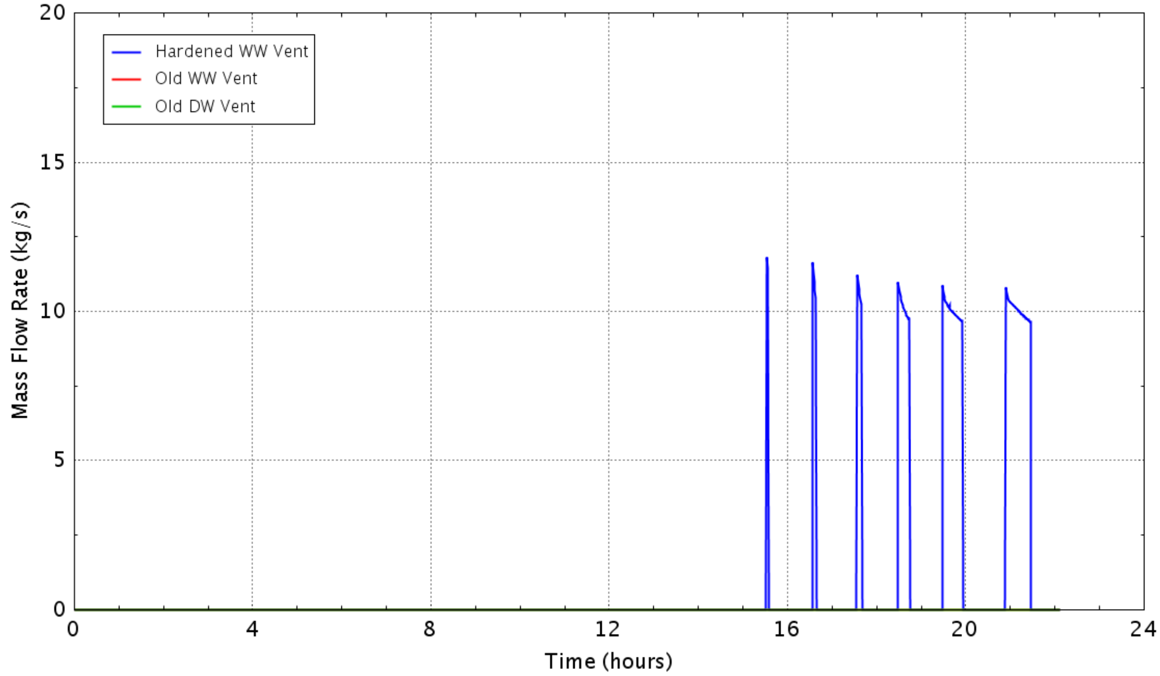

Figure C - 270 Flow rate of the containment vents

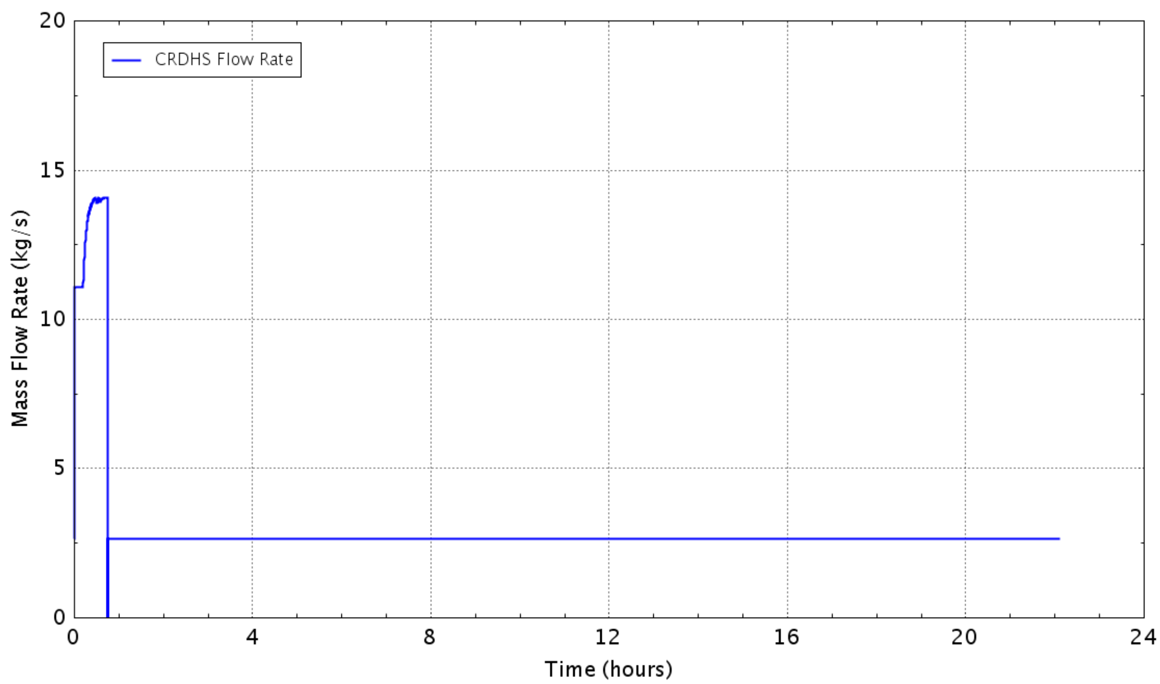

Figure C - 271 Flow rate of the control rod drive hydraulic system

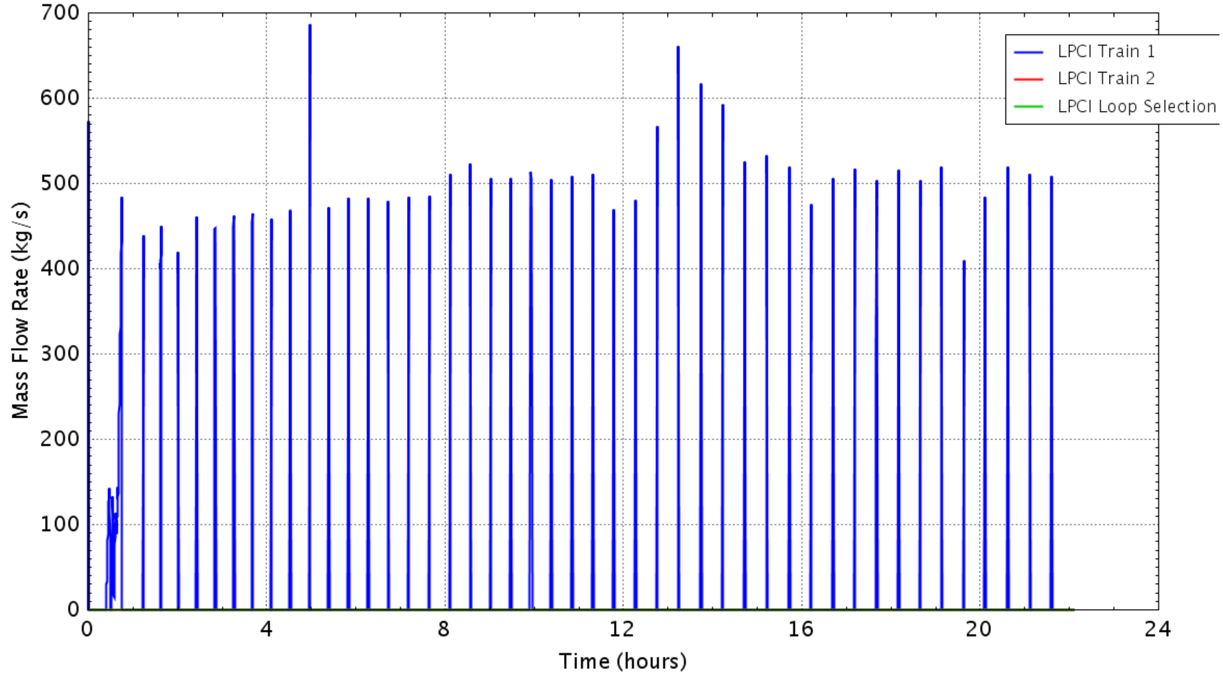

Figure C - 272 Flow rate of the LPCI pump

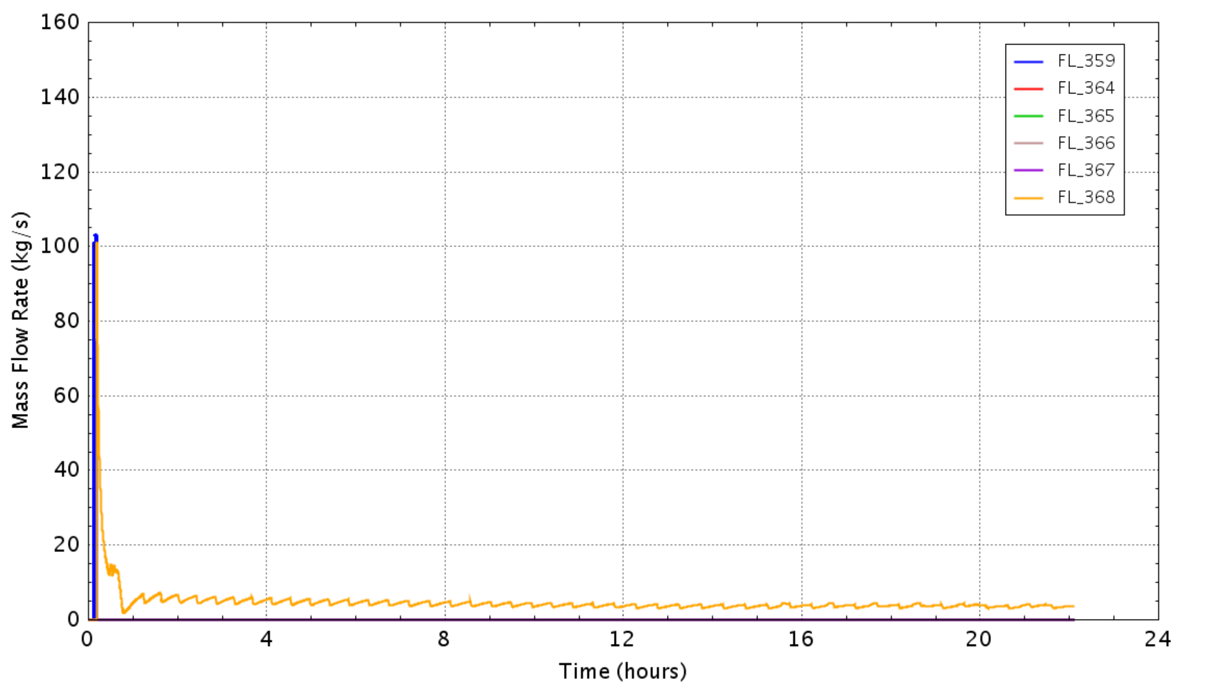

Figure C - 273 Flow rate of the SRVs

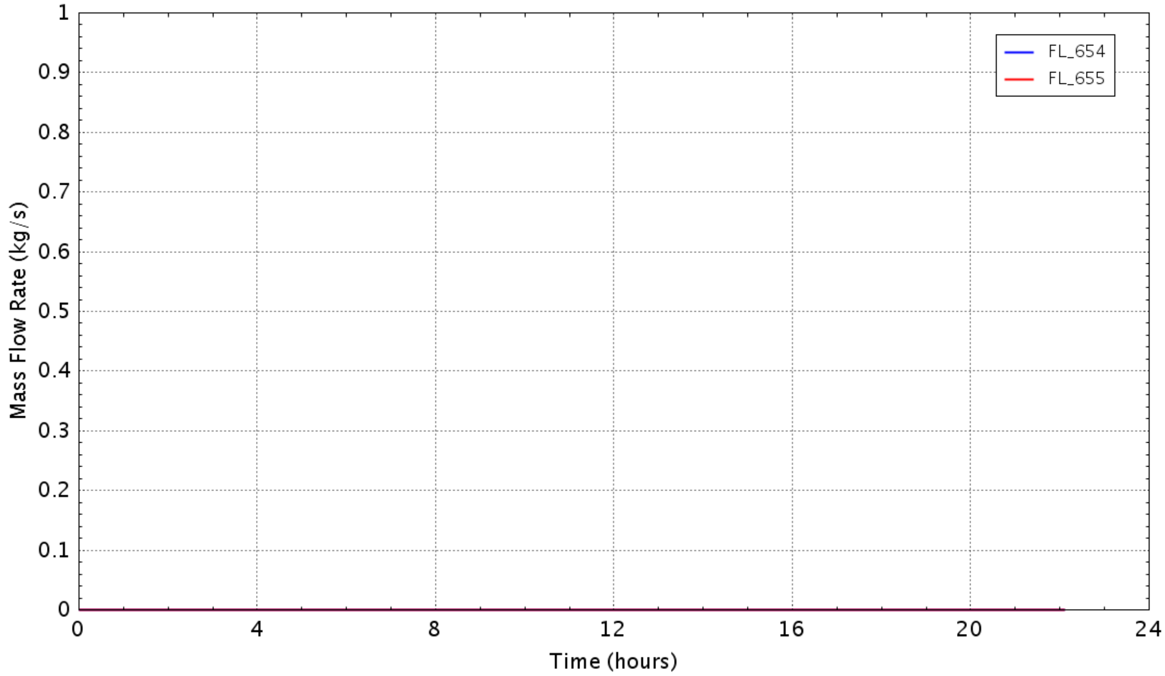

Figure C - 274 Flow rate of the wetwell cooling system

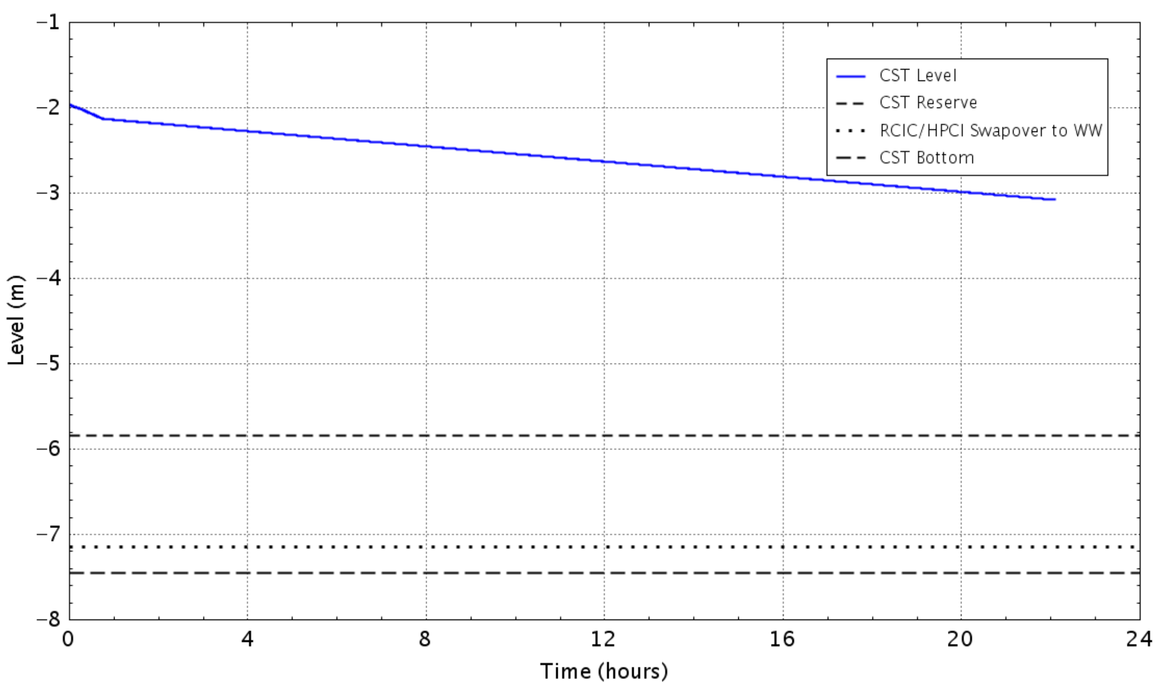

Figure C - 275 Water level in the CST

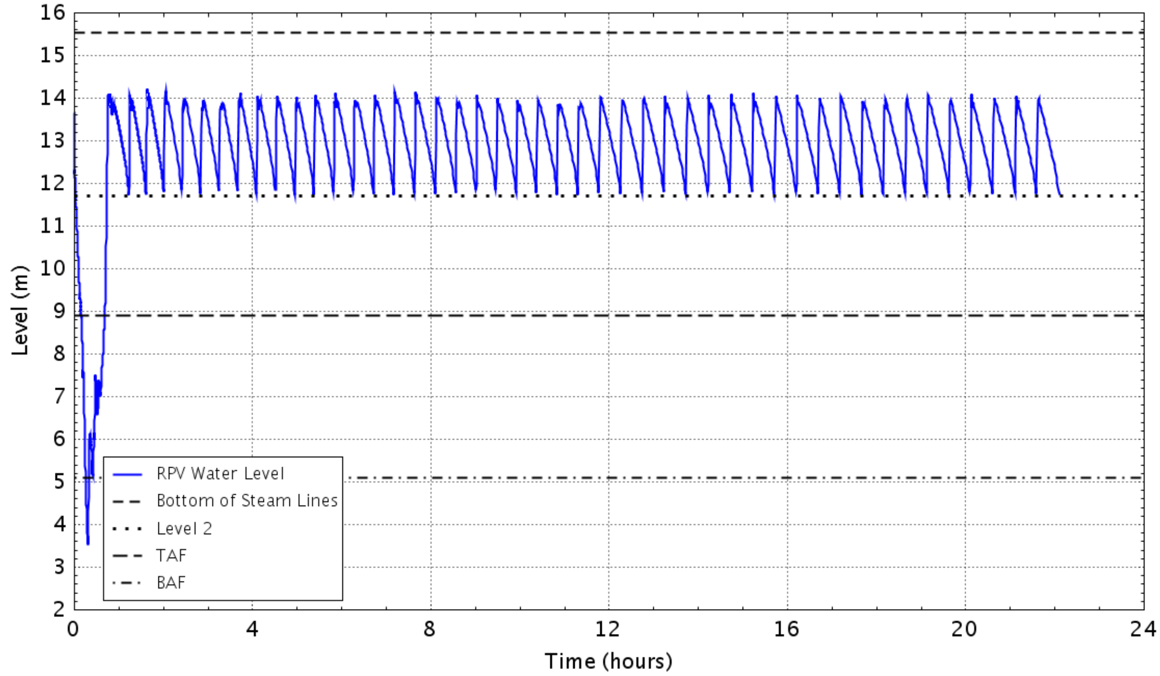

Figure C - 276 RPV Downcomer water level

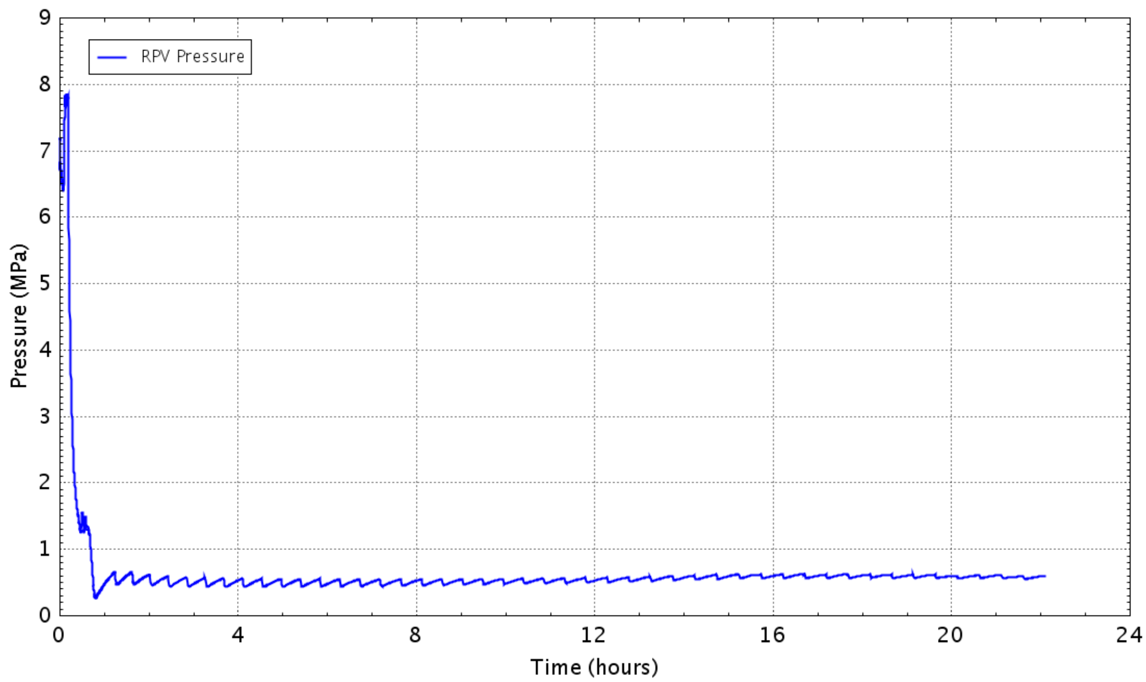

Figure C - 277 Pressure in the RPV

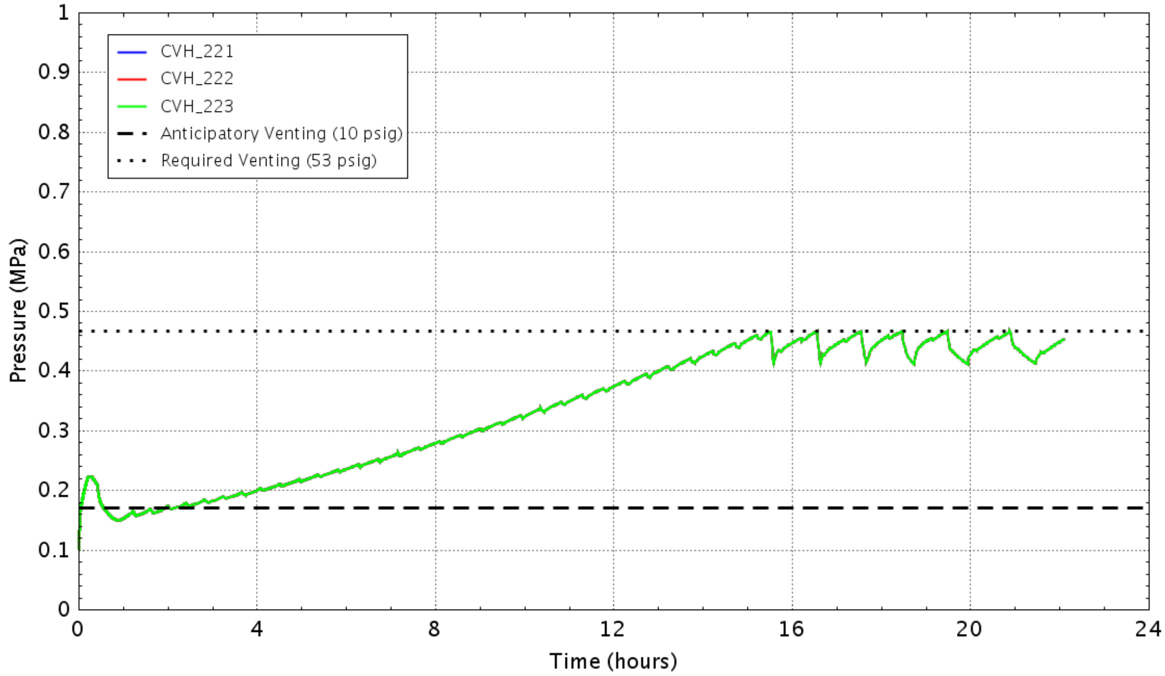

Figure C - 278 Pressure in the wetwell

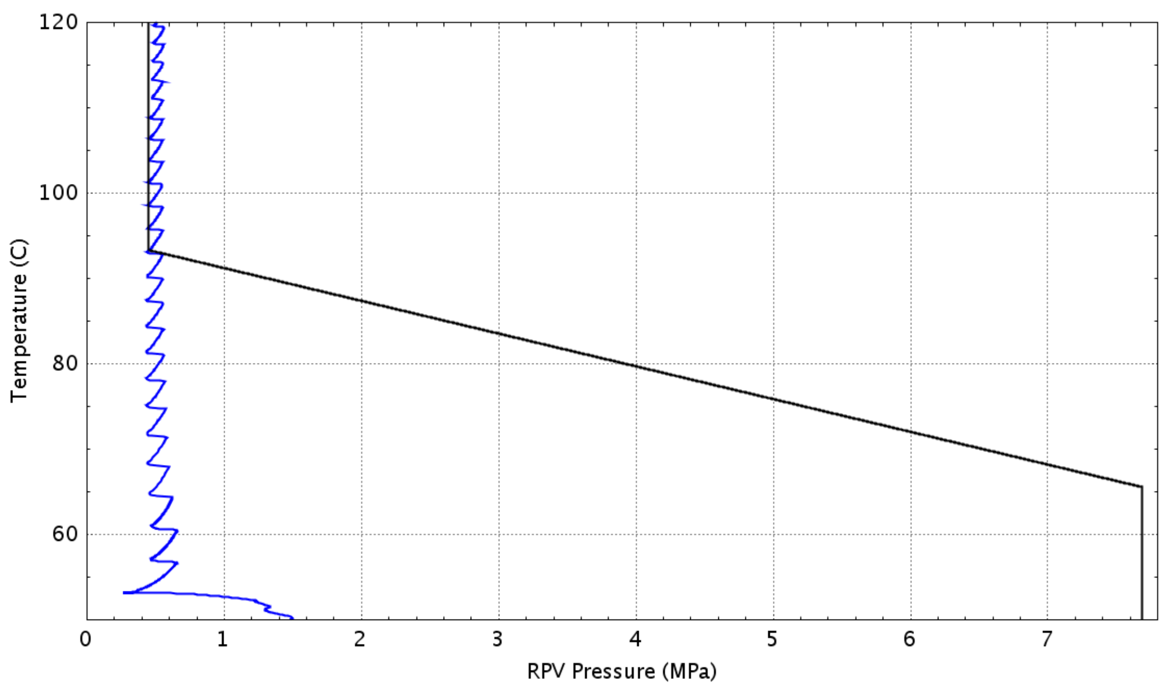

Figure C - 279 Plant status relative to the HCL curve (Graph 4 of the EOPs)

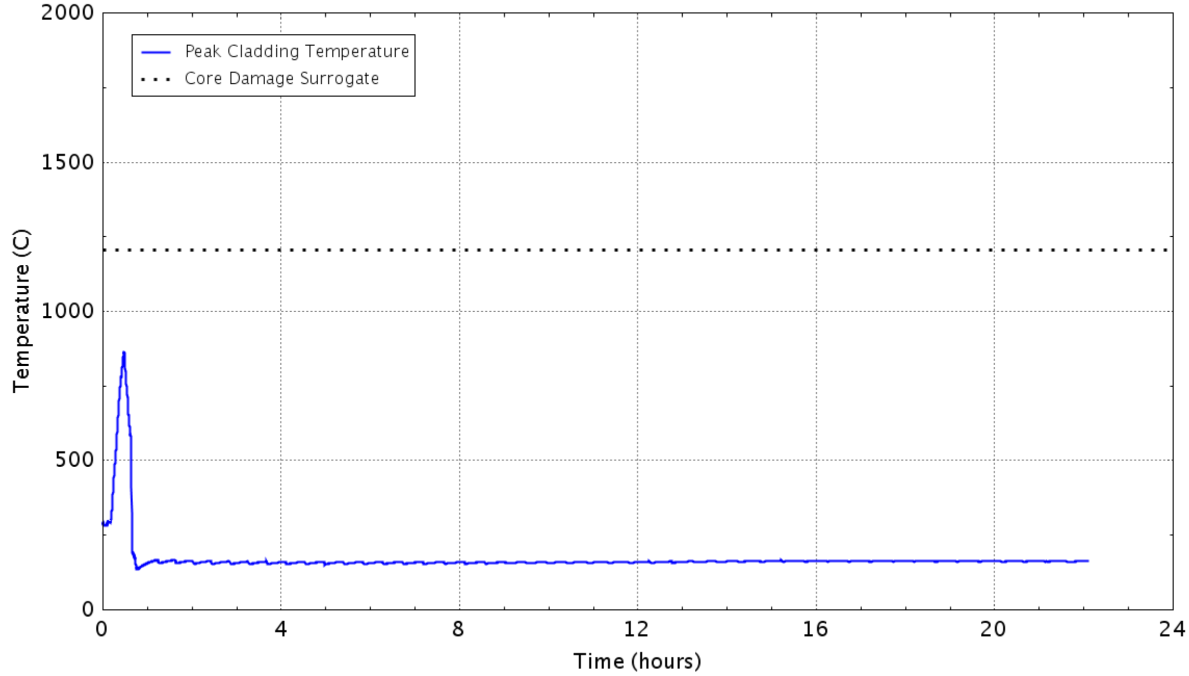

Figure C - 280 Peak temperature of the fuel cladding as a function of time

C.2.6 Case 26: SLOCA-25, 1.8-in. Equivalent Liquid Break, One Trainof CRDHS,ADS at -25 in., Two SRVs

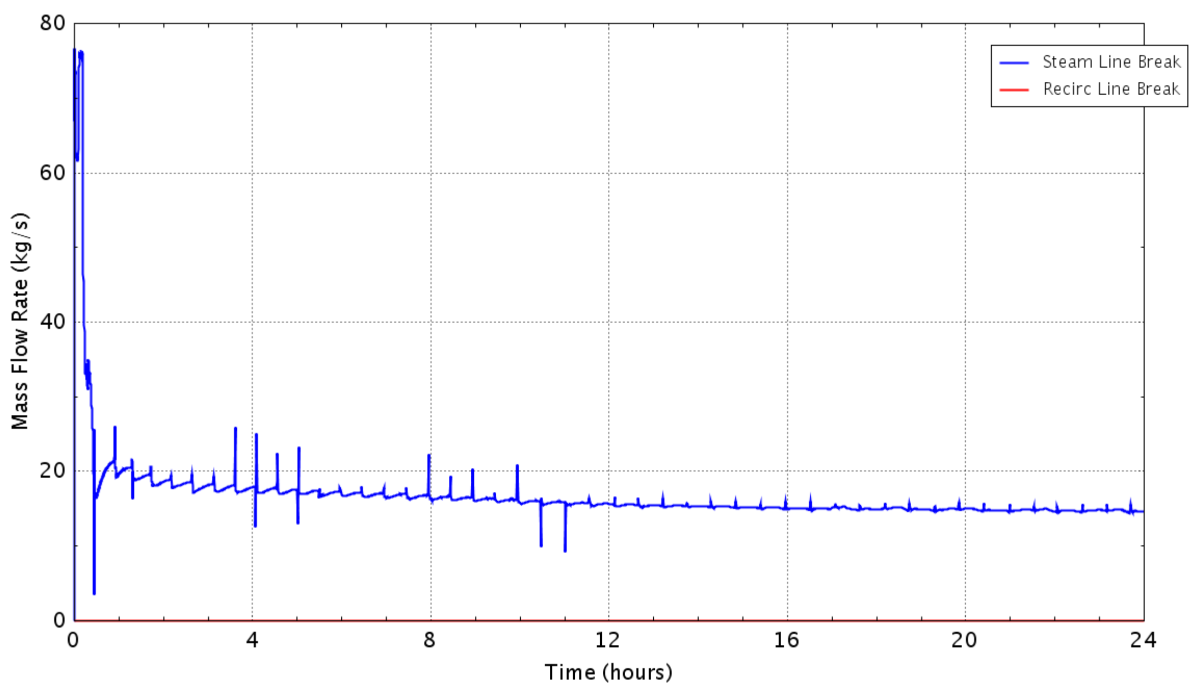

Figure C - 281 Flow rate of the break in the steamline/recirculation line

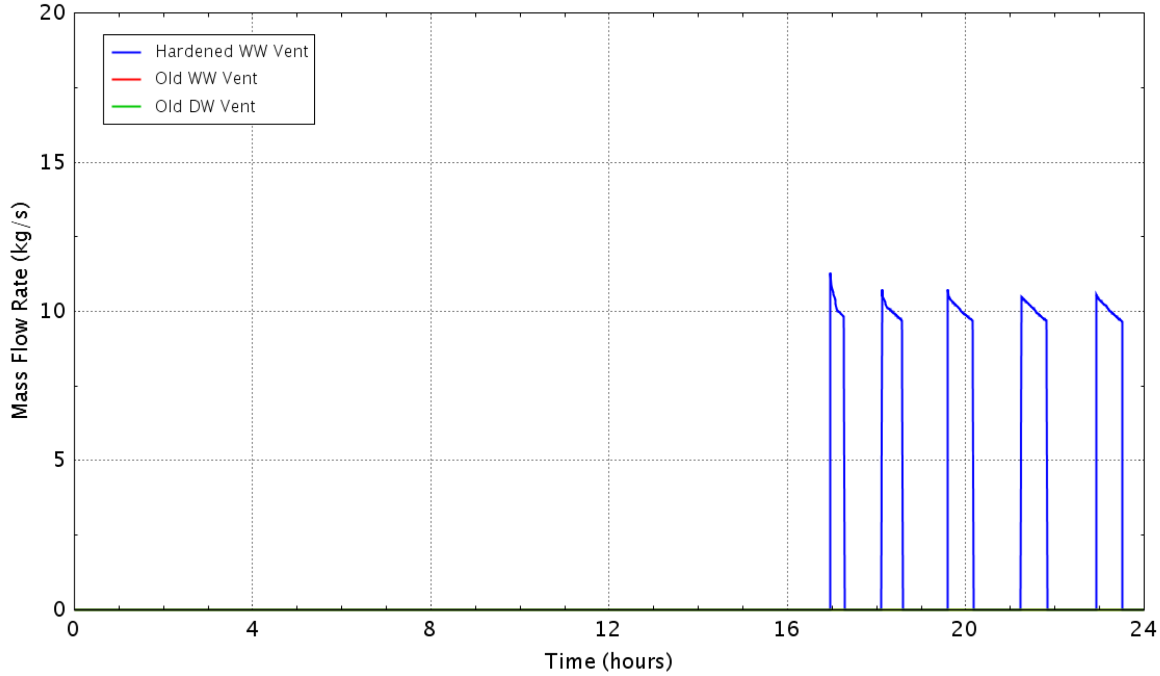

Figure C - 282 Flow rate of the containment vents

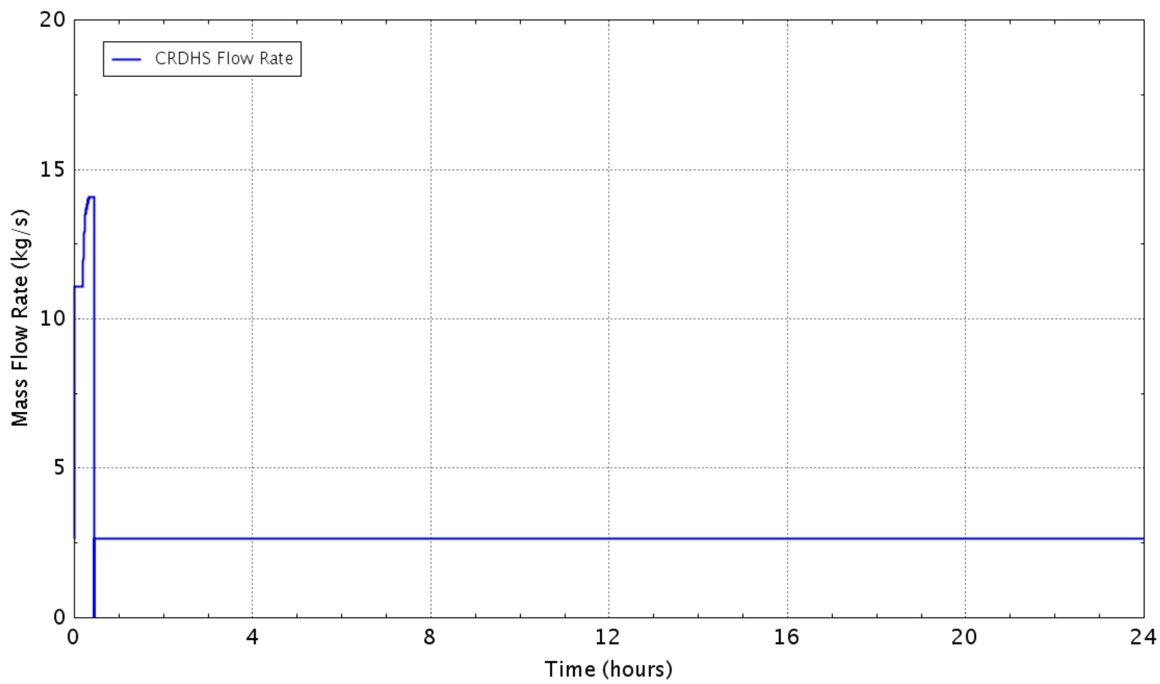

Figure C - 283 Flow rate of the control rod drive hydraulic system

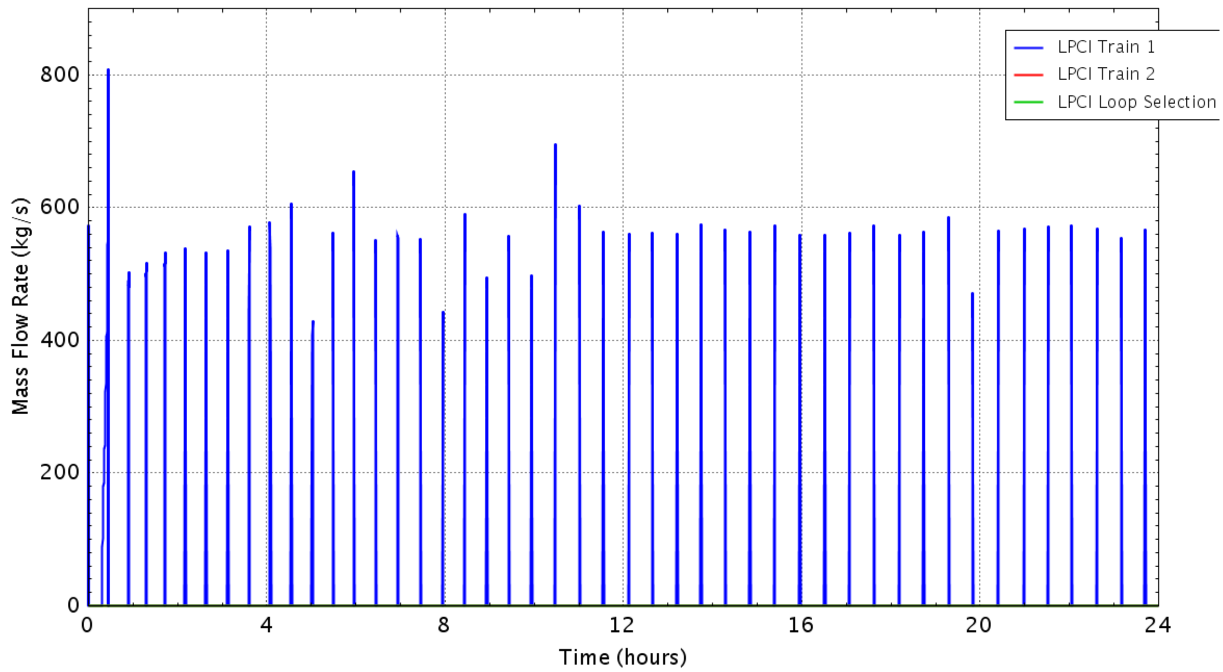

Figure C - 284 Flow rate of the LPCI pump

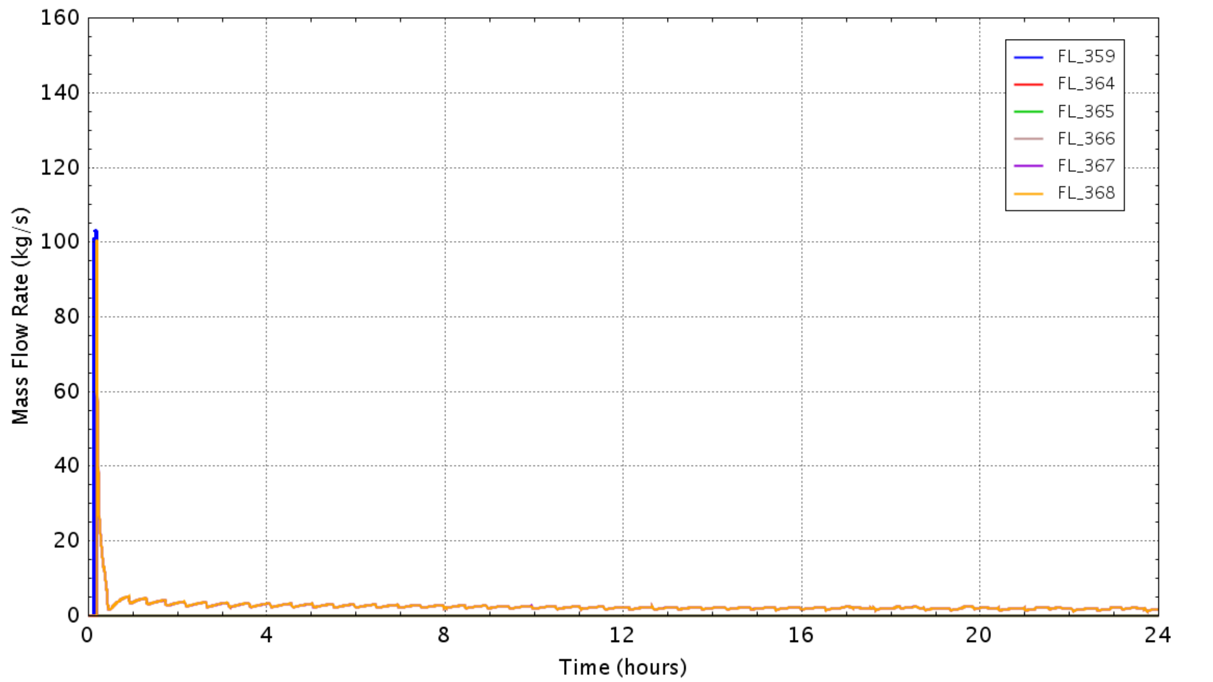

Figure C - 285 Flow rate of the SRVs

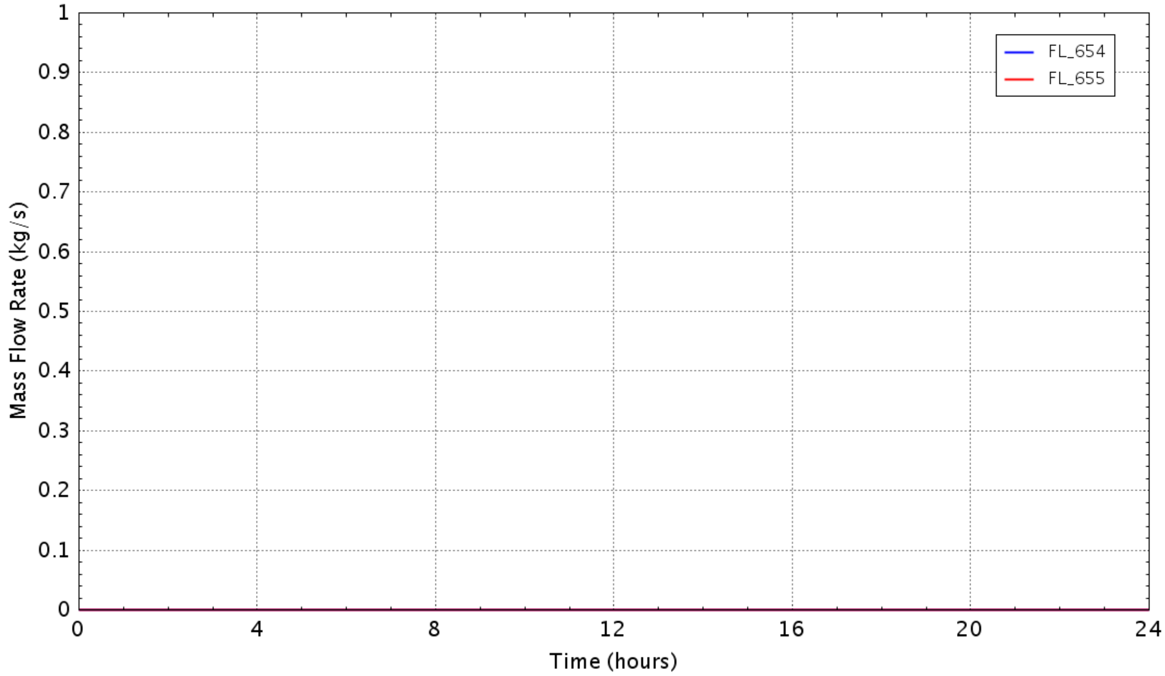

Figure C - 286   Flow rate of the wetwell cooling system

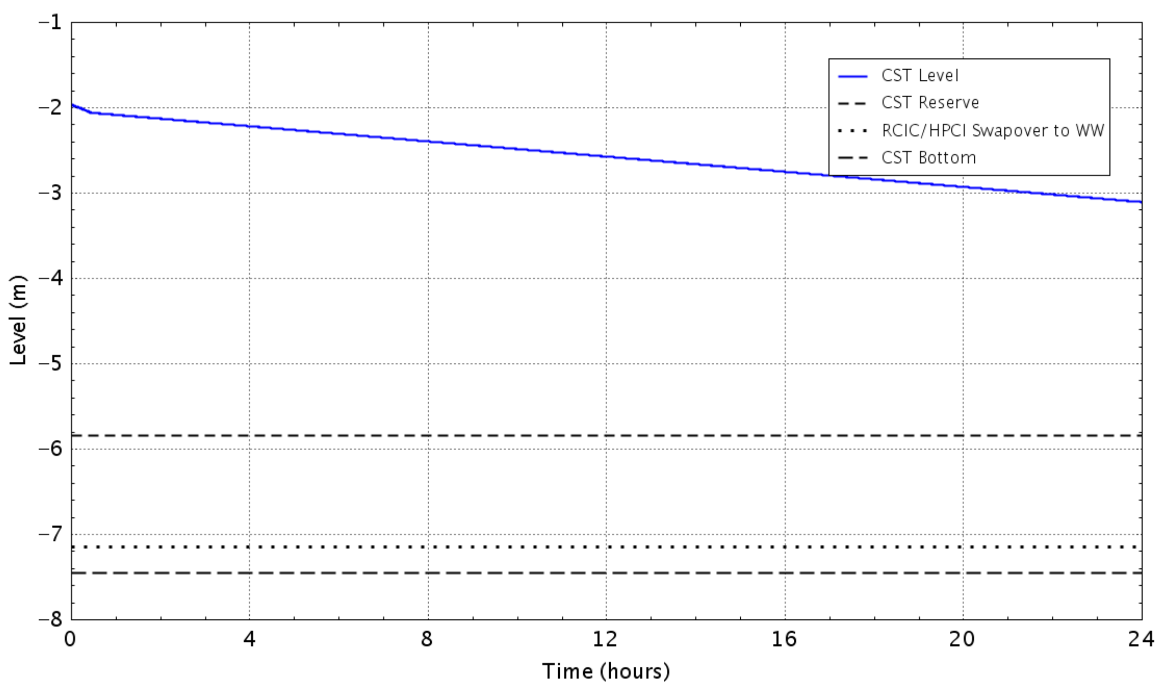

Figure C - 287   Water level in the CST

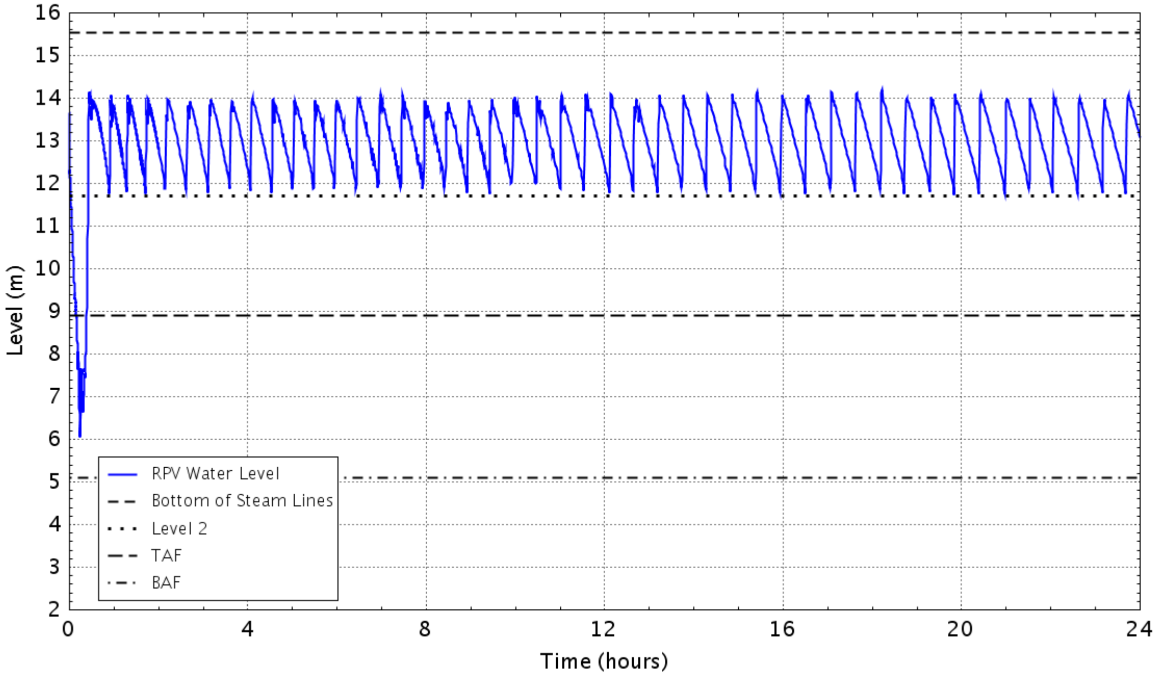

Figure C - 288 RPV Downcomer water level

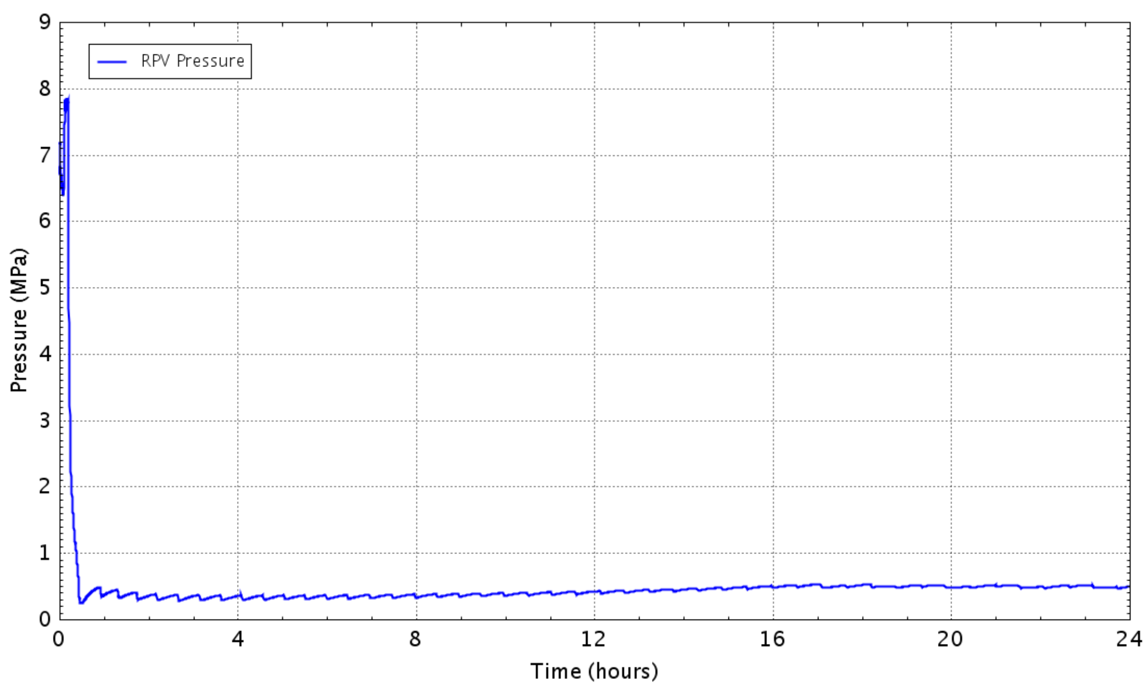

Figure C - 289 Pressure in the RPV

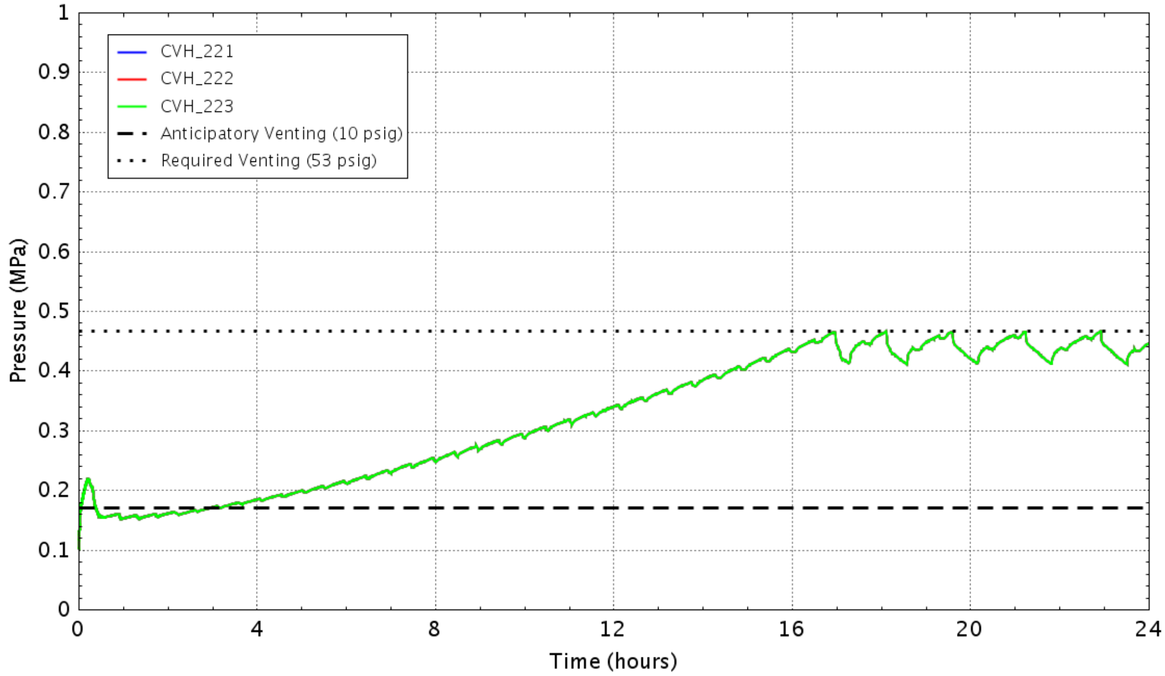

Figure C - 290 Pressure in the wetwell

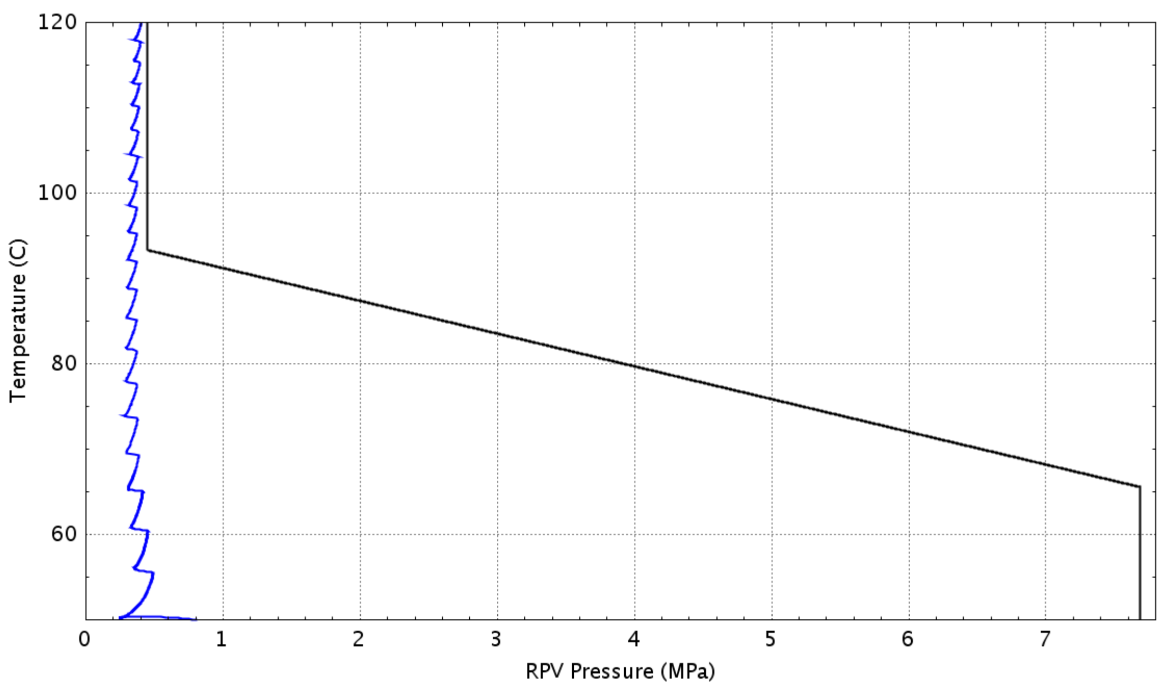

Figure C - 291 Plant status relative to the HCL curve (Graph 4 of the EOPs)

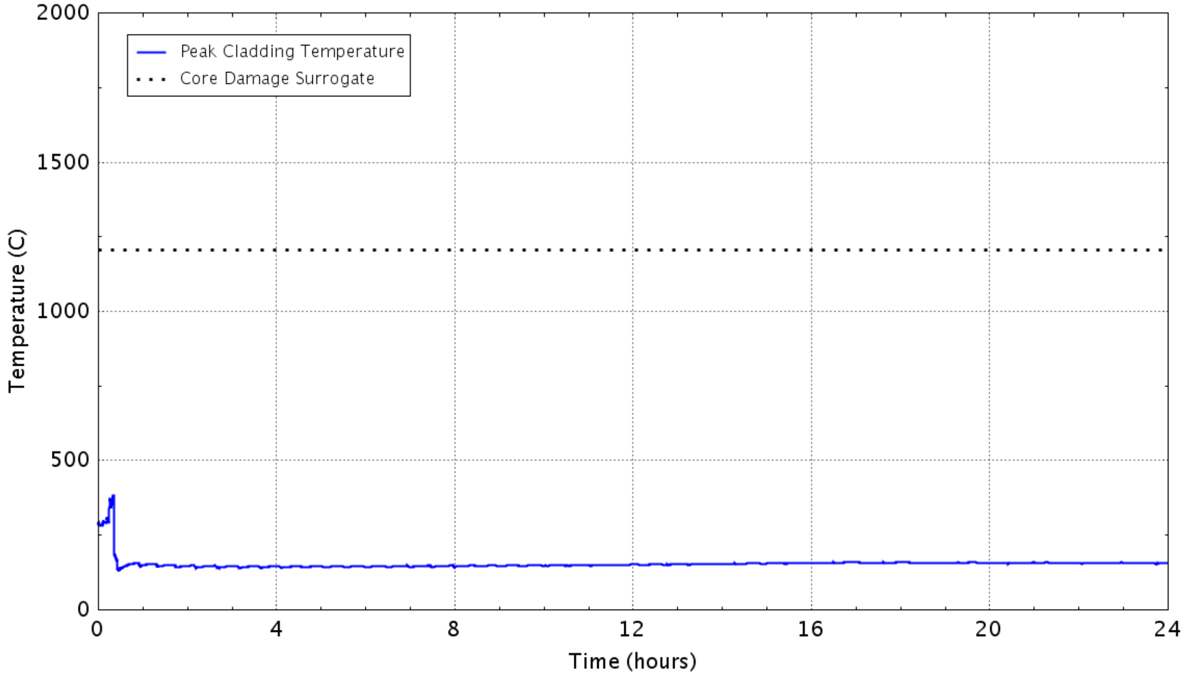

Figure C - 292 Peak temperature of the fuel cladding as a function of time

C.2.7 Case 27: SLOCA-25, 1.8-in. Equivalent Liquid Break, TwoTrains of CRDHS, ADS at +15 in., One SRV

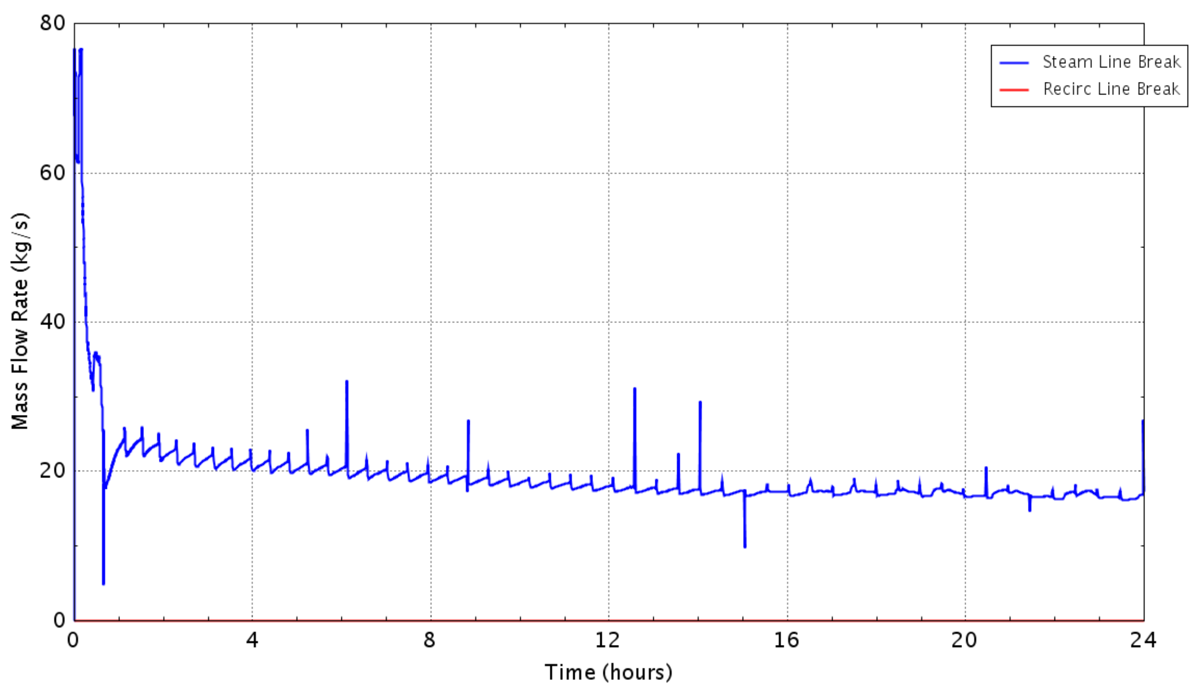

Figure C - 293 Flow rate of the break in the steamline/recirculation line

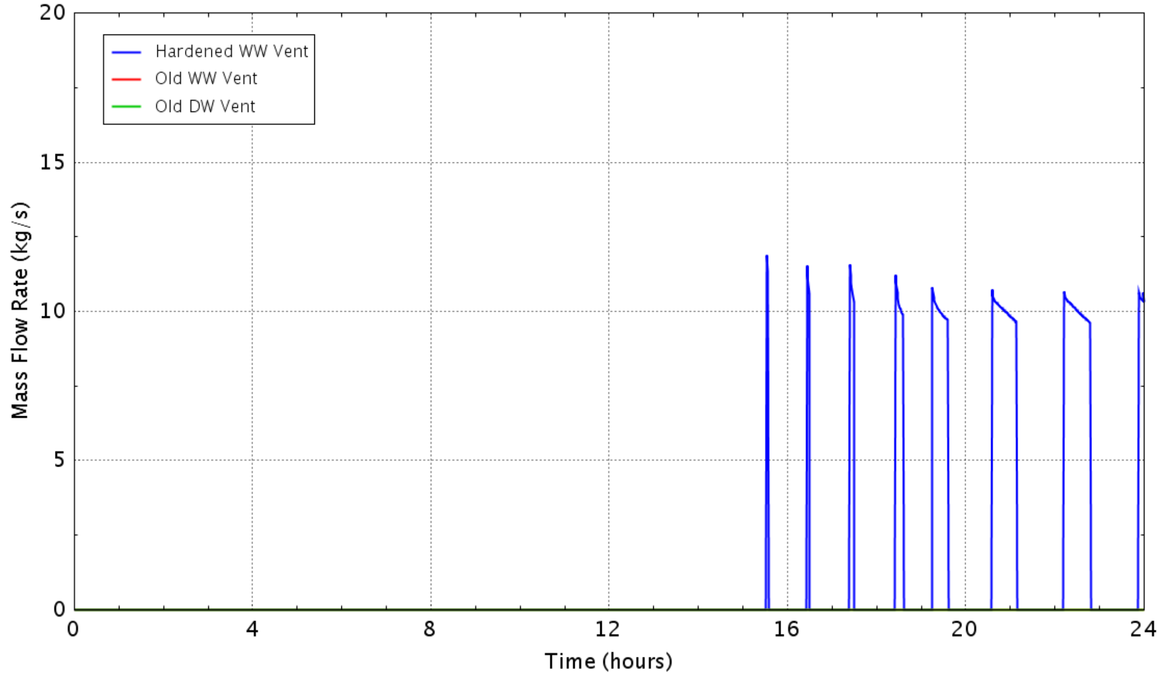

Figure C - 294 Flow rate of the containment vents

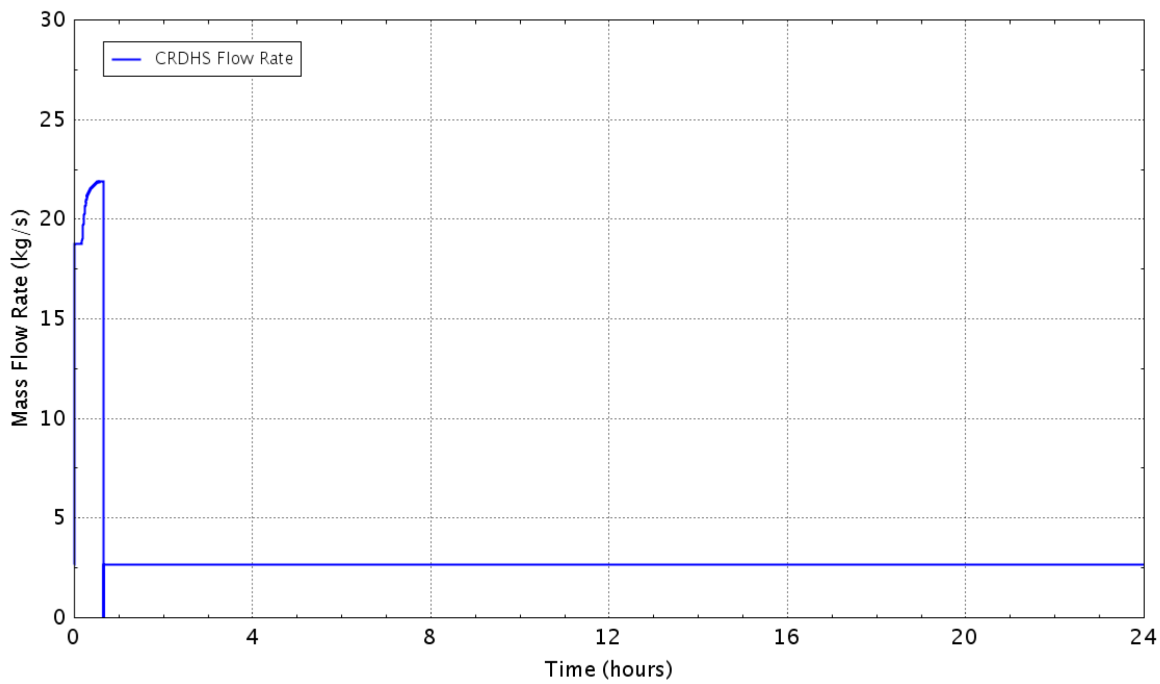

Figure C - 295 Flow rate of the control rod drive hydraulic system

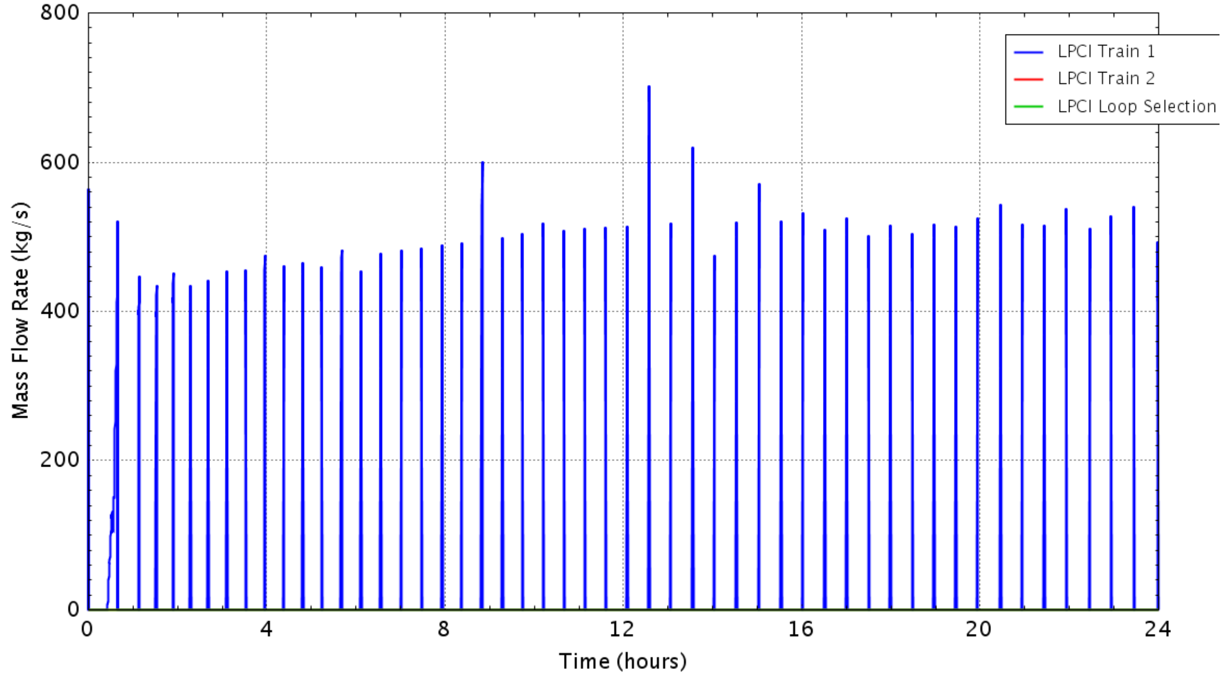

Figure C - 296   Flow rate of the LPCI pump

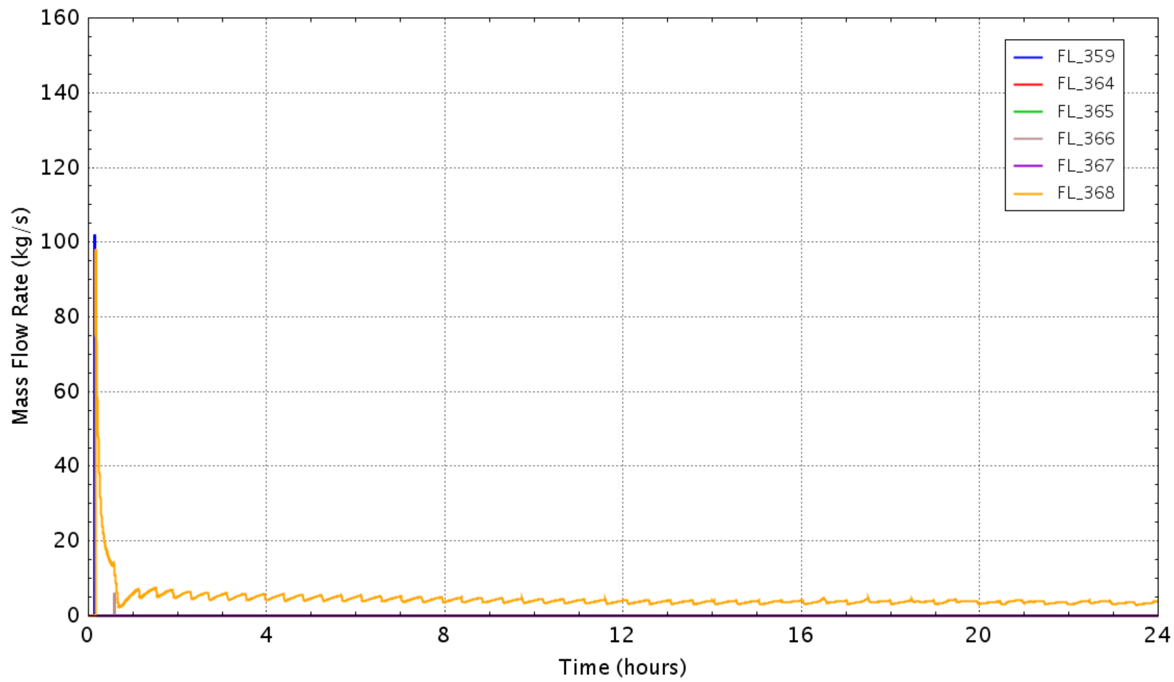

Figure C - 297   Flow rate of the SRVs

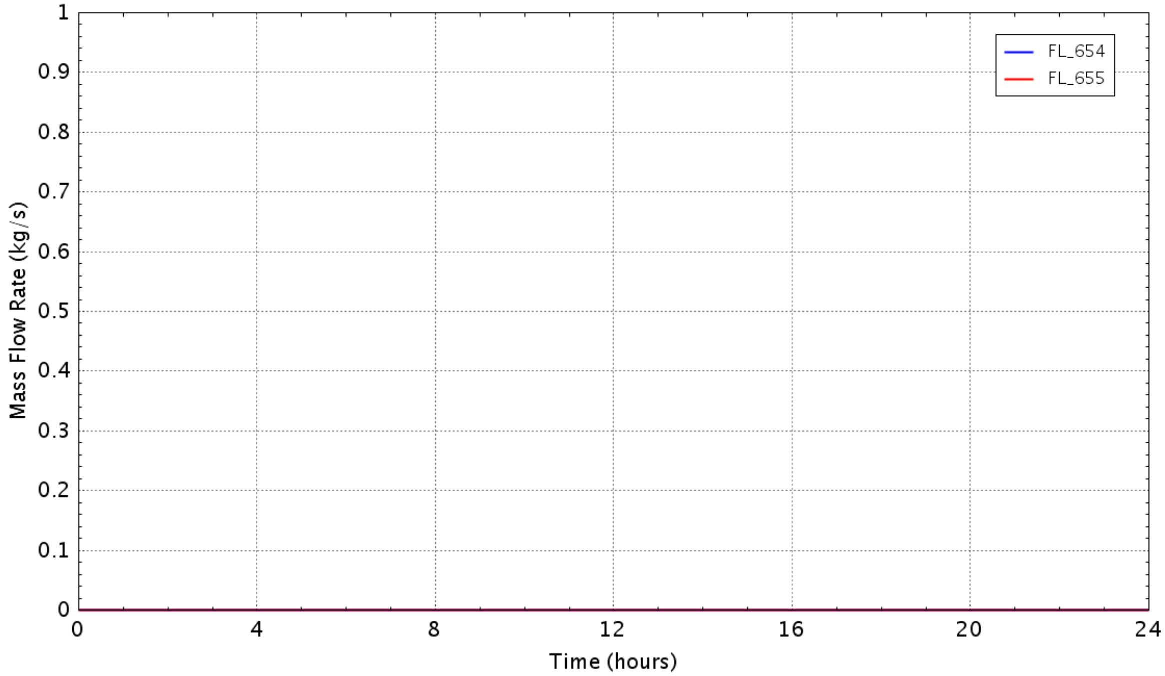

Figure C - 298   Flow rate of the wetwell cooling system

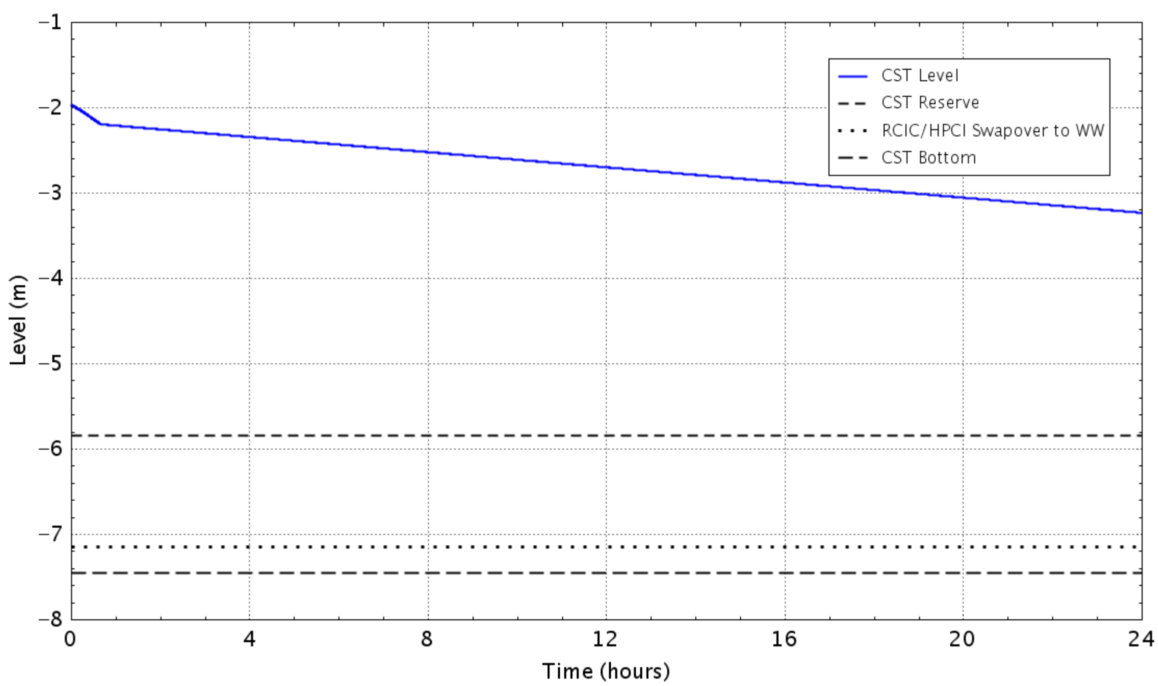

Figure C - 299   Water level in the CST

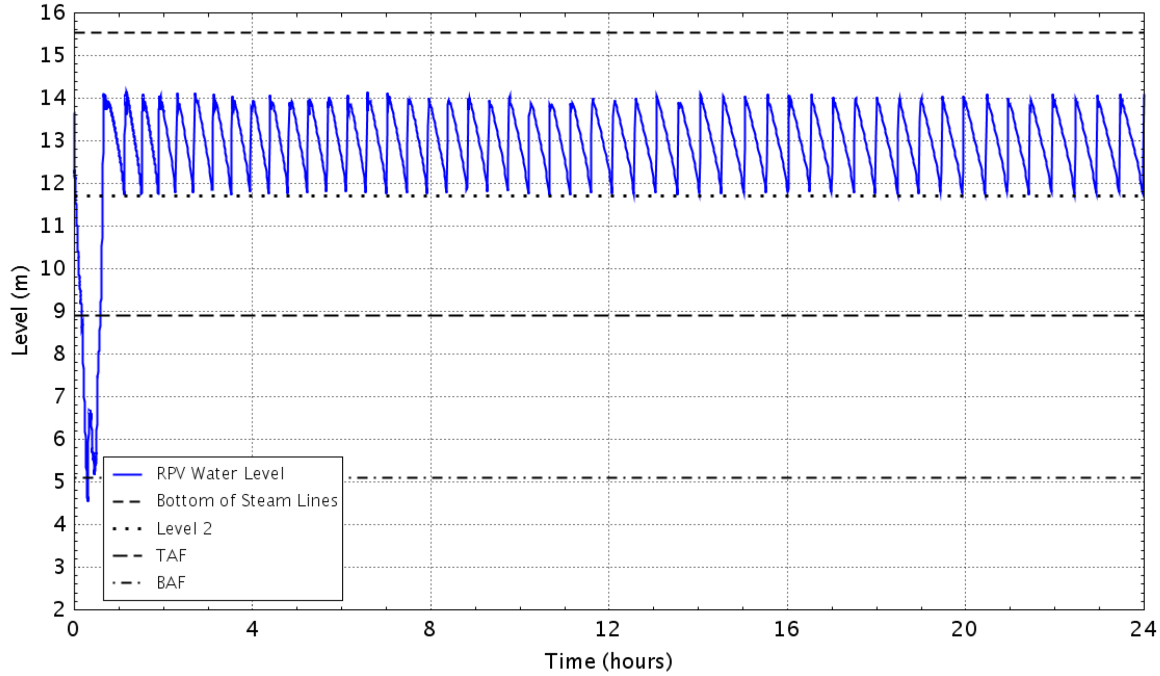

Figure C - 300 RPV Downcomer water level

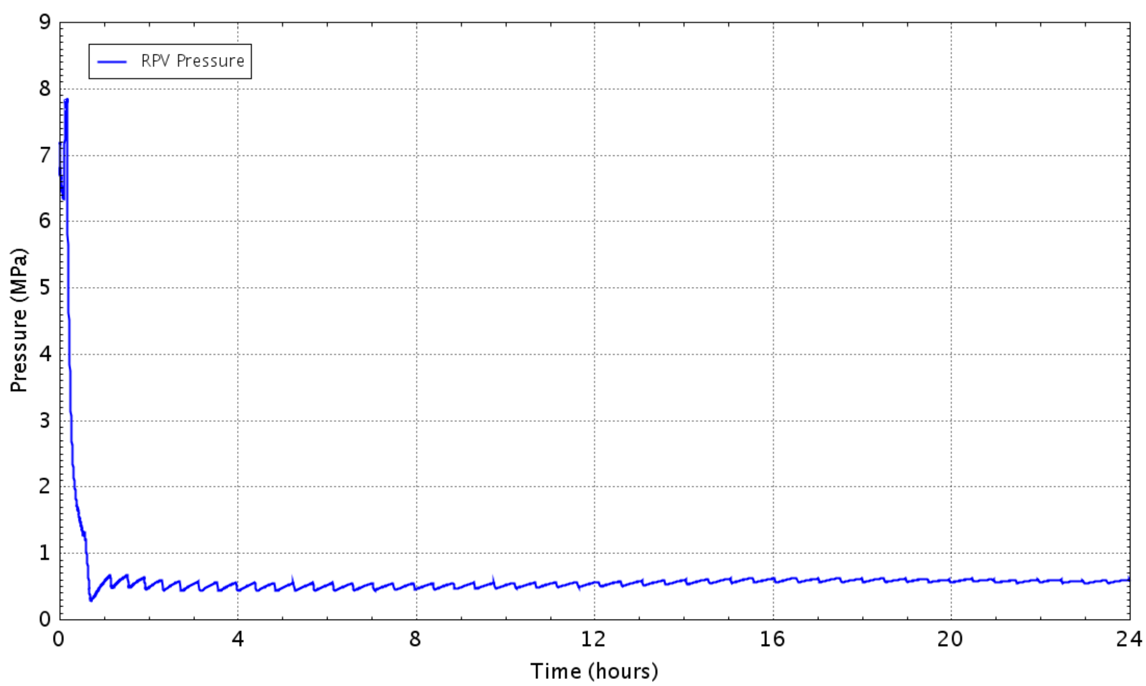

Figure C - 301 Pressure in the RPV

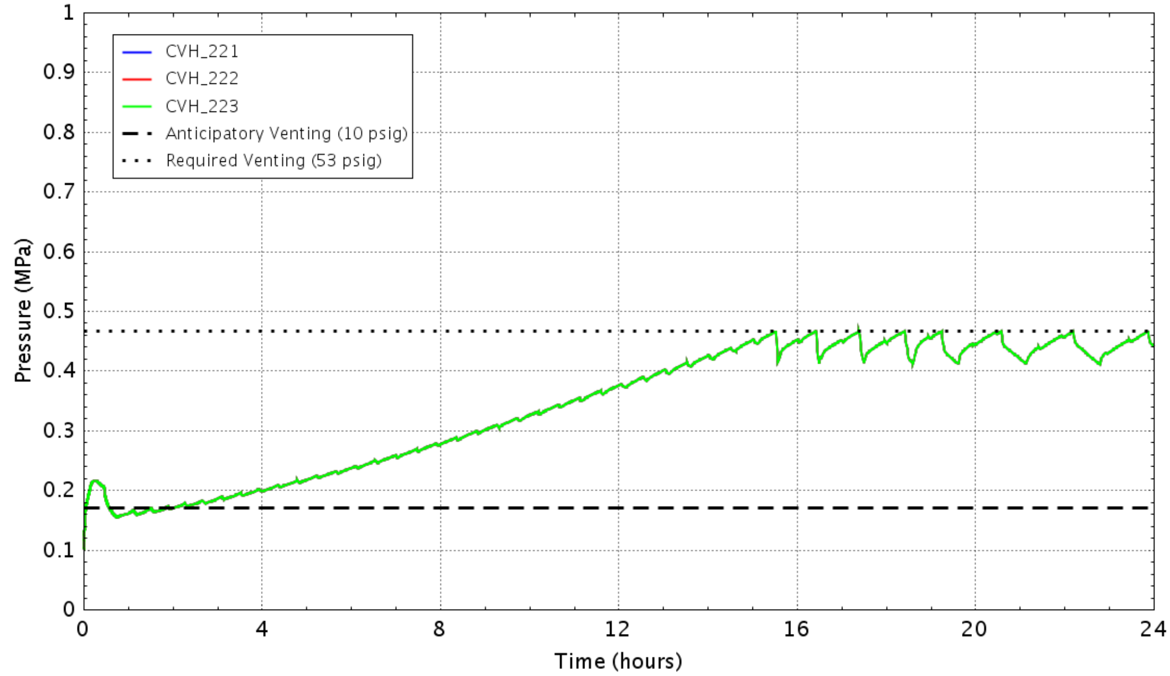

Figure C - 302   Pressure in the wetwell

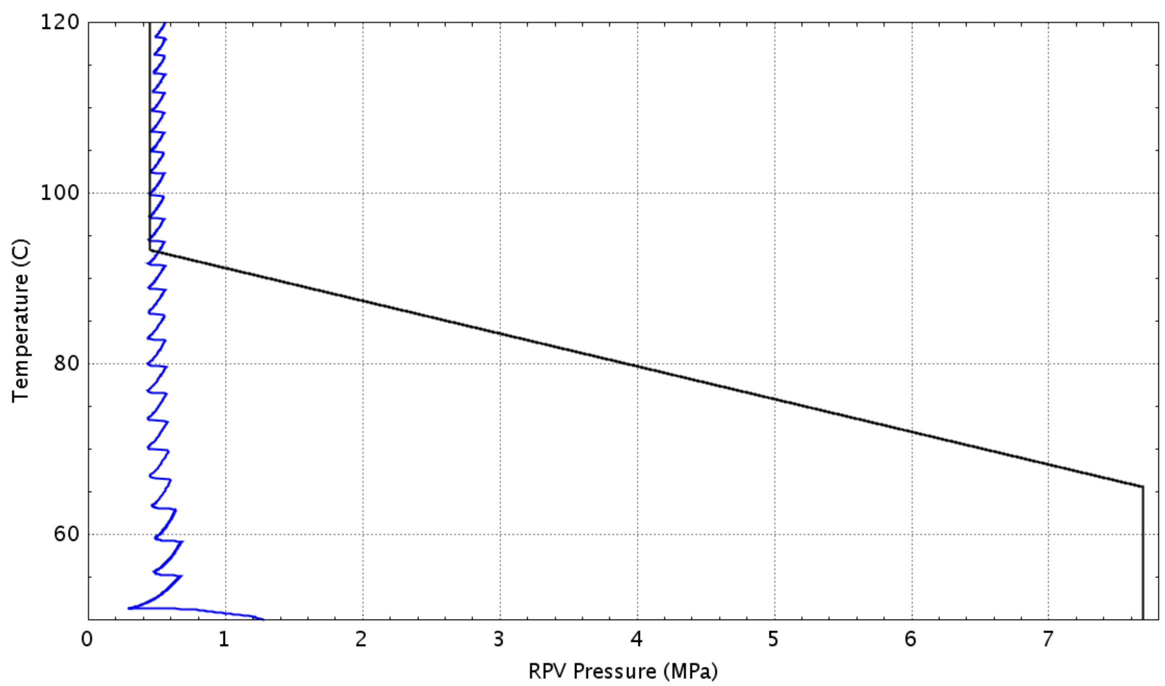

Figure C - 303   Plant status relative to the HCL curve (Graph 4 of the EOPs)

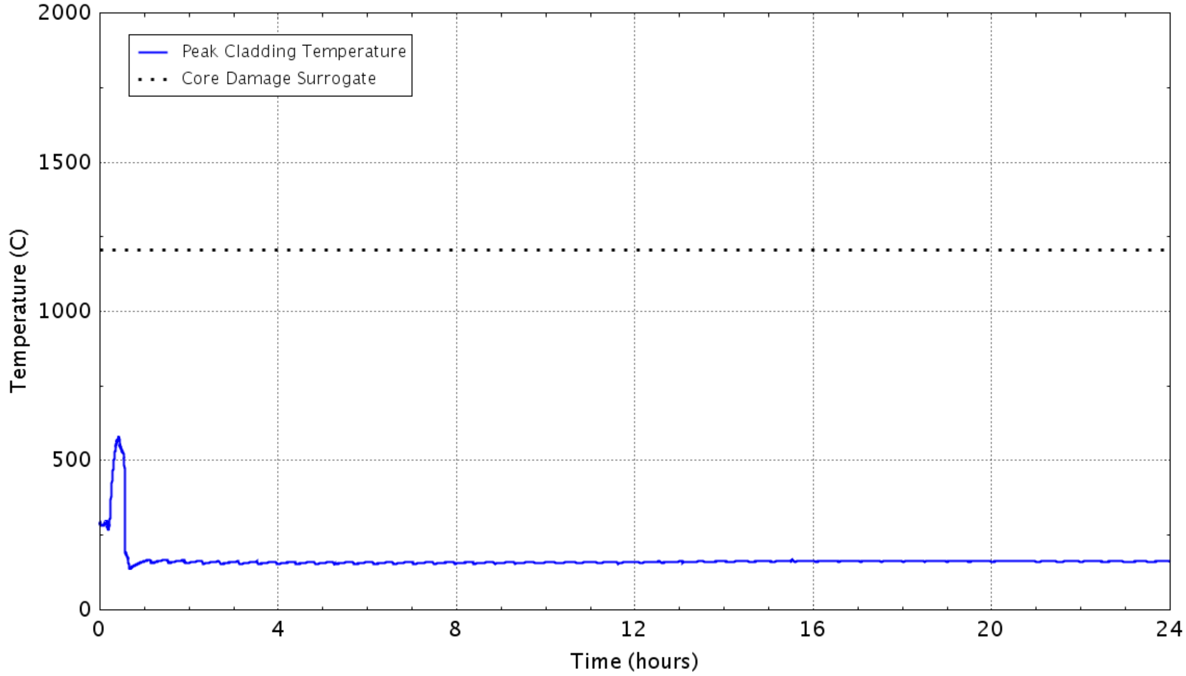

Figure C - 304 Peak temperature of the fuel cladding as a function of time

C.2.8 Case 28: SLOCA-25, 1.8-in. Equivalent Liquid Break, TwoTrains of CRDHS, ADS at +15 in., Two SRVs

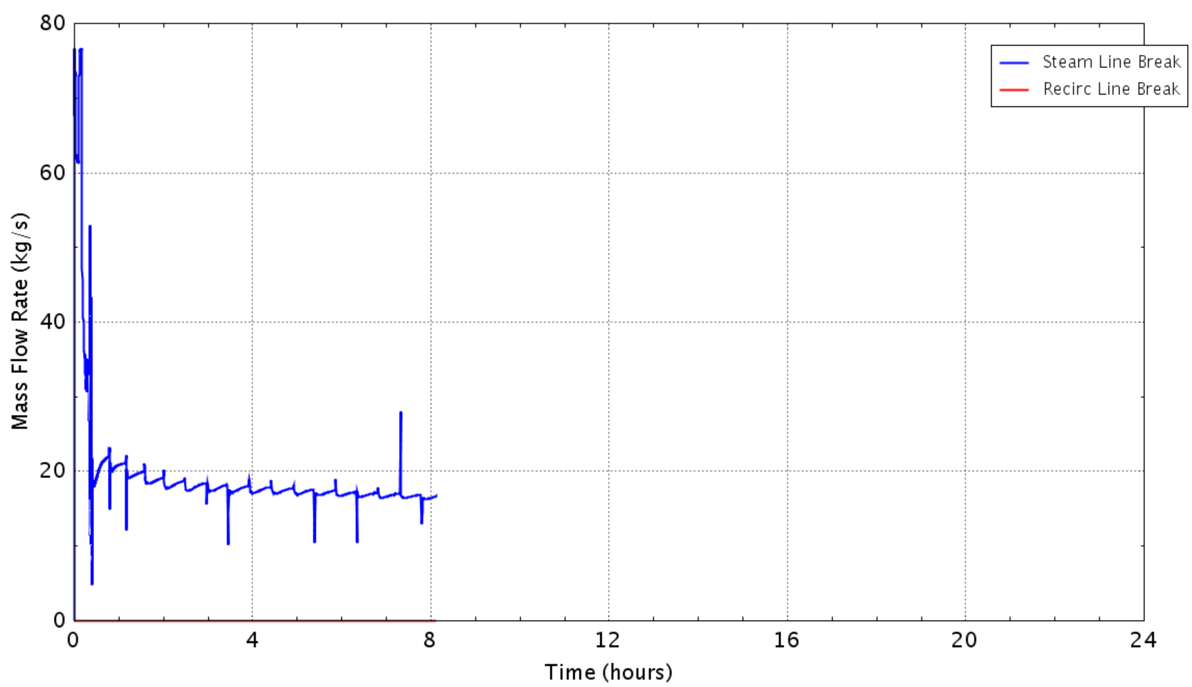

Figure C - 305 Flow rate of the break in the steamline/recirculation line

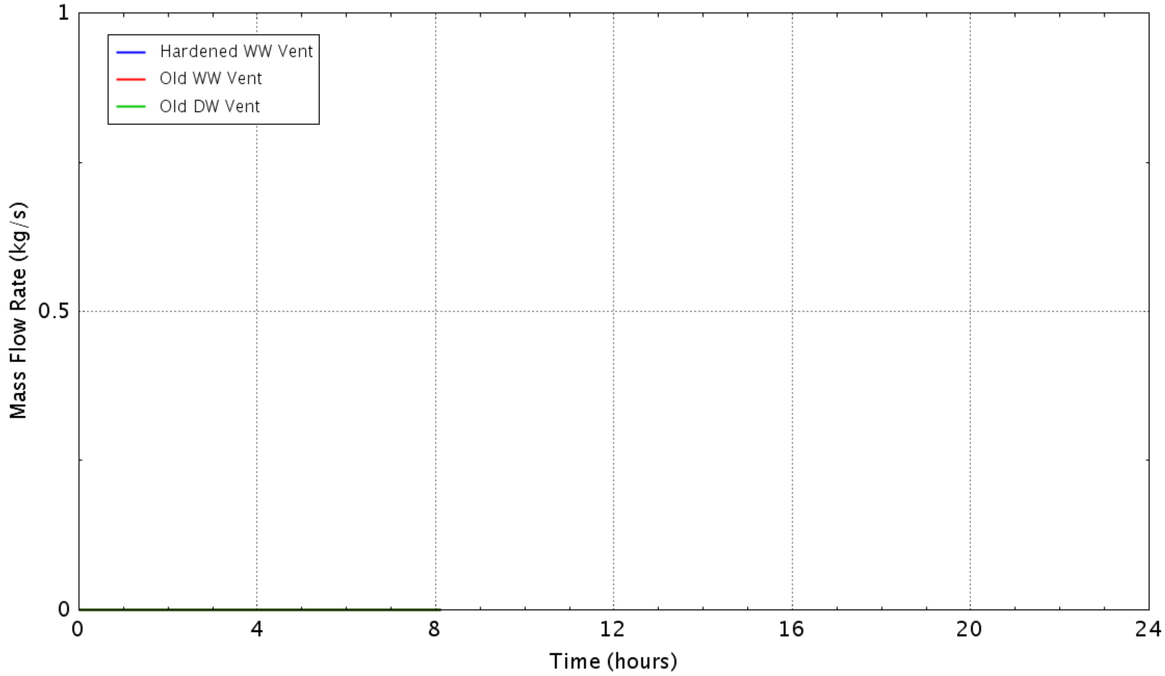

Figure C - 306 Flow rate of the containment vents

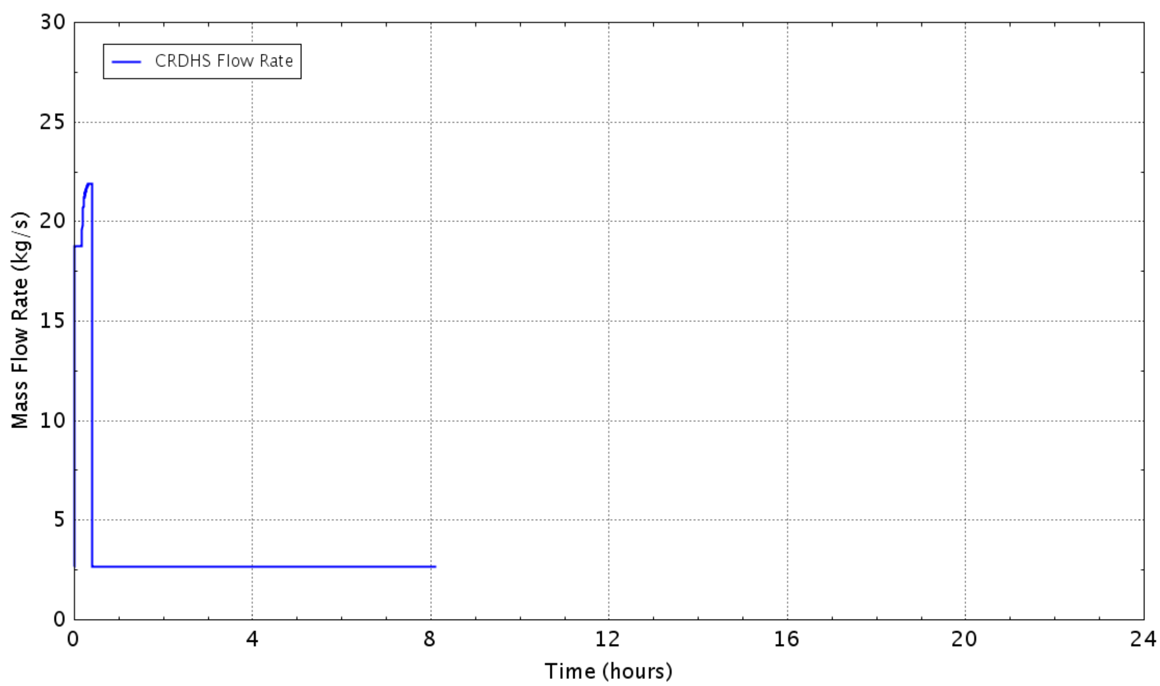

Figure C - 307 Flow rate of the control rod drive hydraulic system

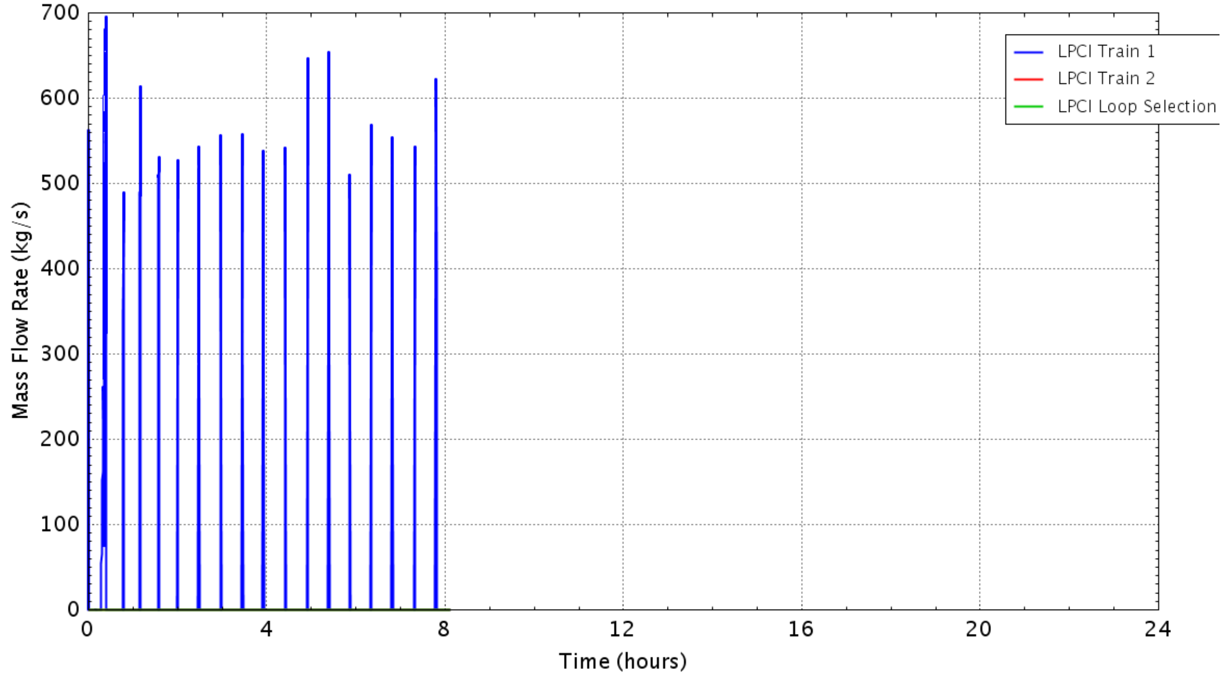

Figure C - 308 Flow rate of the LPCI pump

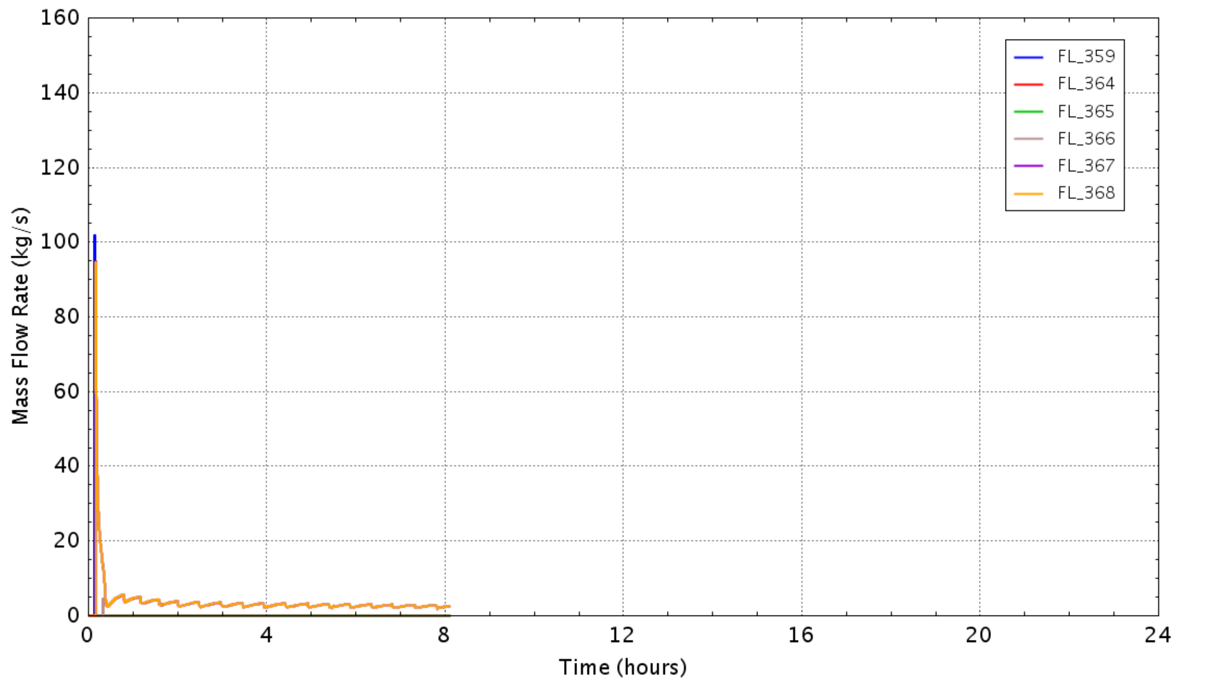

Figure C - 309 Flow rate of the SRVs

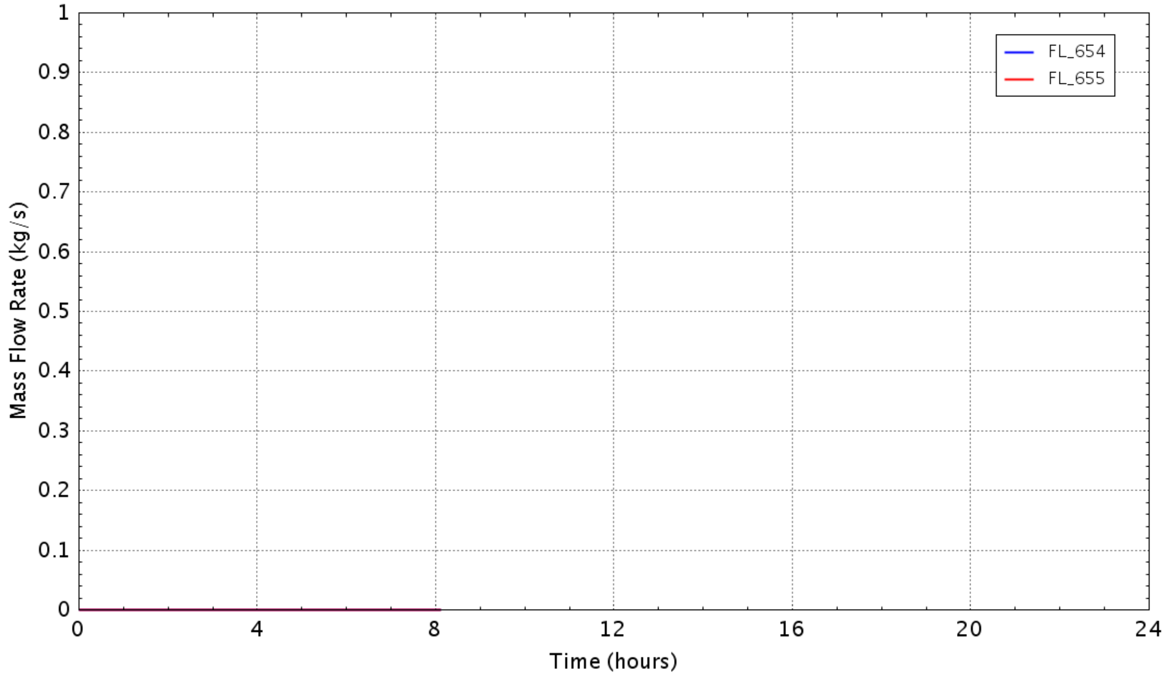

Figure C - 310   Flow rate of the wetwell cooling system

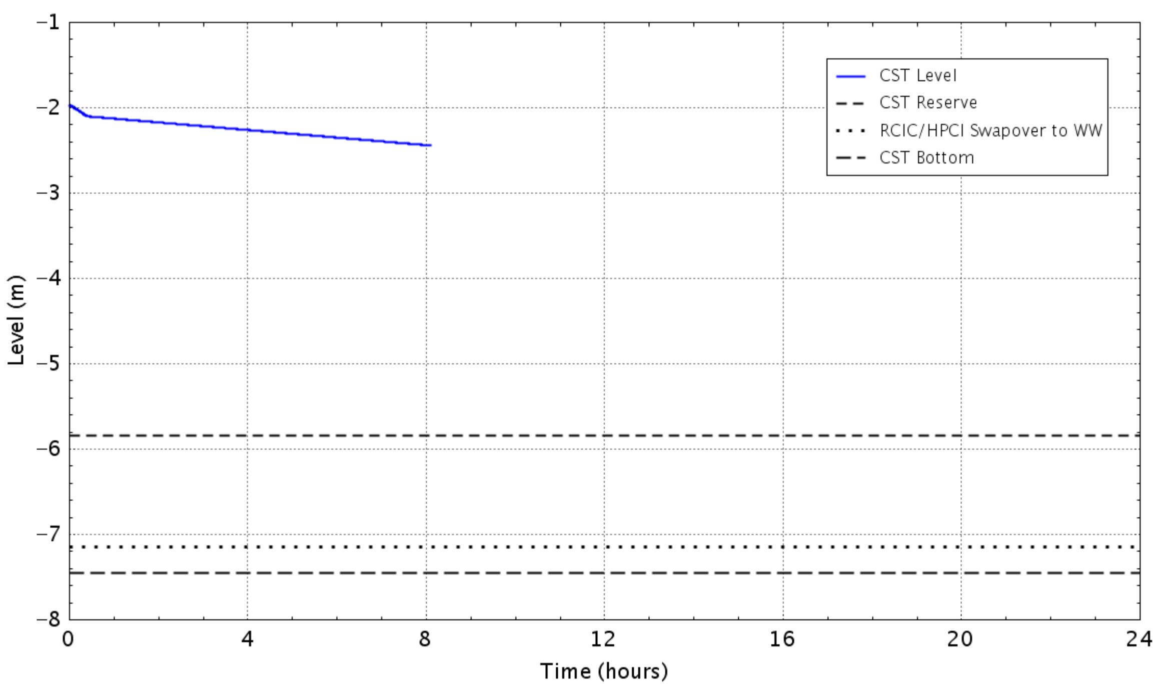

Figure C - 311   Water level in the CST

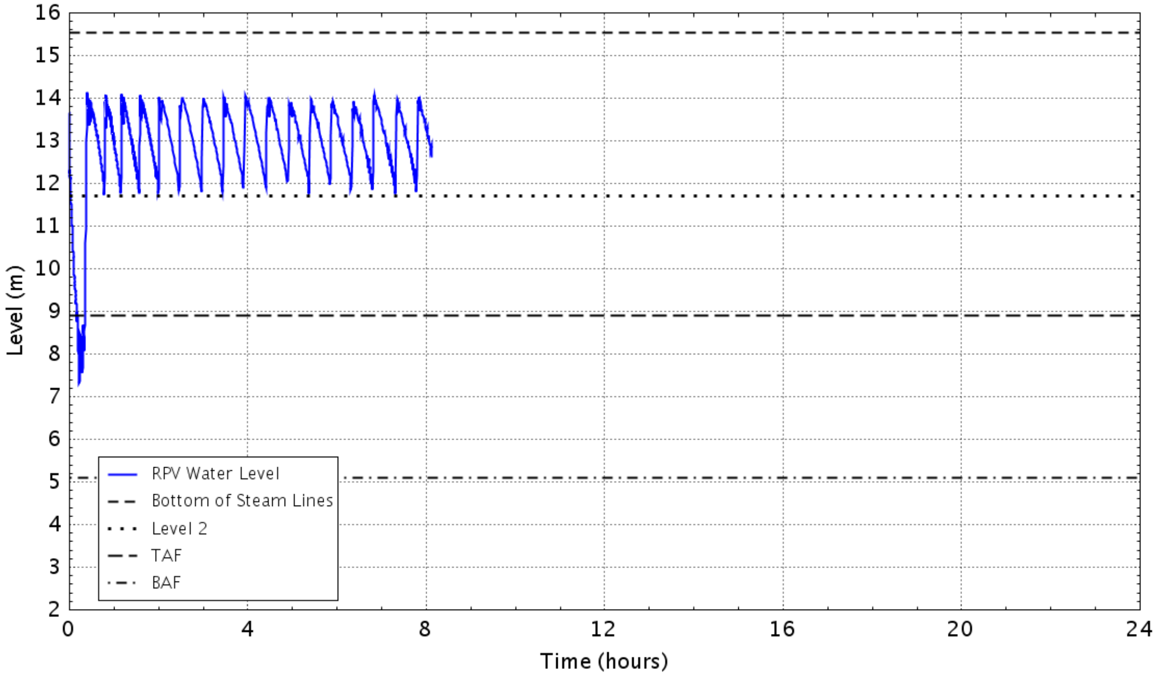

Figure C - 312 RPV Downcomer water level

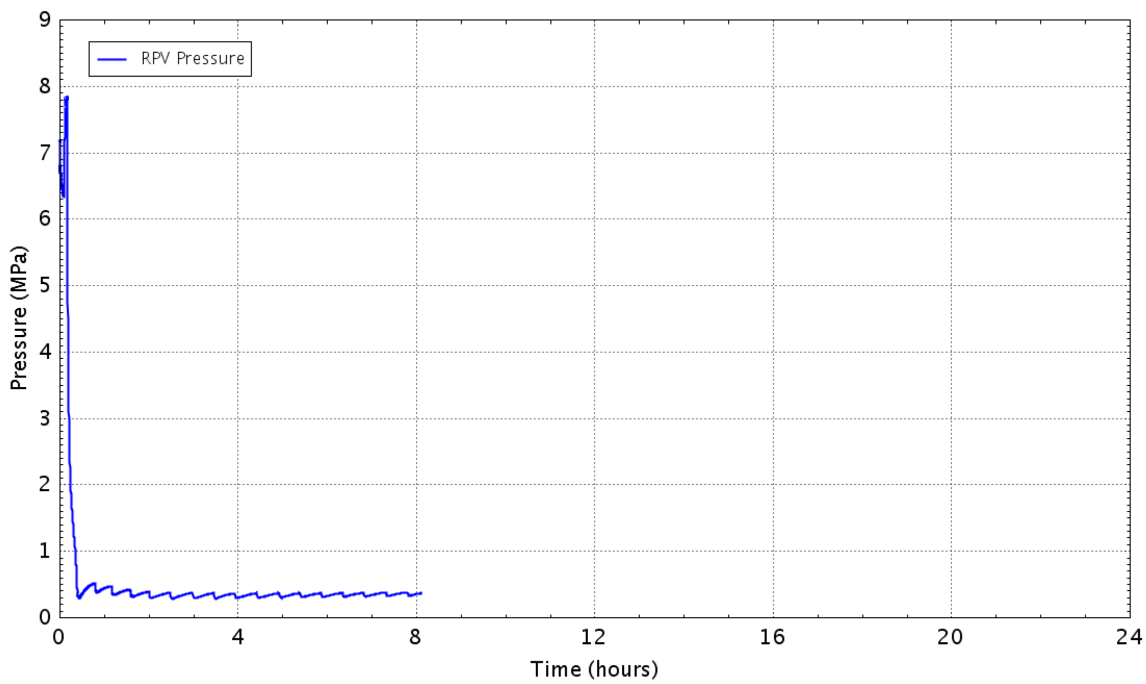

Figure C - 313 Pressure in the RPV

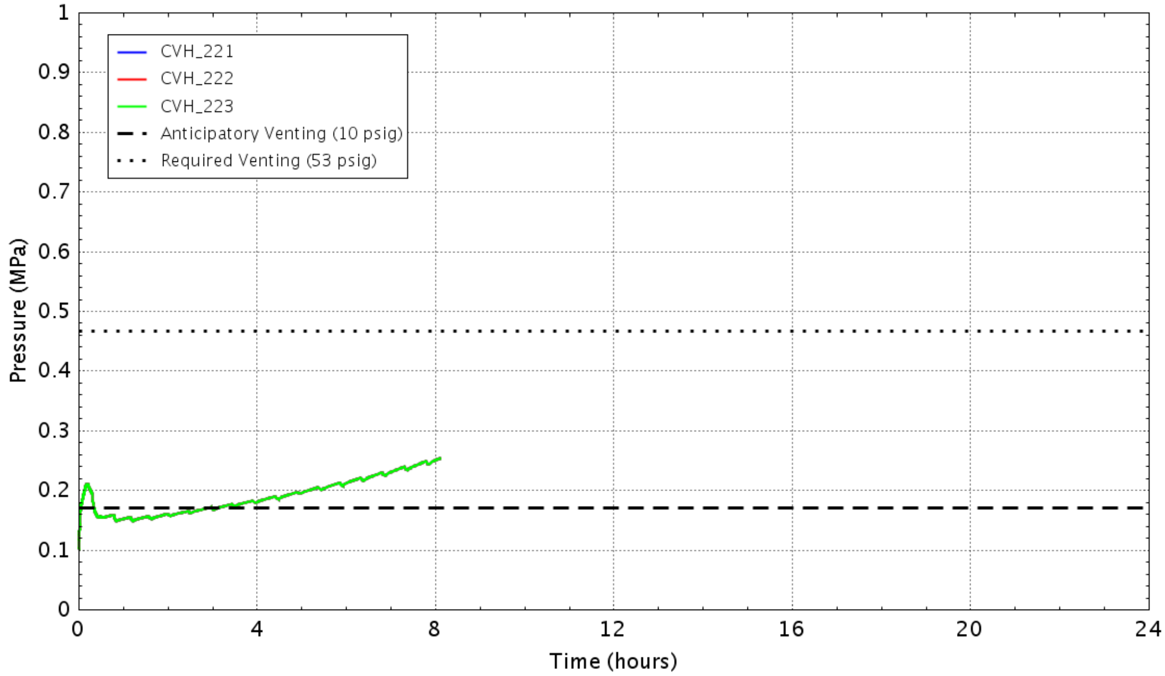

Figure C - 314   Pressure in the wetwell

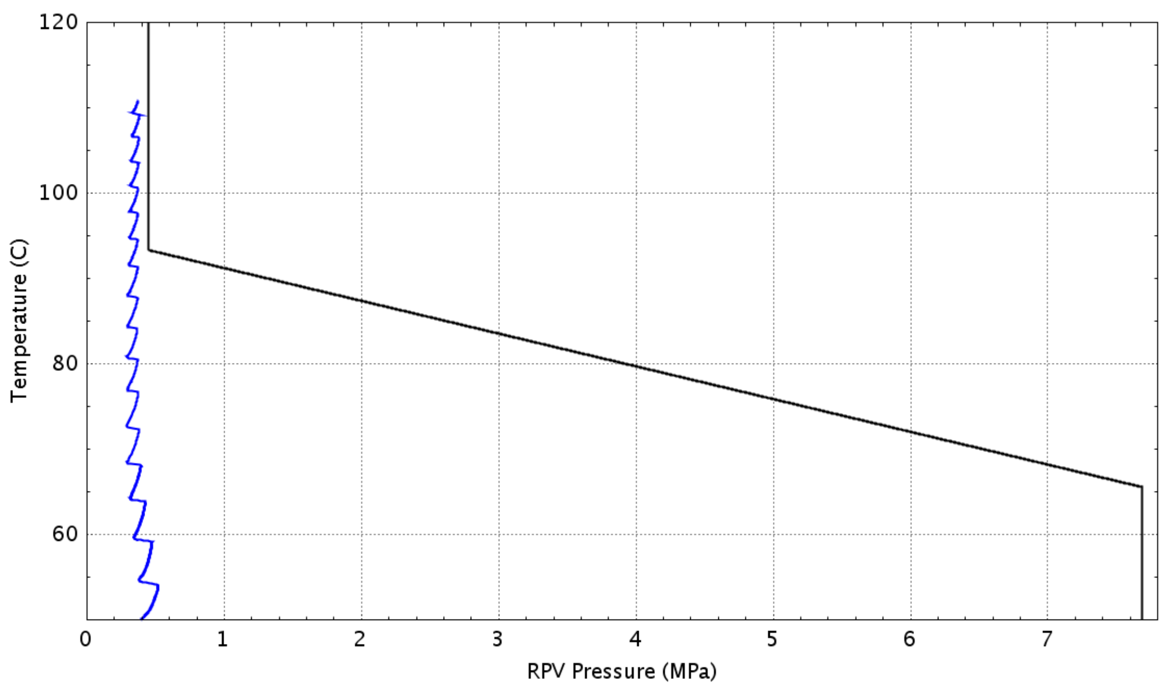

Figure C - 315   Plant status relative to the HCL curve (Graph 4 of the EOPs)

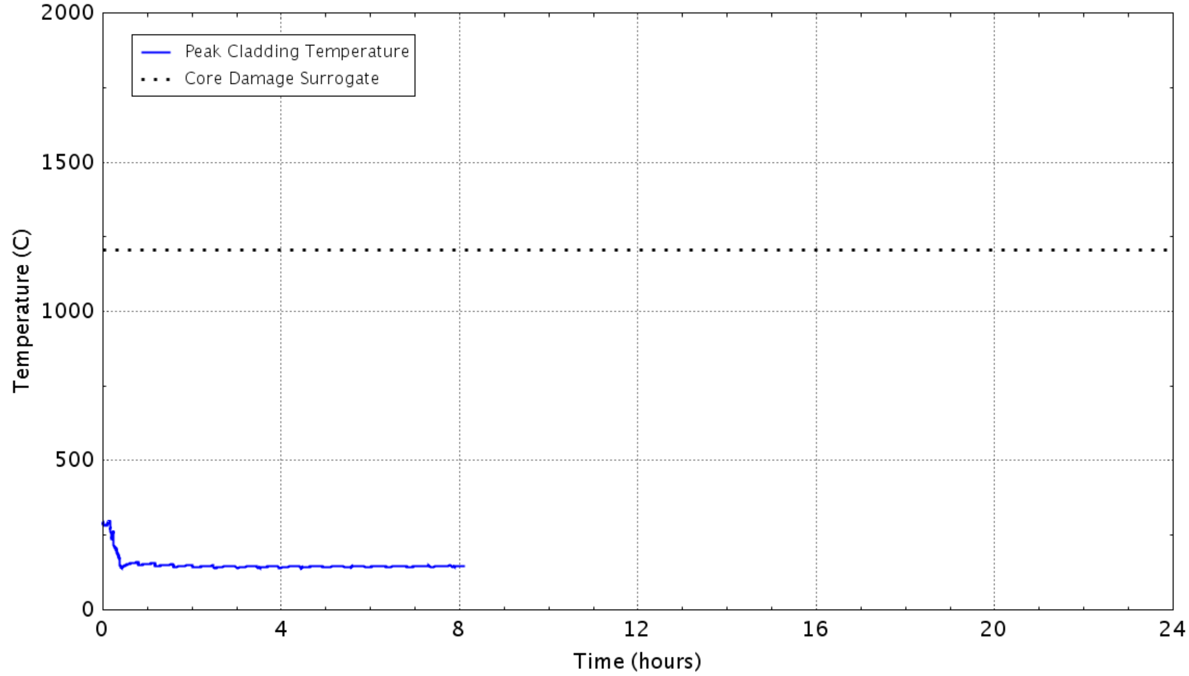

Figure C - 316 Peak temperature of the fuel cladding as a function of time

C.2.9 Case 29: SLOCA-25, 1.8-in. Equivalent Liquid Break, TwoTrains of CRDHS, ADS at -25 in., One SRV

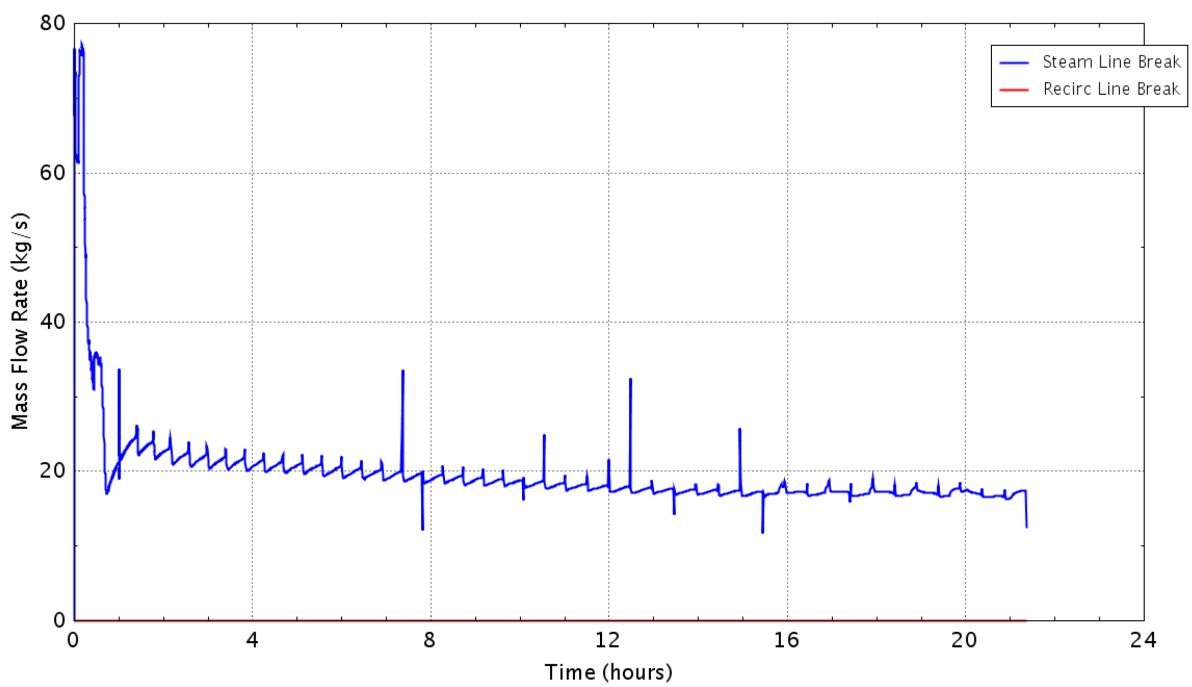

Figure C - 317 Flow rate of the break in the steamline/recirculation line

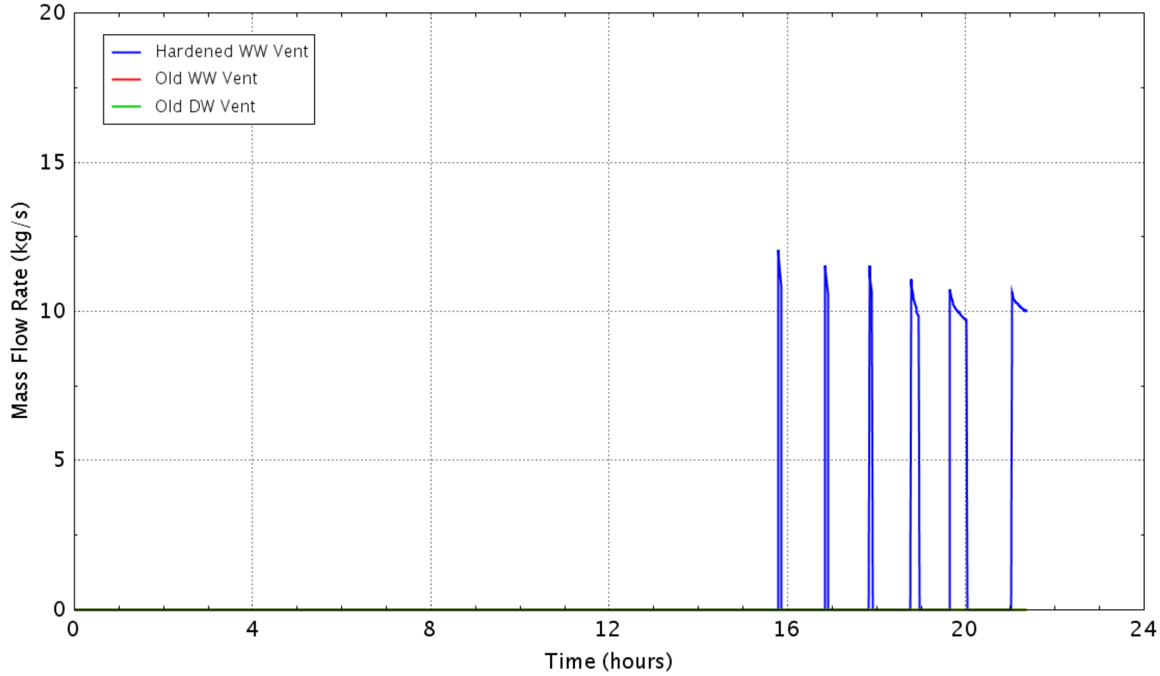

Figure C - 318 Flow rate of the containment vents

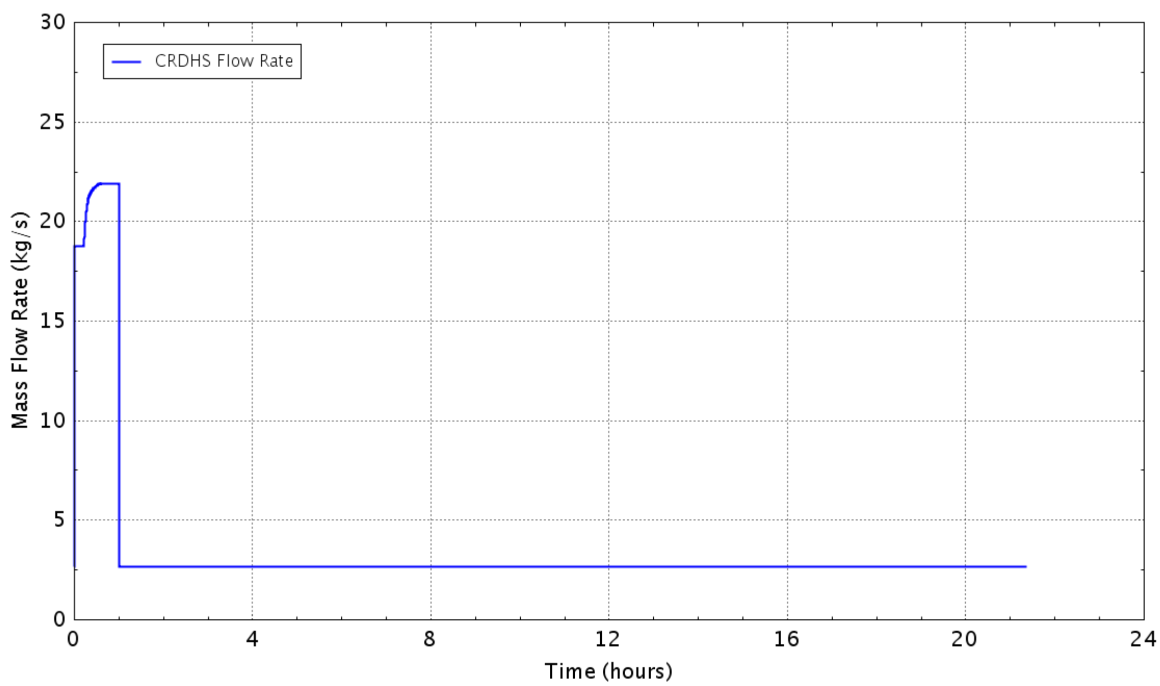

Figure C - 319 Flow rate of the control rod drive hydraulic system

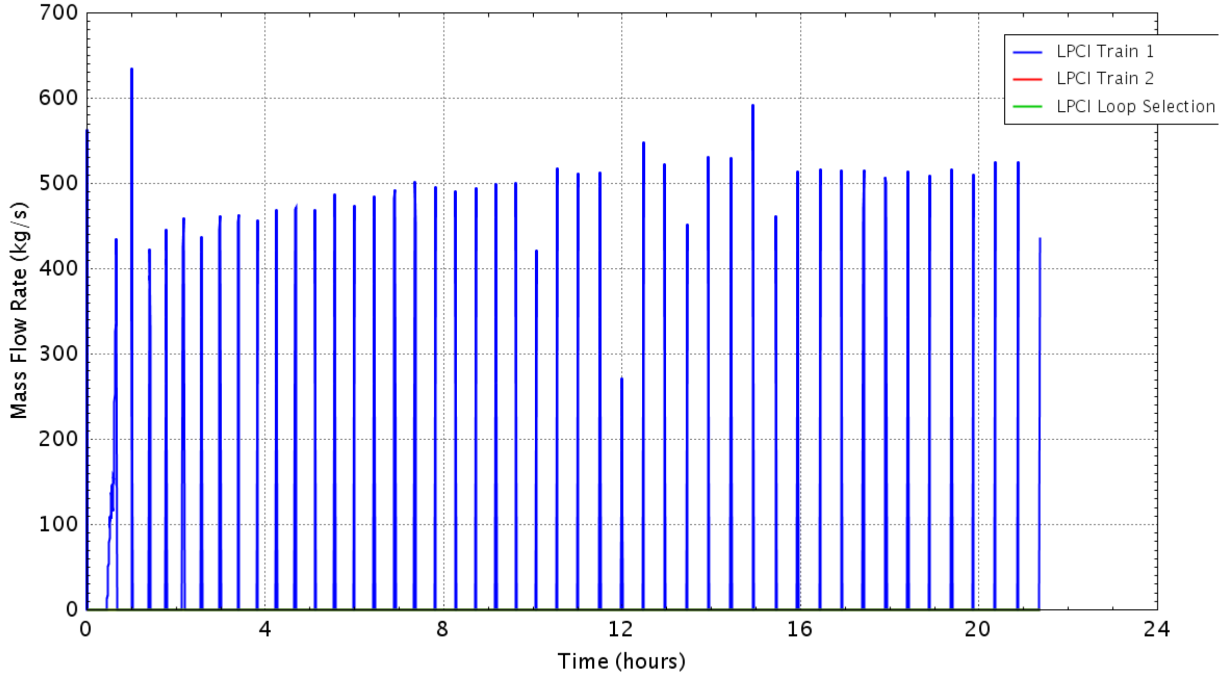

Figure C - 320 Flow rate of the LPCI pump

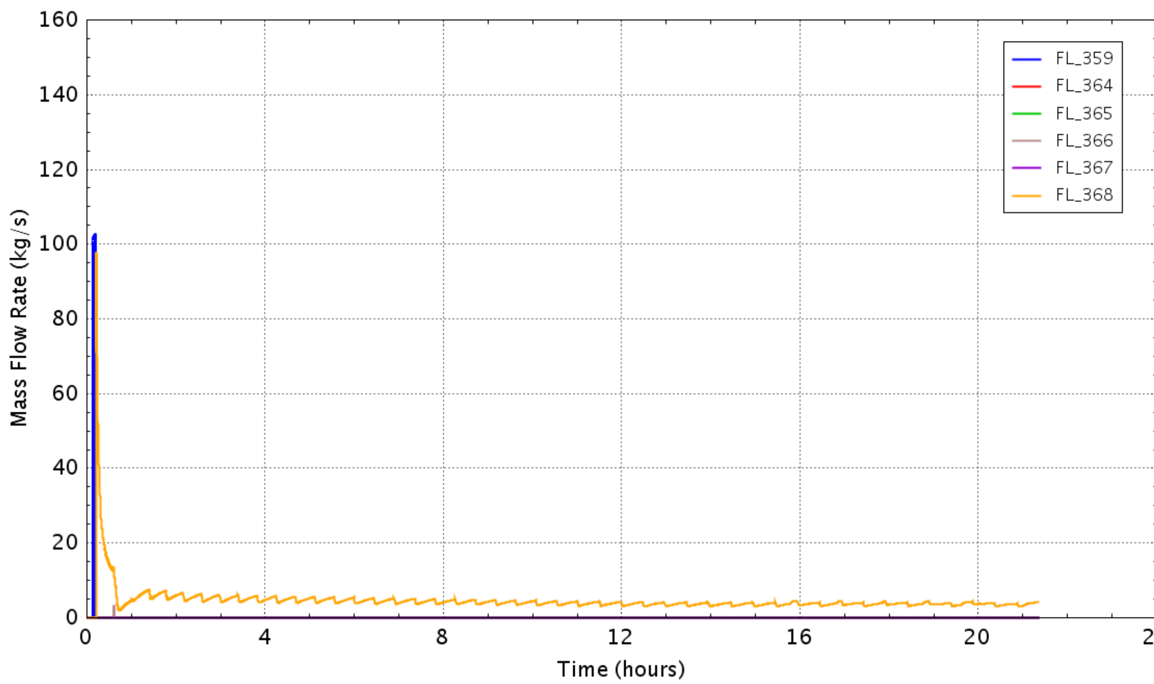

Figure C - 321 Flow rate of the SRVs

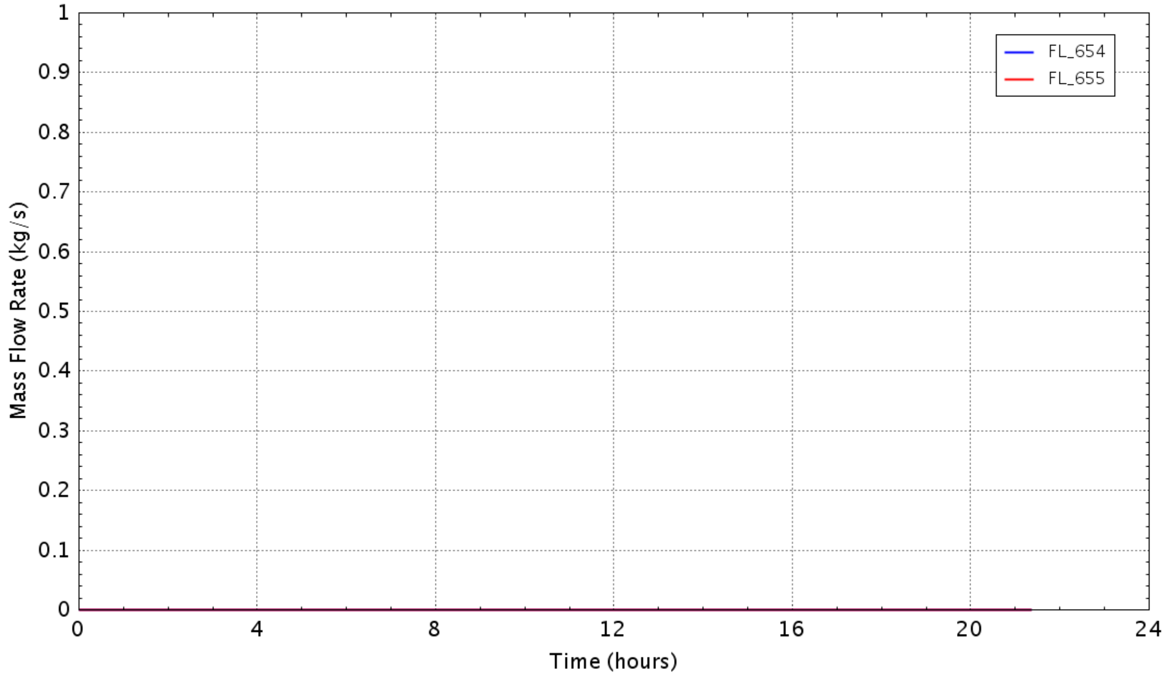

Figure C - 322 Flow rate of the wetwell cooling system

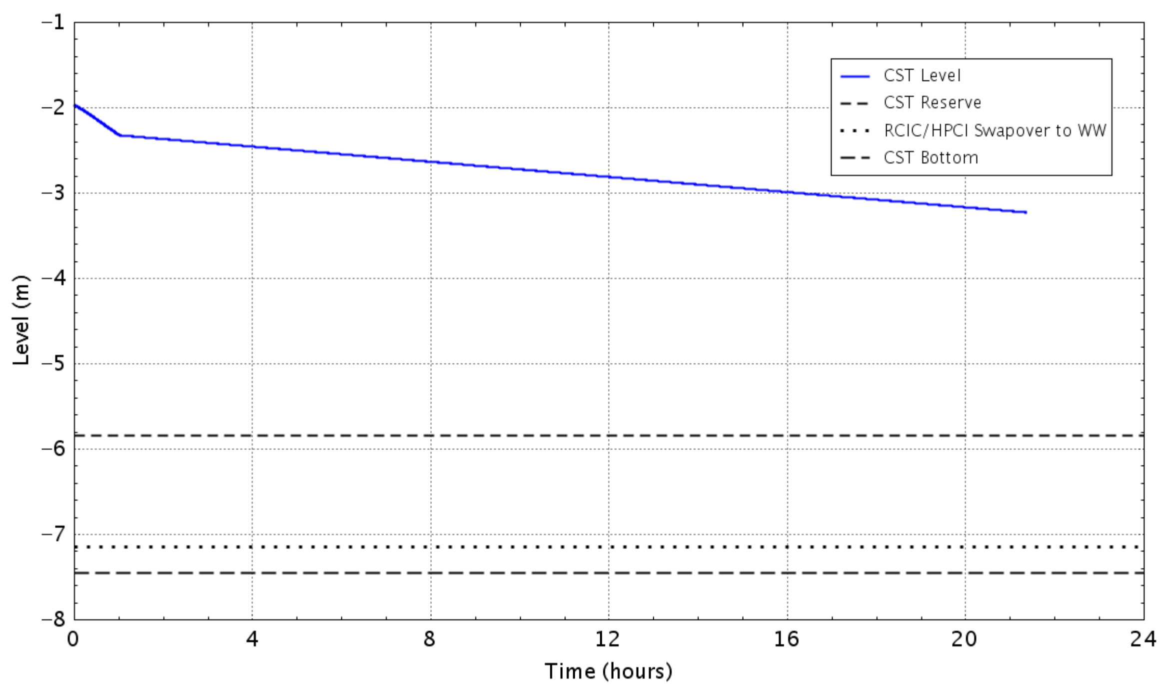

Figure C - 323 Water level in the CST

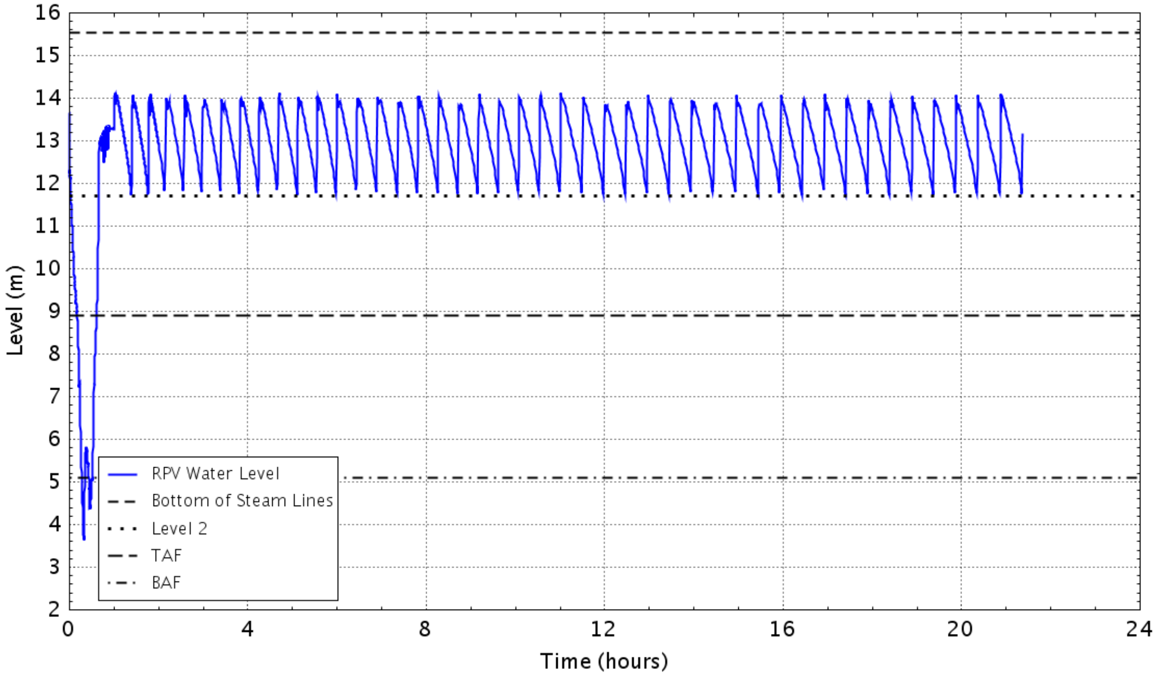

Figure C - 324 RPV Downcomer water level

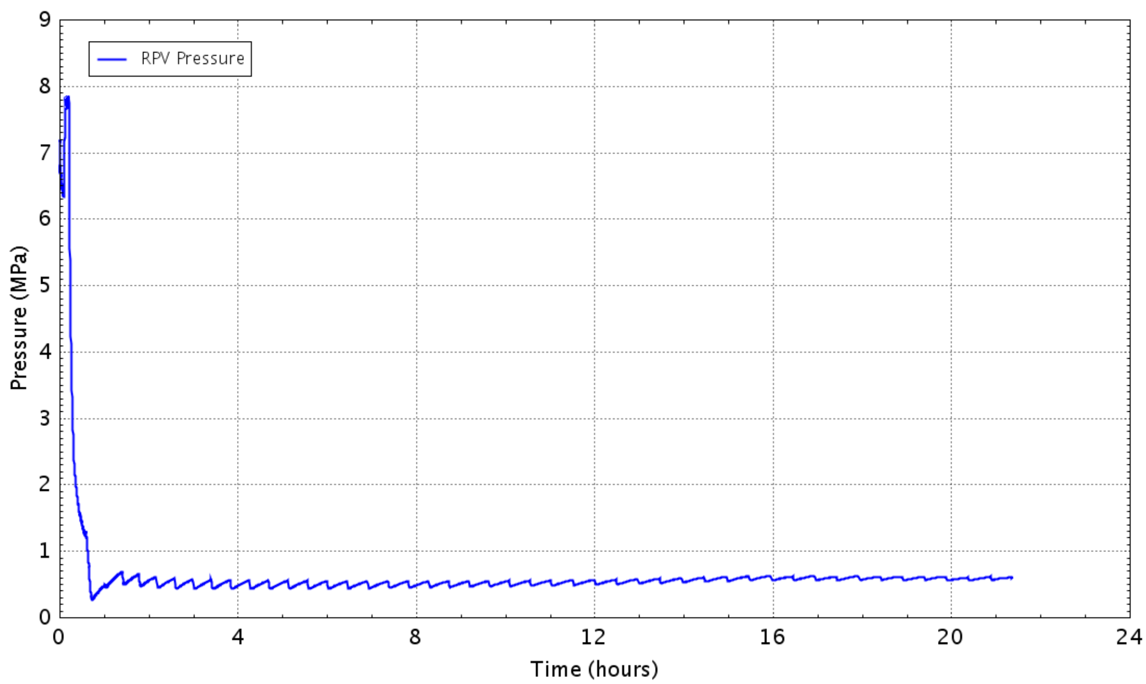

Figure C - 325 Pressure in the RPV

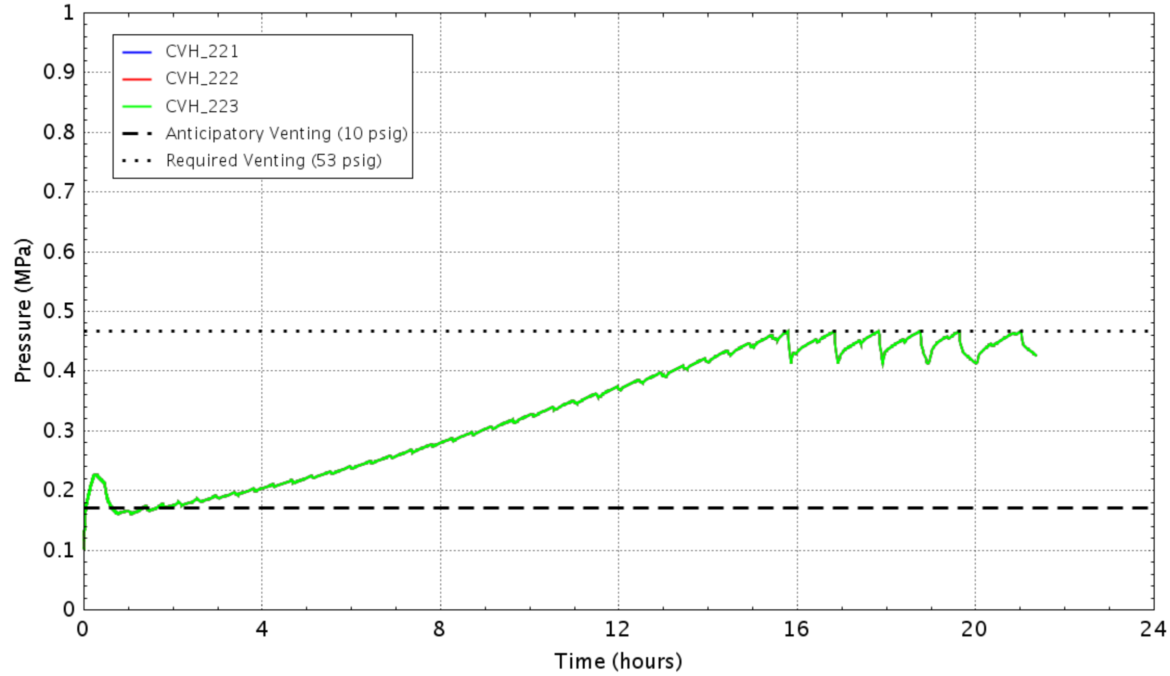

Figure C - 326 Pressure in the wetwell

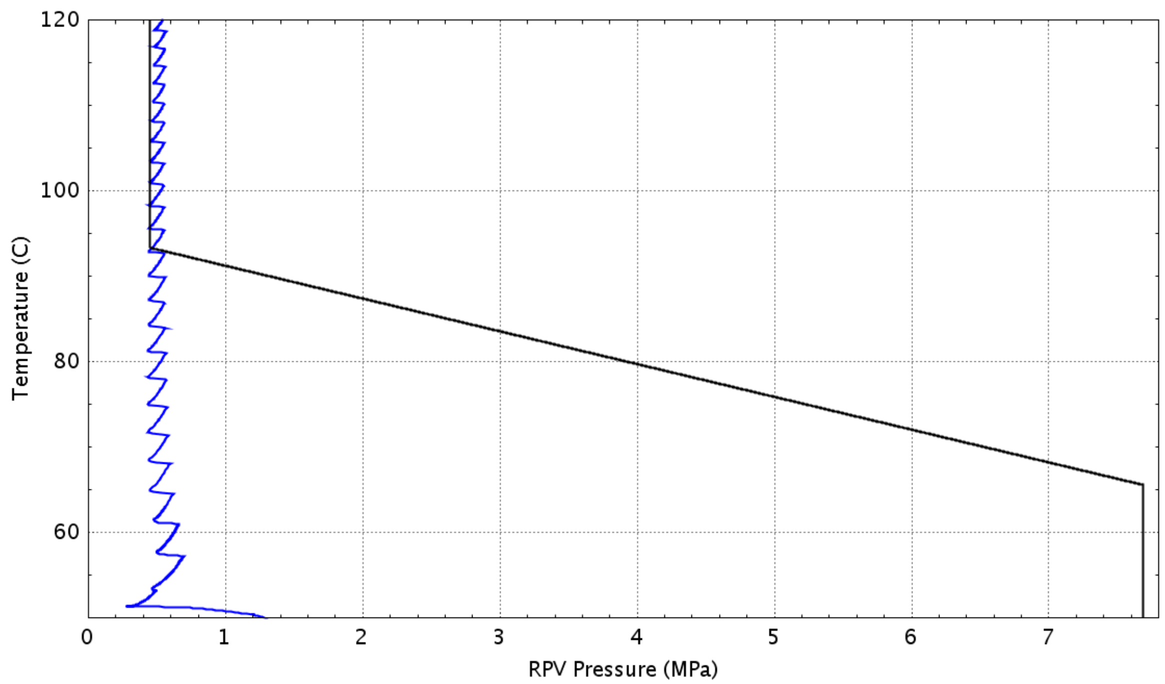

Figure C - 327 Plant status relative to the HCL curve (Graph 4 of the EOPs)

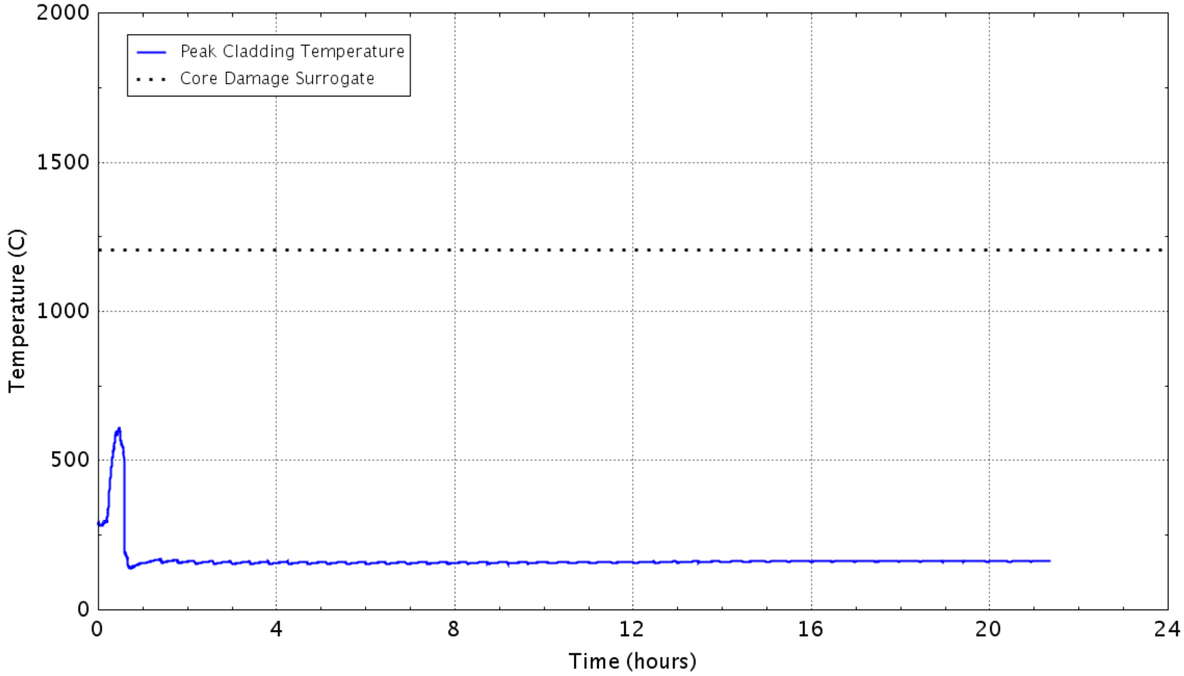

Figure C - 328 Peak temperature of the fuel cladding as a function of time

C.2.10 Case 30: SLOCA-25, 1.8-in. Equivalent Liquid Break, TwoTrains of CRDHS, ADS at -25 in., Two SRVs

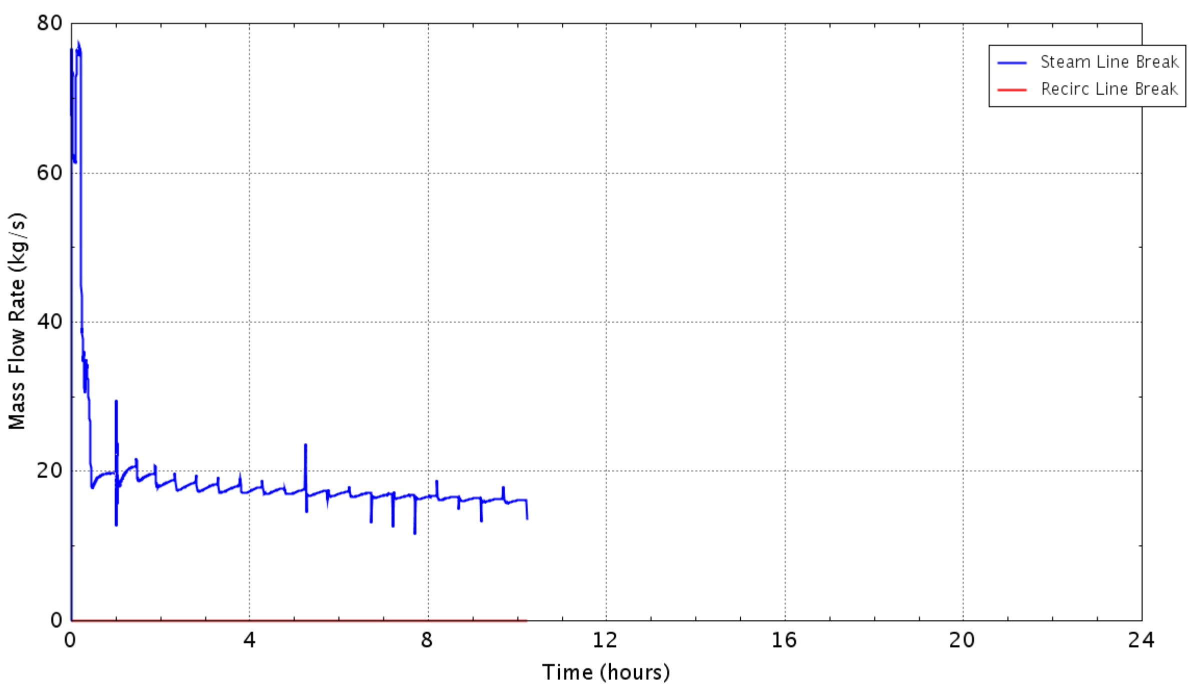

Figure C - 329 Flow rate of the break in the steamline/recirculation line

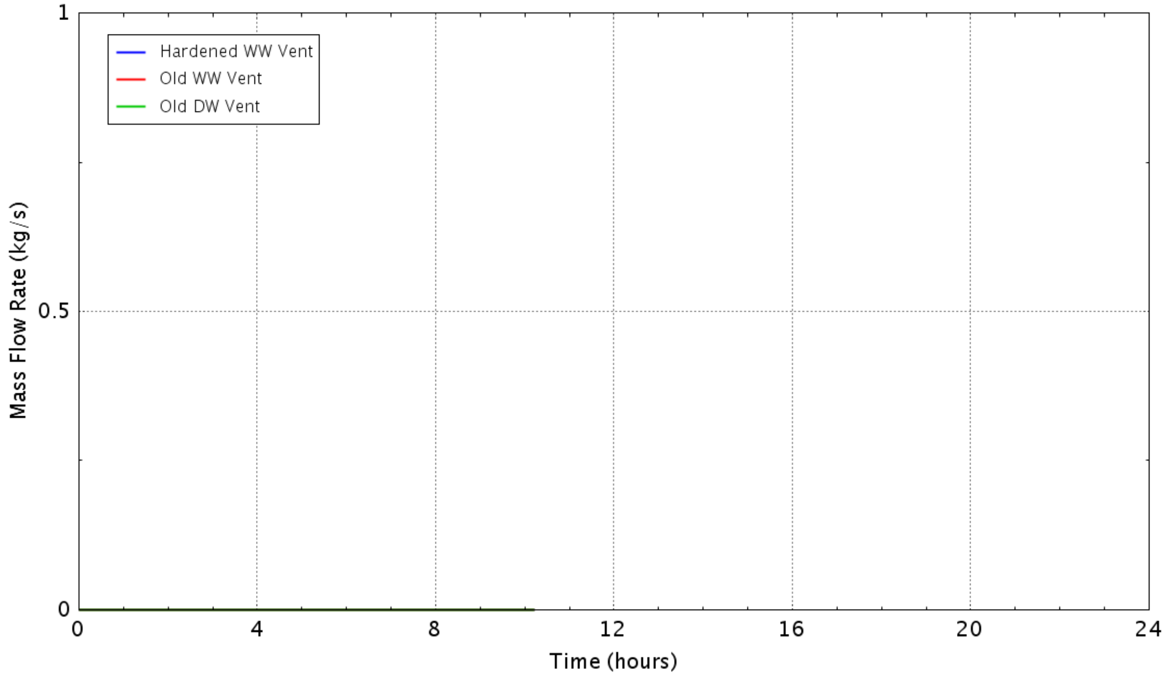

Figure C - 330 Flow rate of the containment vents

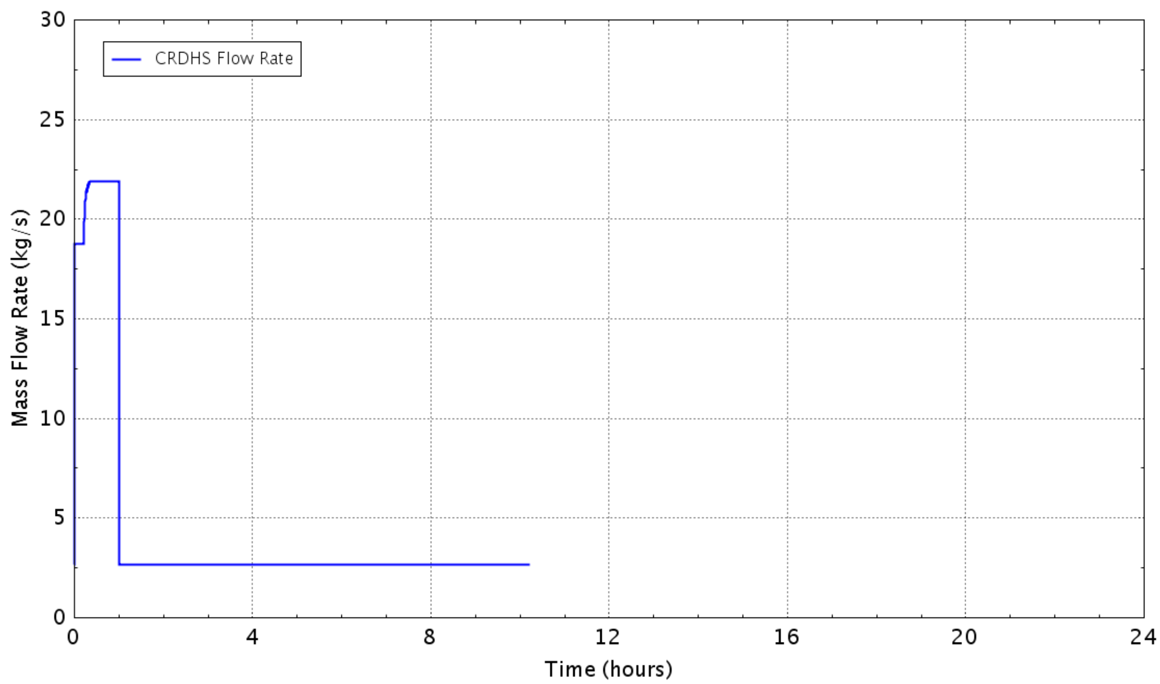

Figure C - 331 Flow rate of the control rod drive hydraulic system

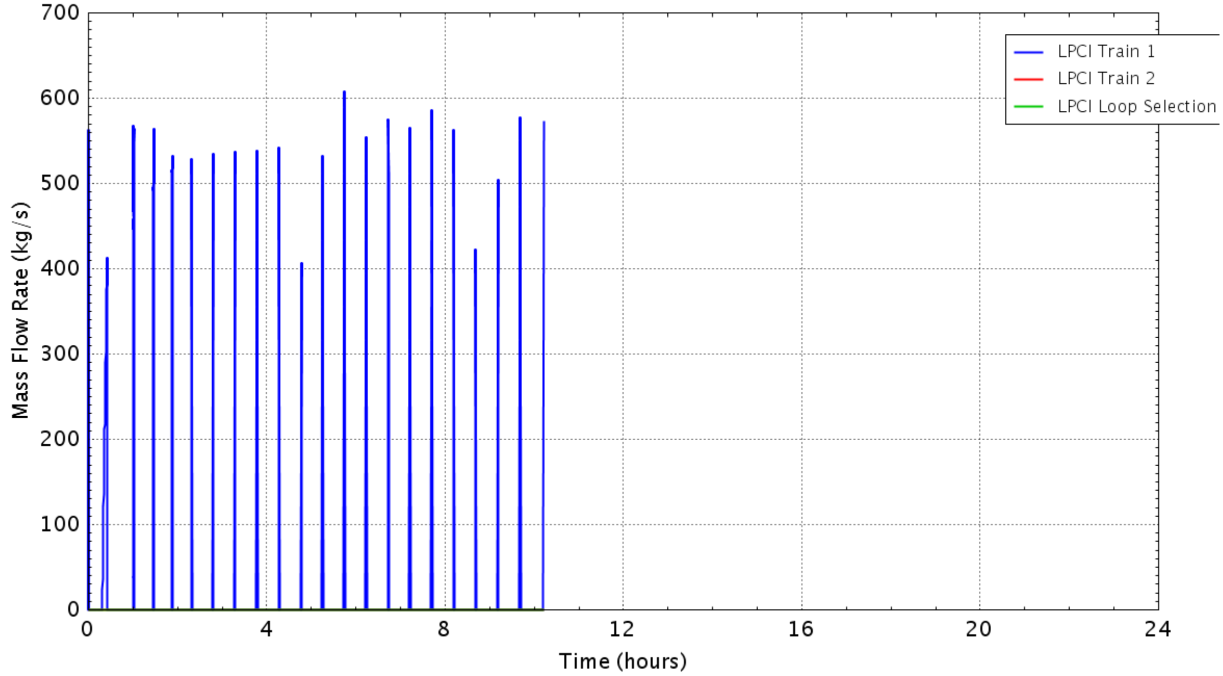

Figure C - 332   Flow rate of the LPCI pump

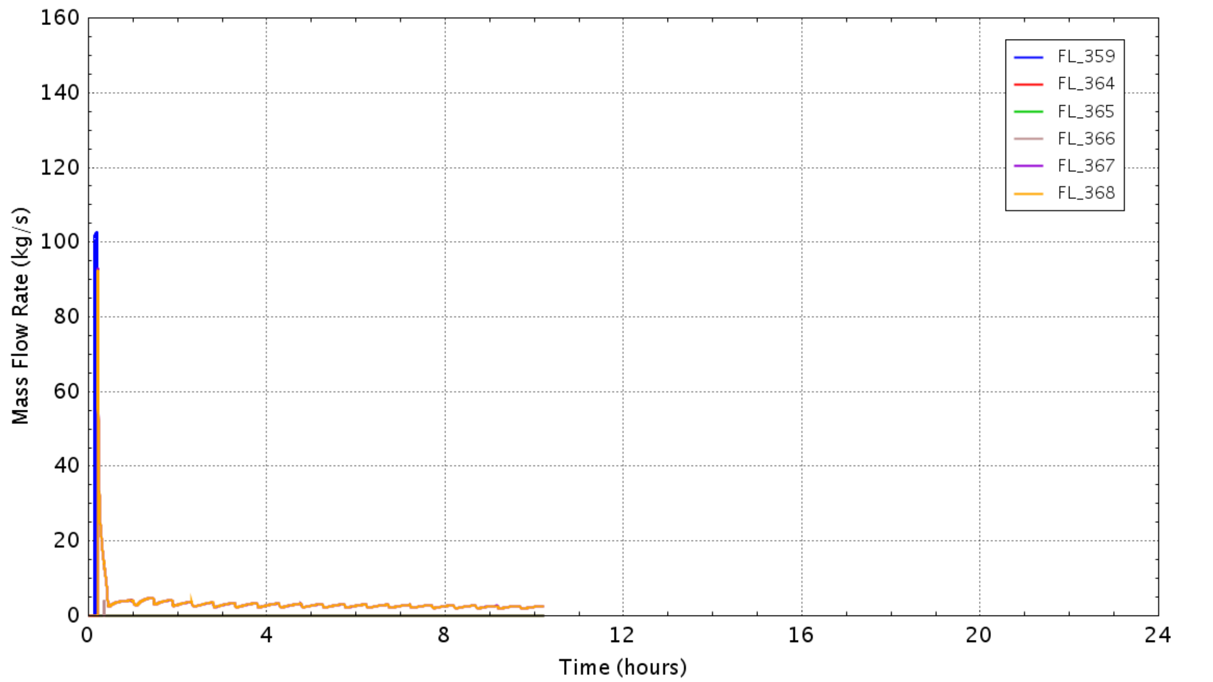

Figure C - 333   Flow rate of the SRVs

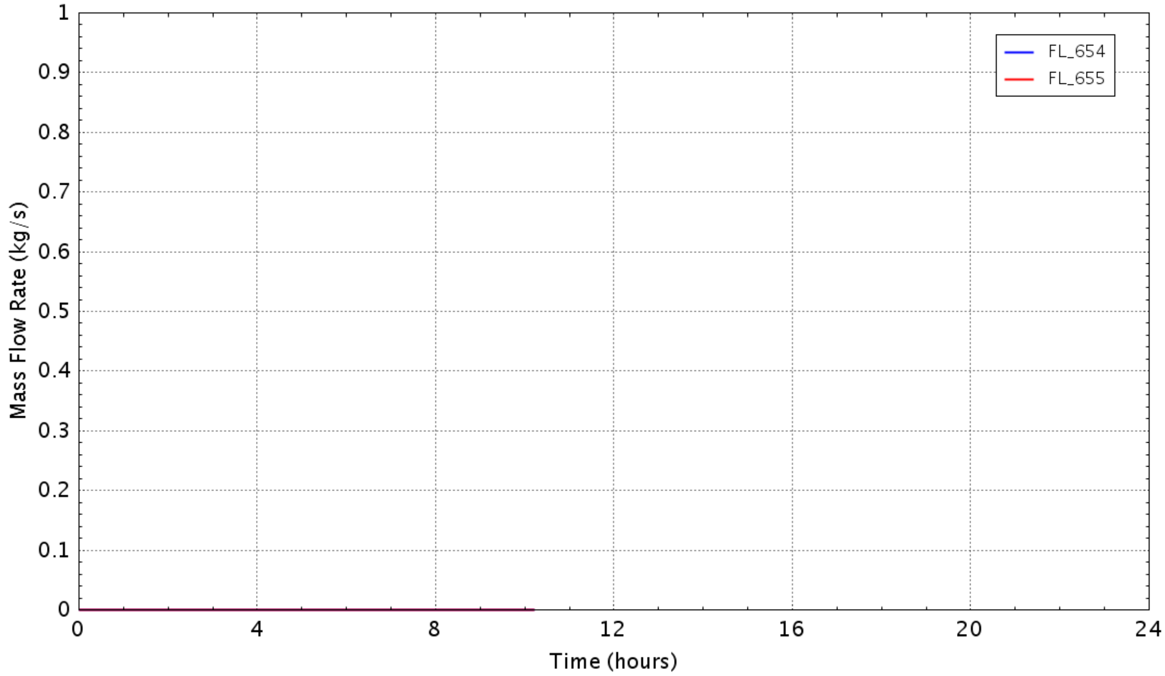

Figure C - 334   Flow rate of the wetwell cooling system

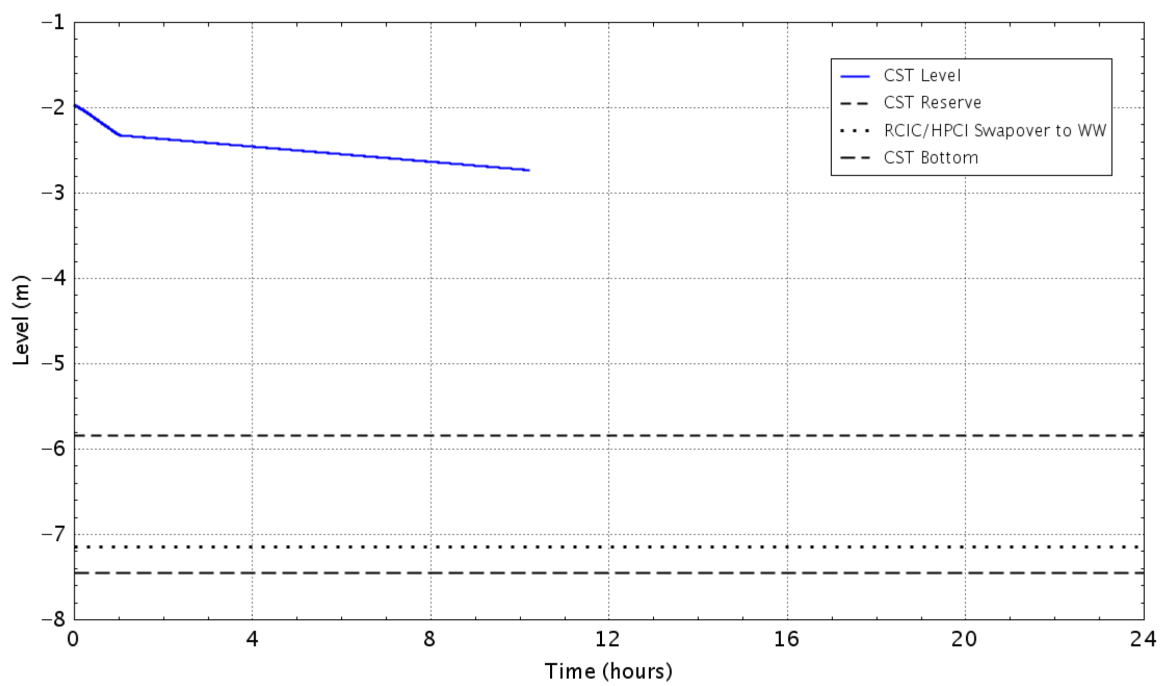

Figure C - 335   Water level in the CST

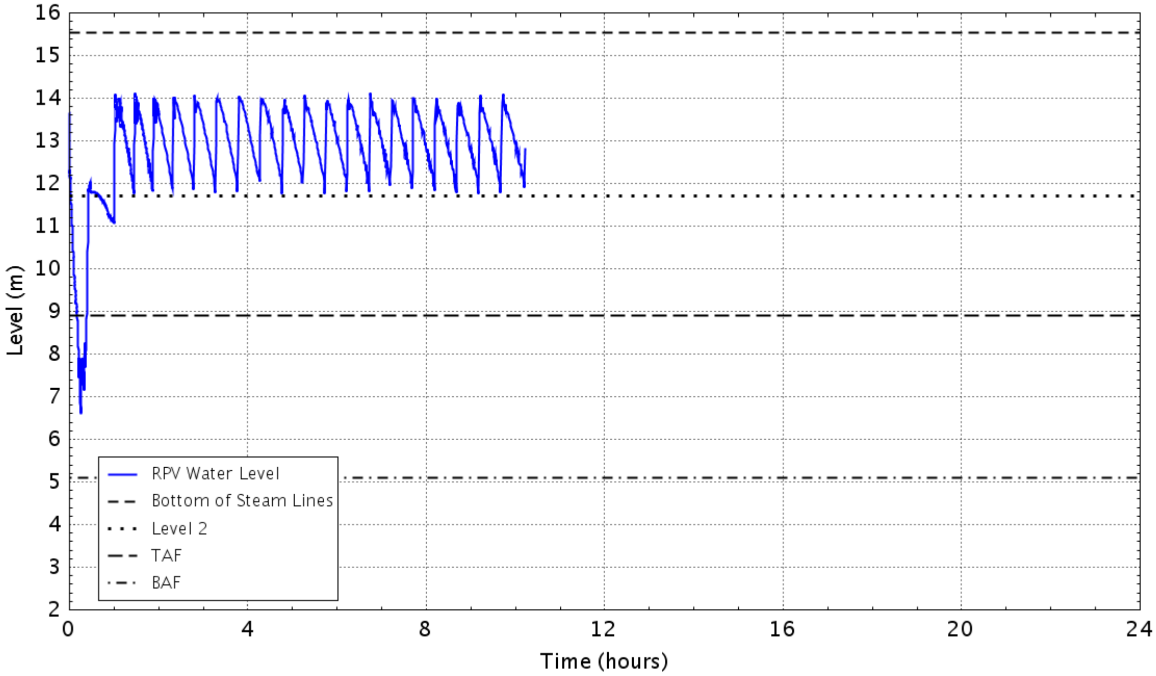

Figure C - 336 RPV Downcomer water level

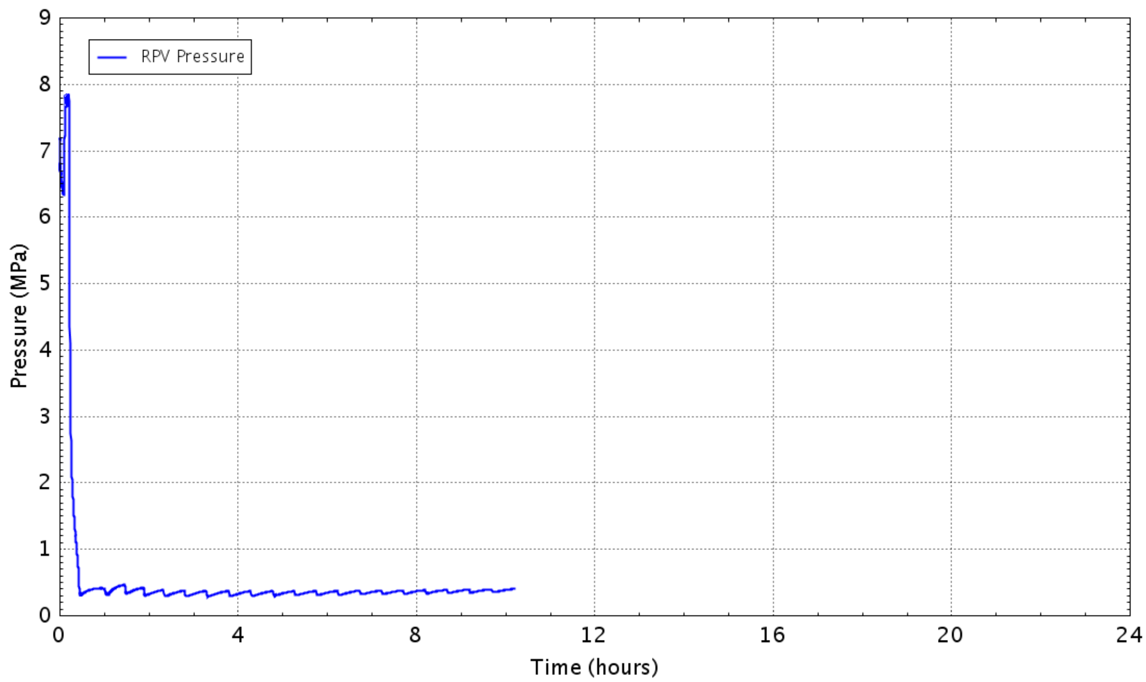

Figure C - 337 Pressure in the RPV

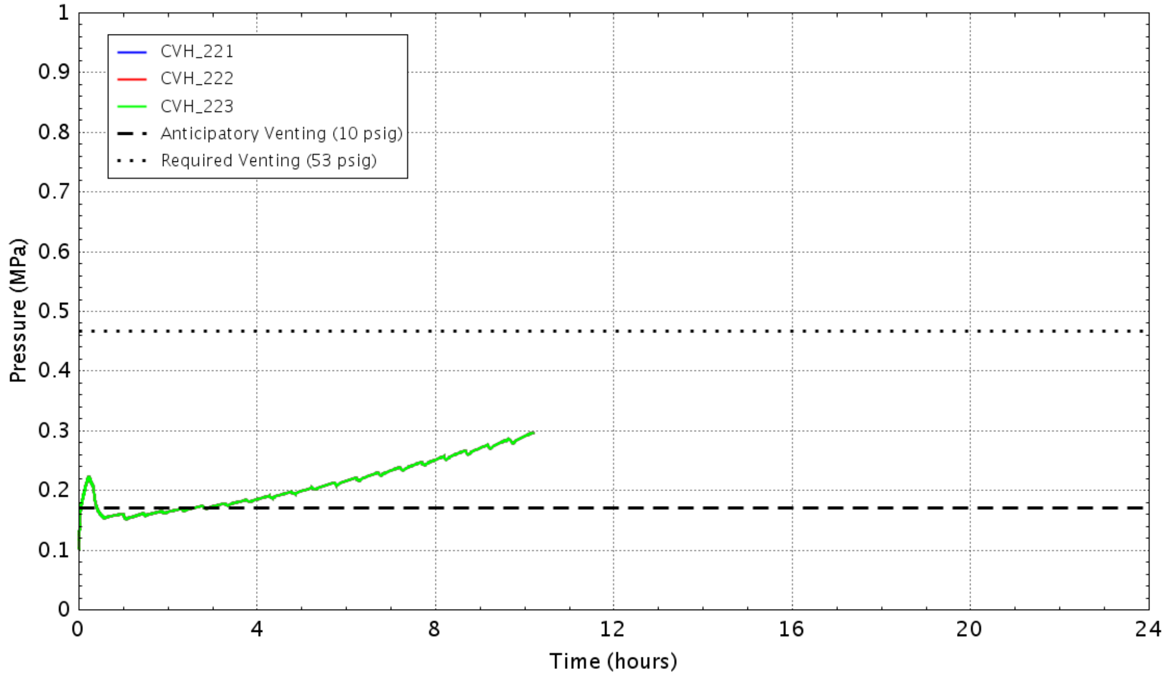

Figure C - 338 Pressure in the wetwell

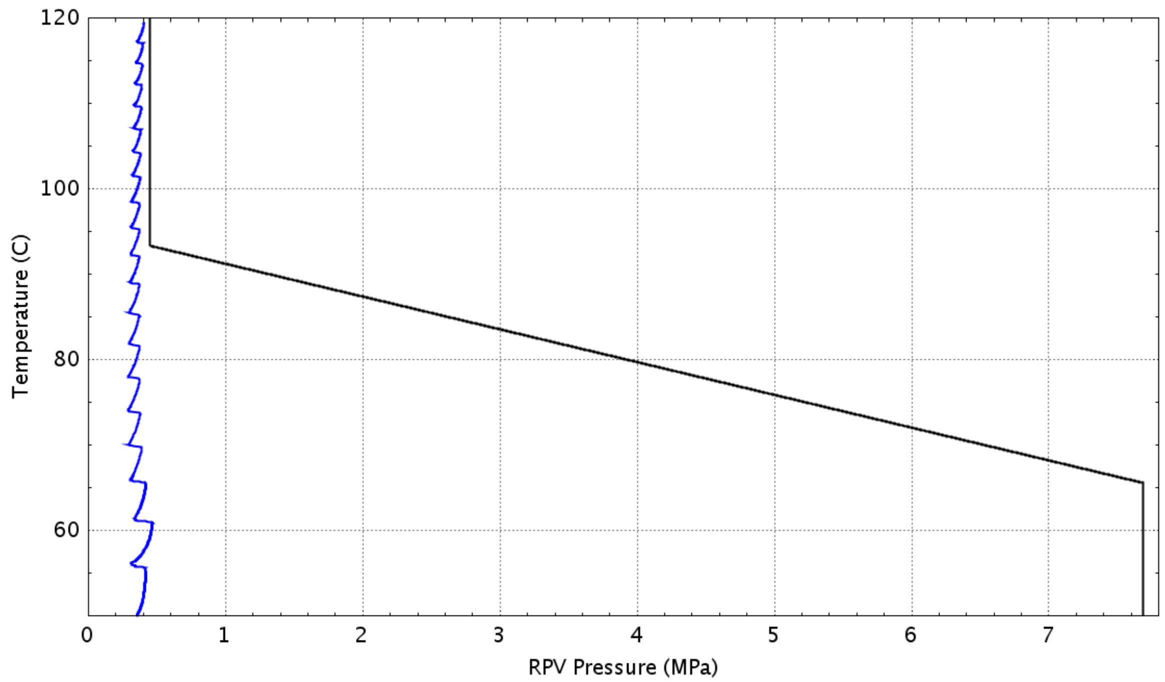

Figure C - 339 Plant status relative to the HCL curve (Graph 4 of the EOPs)

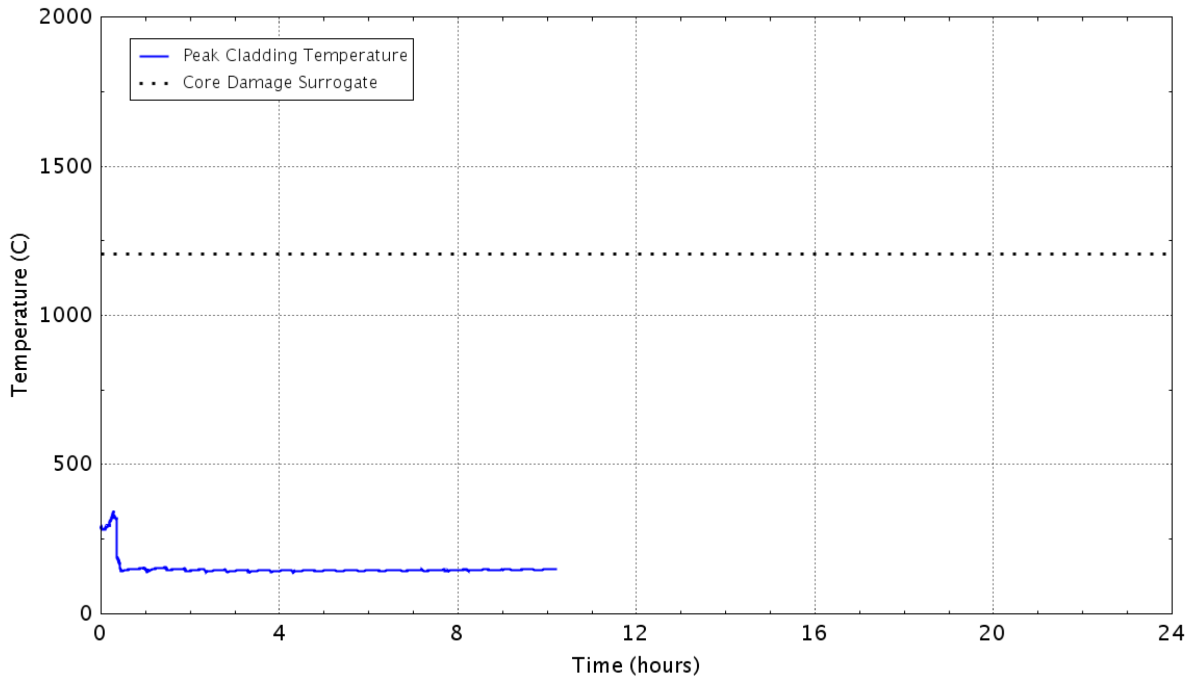

Figure C - 340 Peak temperature of the fuel cladding as a function of time

C.3 Sensitivities Analyses

C.3.1 Case 5a: Sensitivity to TRANS-30 Case 5 with IncreasedCRDHS Flow Rate to Mimic SLC Injection

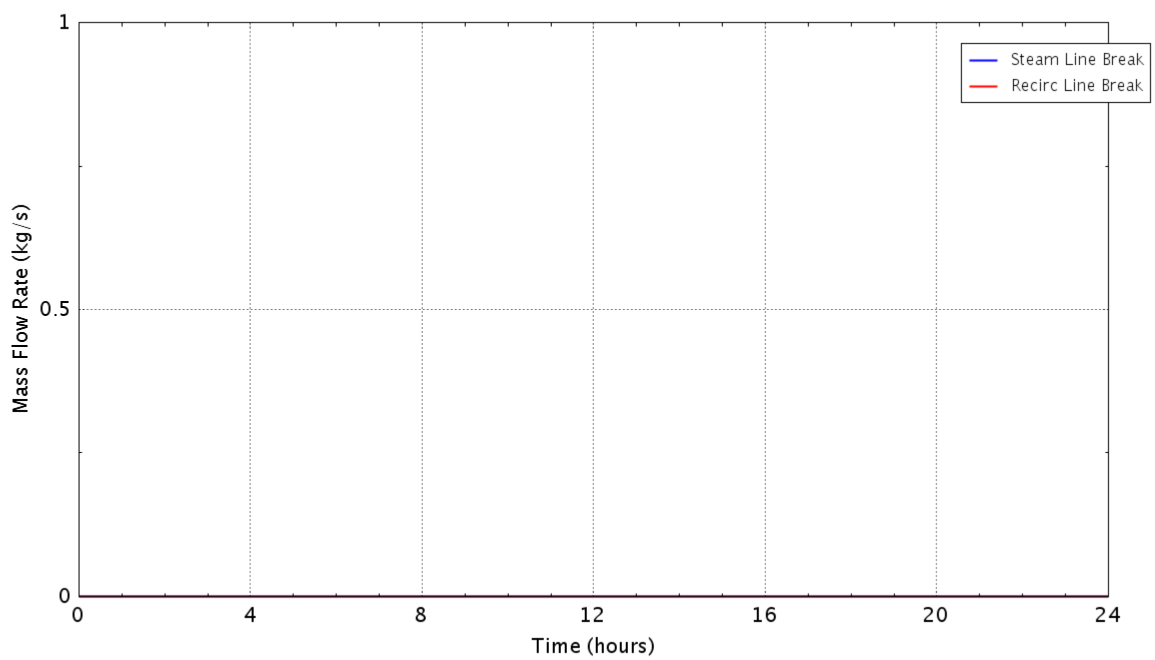

Figure C - 341 Flow rate of the break in the steamline/recirculation line

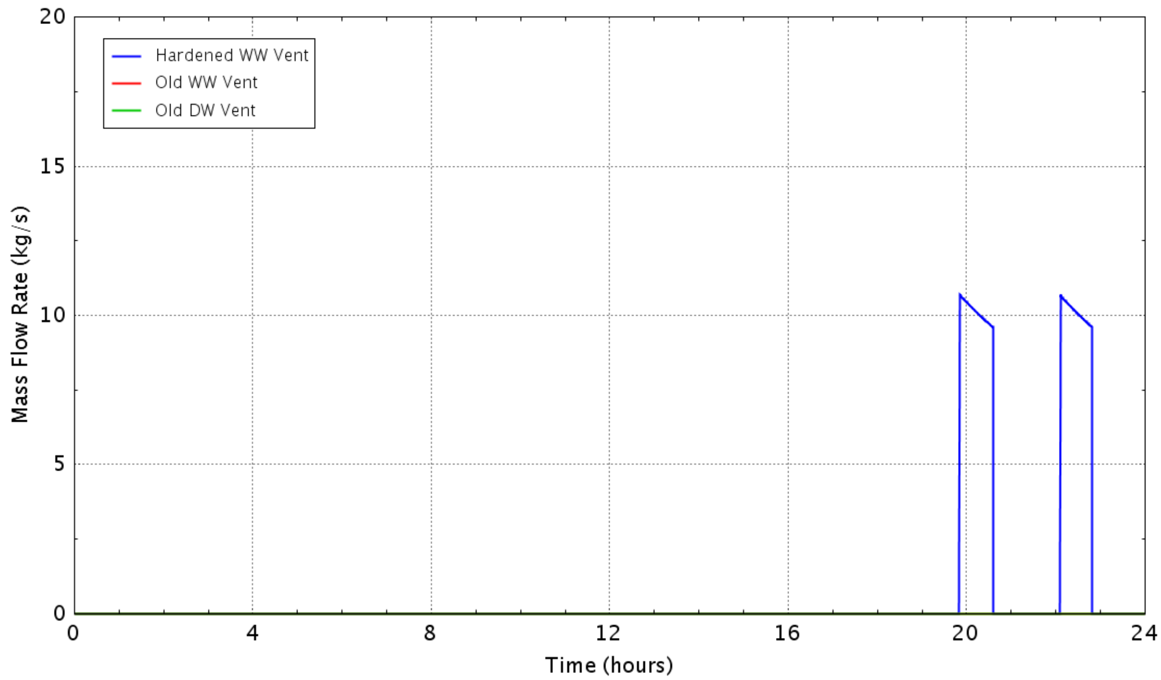

Figure C - 342 Flow rate of the containment vents

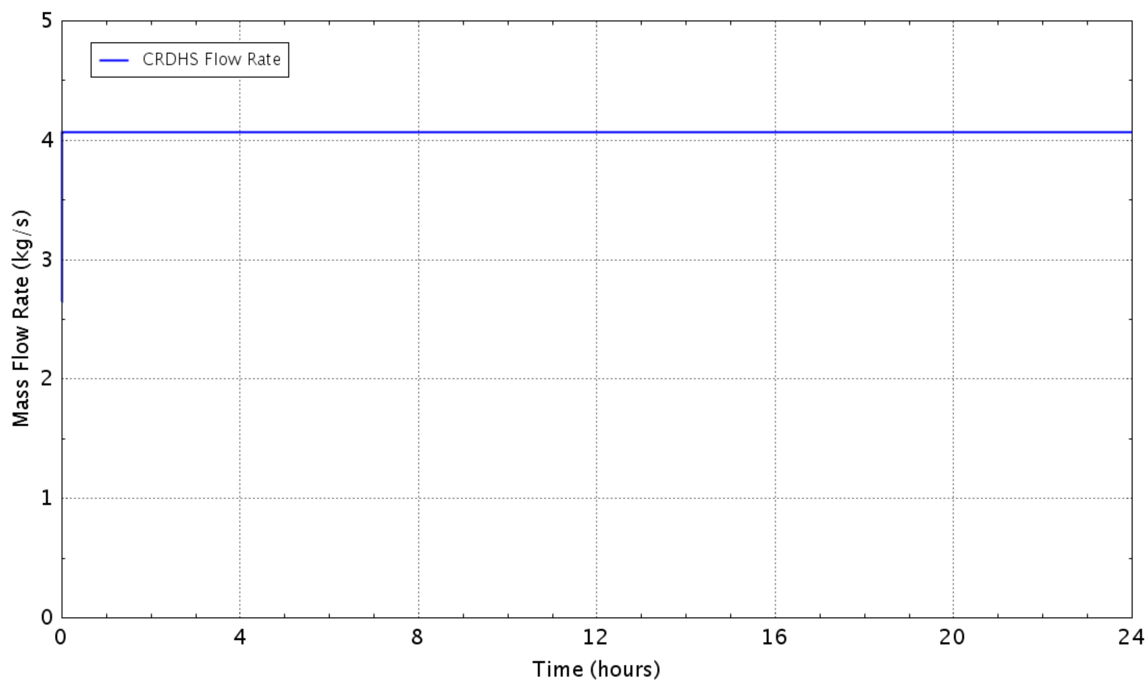

Figure C - 343 Flow rate of the control rod drive hydraulic system

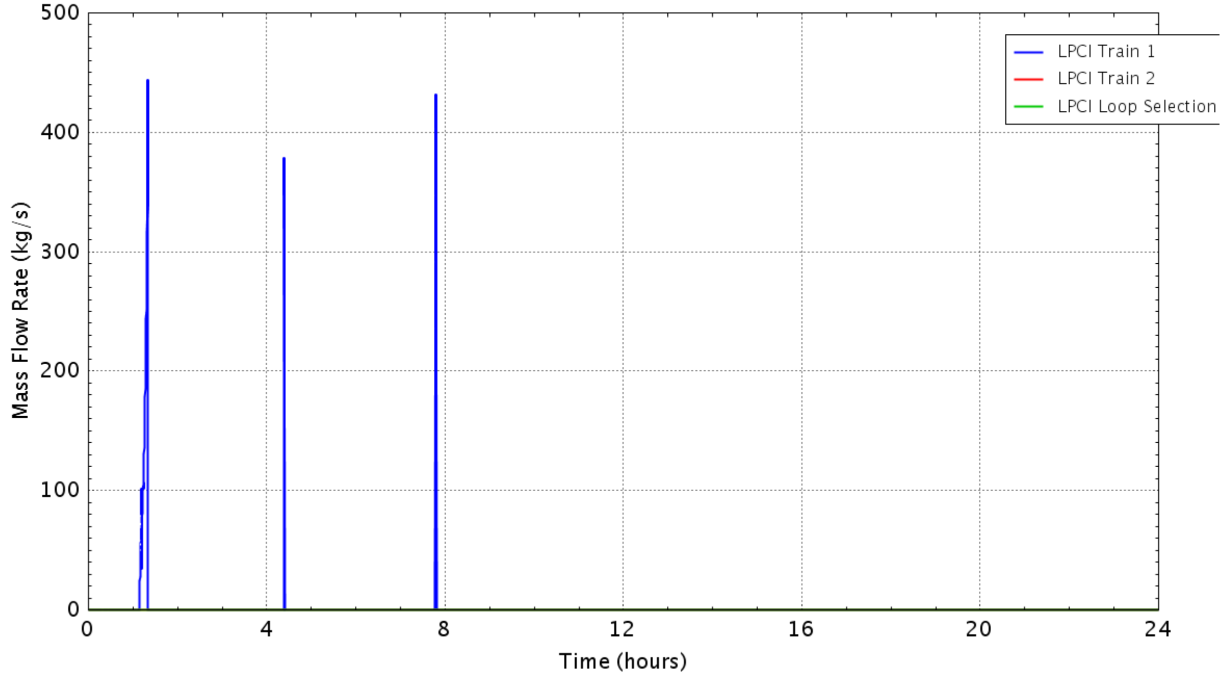

Figure C - 344 Flow rate of the LPCI pump

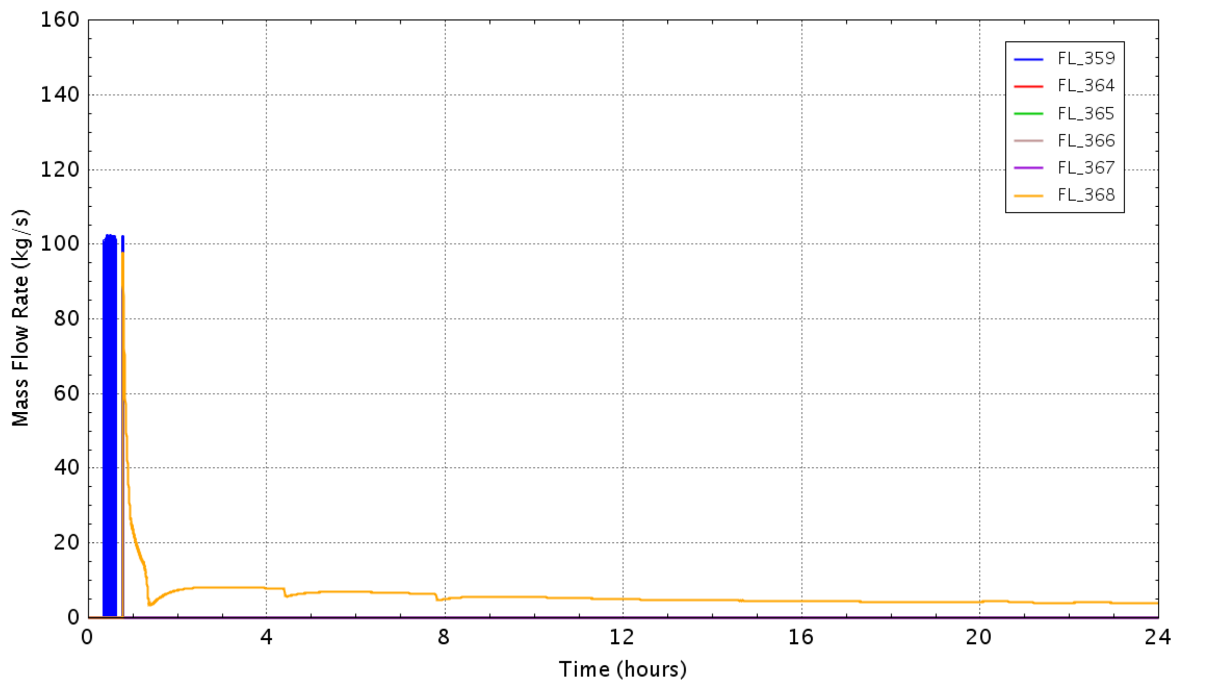

Figure C - 345 Flow rate of the SRVs

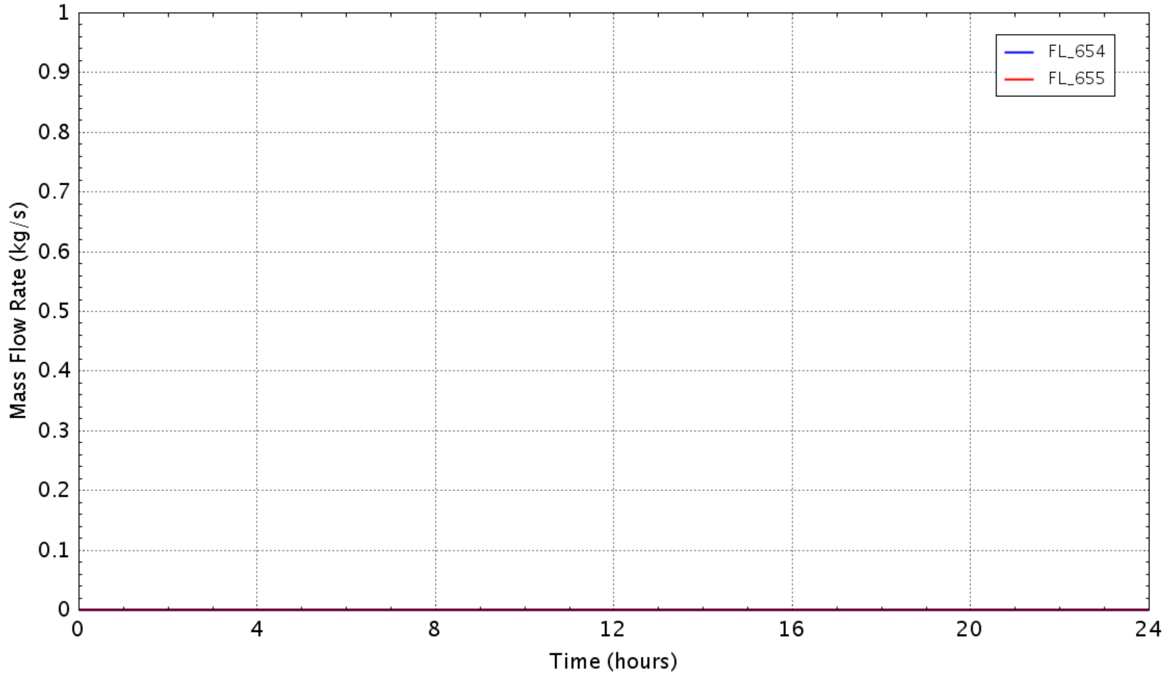

Figure C - 346 Flow rate of the wetwell cooling system

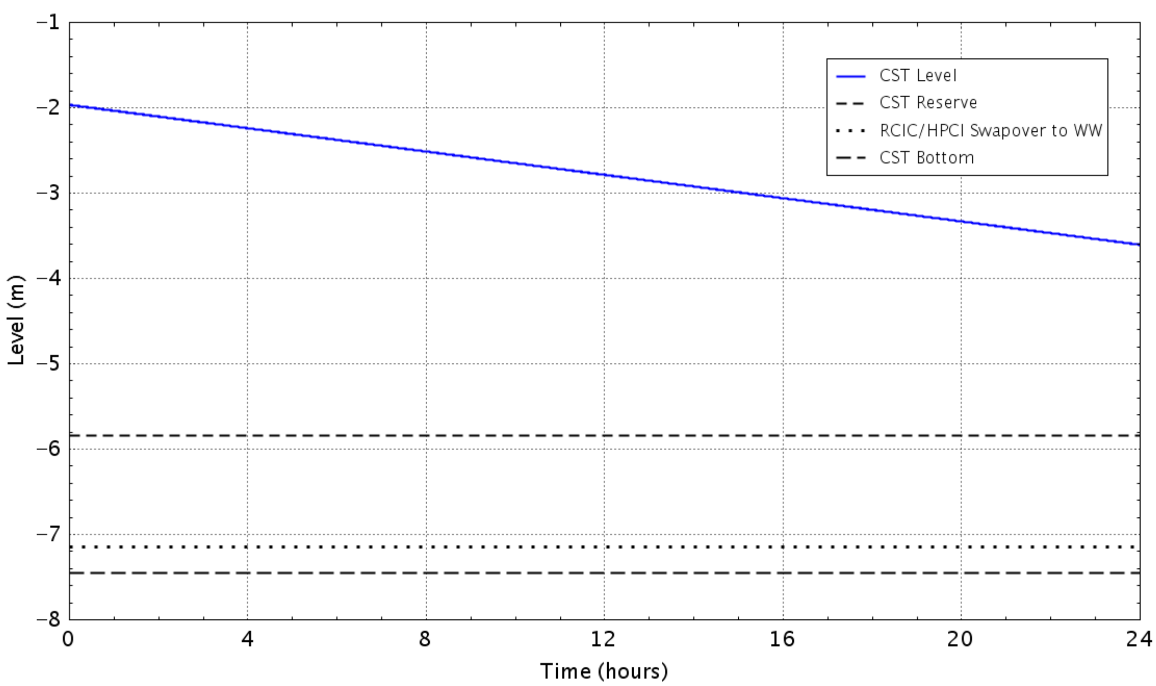

Figure C - 347 Water level in the CST

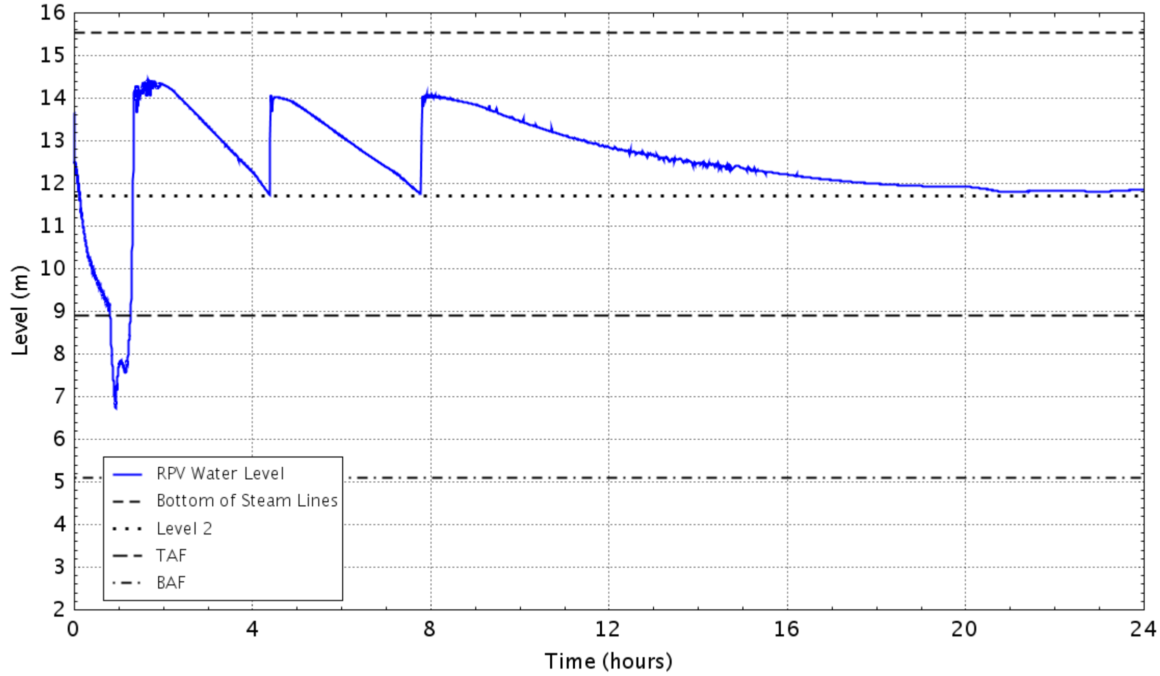

Figure C - 348 RPV Downcomer water level

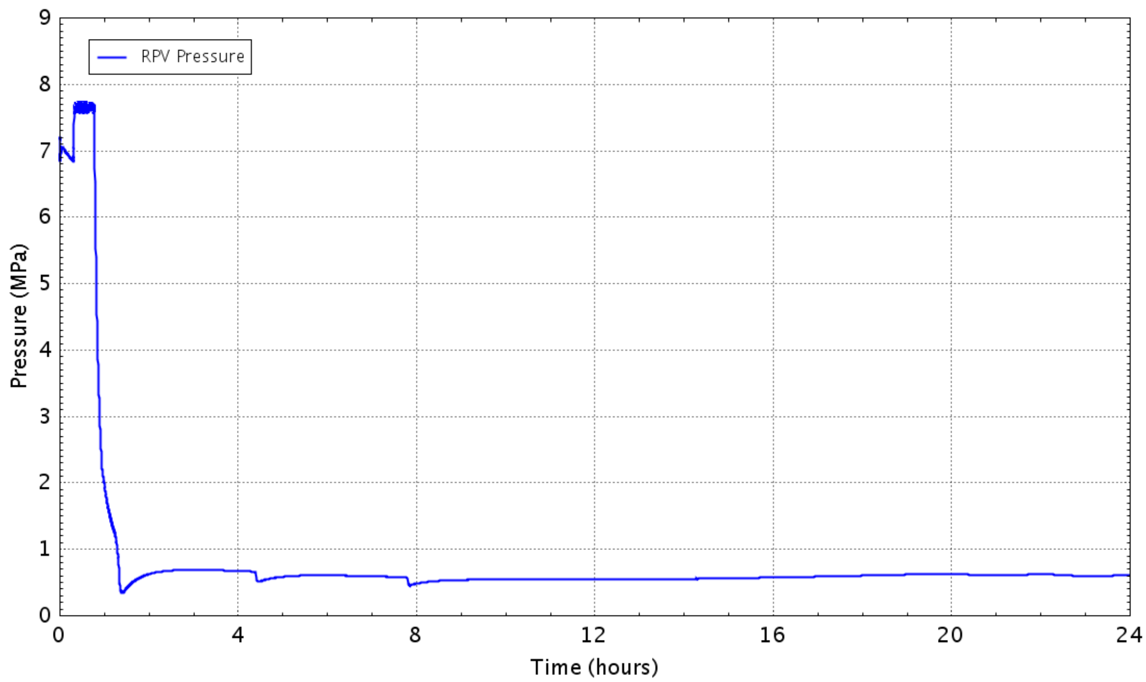

Figure C - 349 Pressure in the RPV

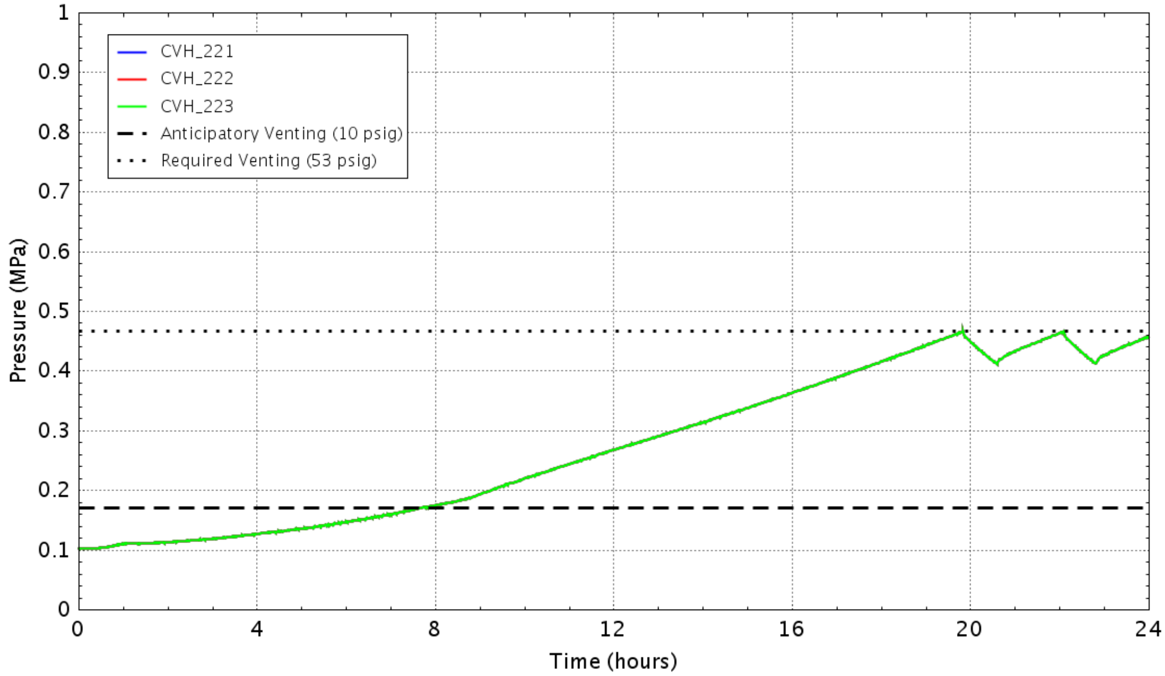

Figure C - 350 Pressure in the wetwell

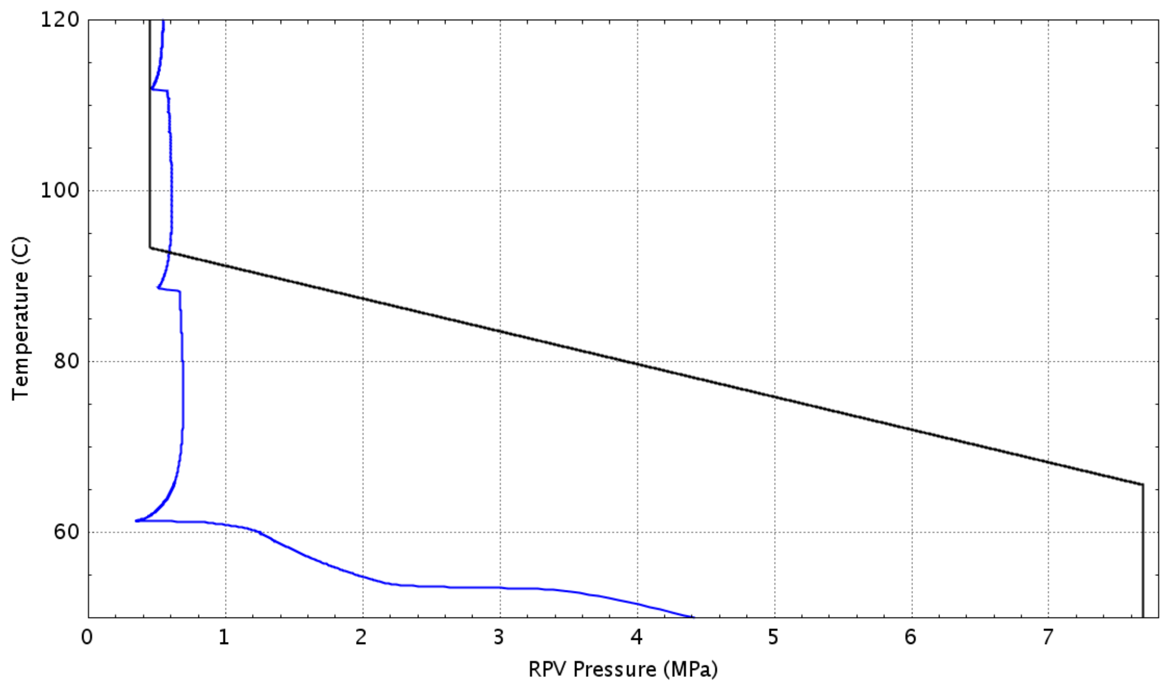

Figure C - 351 Plant status relative to the HCL curve (Graph 4 of the EOPs)

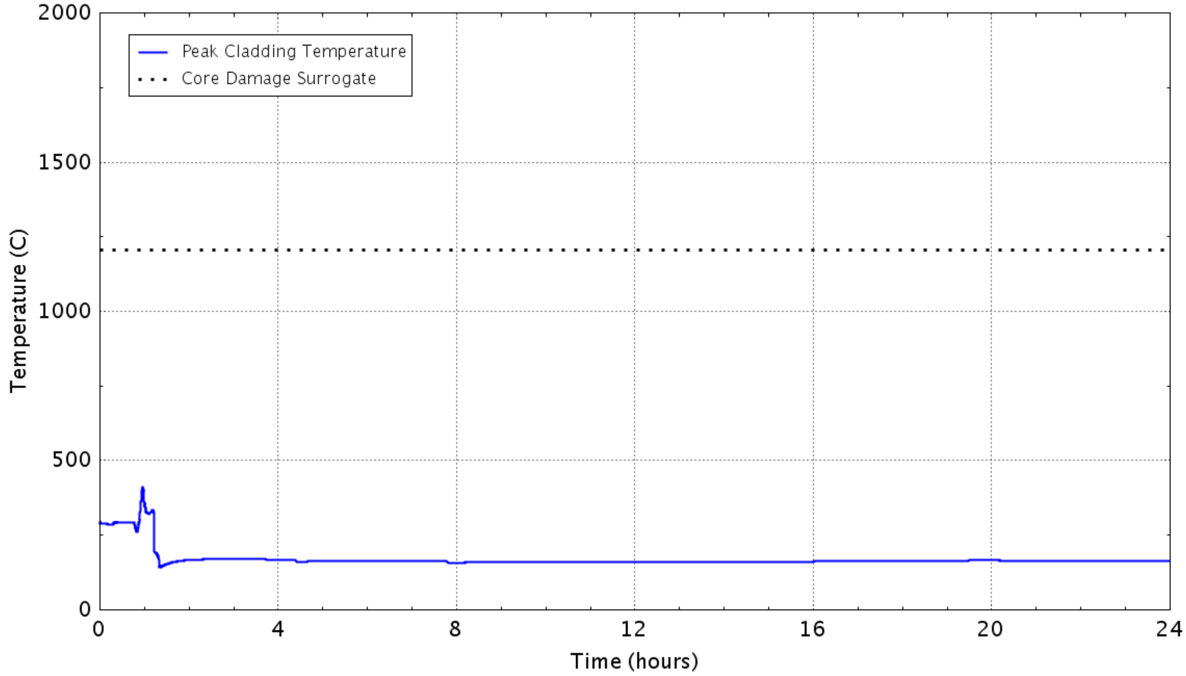

Figure C - 352 Peak temperature of the fuel cladding as a function of time

C.3.2 Case 5b: Sensitivity to TRANS-30 Case 5 with FeedwaterLine Isolated at Time 0

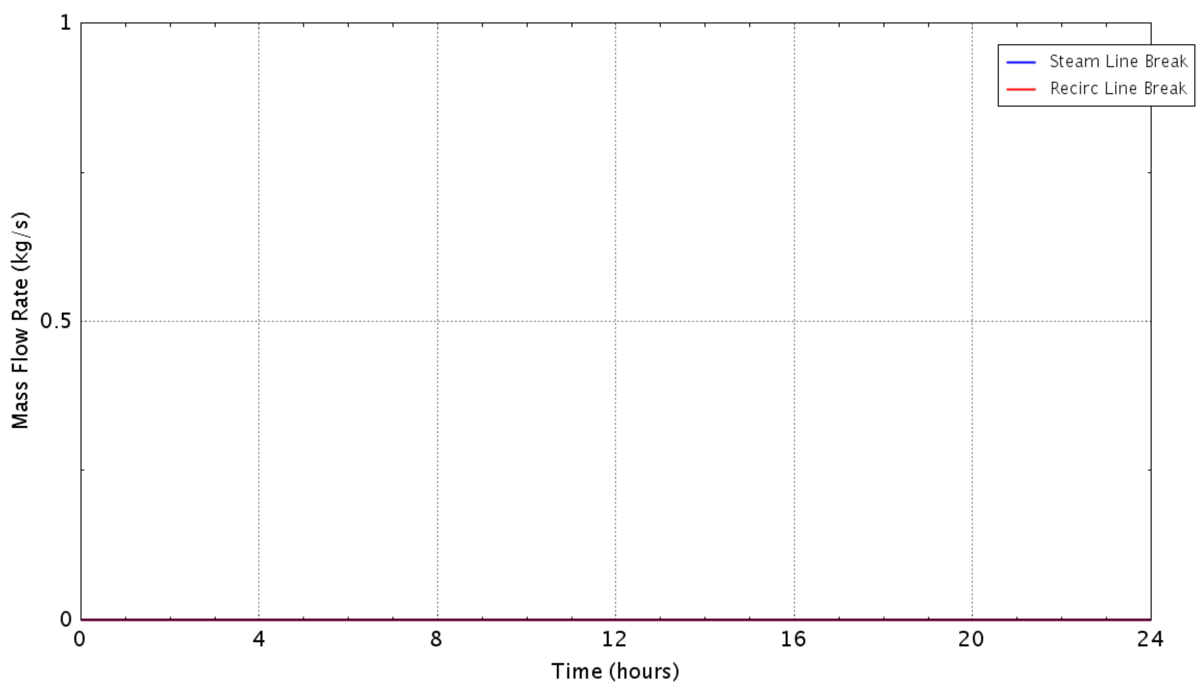

Figure C - 353 Flow rate of the break in the steamline/recirculation line

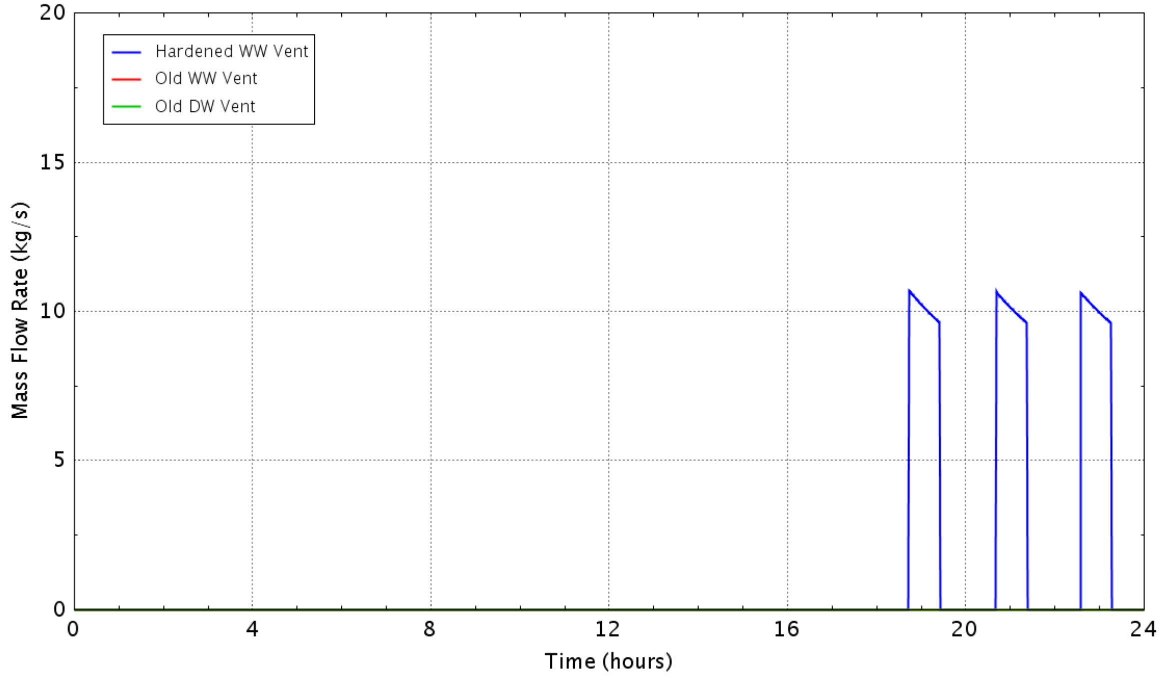

Figure C - 354 Flow rate of the containment vents

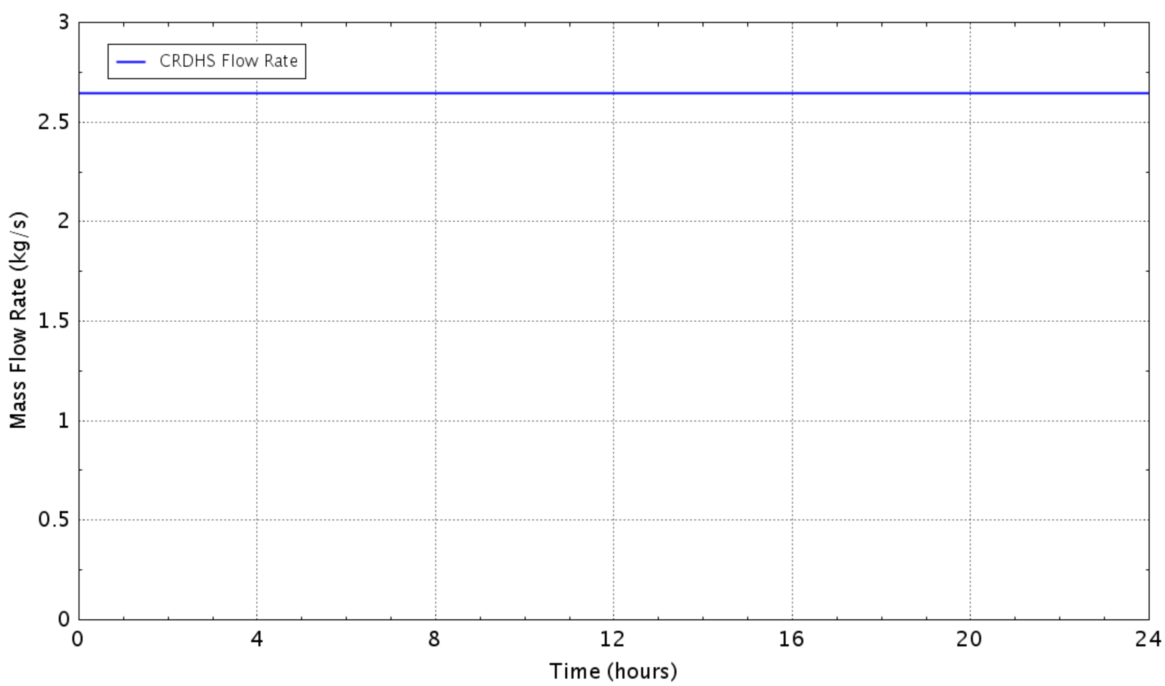

Figure C - 355 Flow rate of the control rod drive hydraulic system

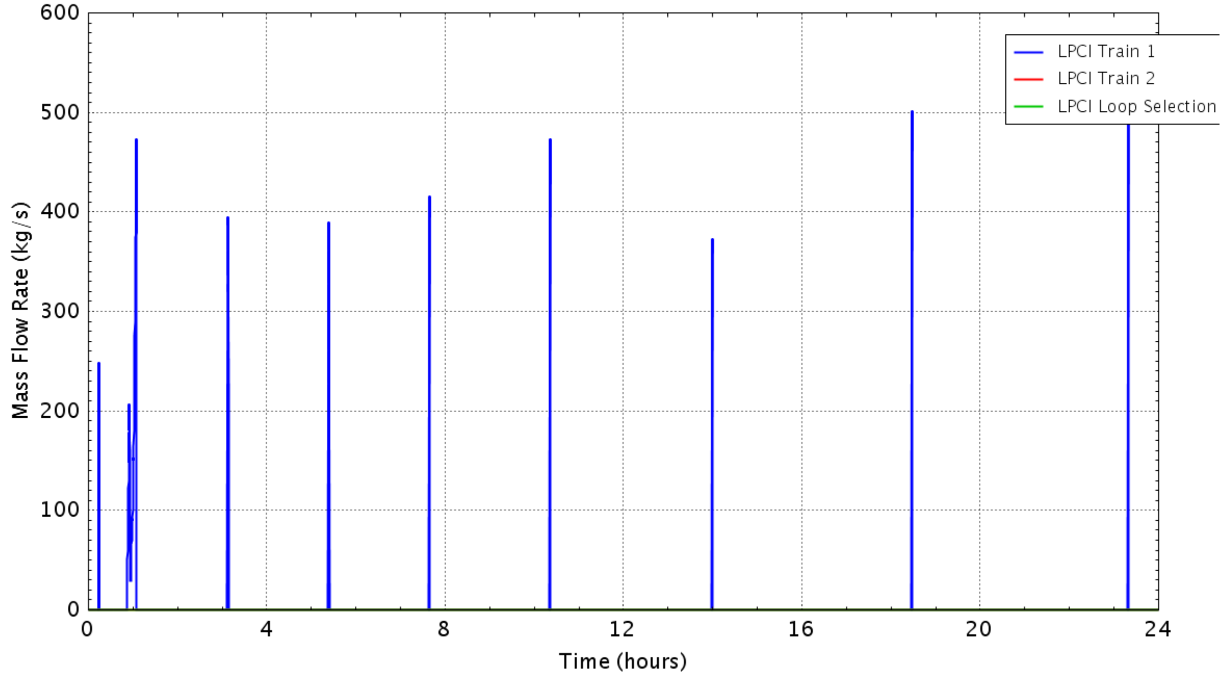

Figure C - 356 Flow rate of the LPCI pump

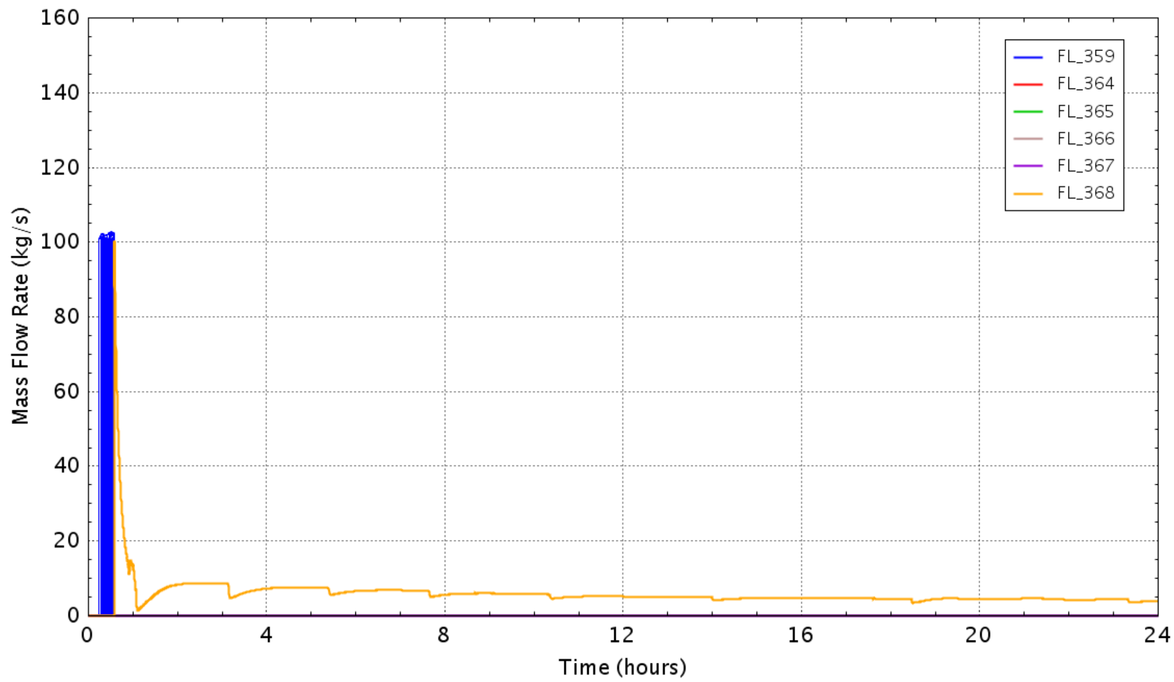

Figure C - 357 Flow rate of the SRVs

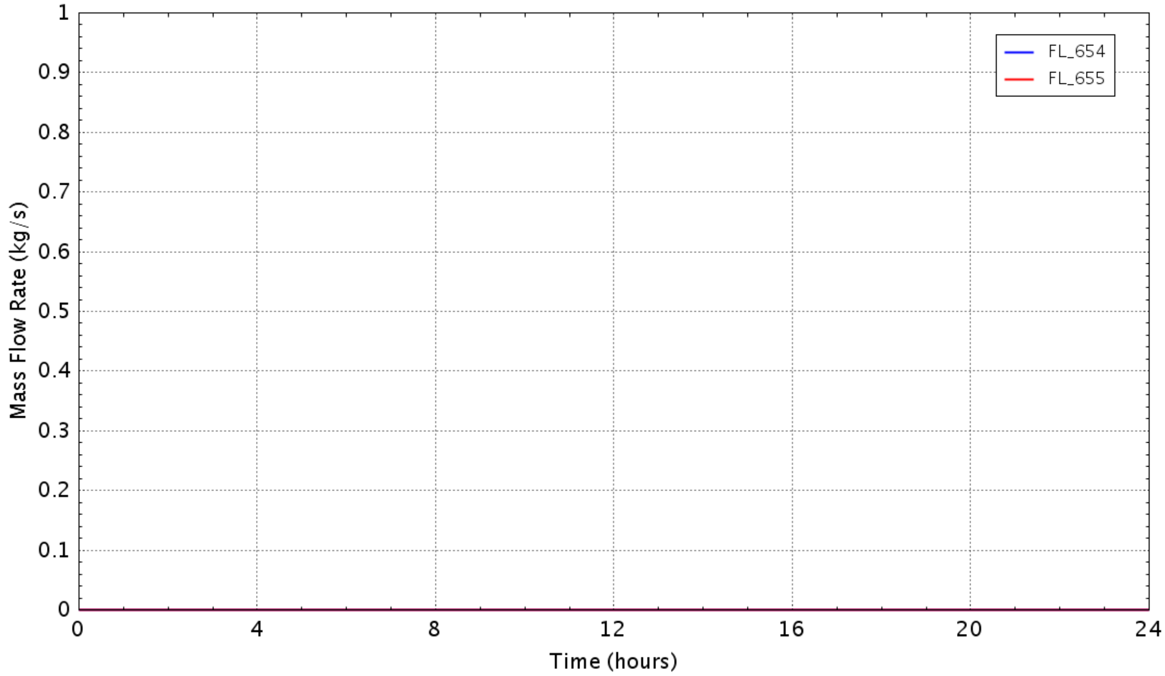

Figure C - 358 Flow rate of the wetwell cooling system

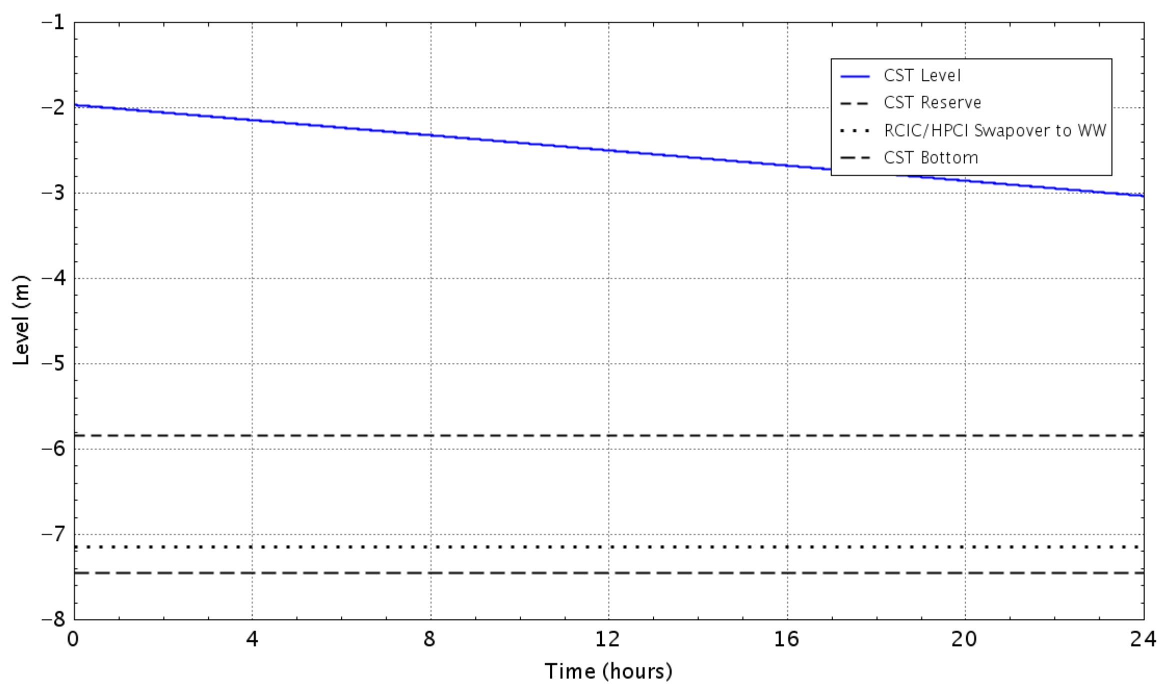

Figure C - 359 Water level in the CST

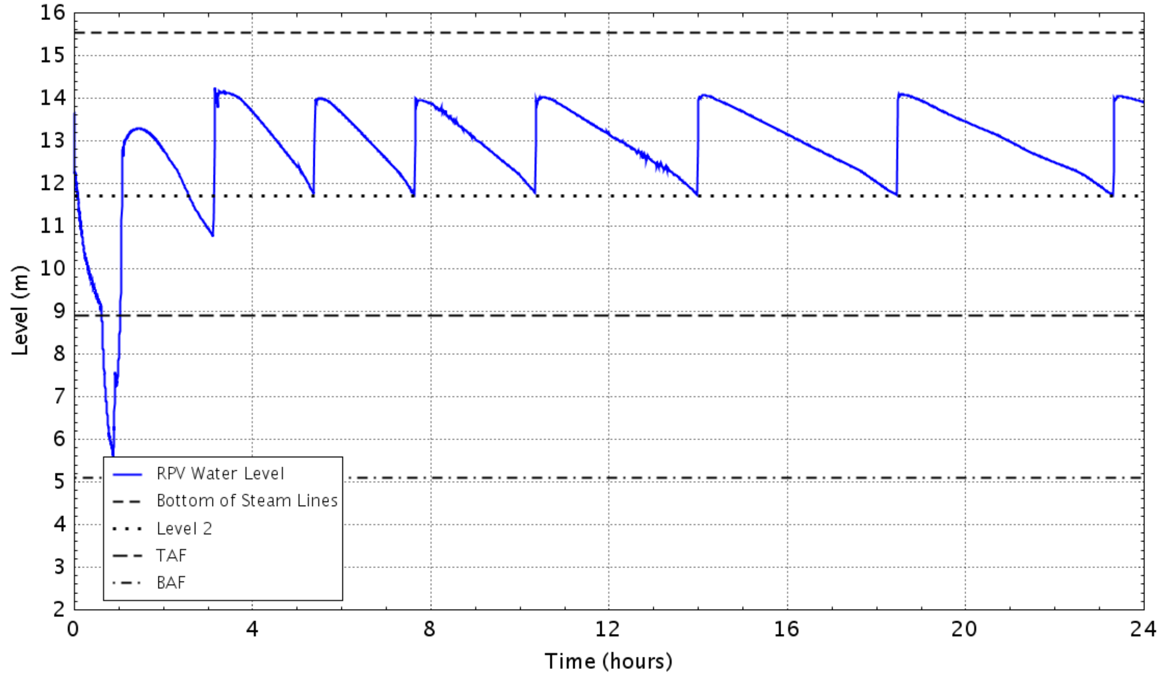

Figure C - 360 RPV Downcomer water level

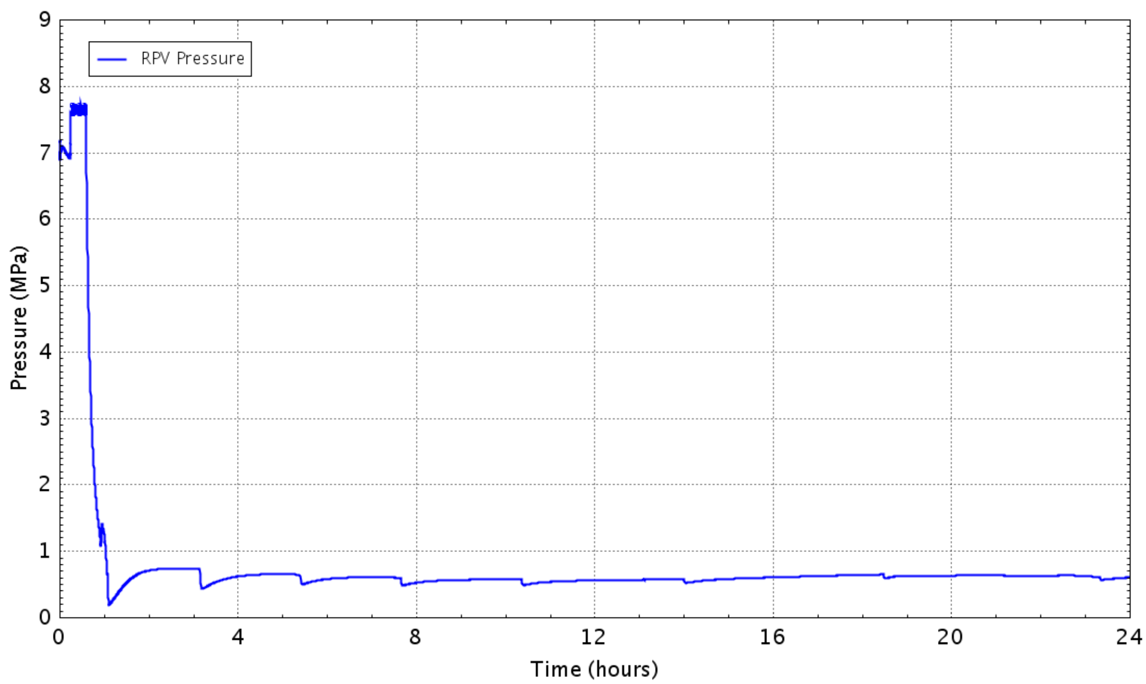

Figure C - 361 Pressure in the RPV

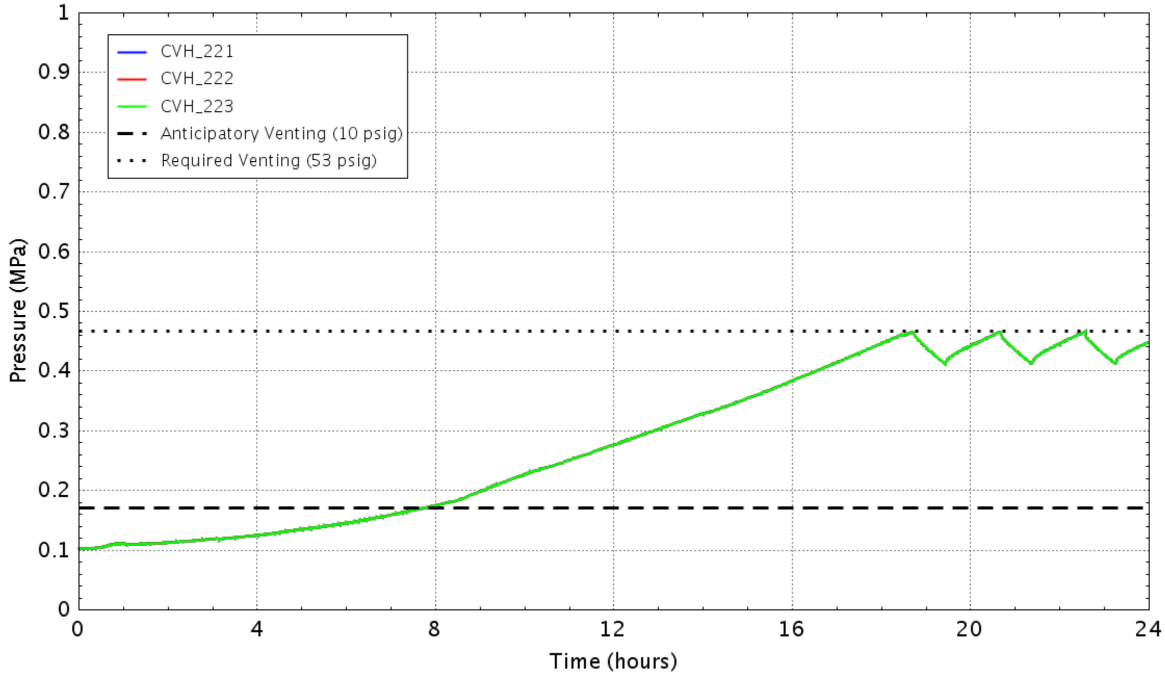

Figure C - 362 Pressure in the wetwell

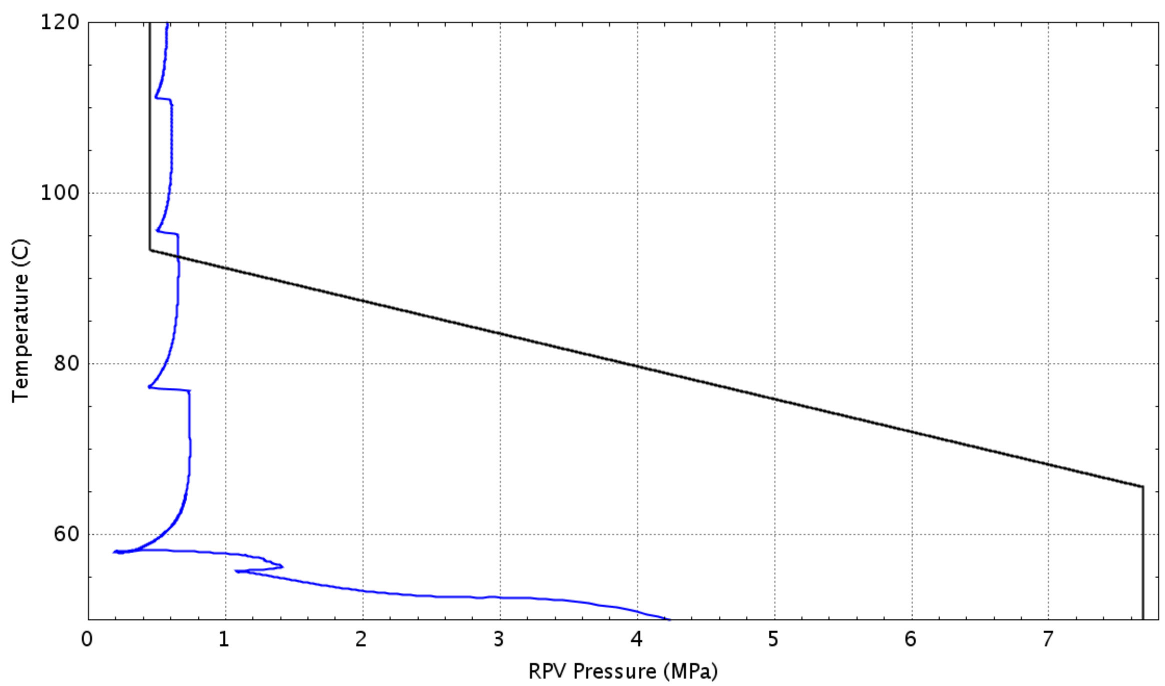

Figure C - 363 Plant status relative to the HCL curve (Graph 4 of the EOPs)

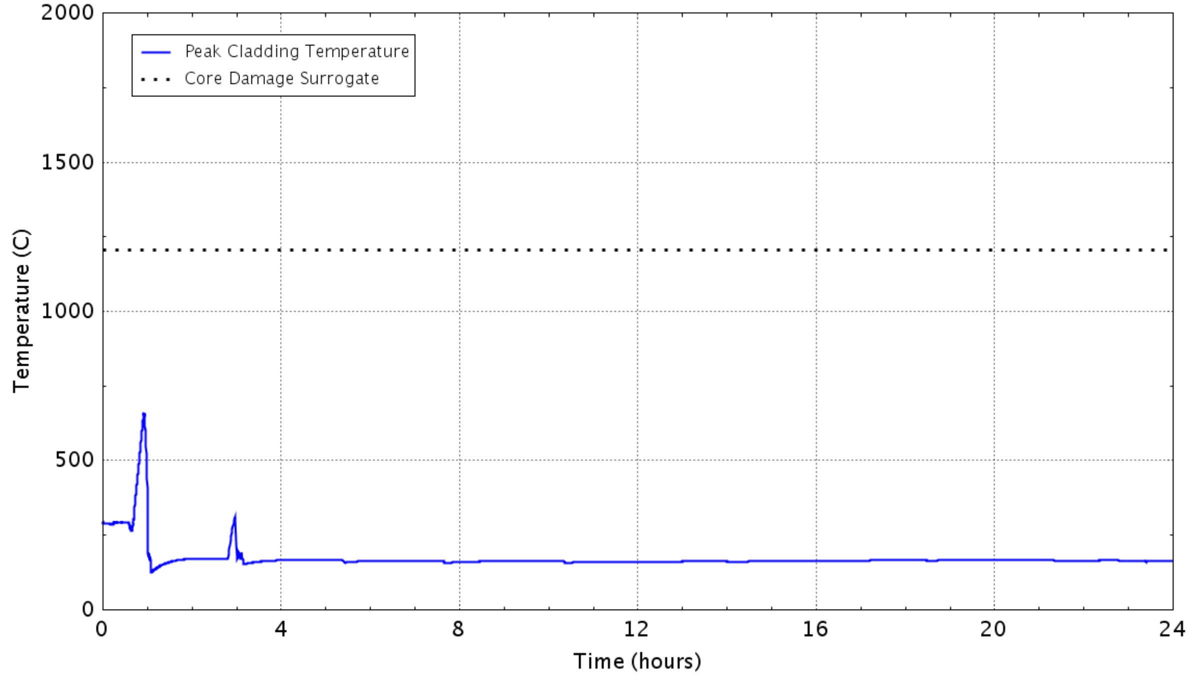

Figure C - 364 Peak temperature of the fuel cladding as a function of time

C.3.3 Case 6a: Sensitivity to TRANS-30 Case 6 with Low-Pressure Injection Provided by Core Spray Rather Than LPCI

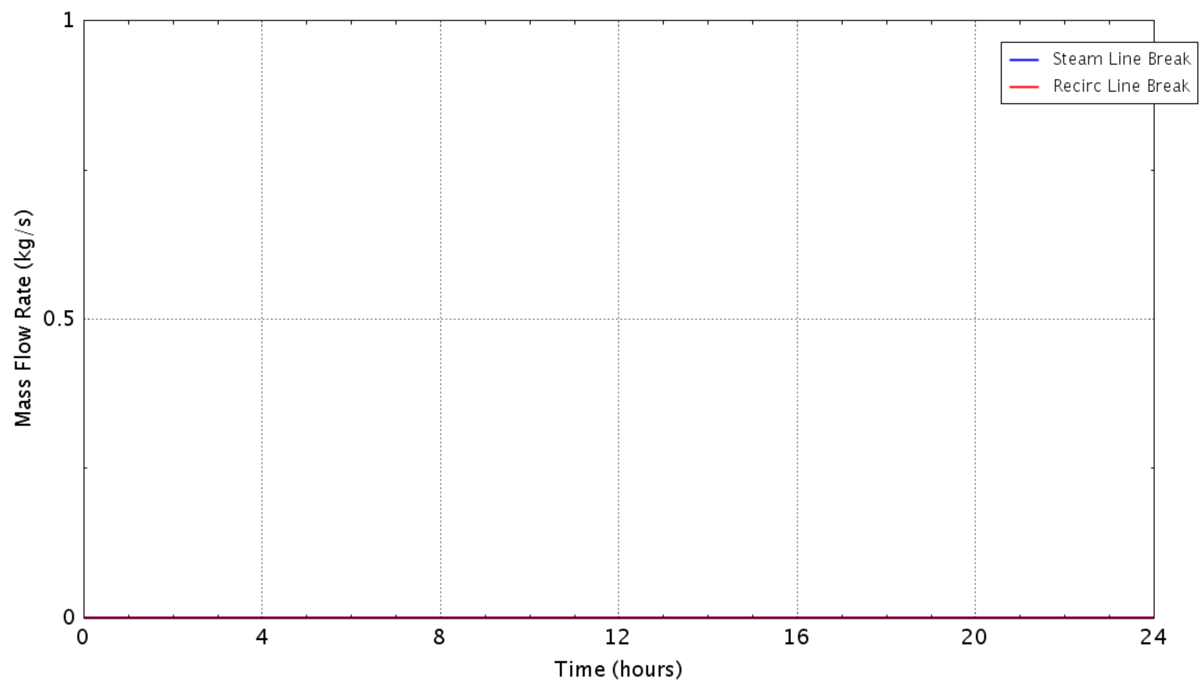

Figure C - 365 Flow rate of the break in the steamline/recirculation line

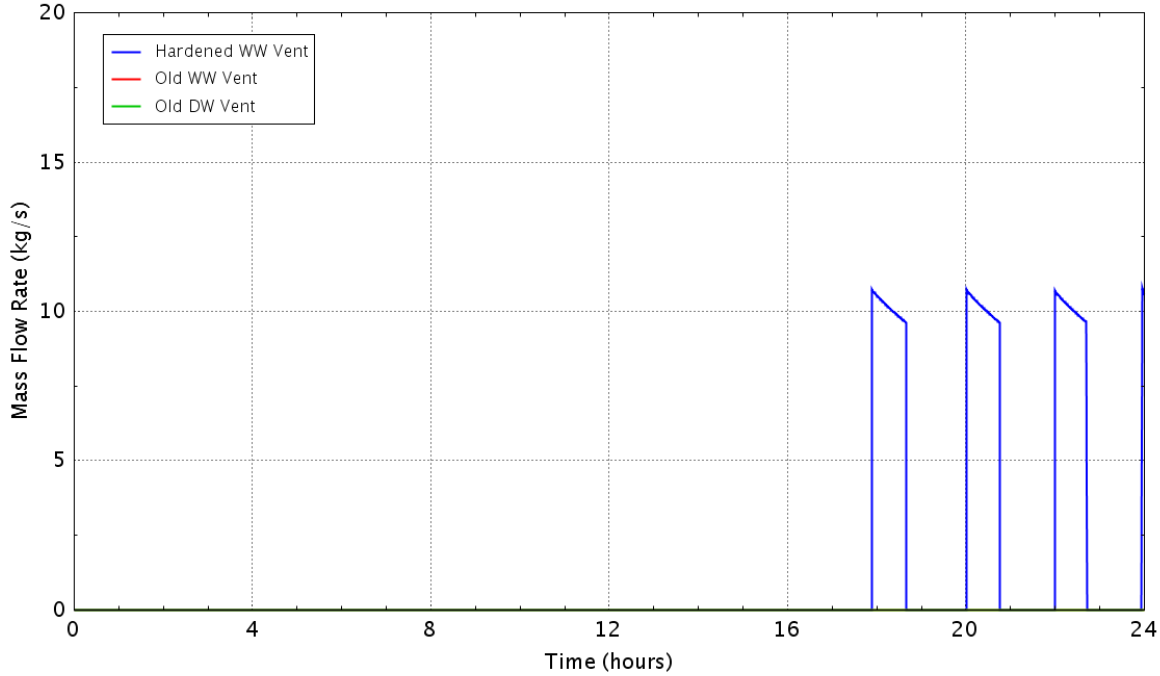

Figure C - 366 Flow rate of the containment vents

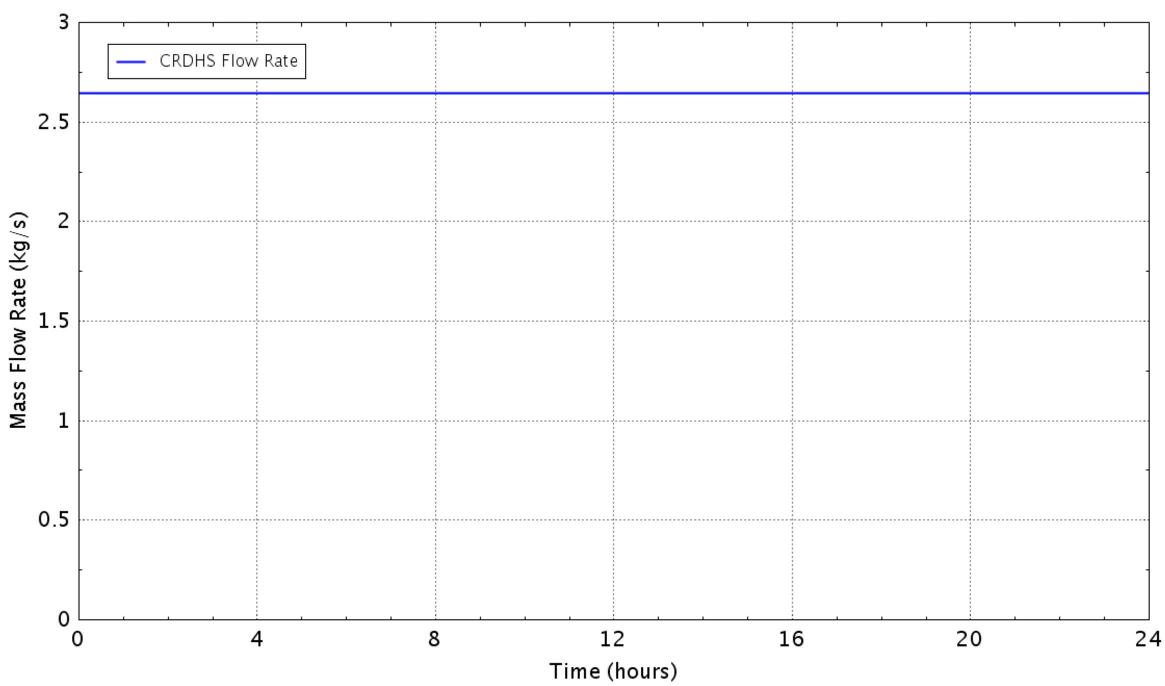

Figure C - 367 Flow rate of the control rod drive hydraulic system

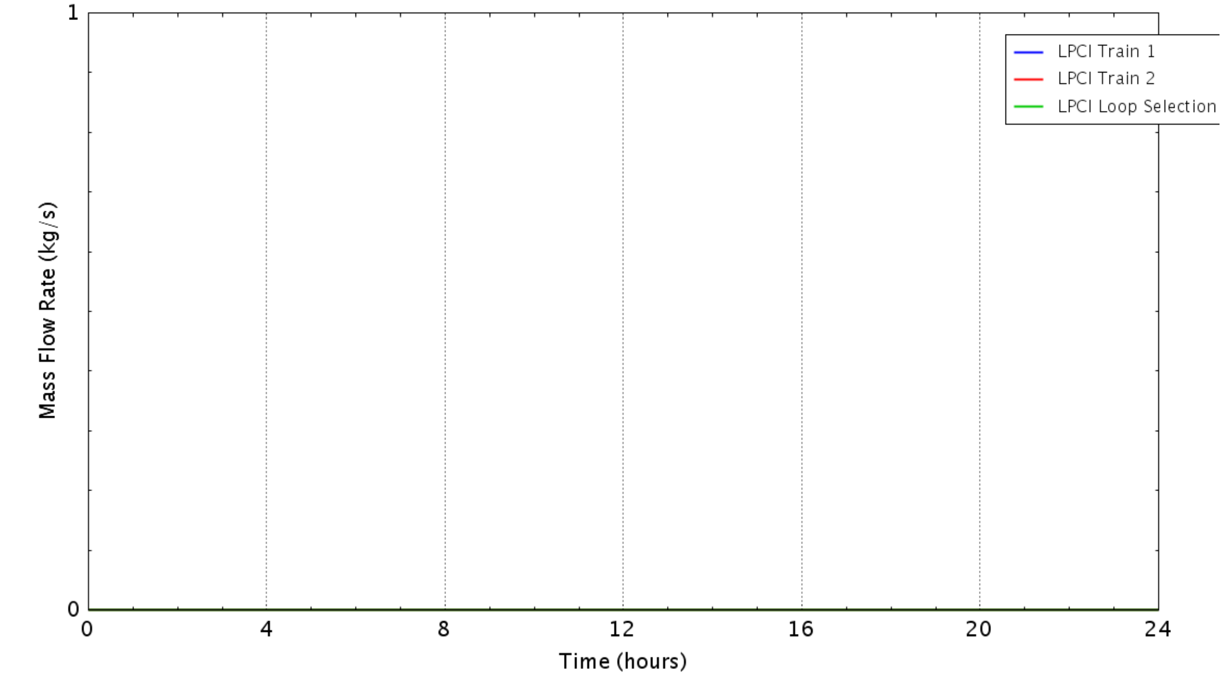

Figure C - 368   Flow rate of the LPCI pump

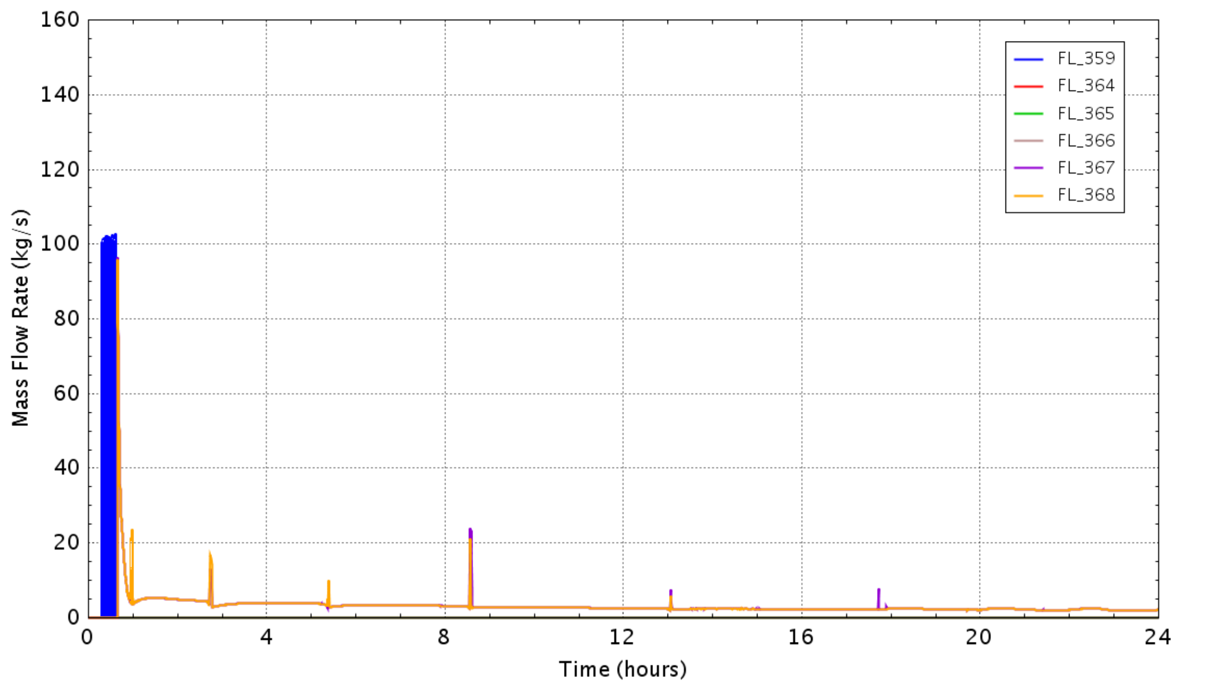

Figure C - 369   Flow rate of the SRVs

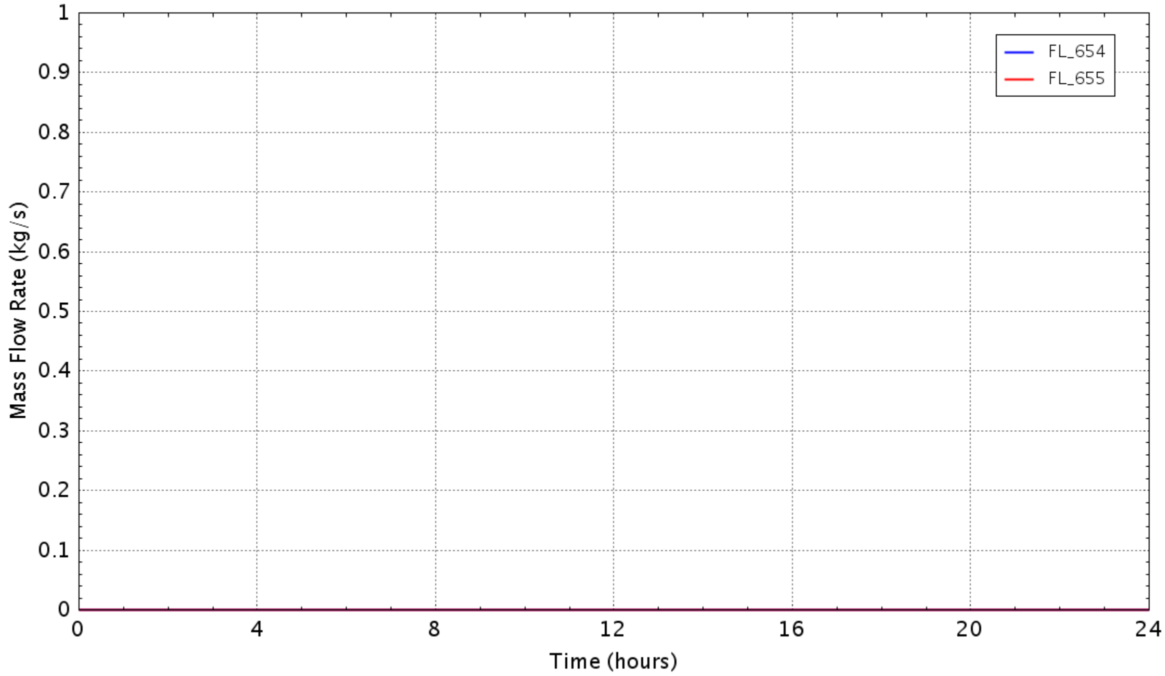

Figure C - 370 Flow rate of the wetwell cooling system

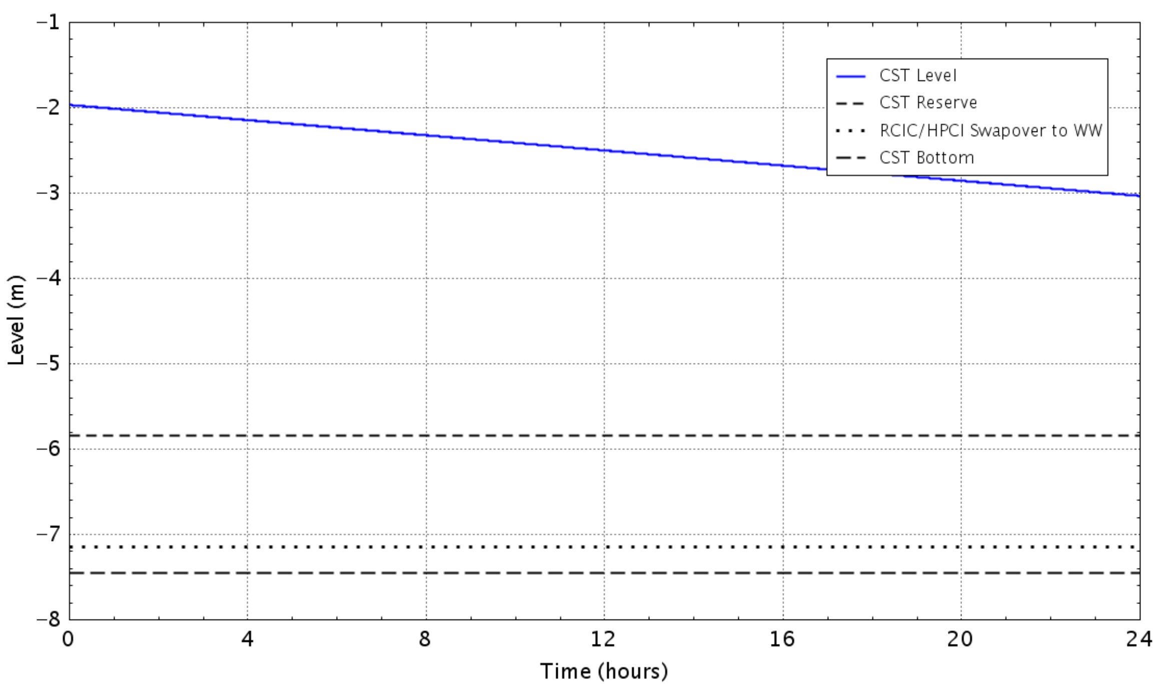

Figure C - 371 Water level in the CST

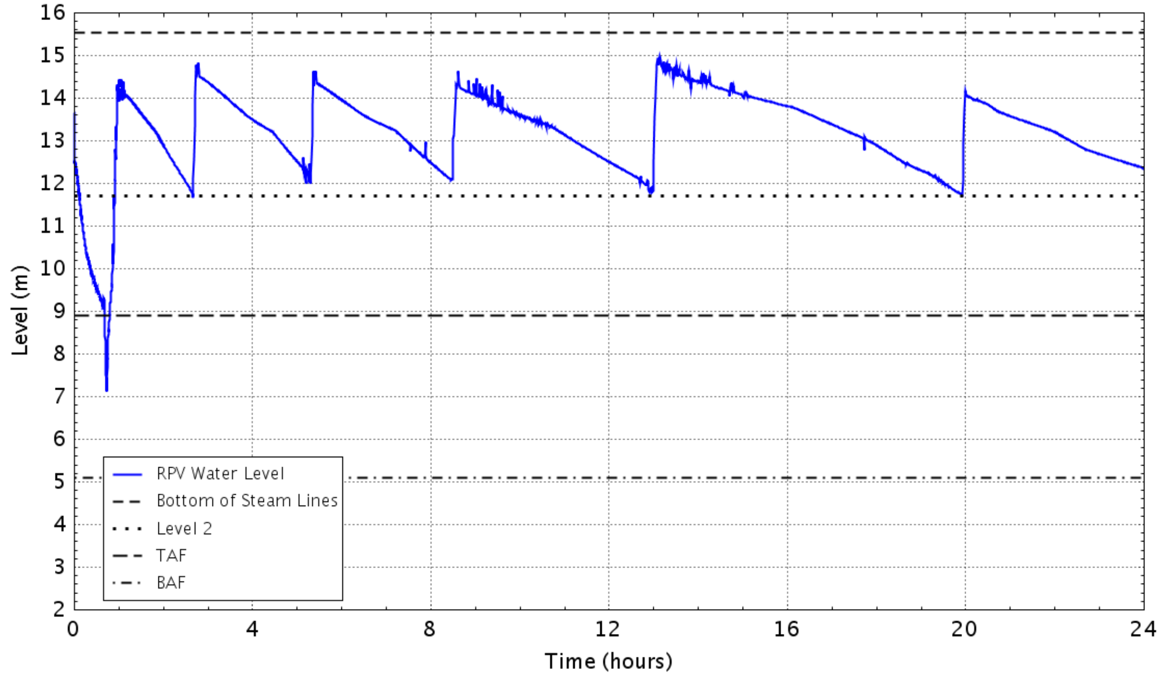

Figure C - 372 RPV Downcomer water level

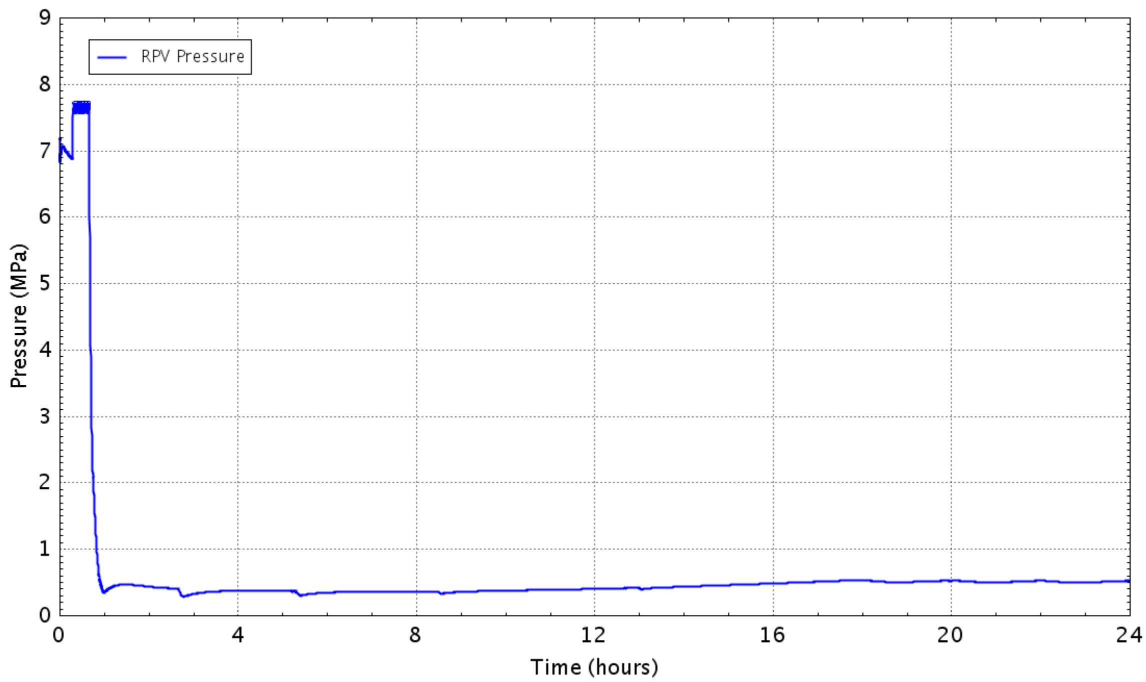

Figure C - 373 Pressure in the RPV

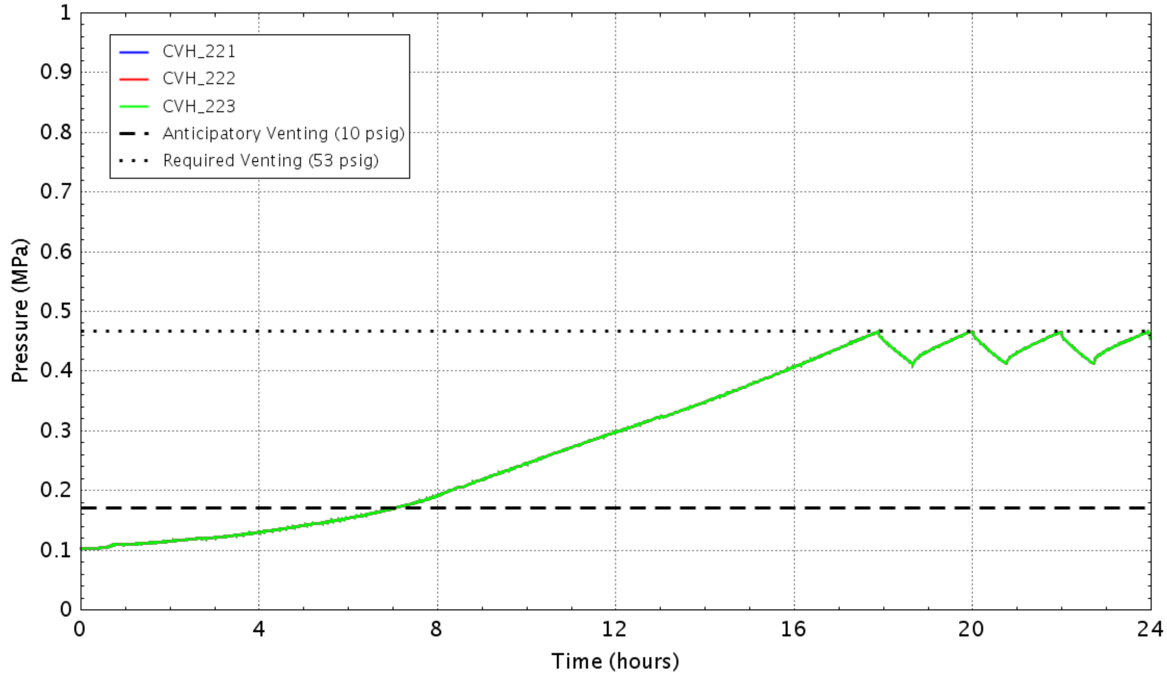

Figure C - 374 Pressure in the wetwell

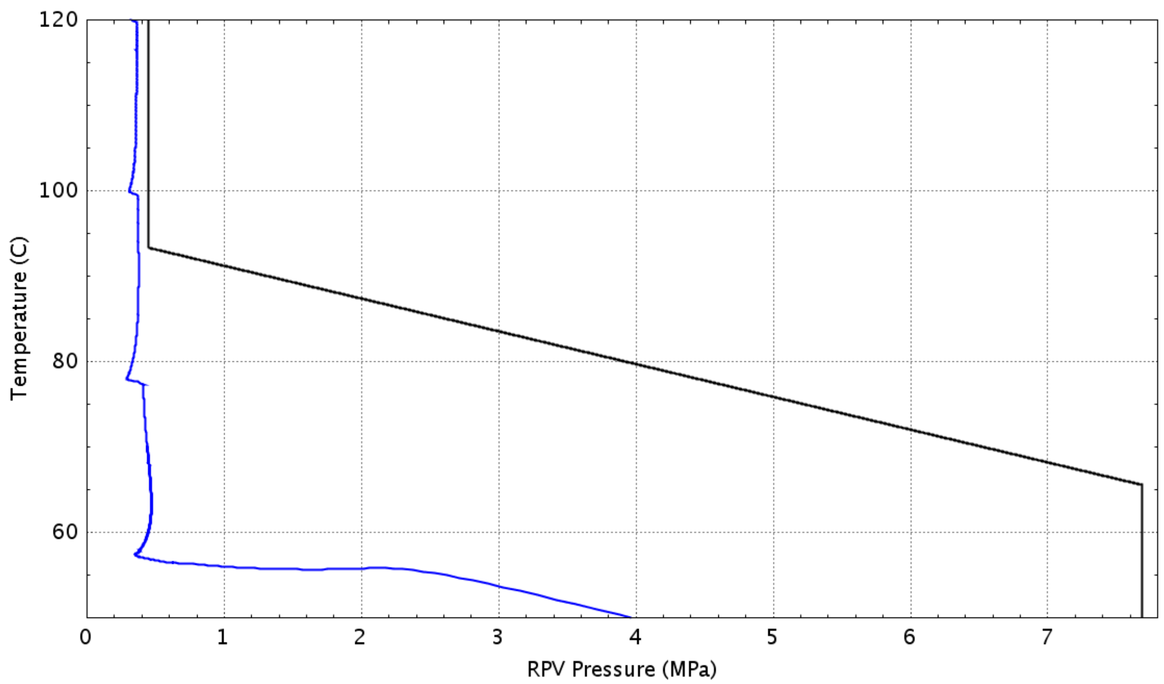

Figure C - 375 Plant status relative to the HCL curve (Graph 4 of the EOPs)

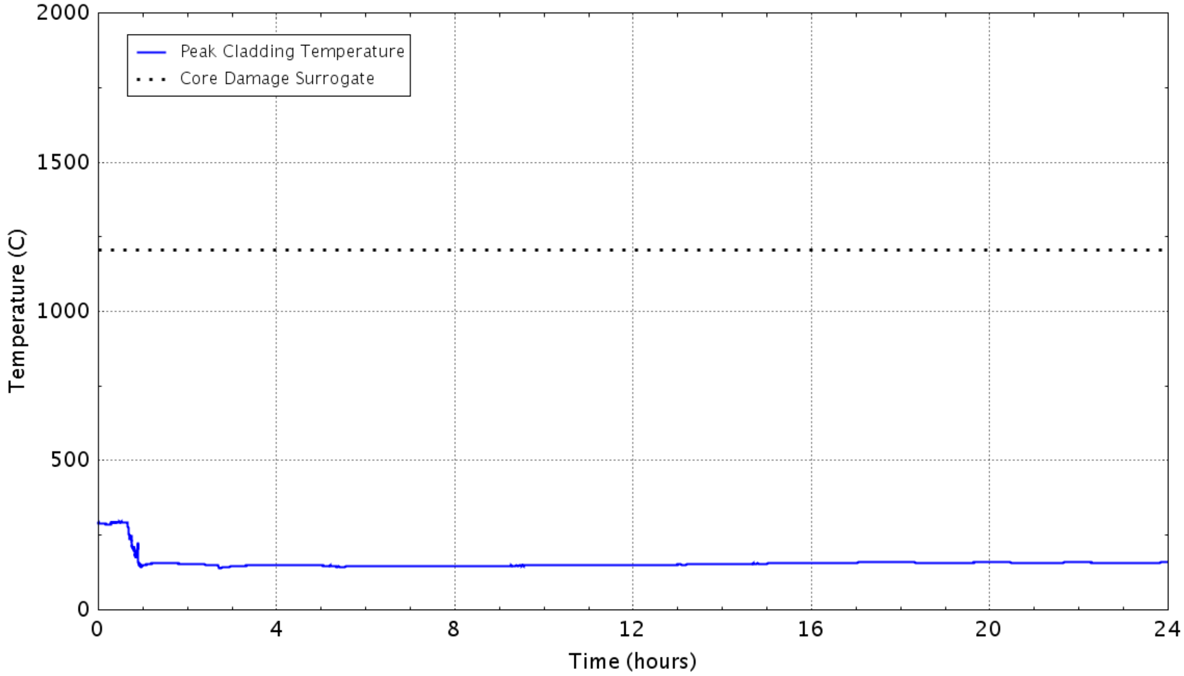

Figure C - 376 Peak temperature of the fuel cladding as a function of time

C.3.4 Case 6b: Sensitivity to TRANS-30 Case 6 with Automatic Initiation of ADS

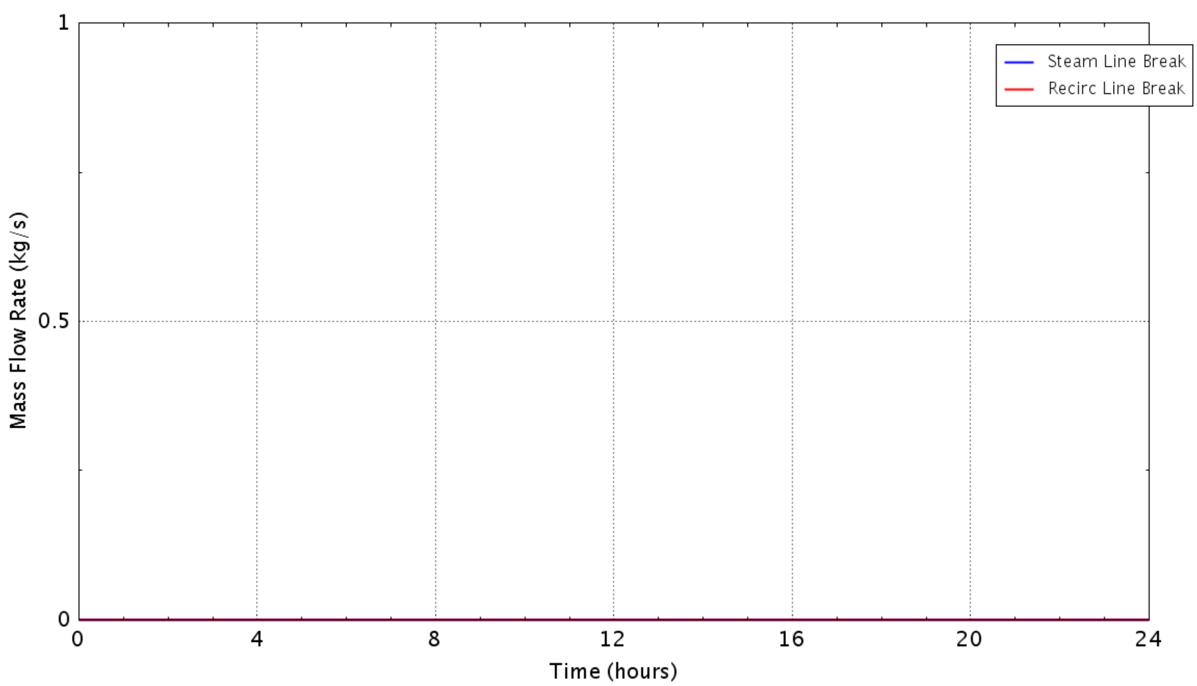

Figure C - 377 Flow rate of the break in the steamline/recirculation line

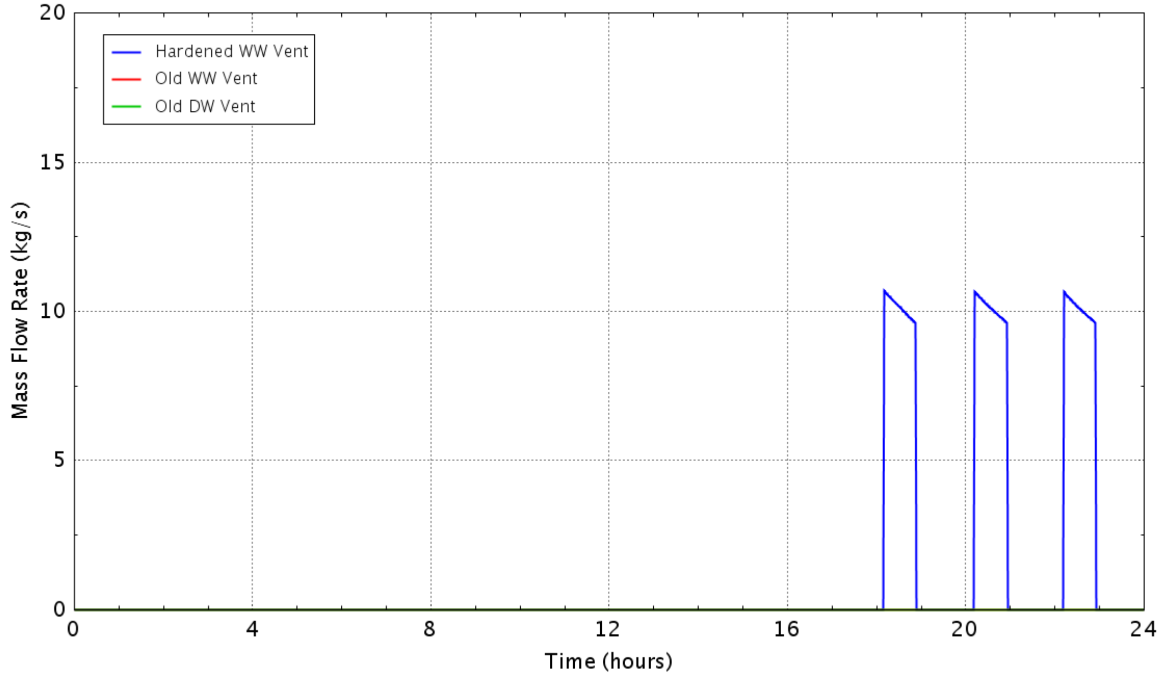

Figure C - 378 Flow rate of the containment vents

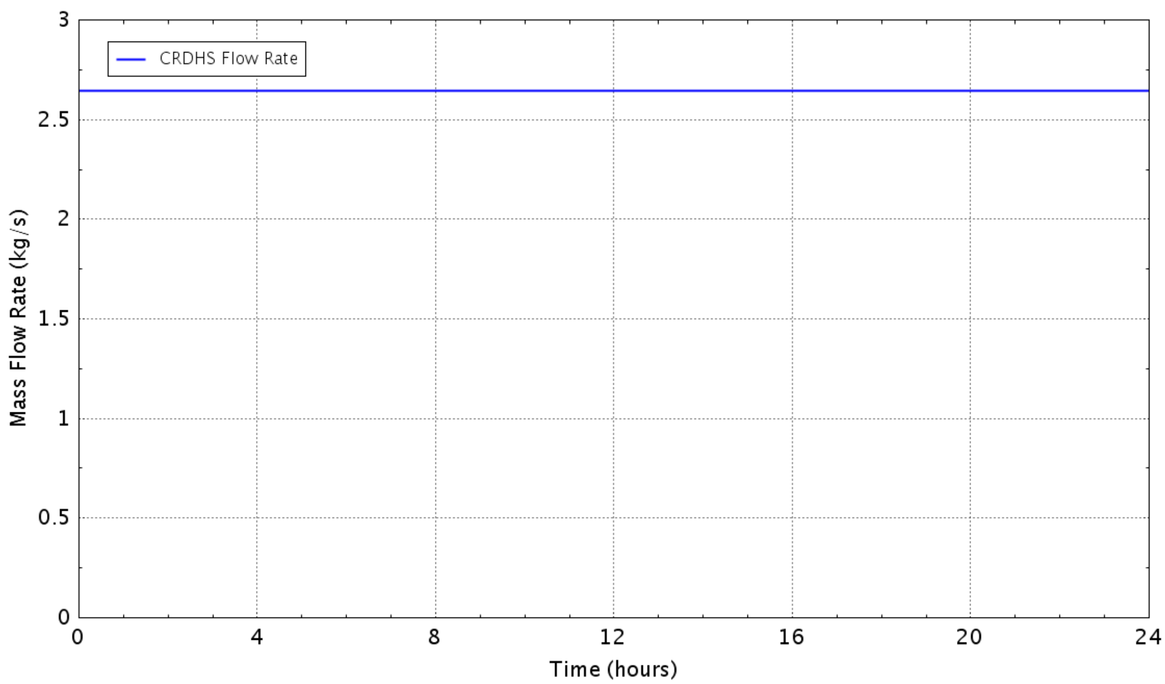

Figure C - 379 Flow rate of the control rod drive hydraulic system

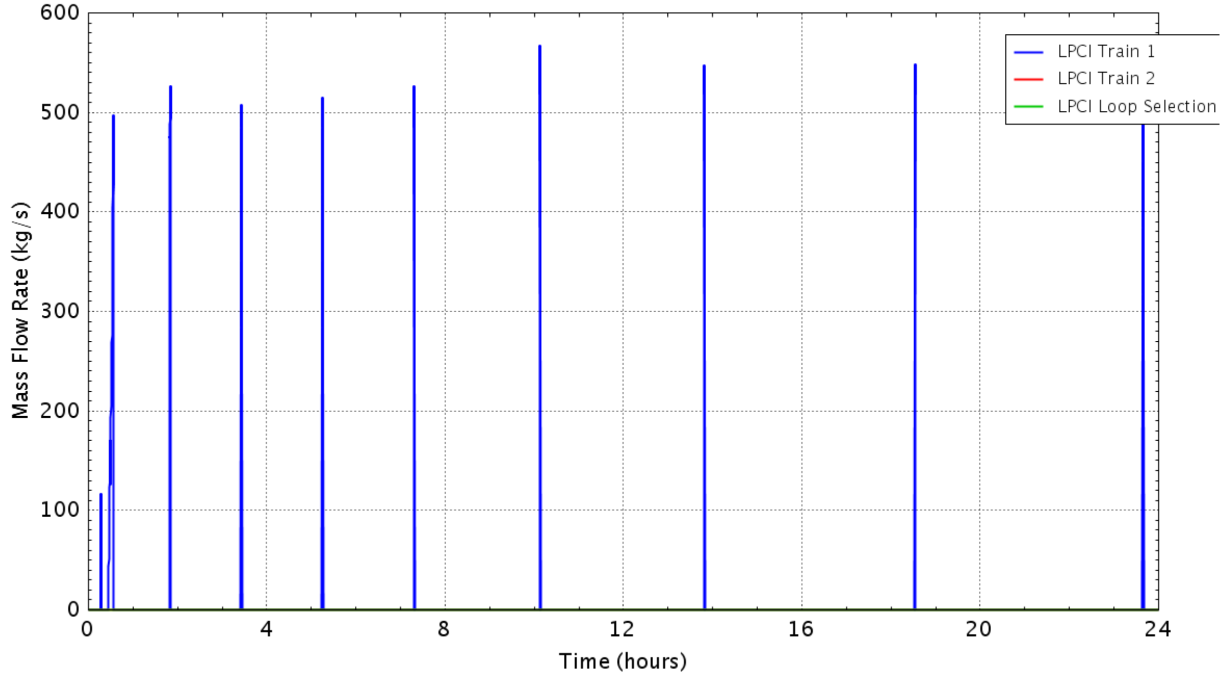

Figure C - 380 Flow rate of the LPCI pump

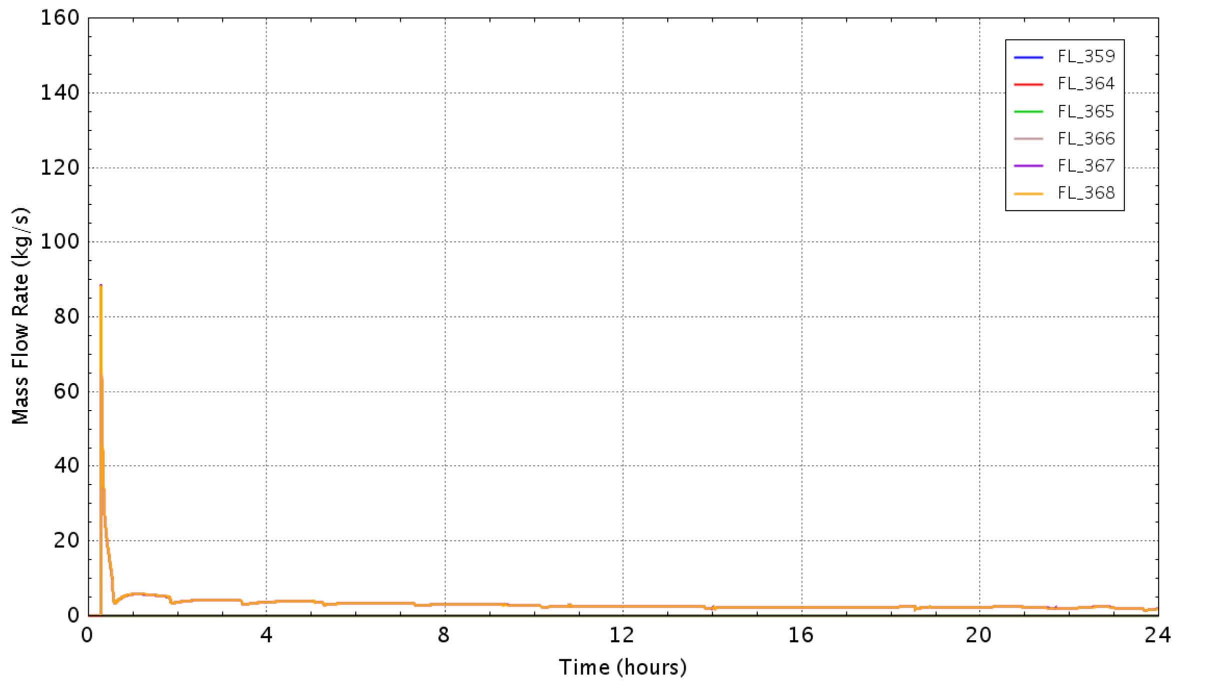

Figure C - 381 Flow rate of the SRVs

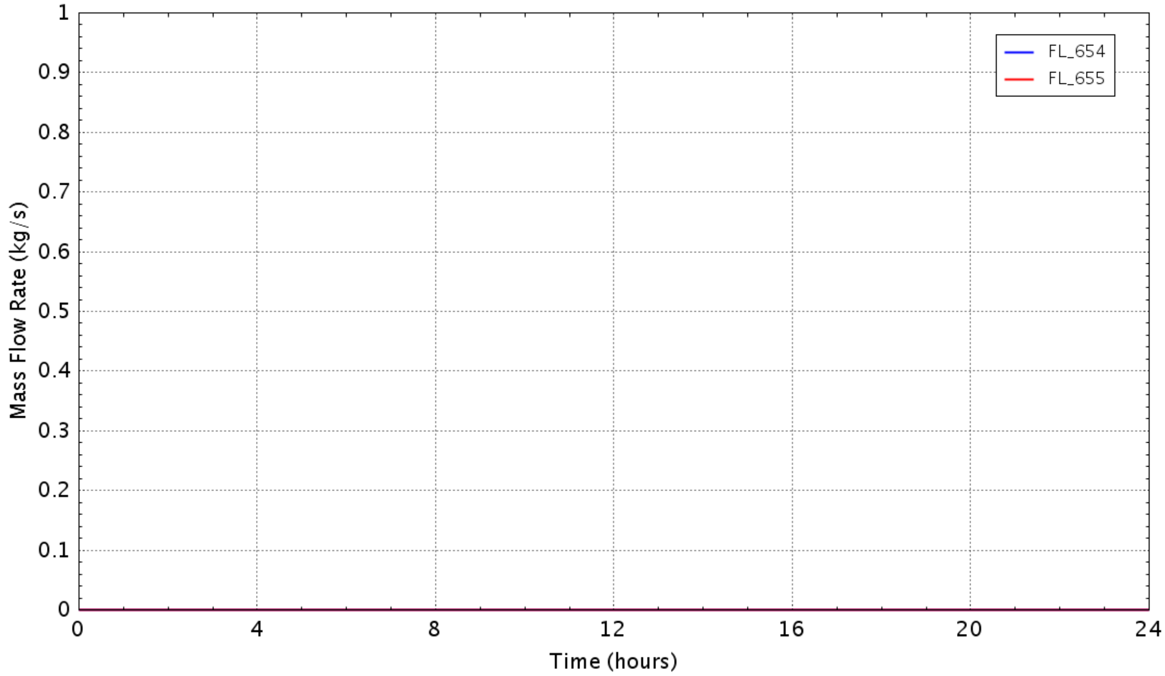

Figure C - 382   Flow rate of the wetwell cooling system

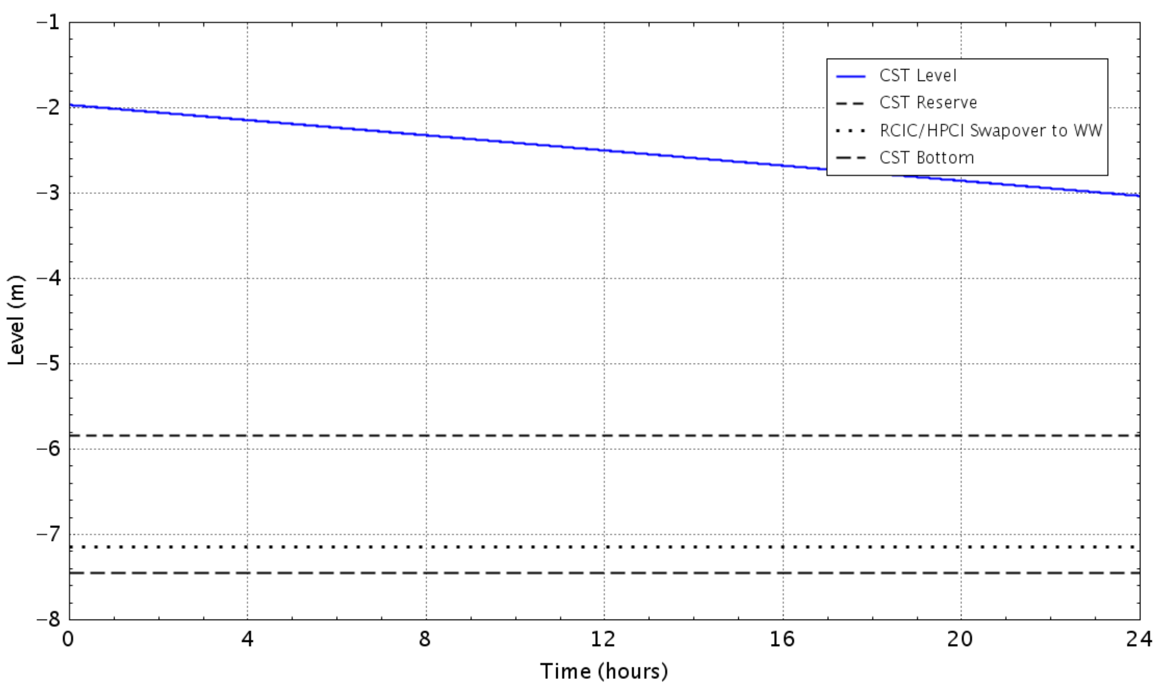

Figure C - 383   Water level in the CST

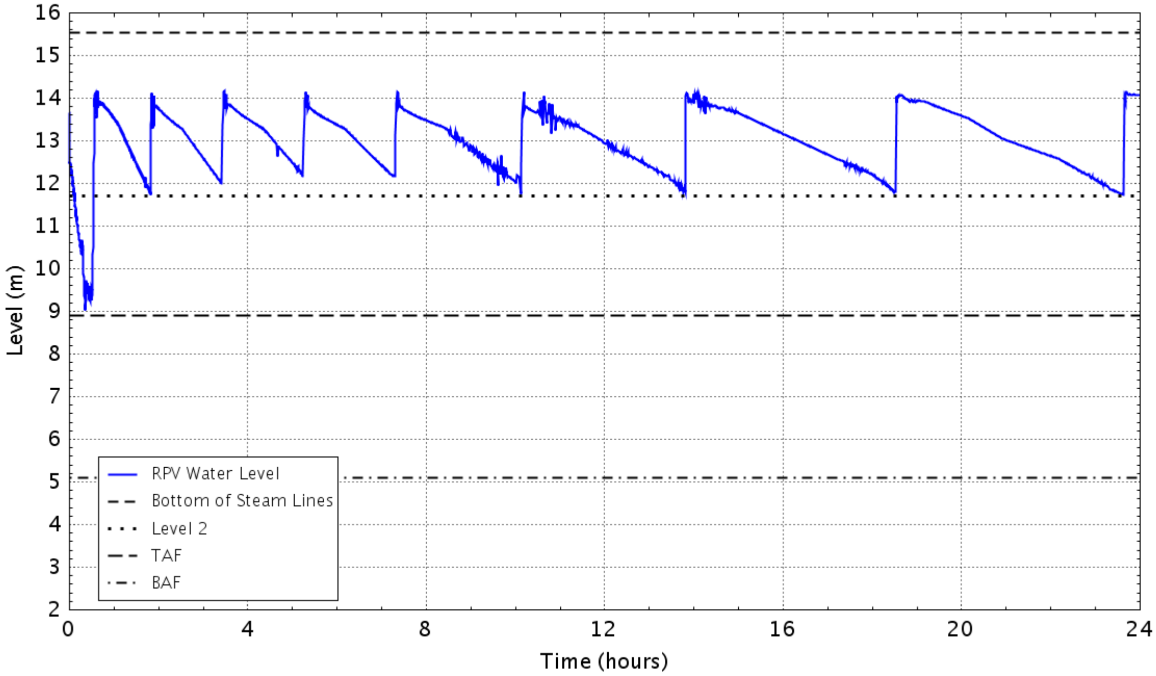

Figure C - 384 RPV Downcomer water level

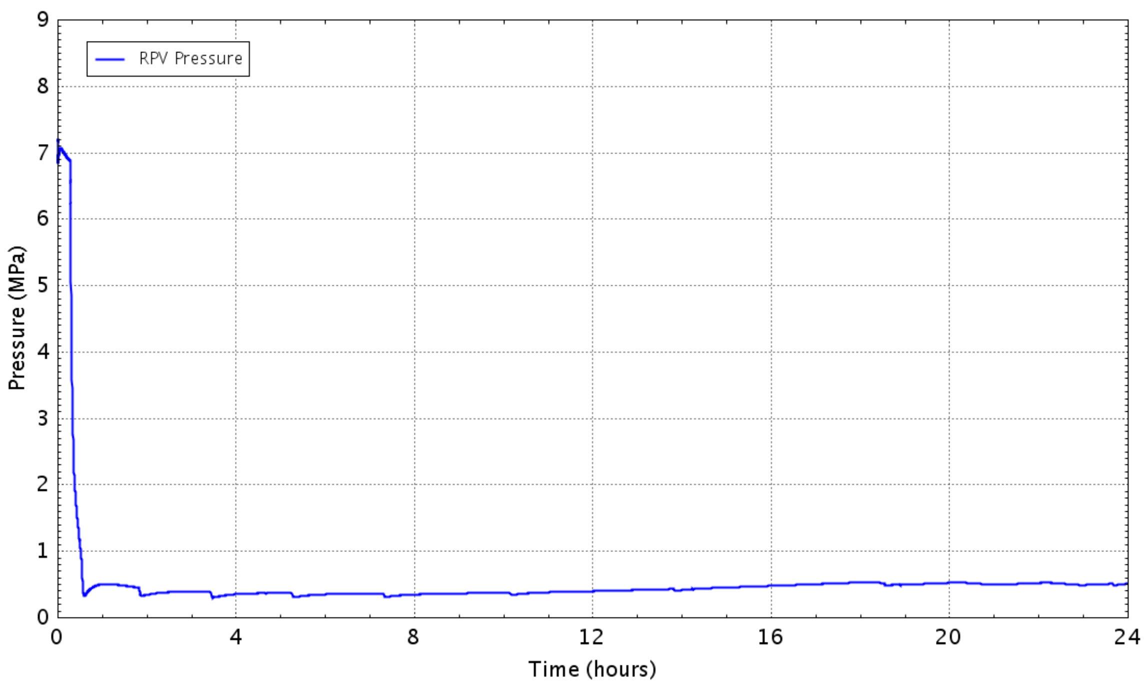

Figure C - 385 Pressure in the RPV

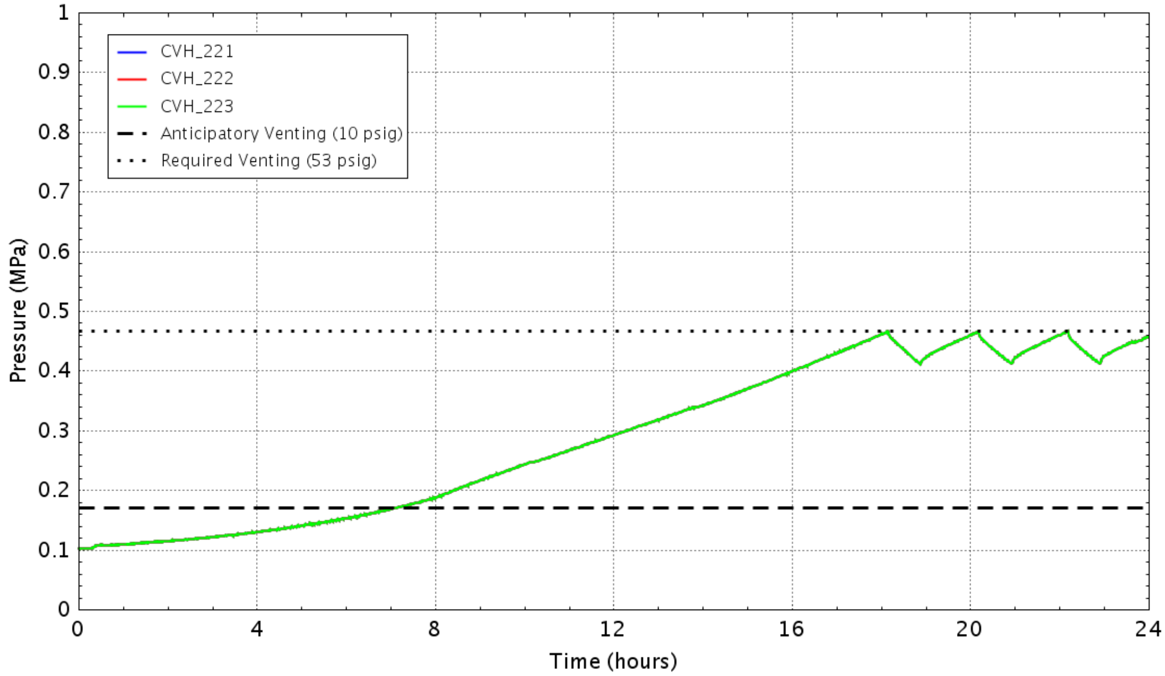

Figure C - 386   Pressure in the wetwell

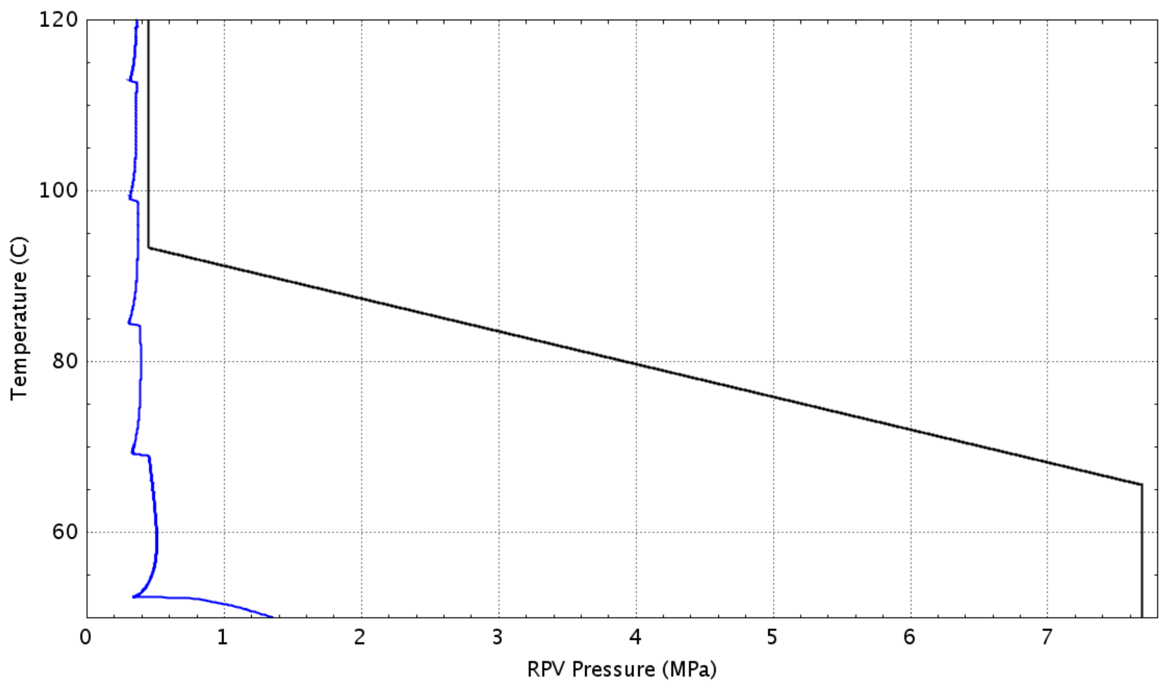

Figure C - 387   Plant status relative to the HCL curve (Graph 4 of the EOPs)

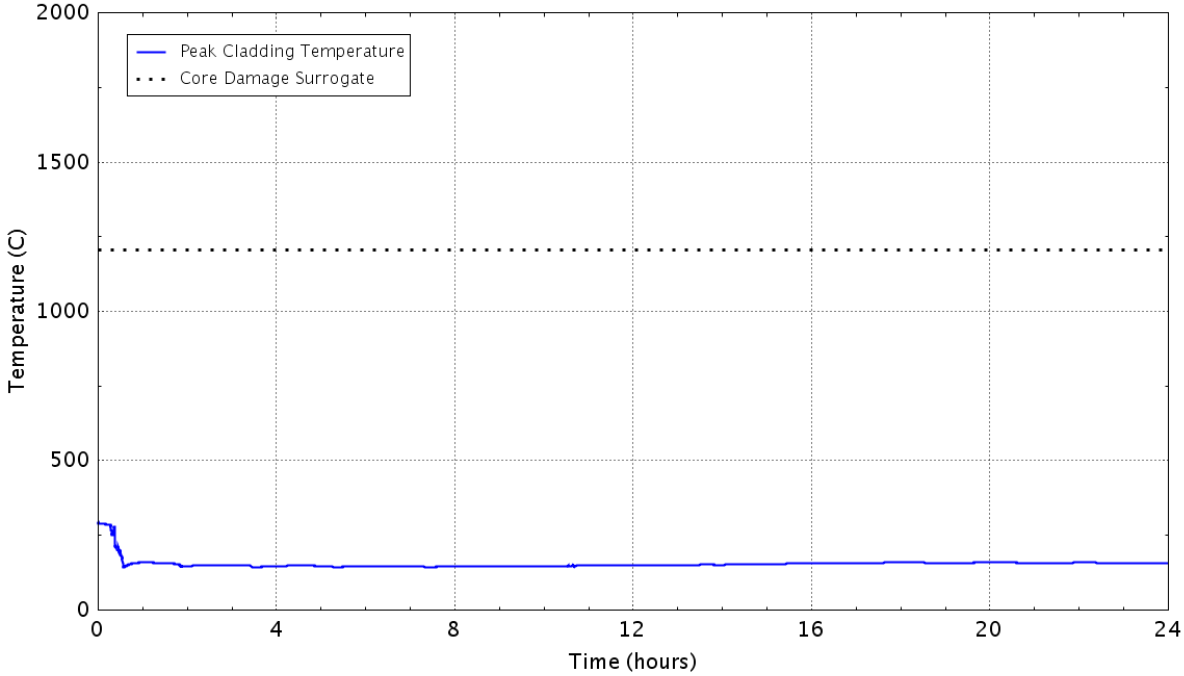

Figure C - 388 Peak temperature of the fuel cladding as a function of time

C.3.5 Case 6c: Sensitivity to TRANS-30 Case 6 with Nominal Recirculation Pump Seal Leakage

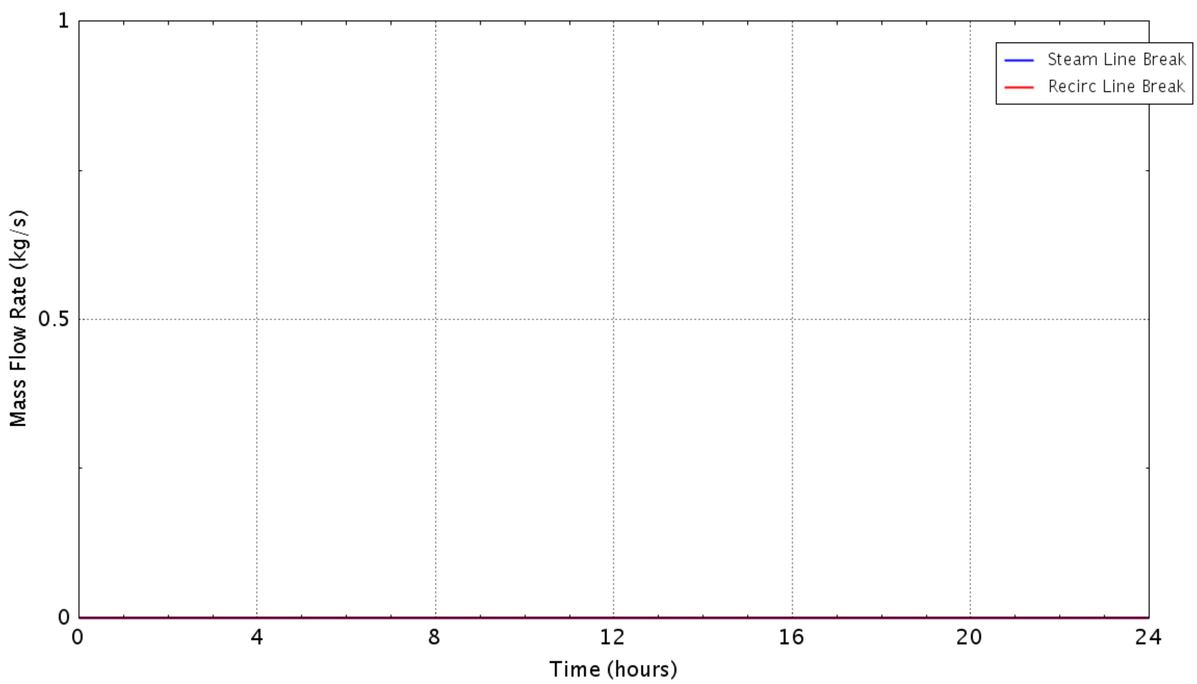

Figure C - 389 Flow rate of the break in the steamline/recirculation line

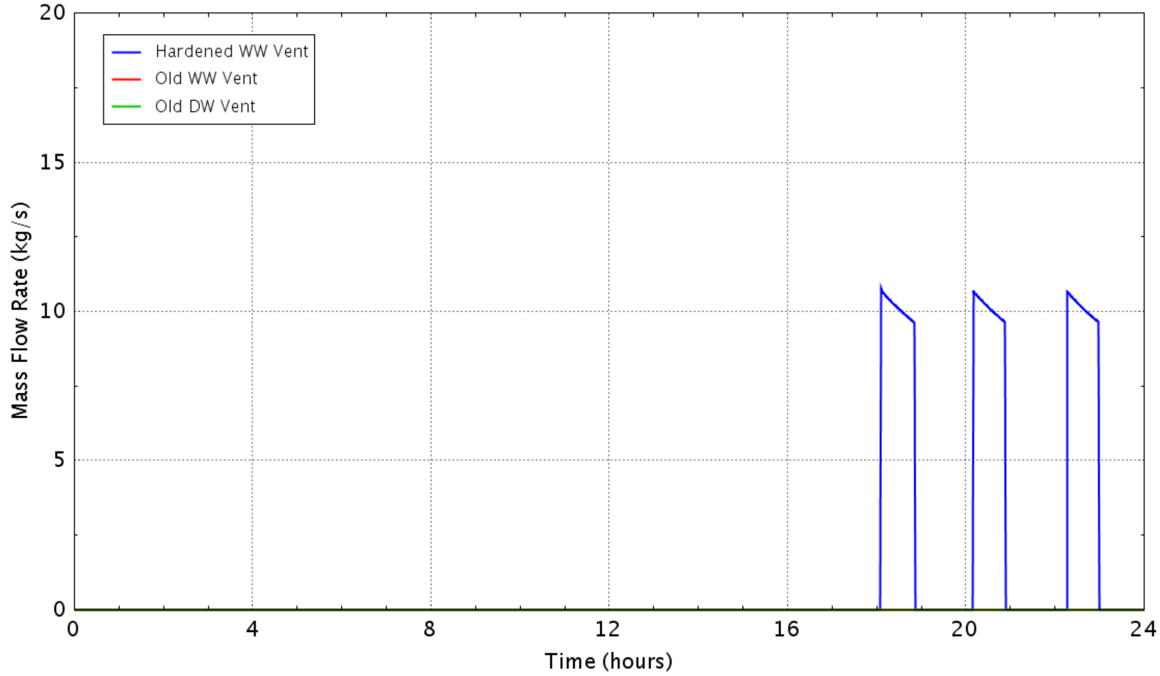

Figure C - 390 Flow rate of the containment vents

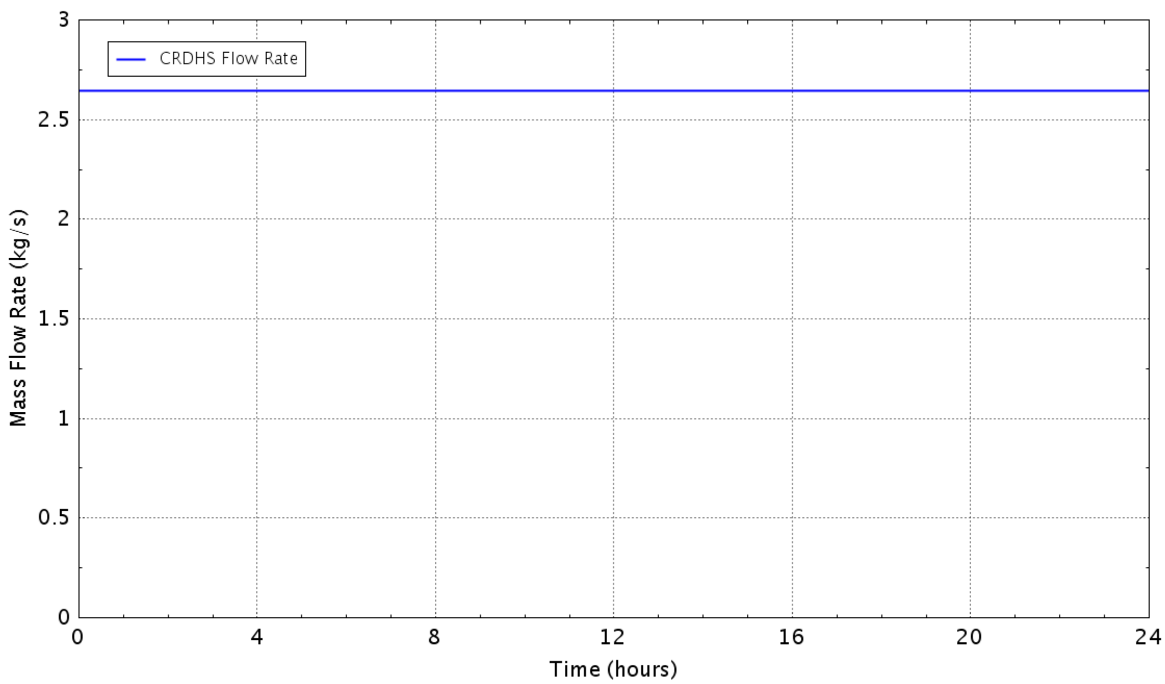

Figure C - 391 Flow rate of the control rod drive hydraulic system

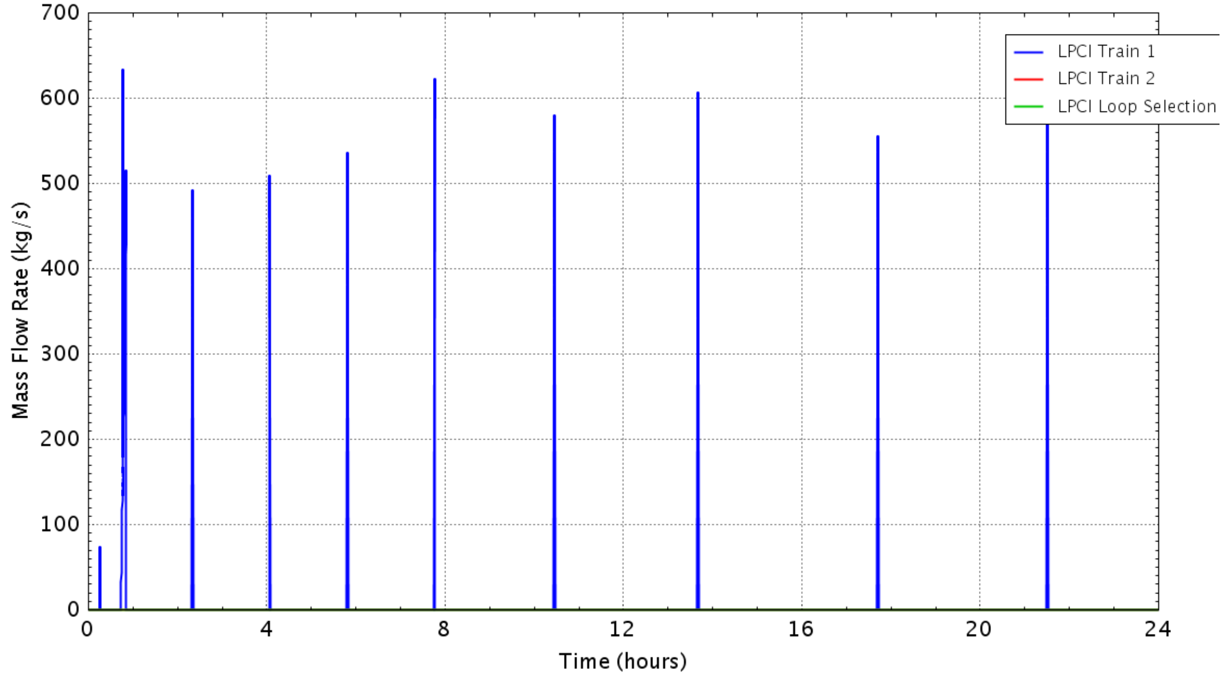

Figure C - 392 Flow rate of the LPCI pump

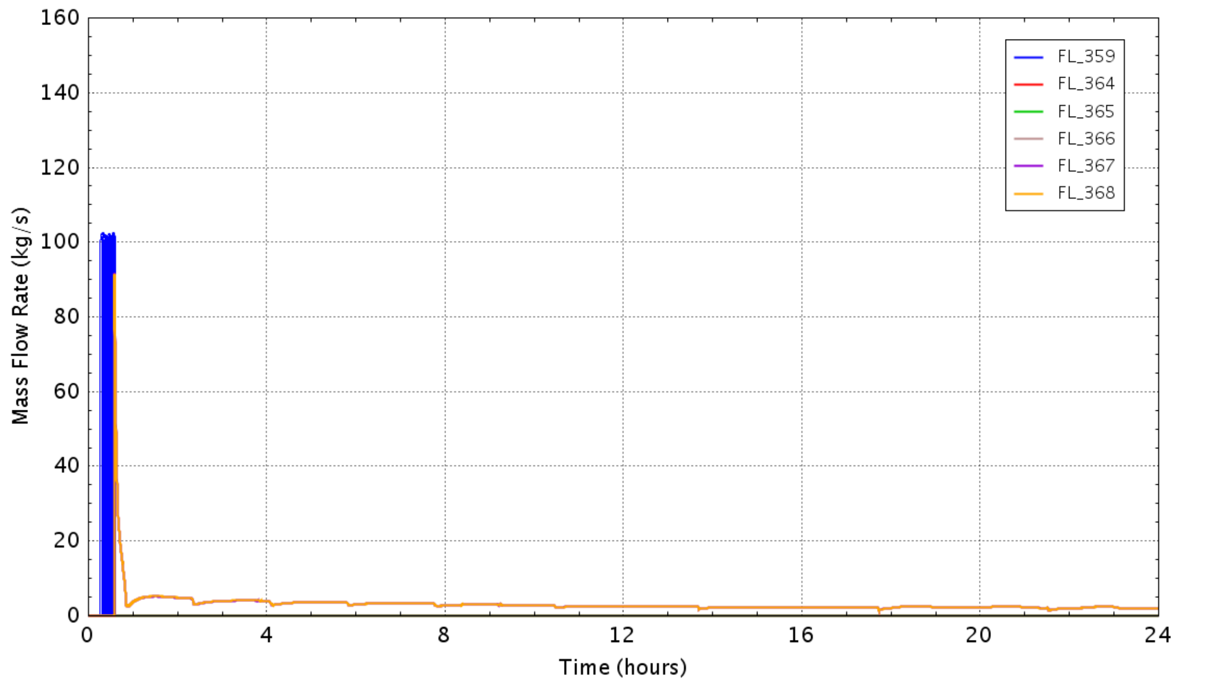

Figure C - 393 Flow rate of the SRVs

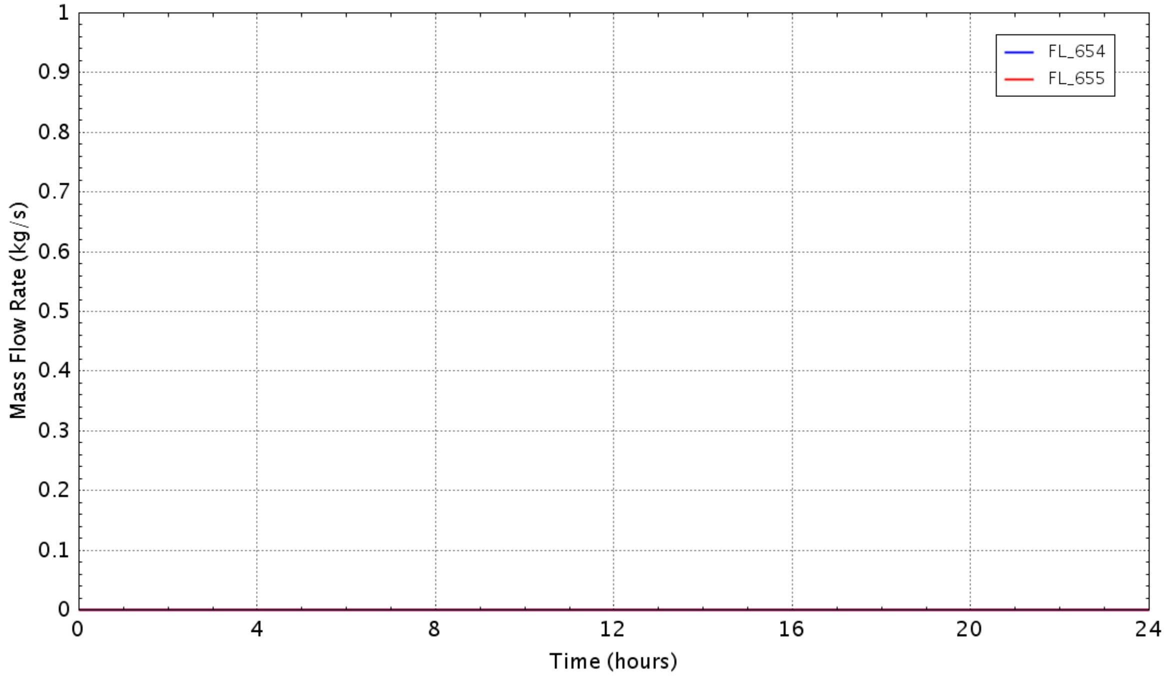

Figure C - 394 Flow rate of the wetwell cooling system

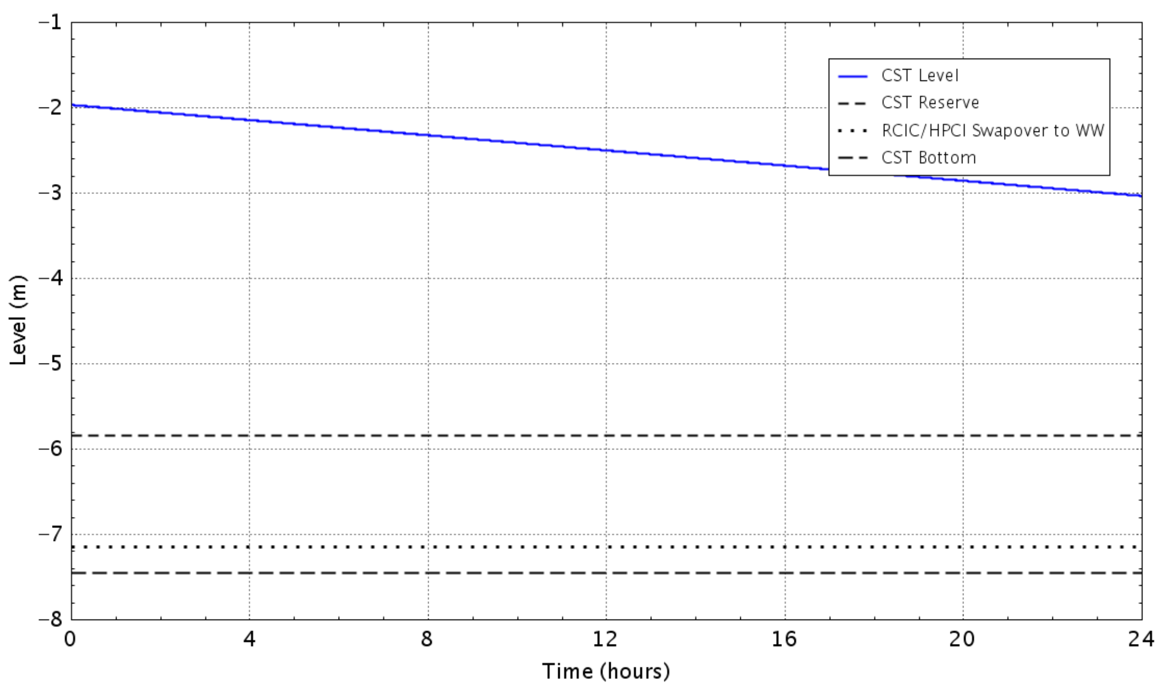

Figure C - 395 Water level in the CST

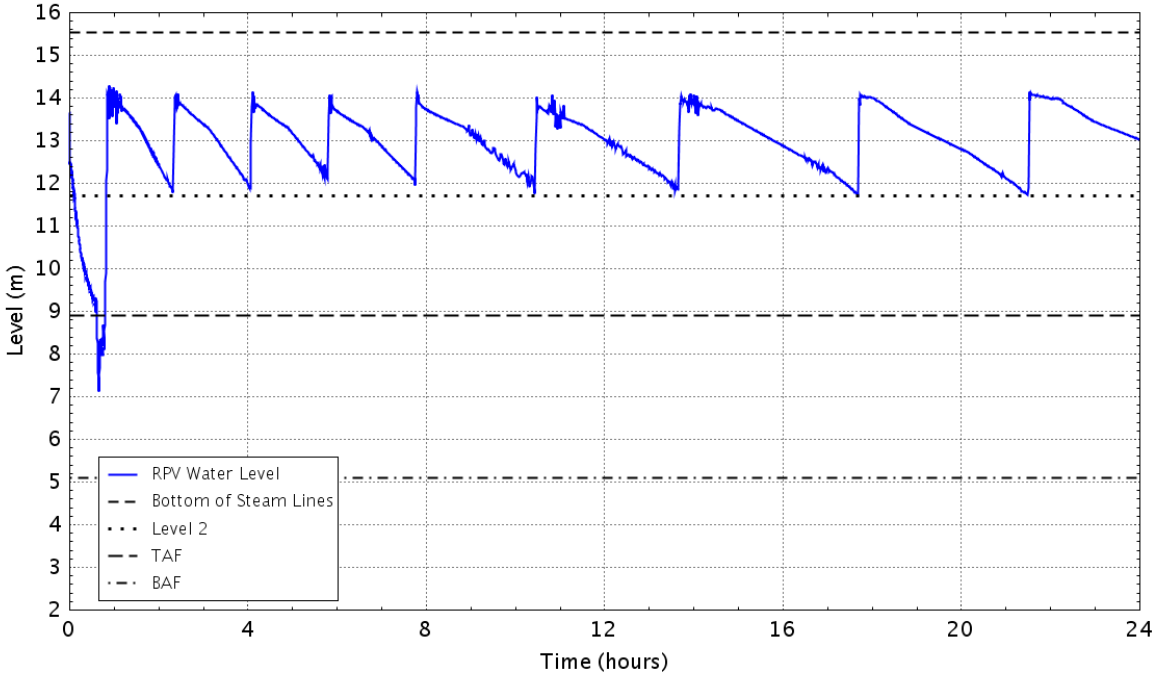

Figure C - 396   RPV Downcomer water level

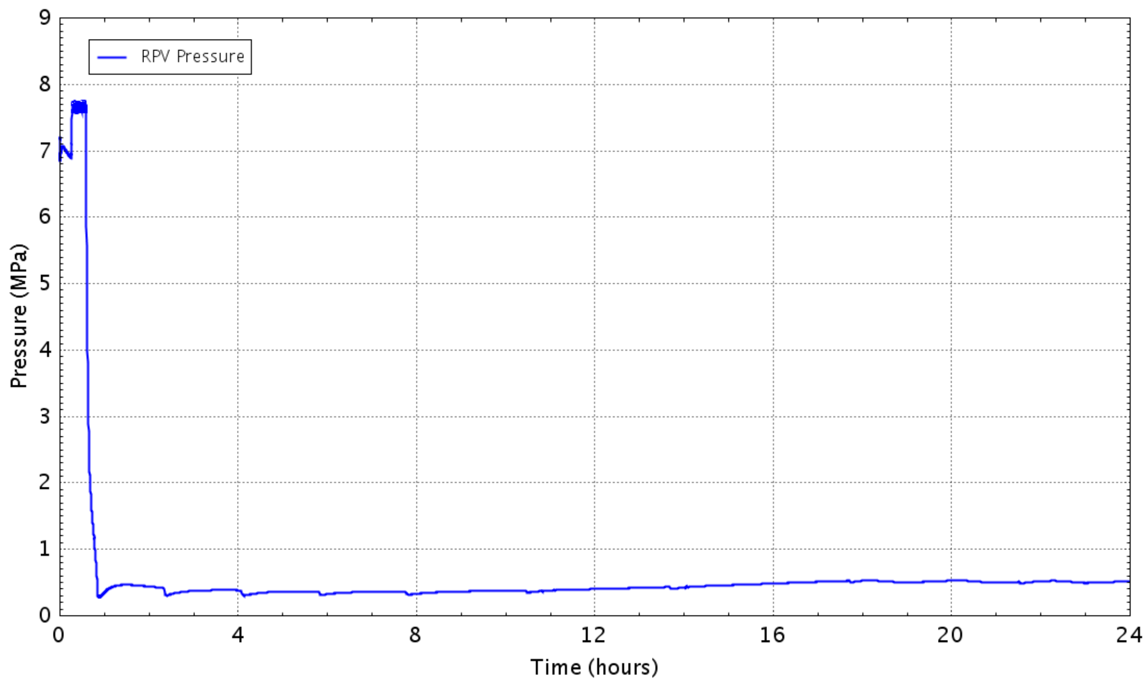

Figure C - 397 Pressure in the RPV

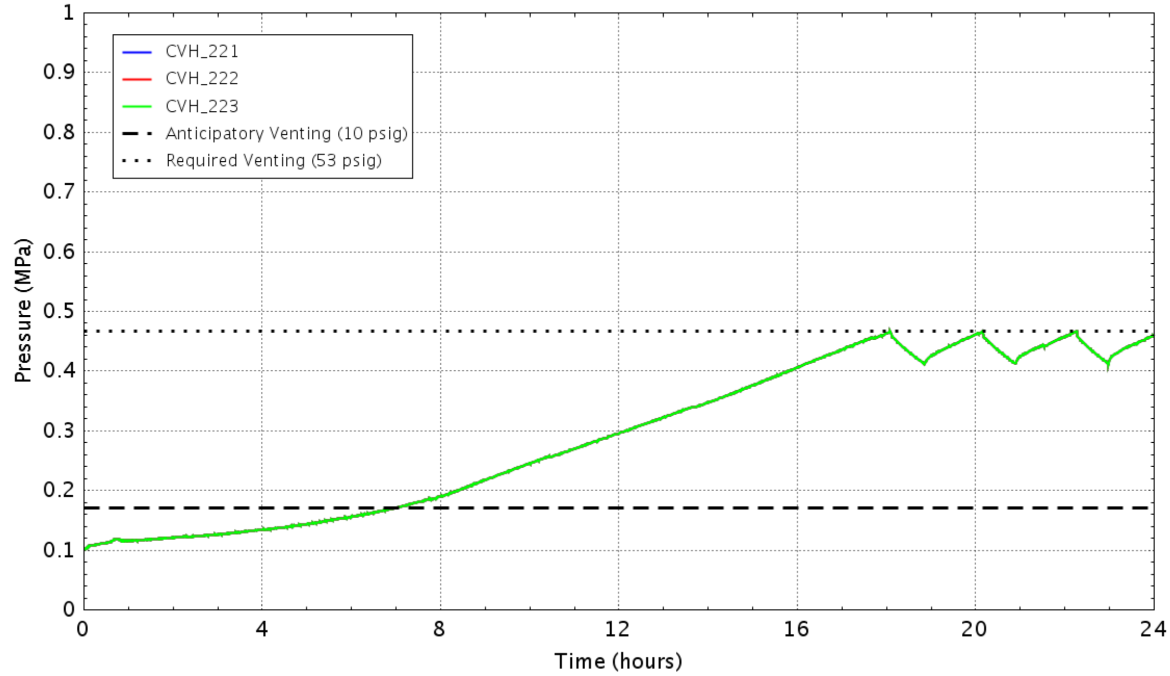

Figure C - 398 Pressure in the wetwell

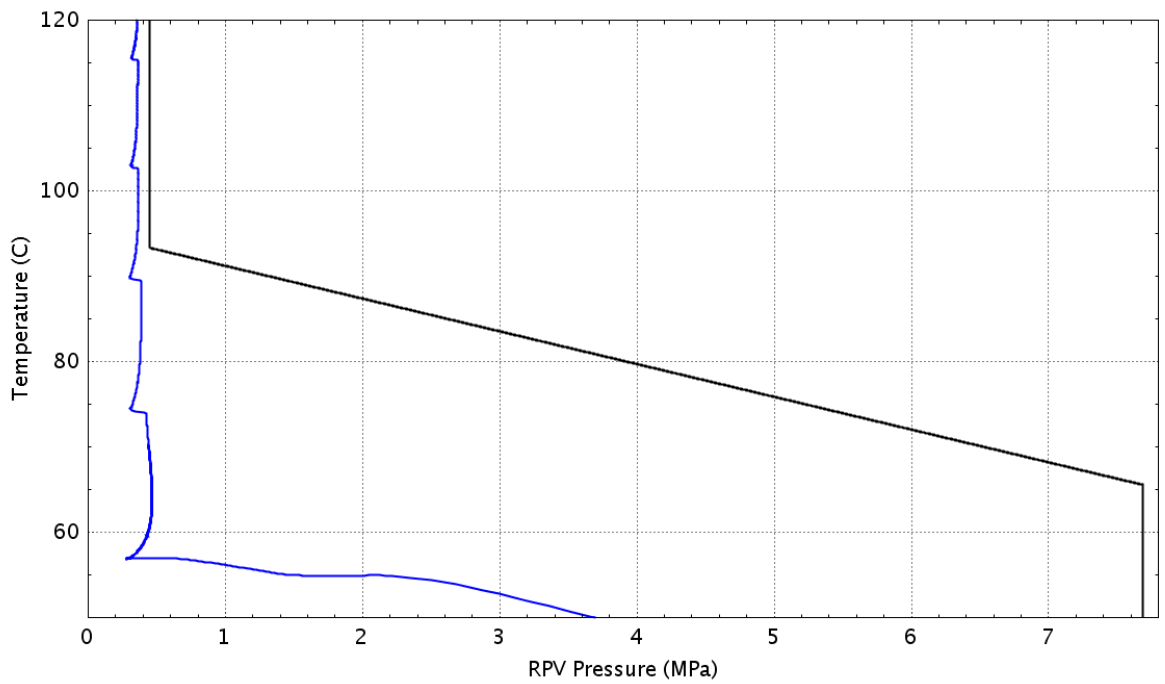

Figure C - 399 Plant status relative to the HCL curve (Graph 4 of the EOPs)

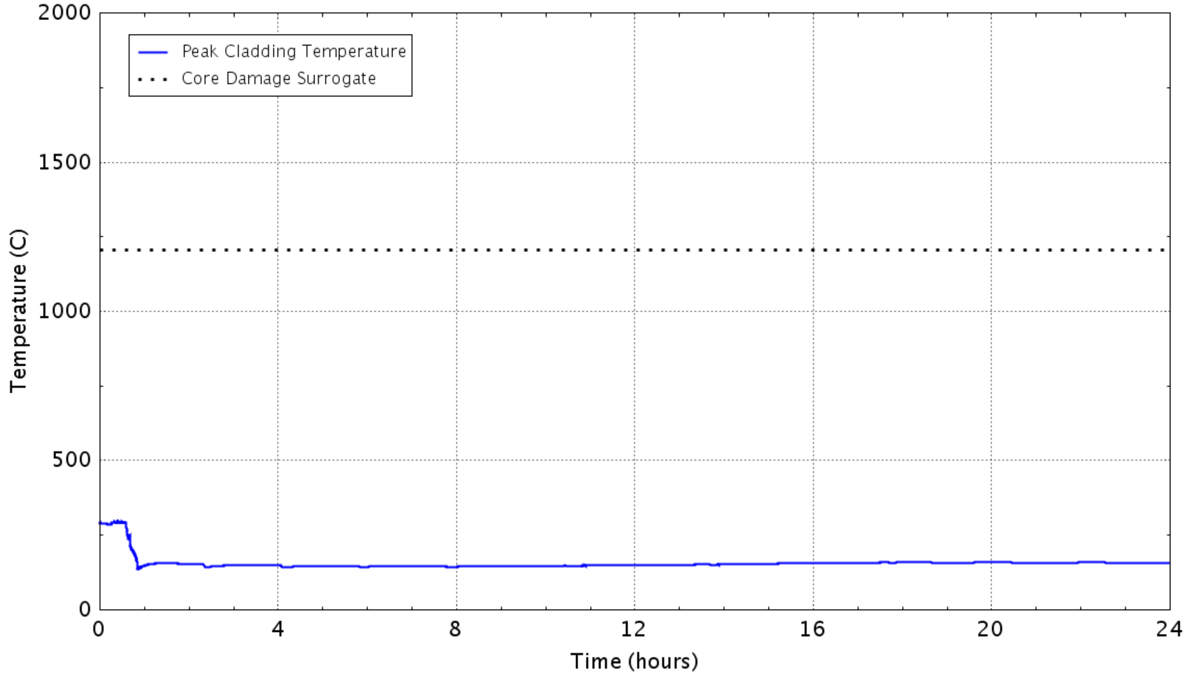

Figure C - 400 Peak temperature of the fuel cladding as a function of time

C.3.6 Case 7a: Sensitivity to TRANS-30 Case 7 with FeedwaterLine Isolated at Time 0

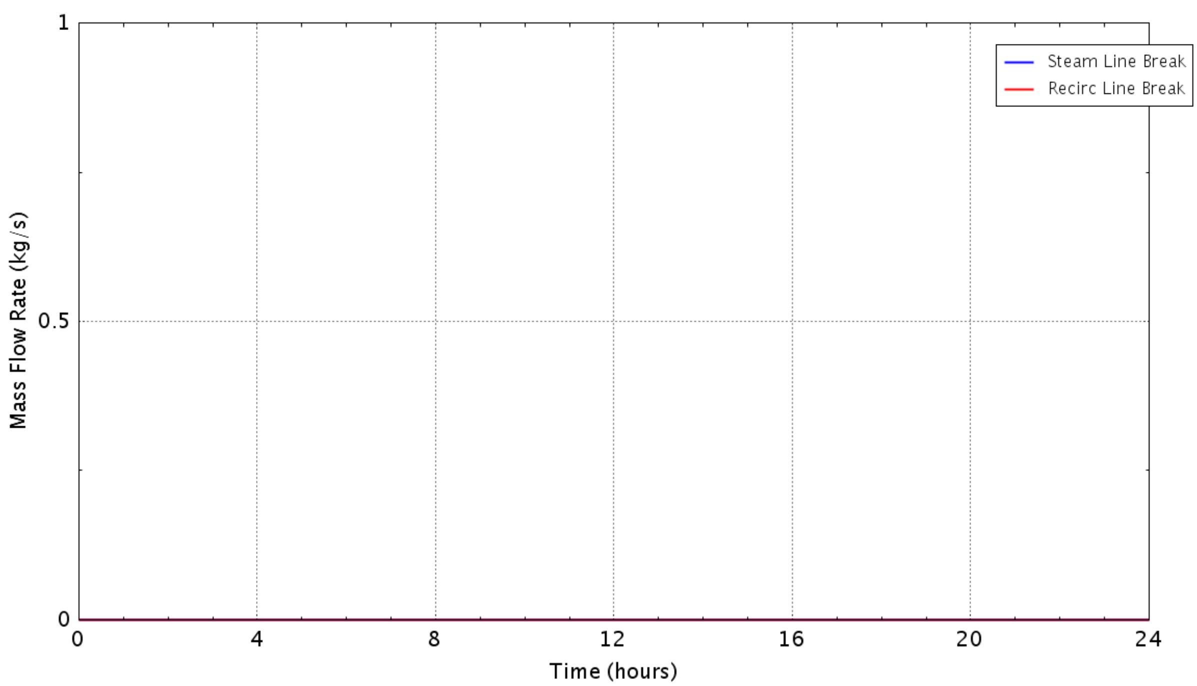

Figure C - 401 Flow rate of the break in the steamline/recirculation line

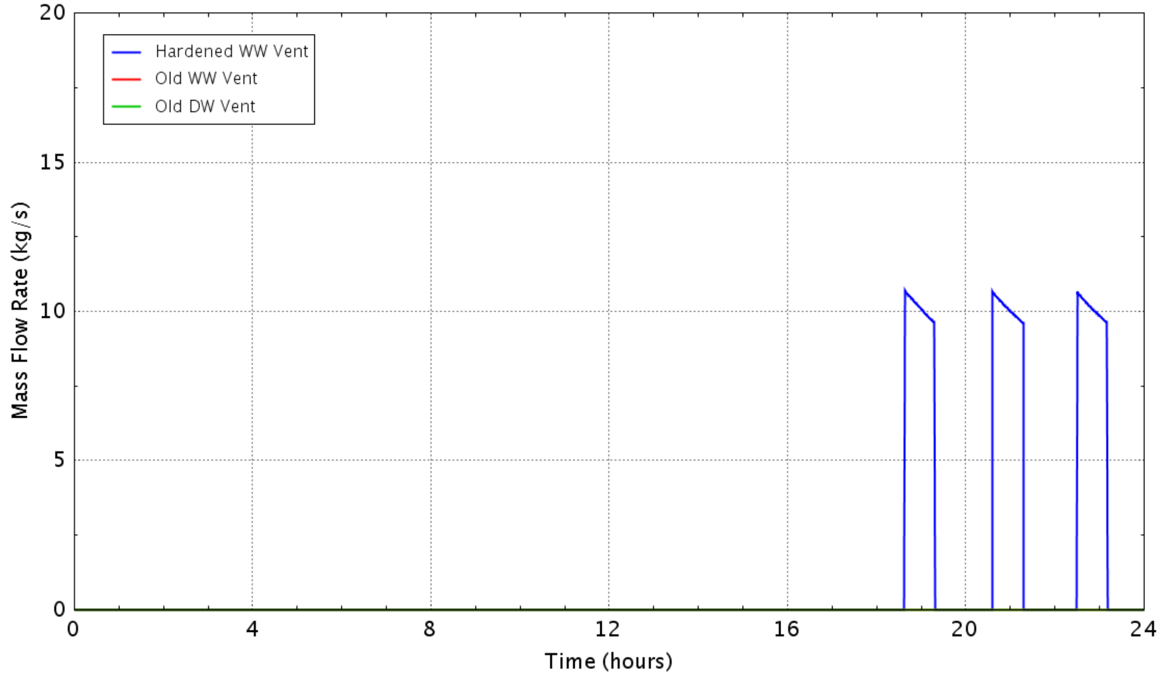

Figure C - 402 Flow rate of the containment vents

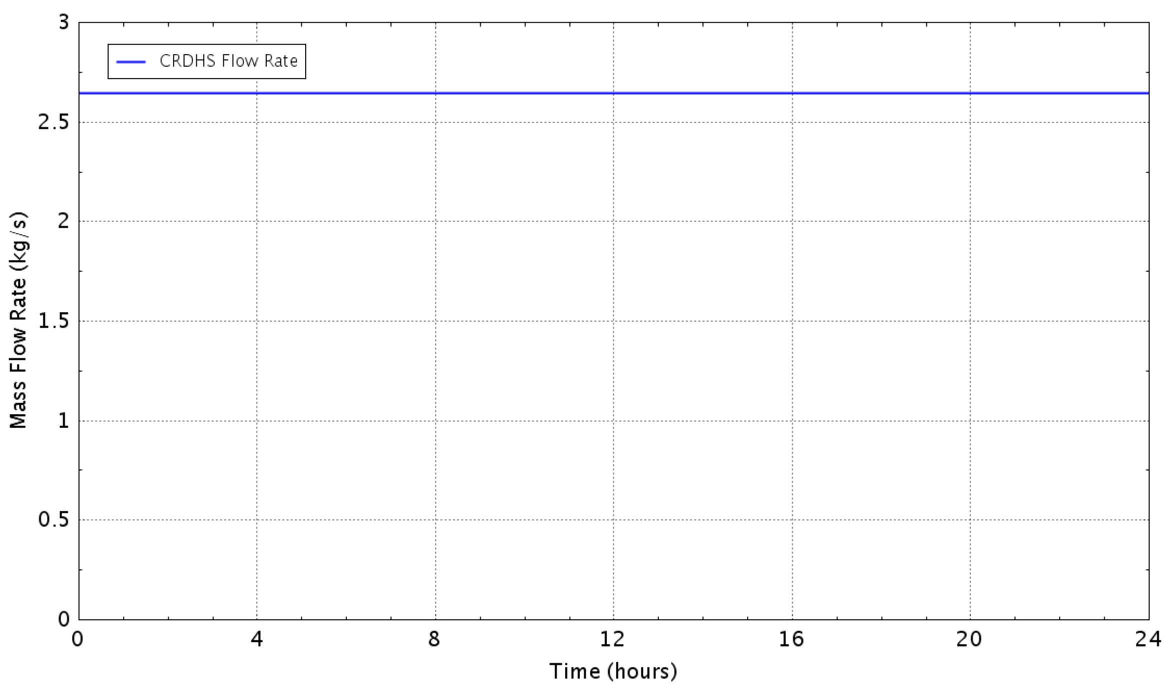

Figure C - 403 Flow rate of the control rod drive hydraulic system

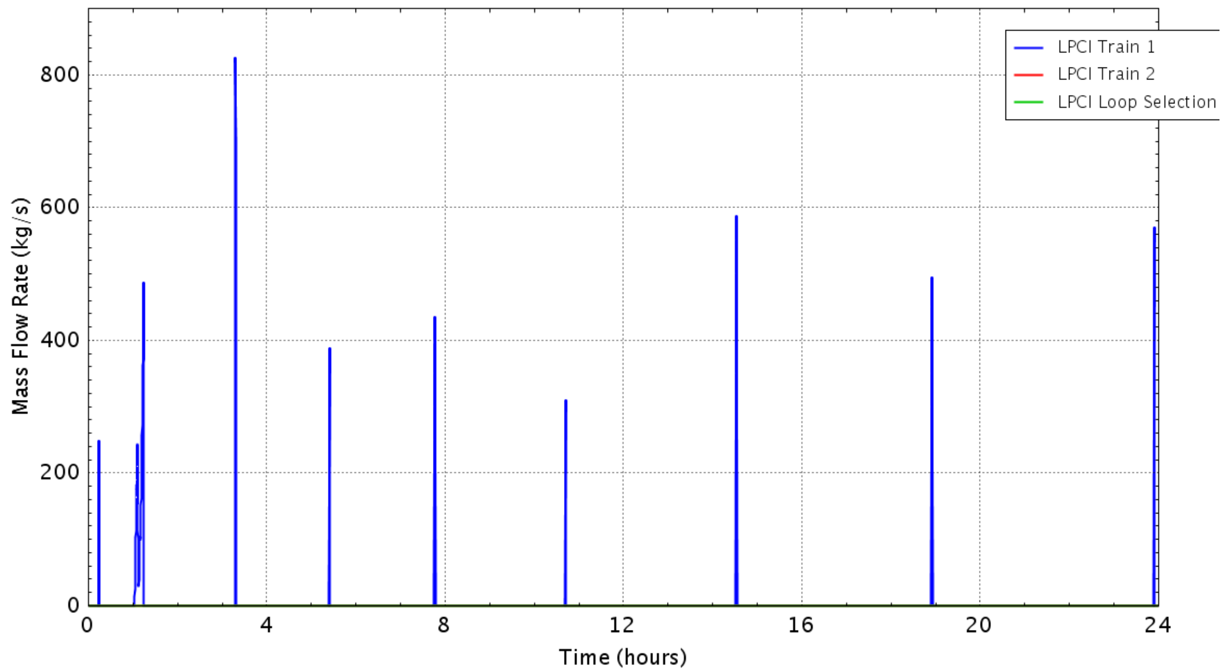

Figure C - 404 Flow rate of the LPCI pump

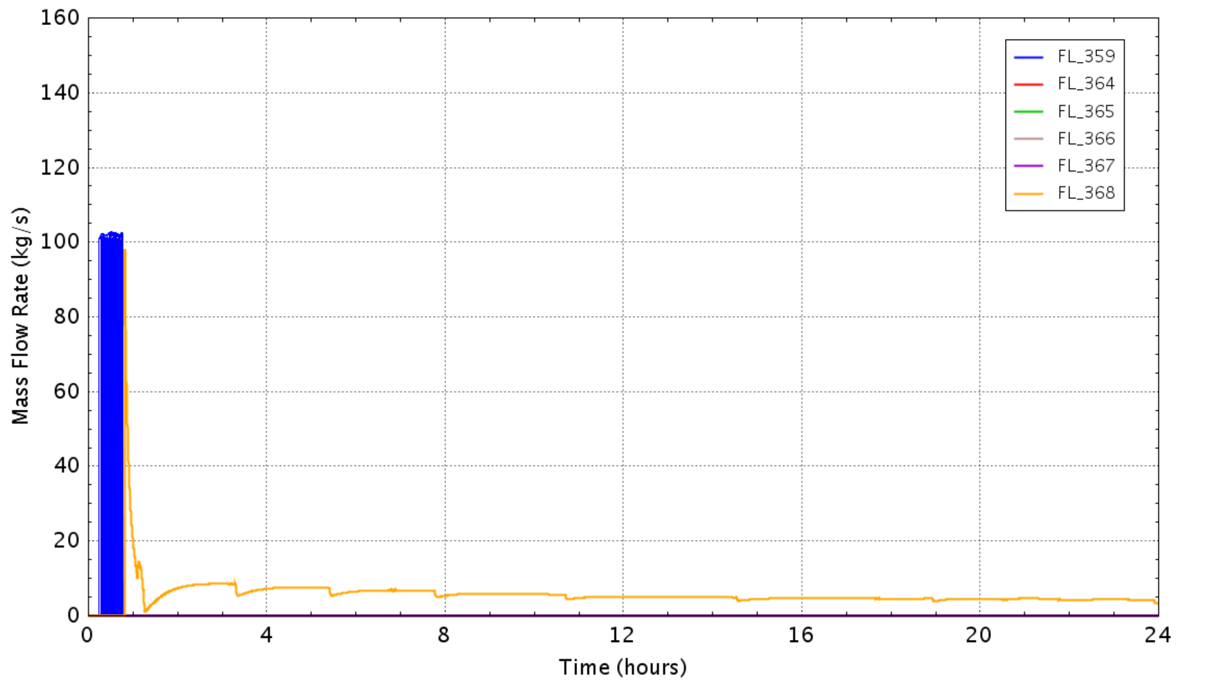

Figure C - 405 Flow rate of the SRVs

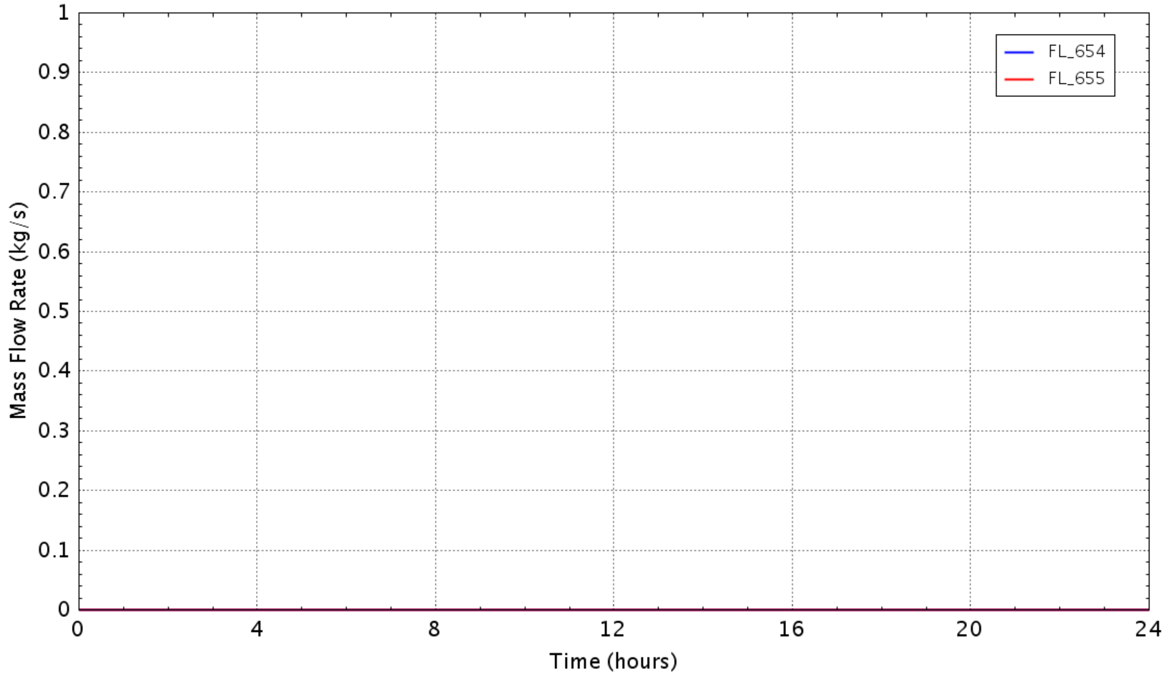

Figure C - 406   Flow rate of the wetwell cooling system

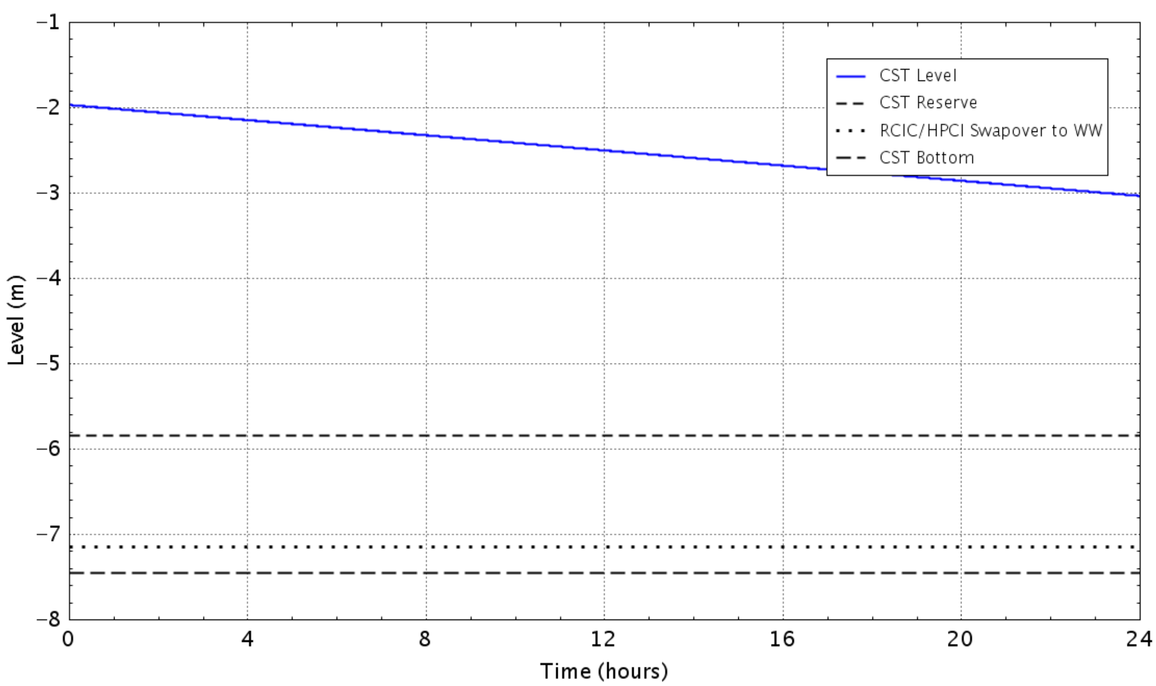

Figure C - 407   Water level in the CST

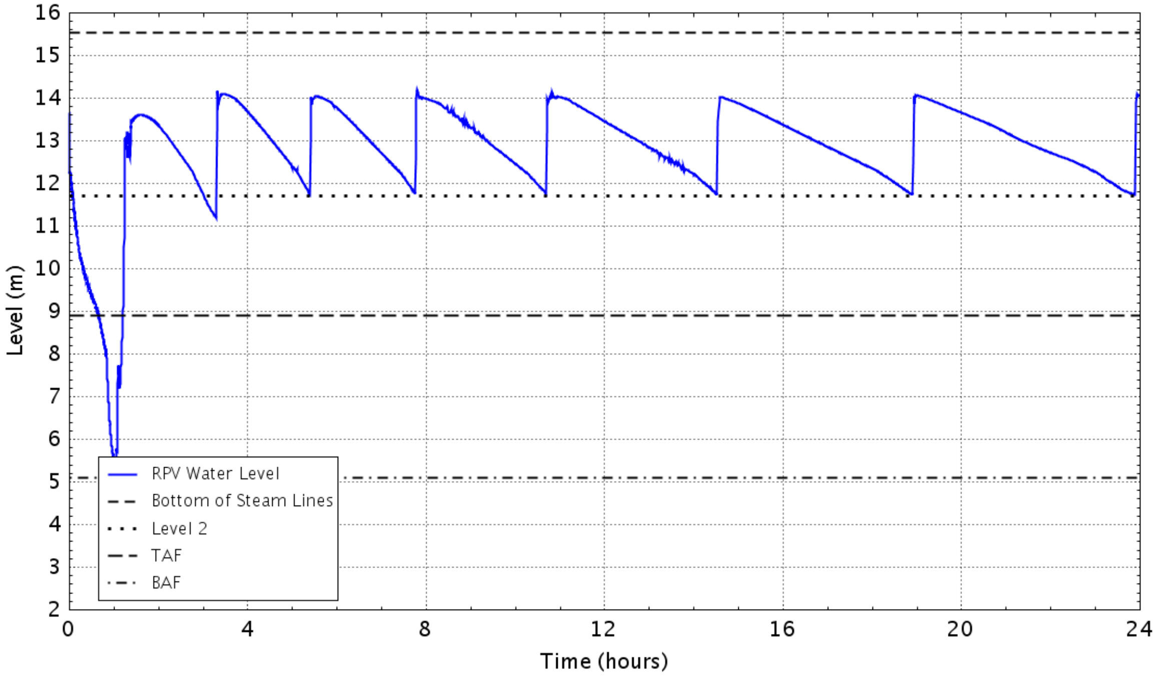

Figure C - 408 RPV Downcomer water level

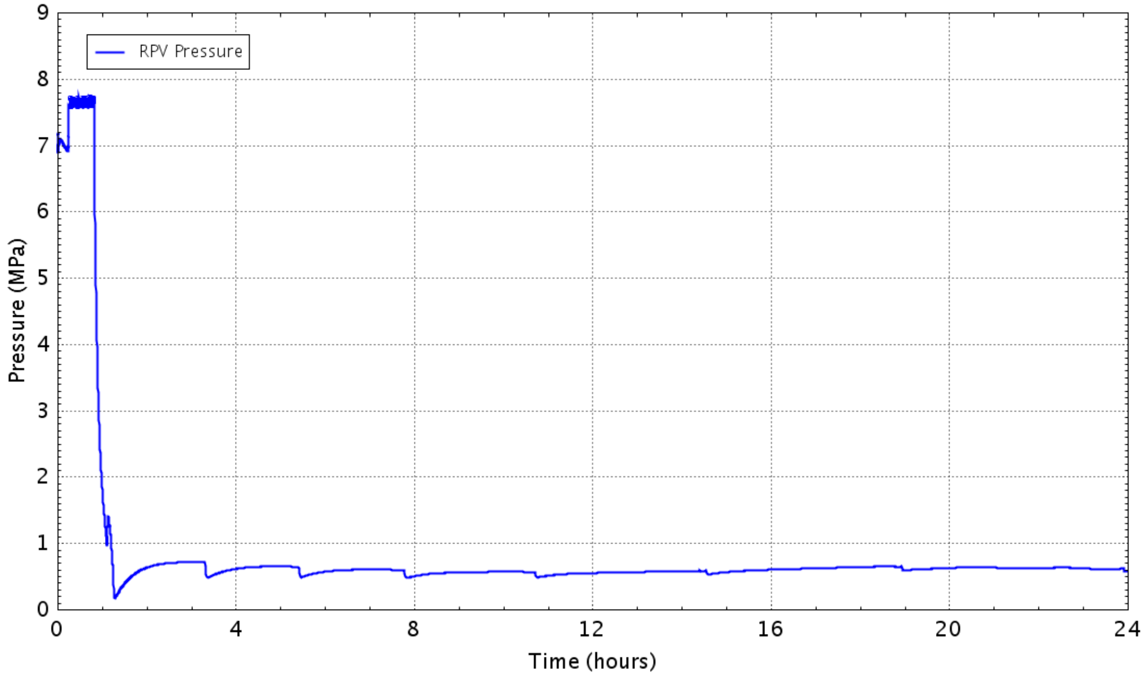

Figure C - 409 Pressure in the RPV

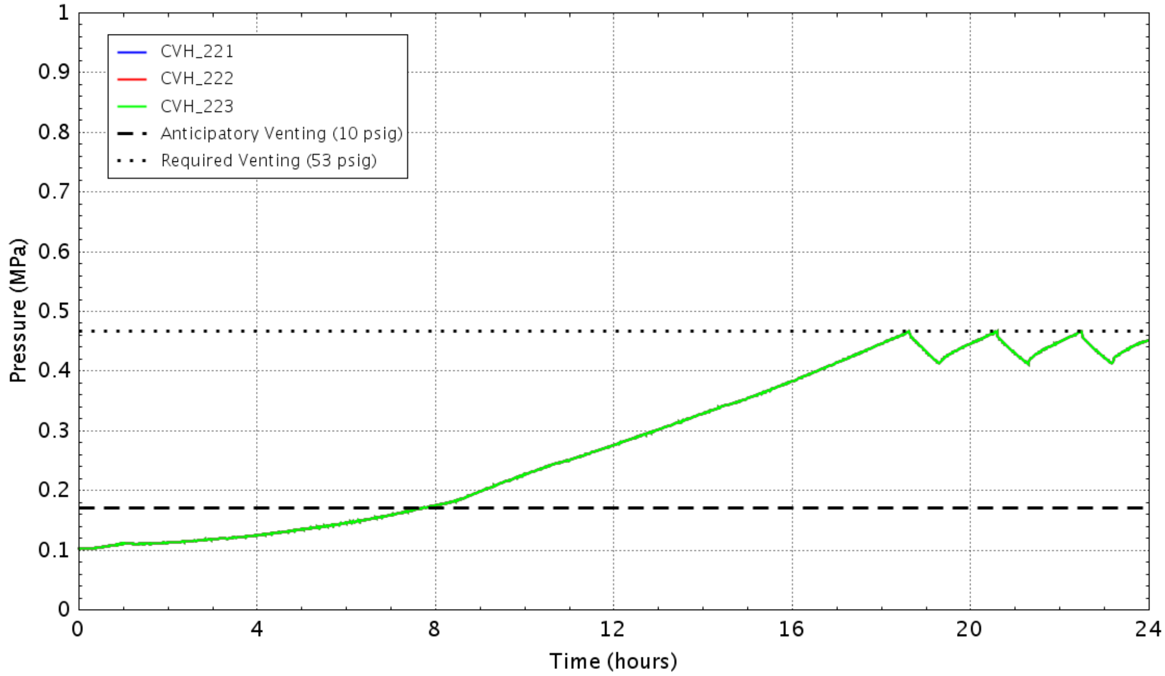

Figure C - 410   Pressure in the wetwell

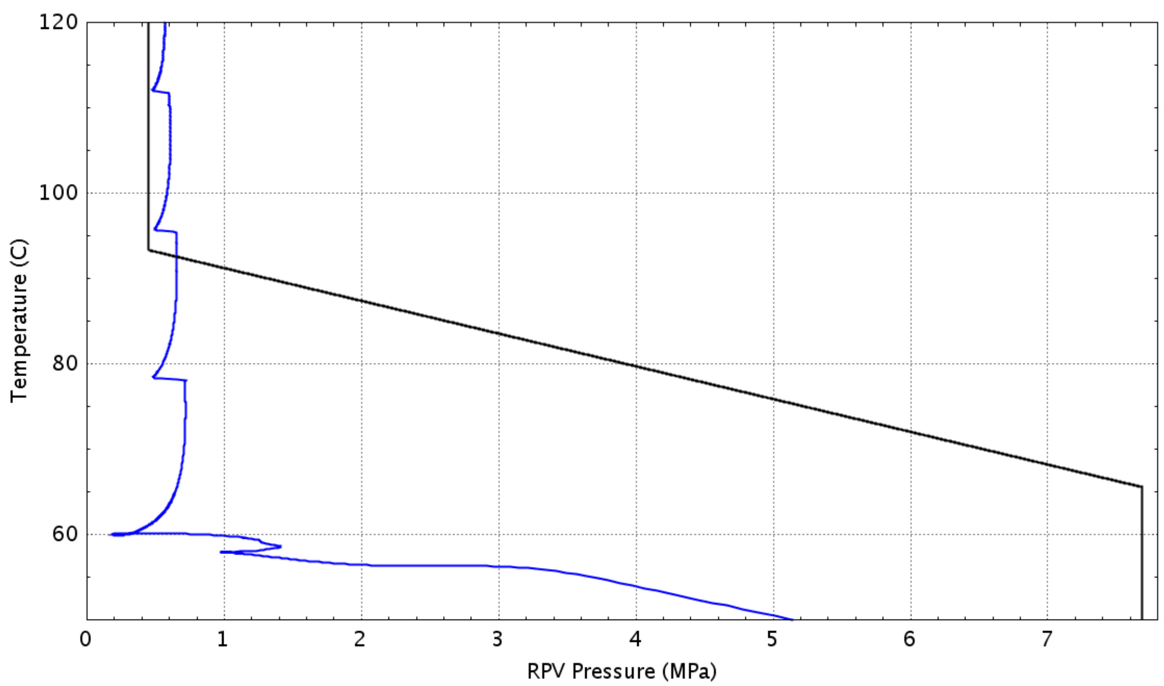

Figure C - 411   Plant status relative to the HCL curve (Graph 4 of the EOPs)

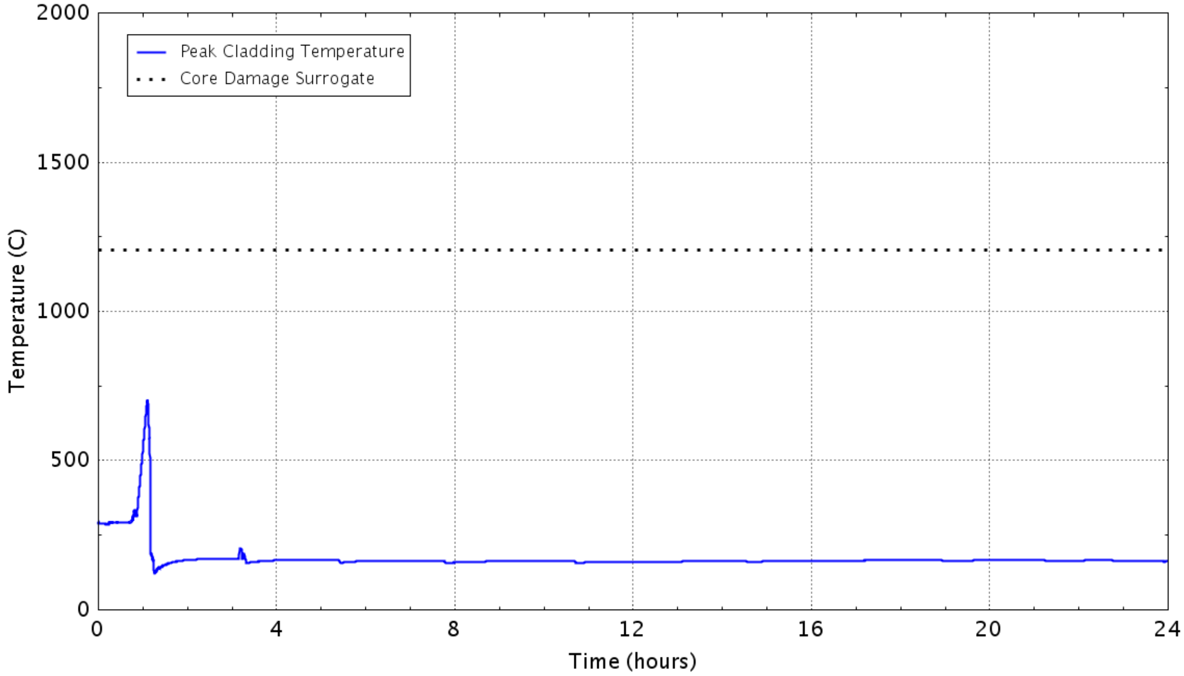

Figure C - 412 Peak temperature of the fuel cladding as a function of time

C.3.7 Case 21a: Sensitivity to SLOCA-25 Case 21 Early Closure ofthe MSIVs (at 10 min.)

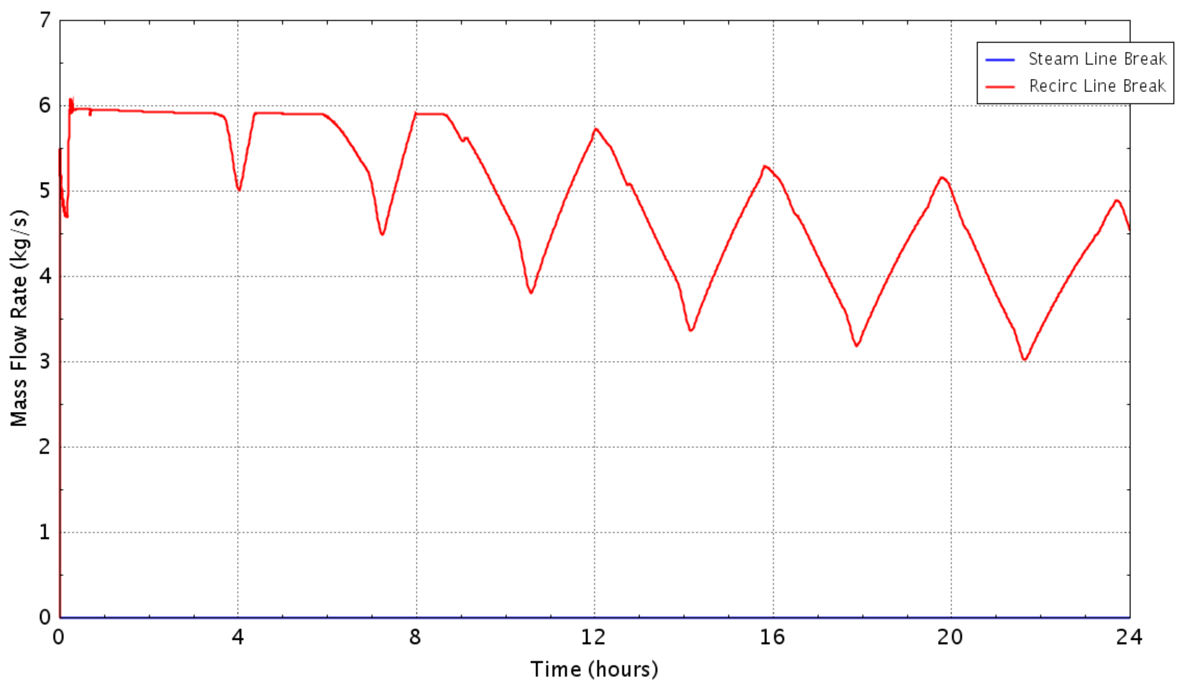

Figure C - 413 Flow rate of the break in the steamline/recirculation line

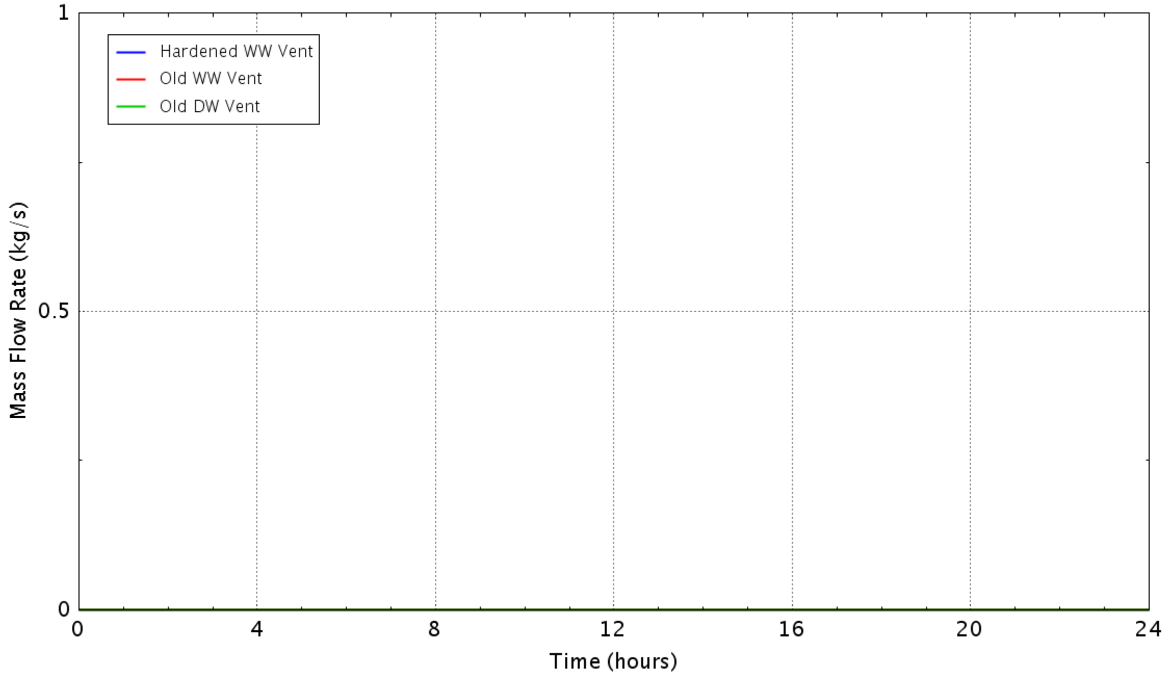

Figure C - 414 Flow rate of the containment vents

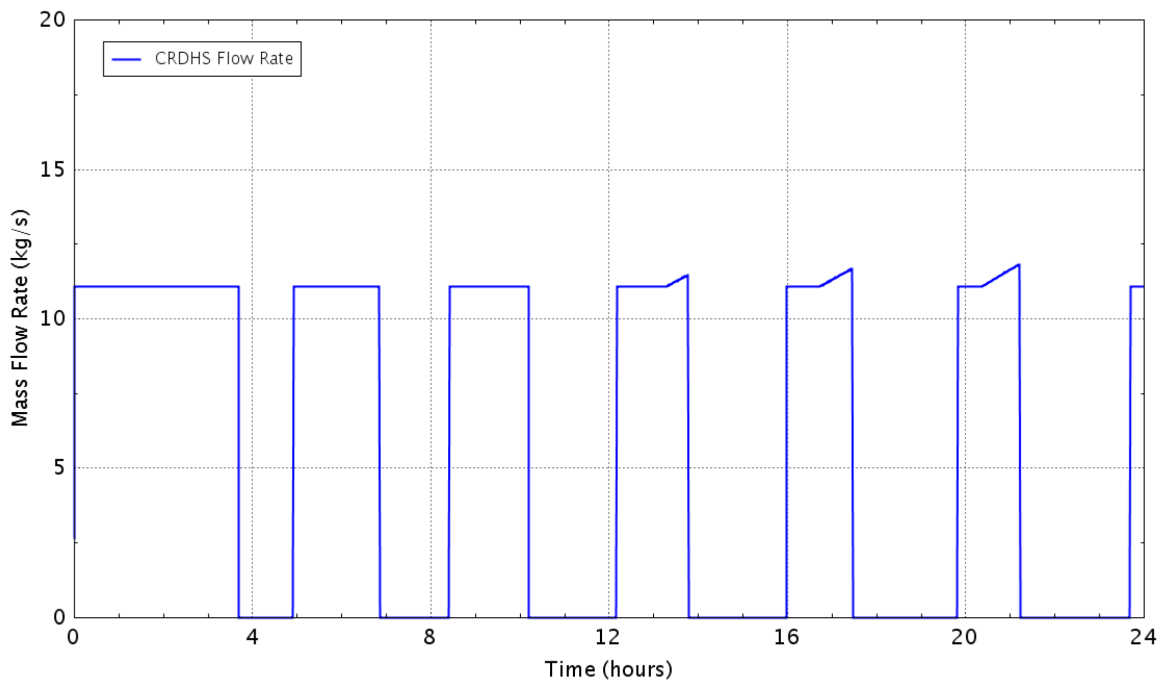

Figure C - 415 Flow rate of the control rod drive hydraulic system

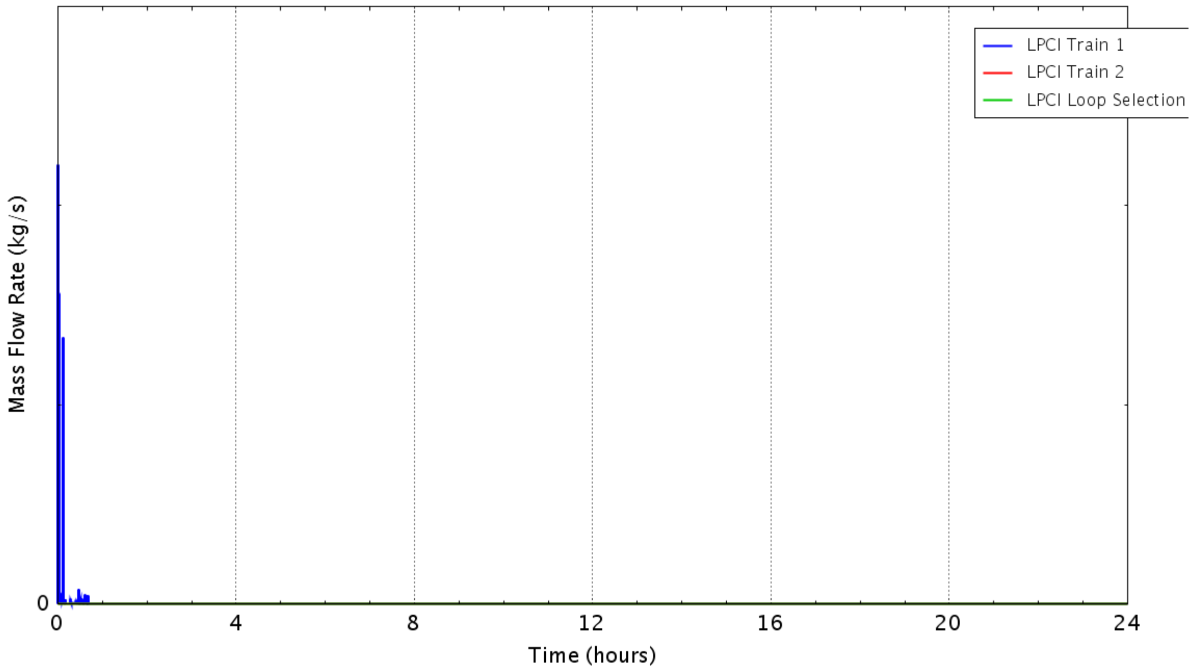

Figure C - 416   Flow rate of the LPCI pump

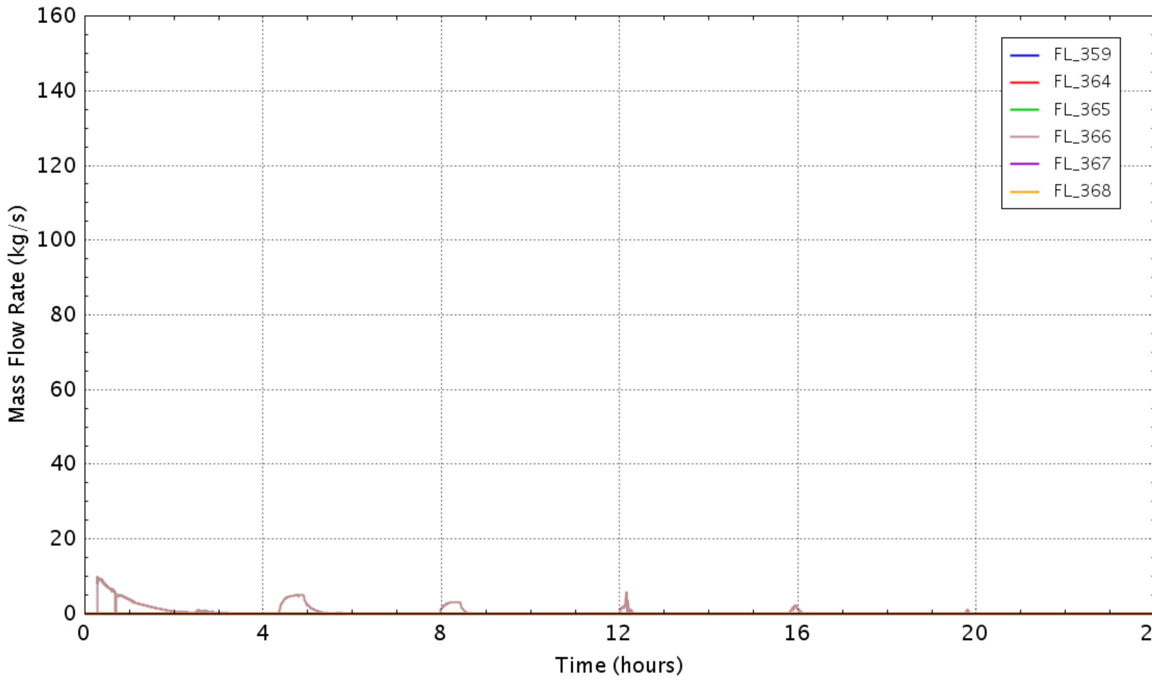

Figure C - 417   Flow rate of the SRVs

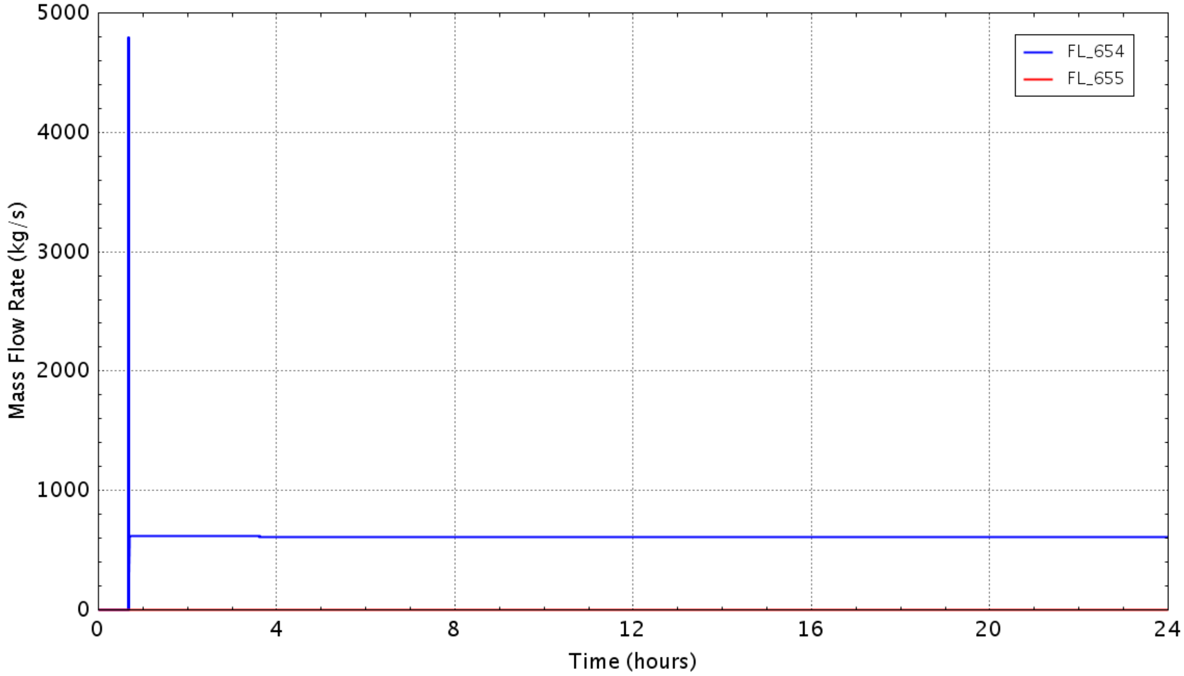

Figure C - 418 Flow rate of the wetwell cooling system

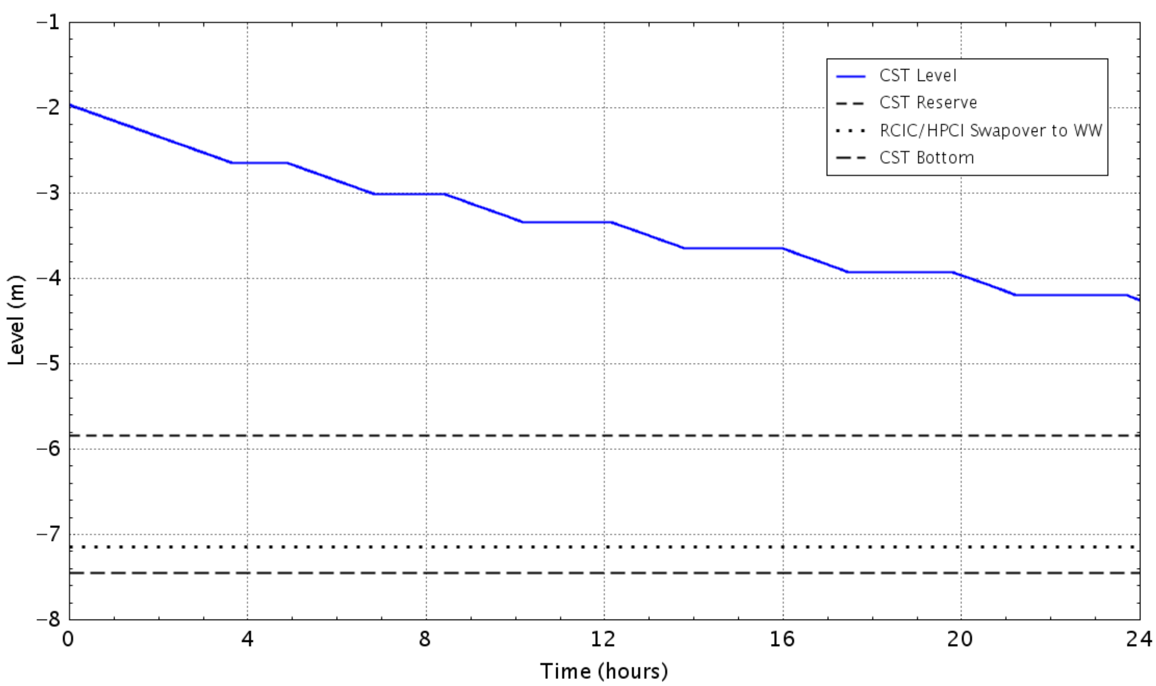

Figure C - 419 Water level in the CST

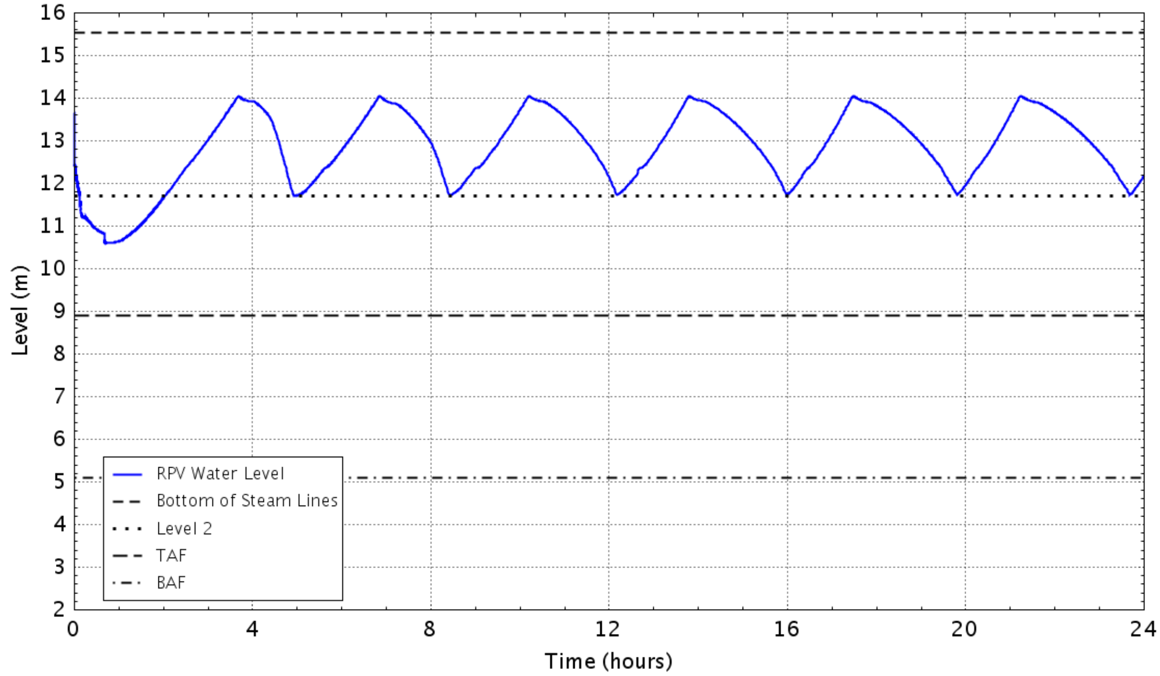

Figure C - 420 RPV Downcomer water level

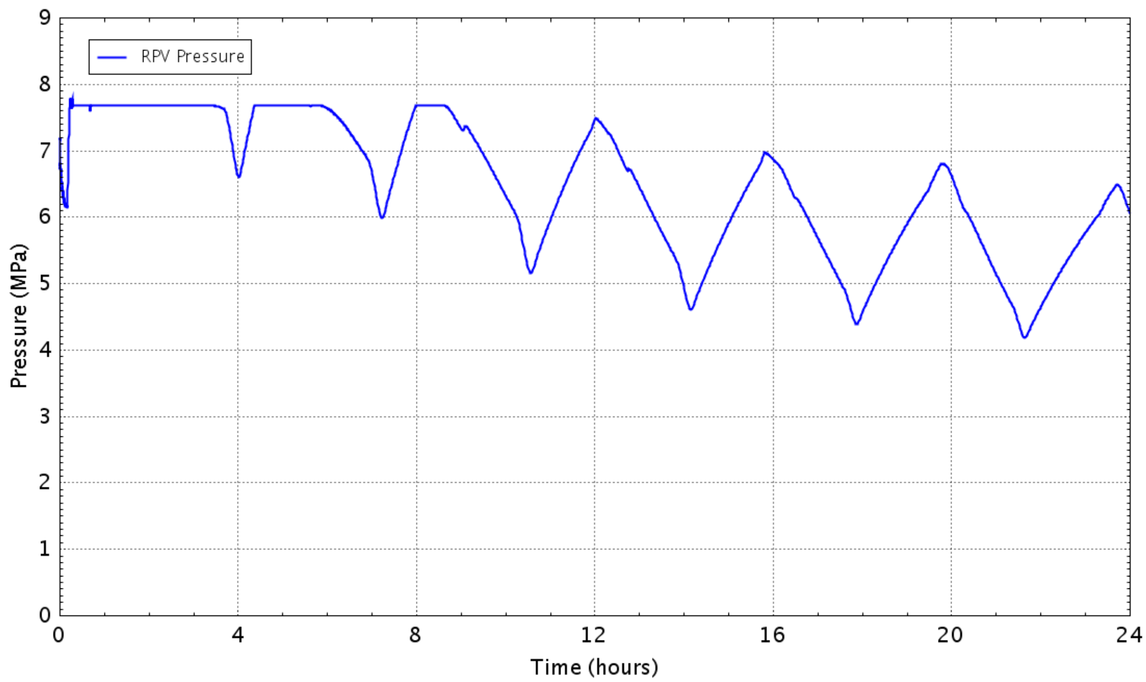

Figure C - 421 Pressure in the RPV

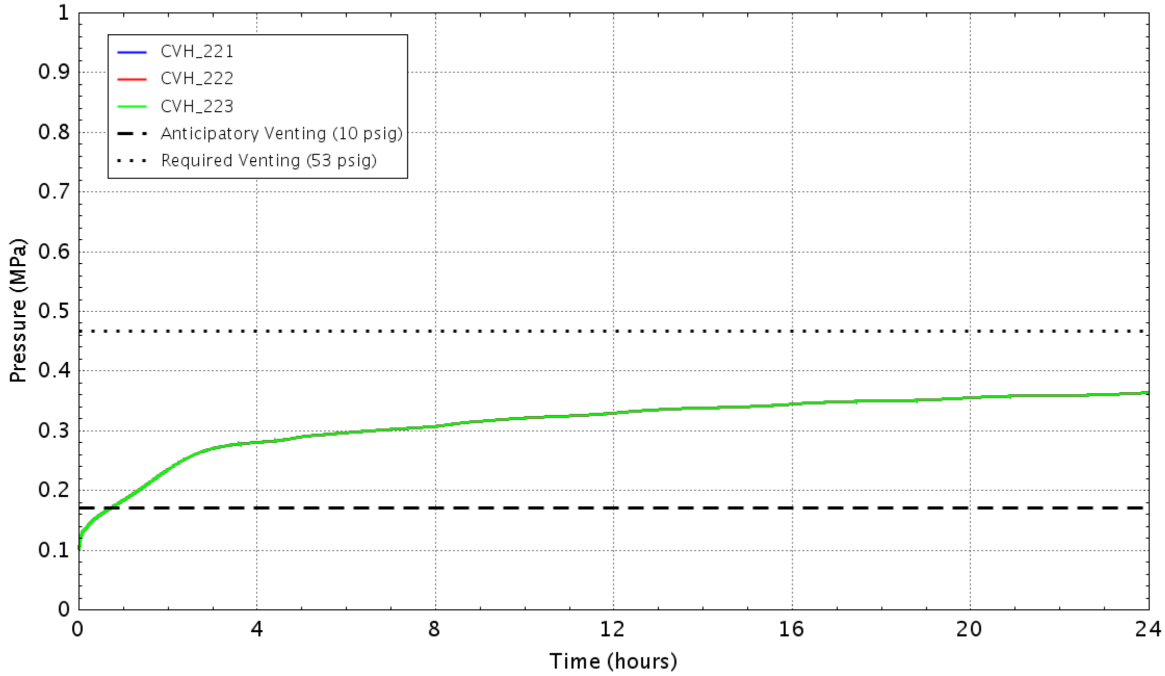

Figure C - 422   Pressure in the wetwell

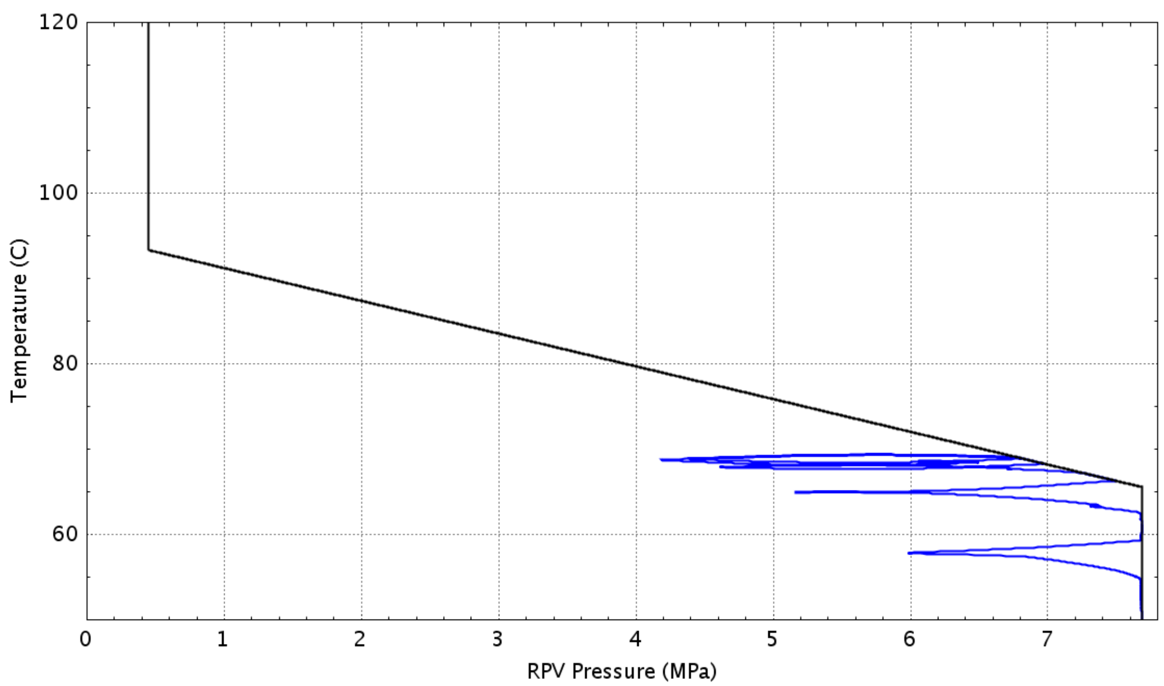

Figure C - 423   Plant status relative to the HCL curve (Graph 4 of the EOPs)

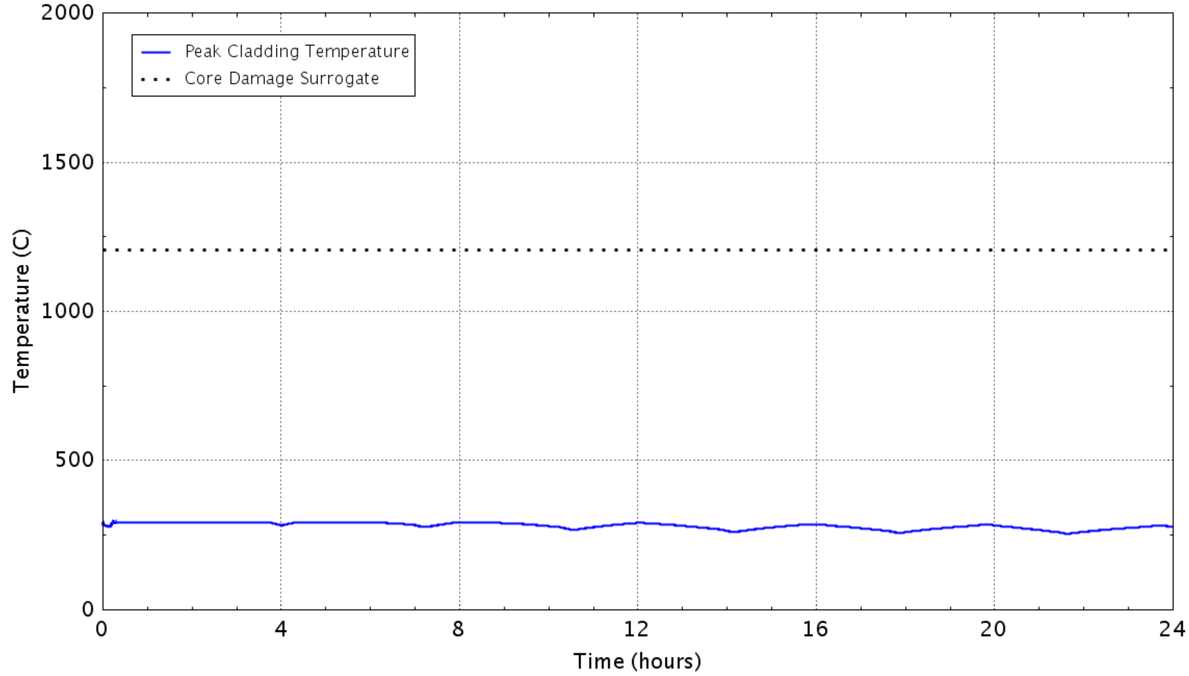

Figure C - 424 Peak temperature of the fuel cladding as a function of time

C.3.8 Case 21b: Sensitivity to SLOCA-25 Case 21 with Break Sizeand Location Exchanged

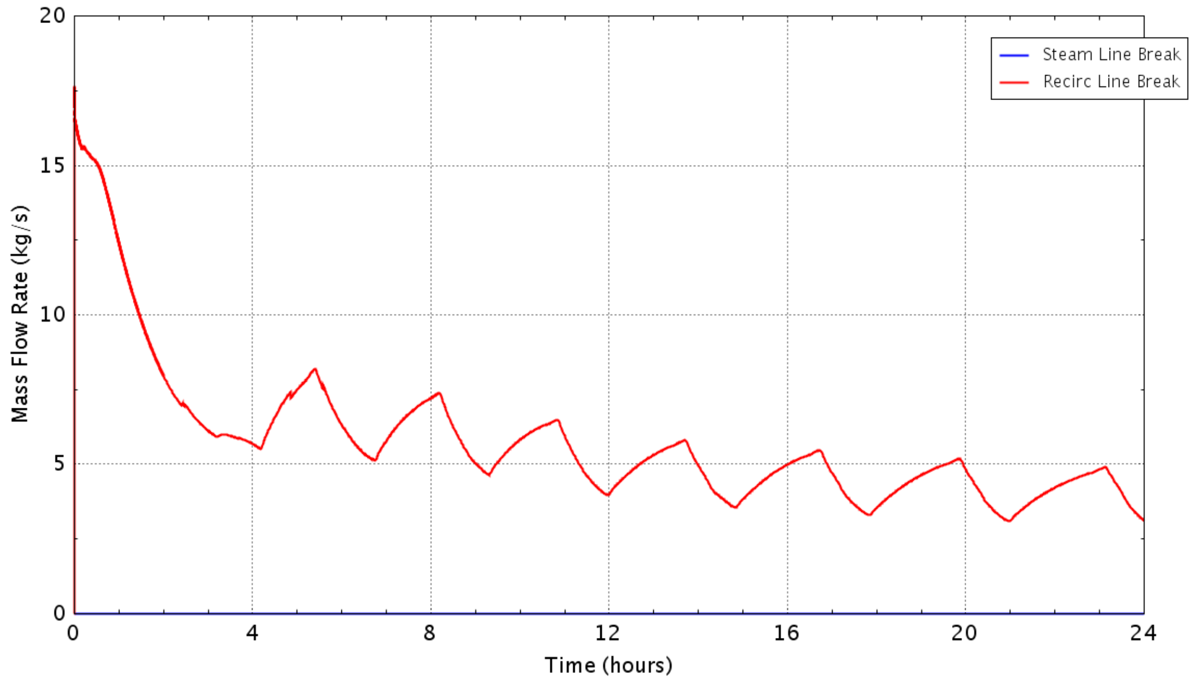

Figure C - 425 Flow rate of the break in the steamline/recirculation line

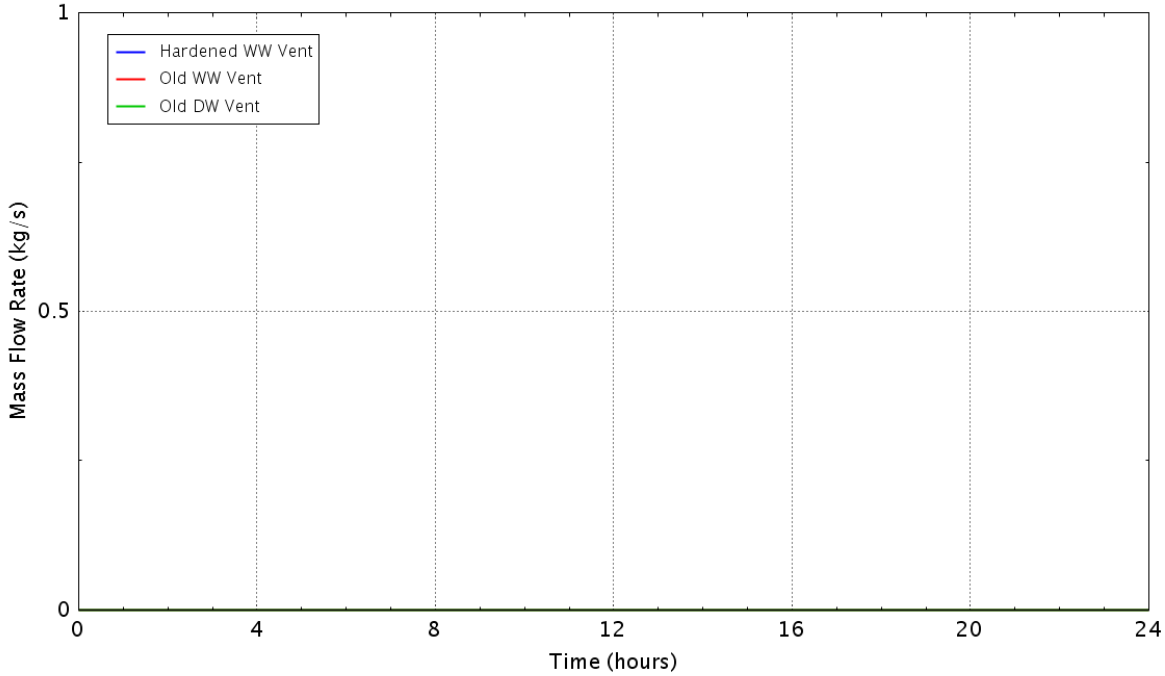

Figure C - 426 Flow rate of the containment vents

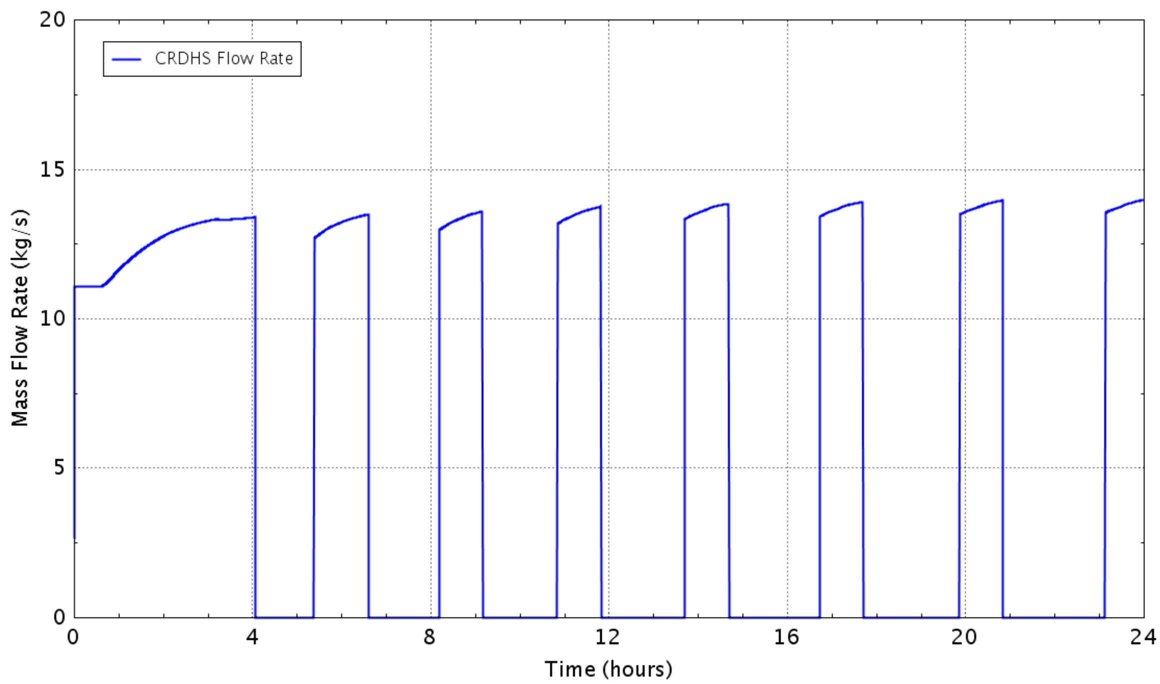

Figure C - 427 Flow rate of the control rod drive hydraulic system

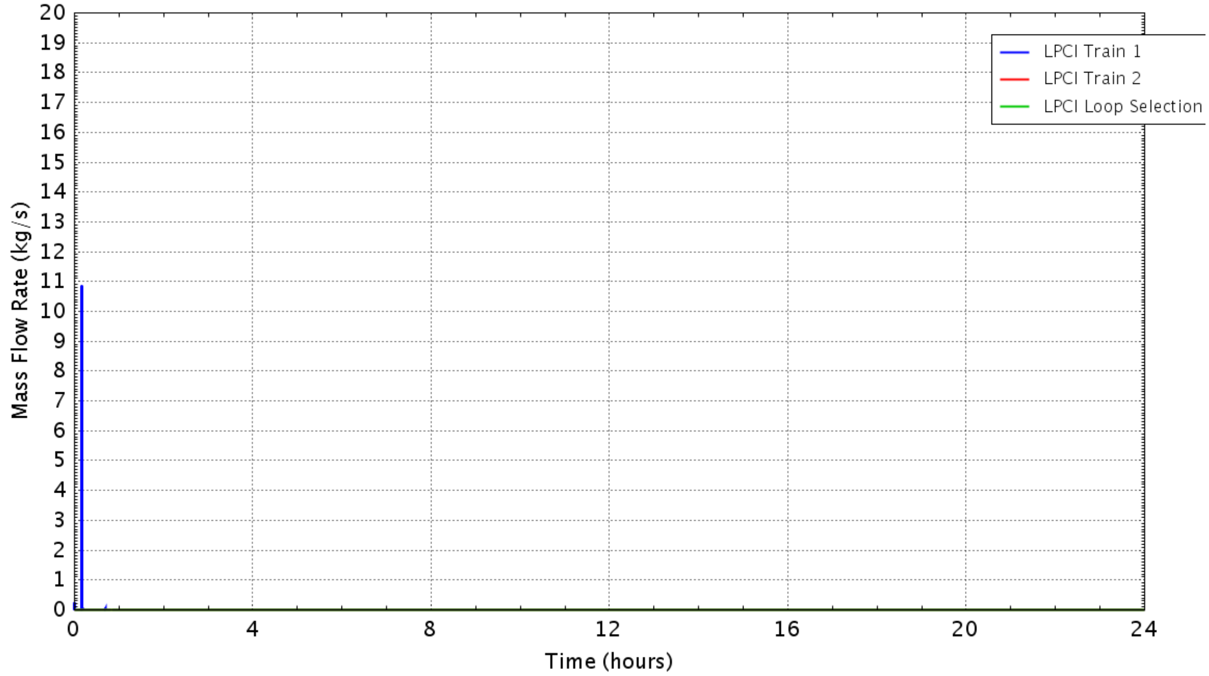

Figure C - 428 Flow rate of the LPCI pump

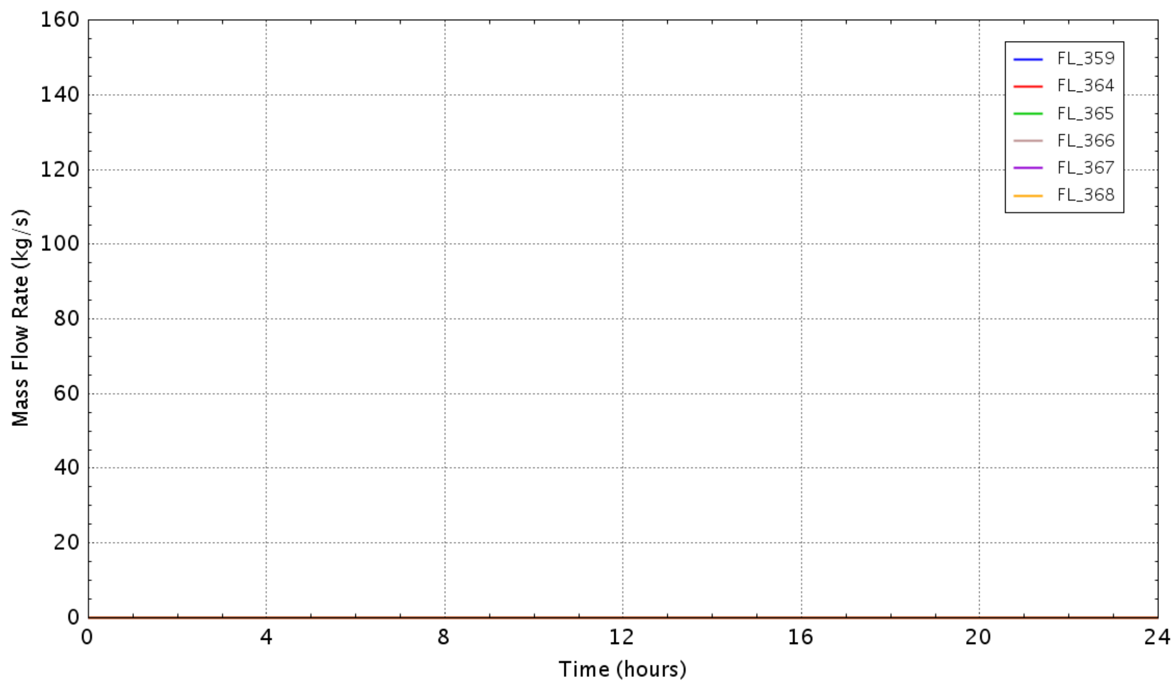

Figure C - 429 Flow rate of the SRVs

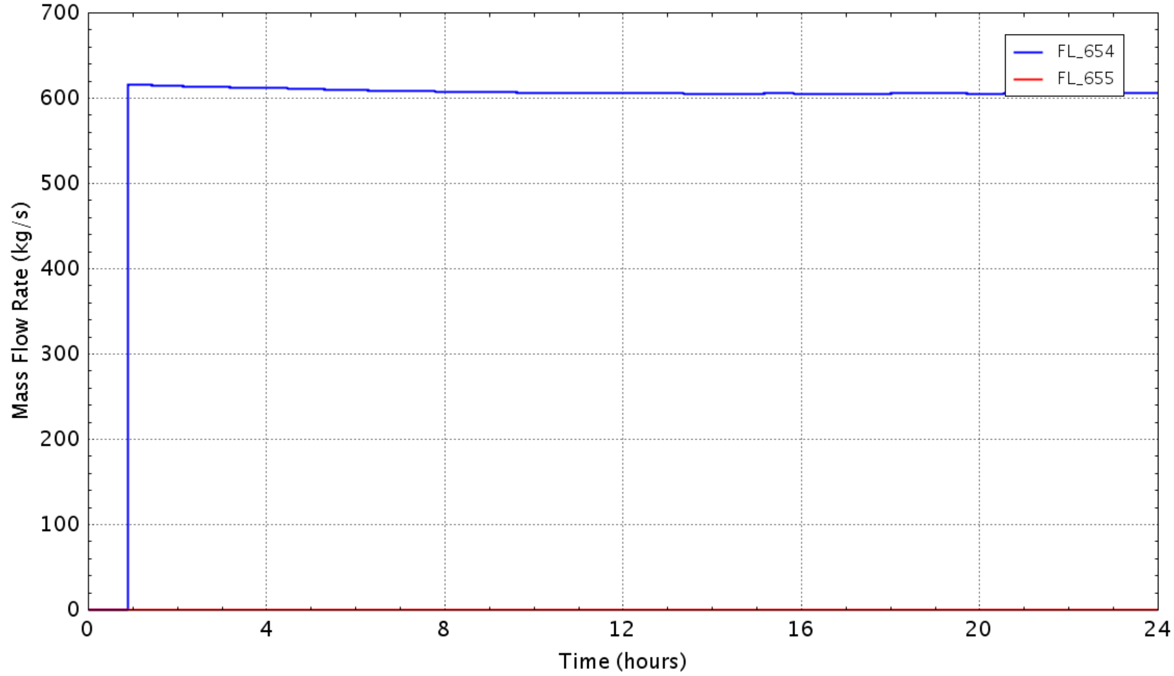

Figure C - 430 Flow rate of the wetwell cooling system

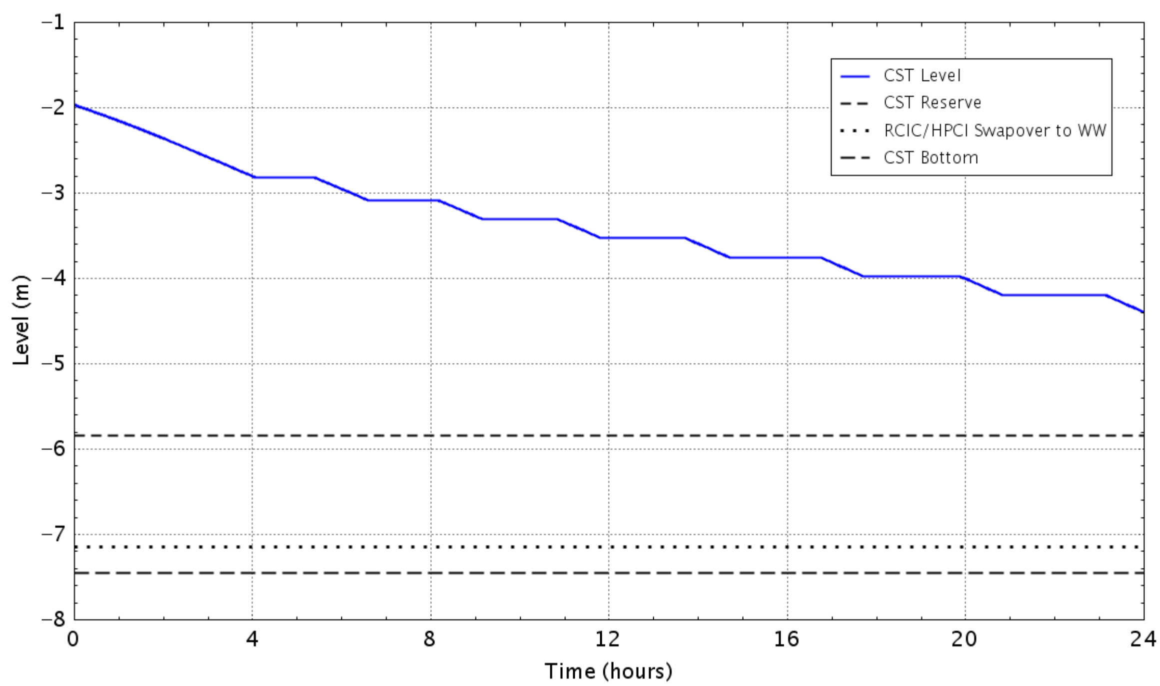

Figure C - 431 Water level in the CST

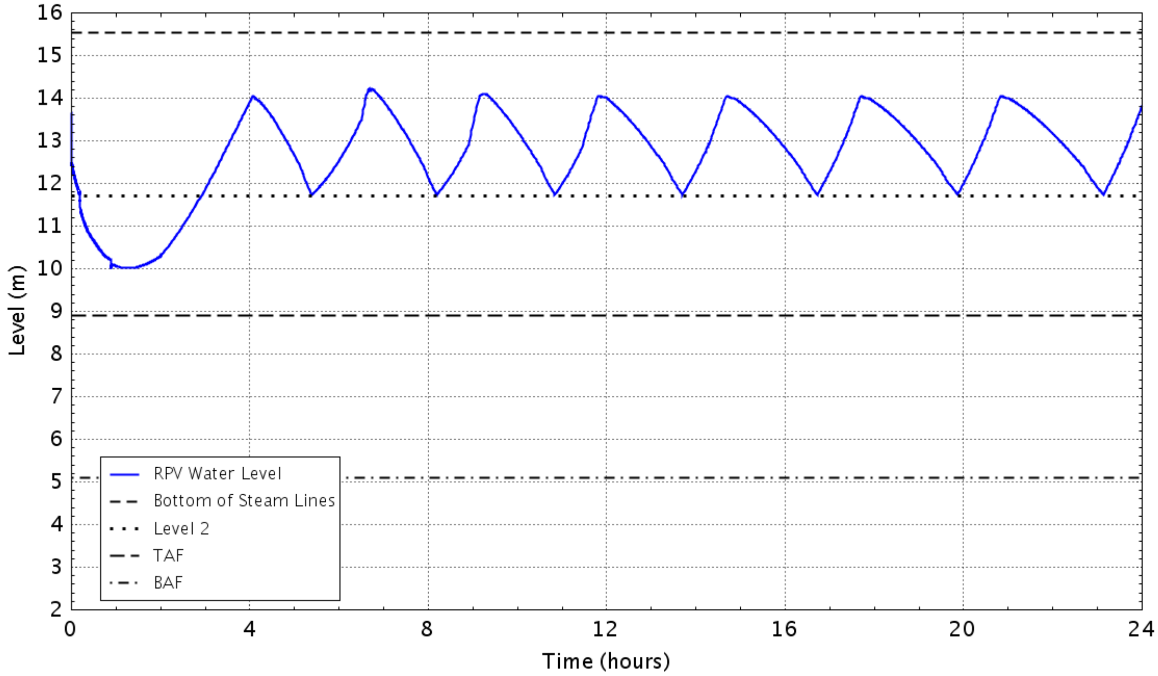

Figure C - 432 RPV Downcomer water level

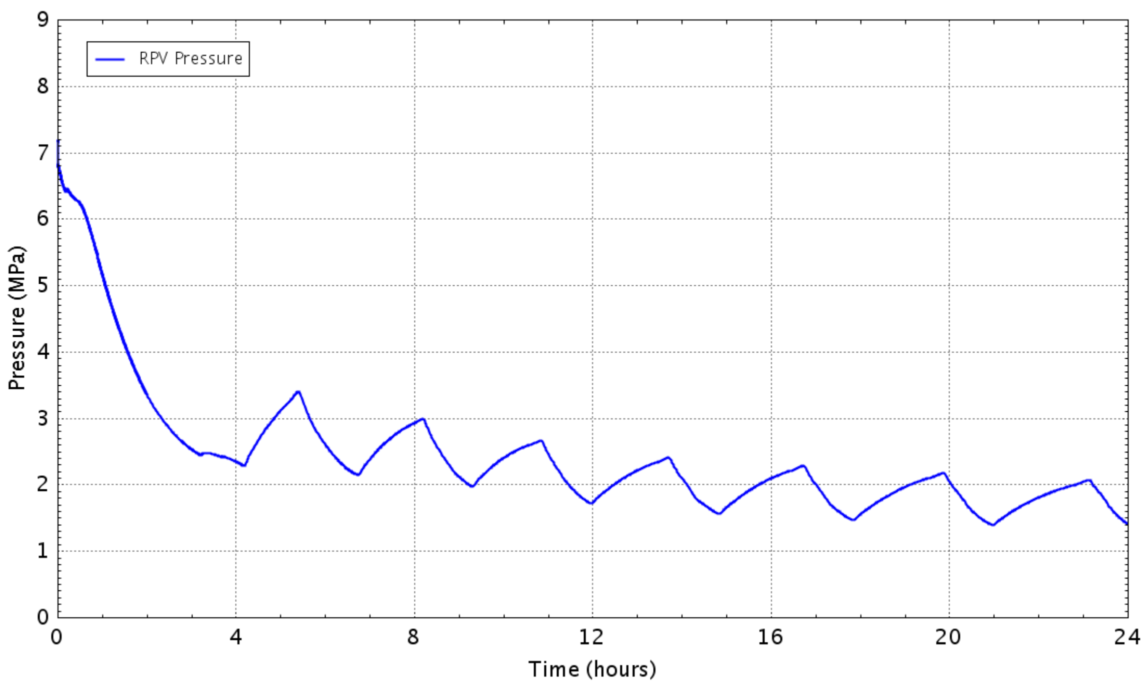

Figure C - 433 Pressure in the RPV

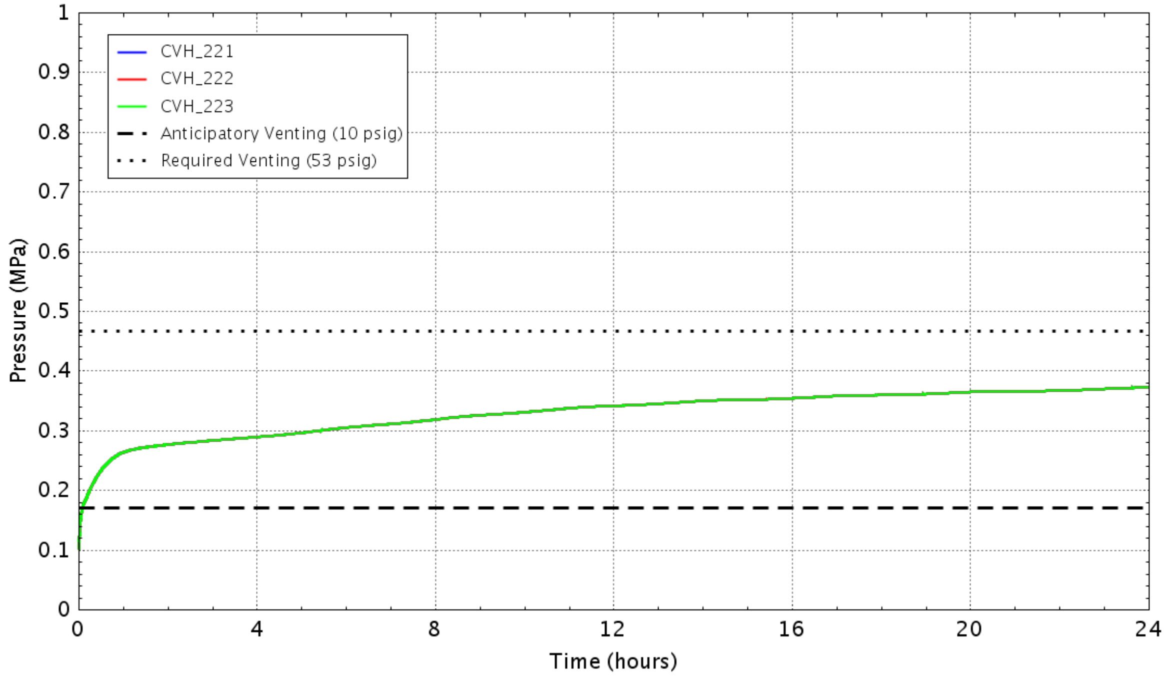

Figure C - 434 Pressure in the wetwell

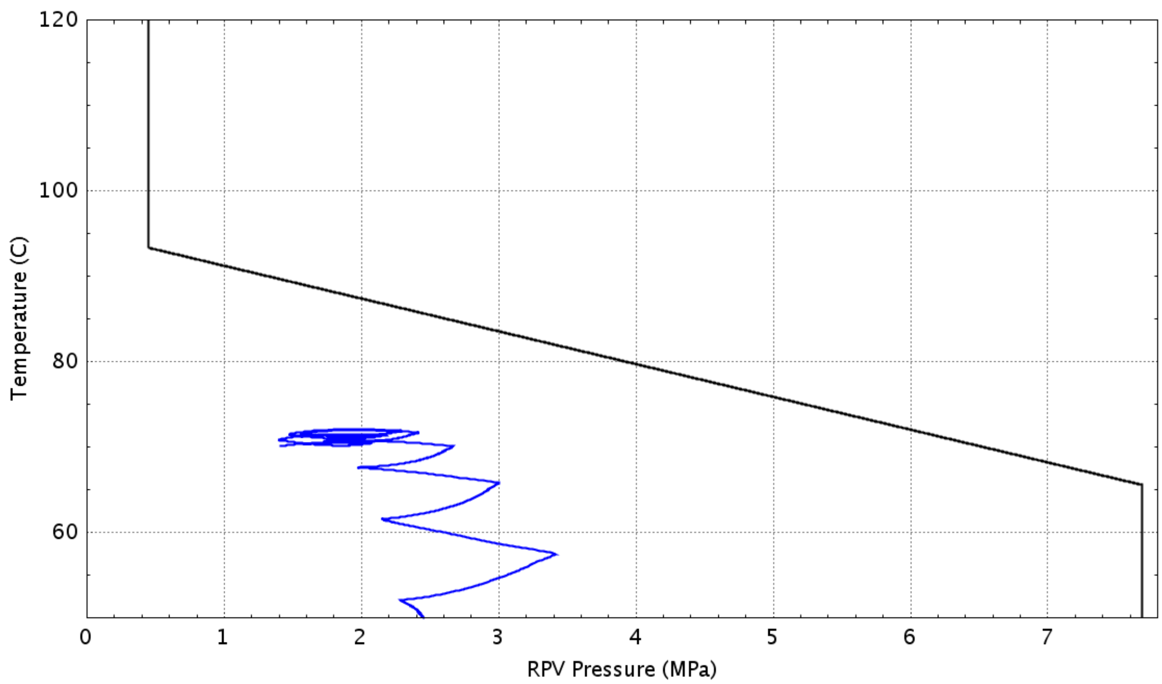

Figure C - 435 Plant status relative to the HCL curve (Graph 4 of the EOPs)

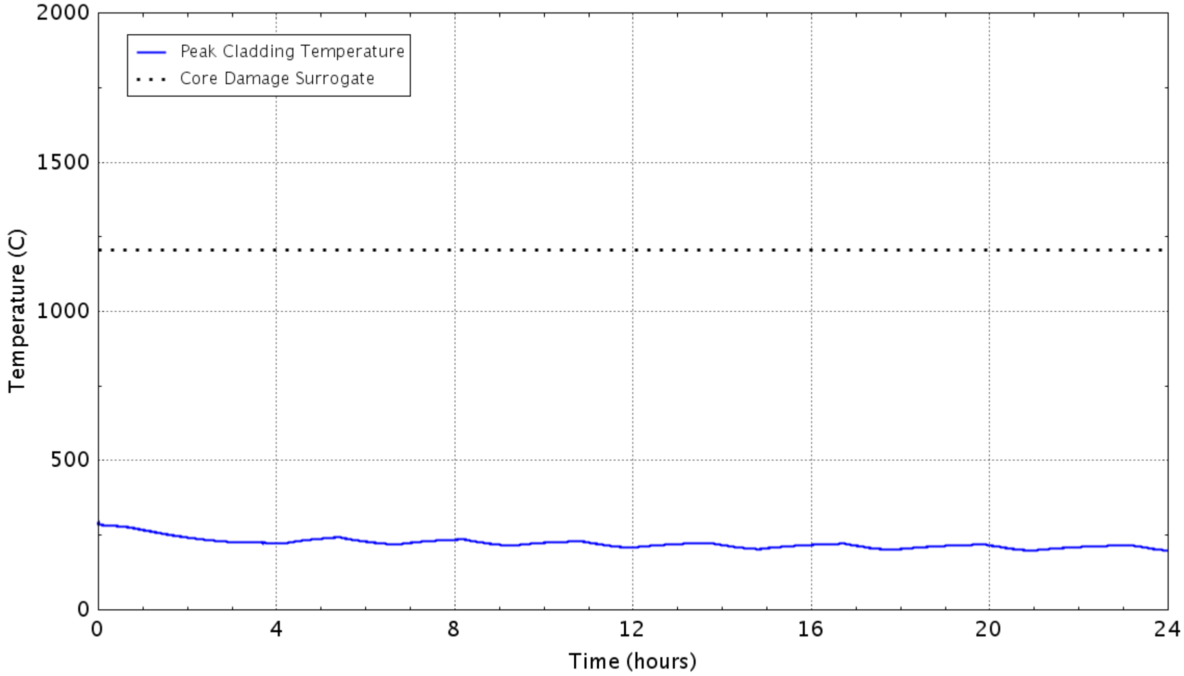

Figure C - 436 Peak temperature of the fuel cladding as a function of time

C.3.9 Case 23a: Sensitivity to SLOCA-25 Case 23 with Nominal Recirculation Pump Seal Leakage

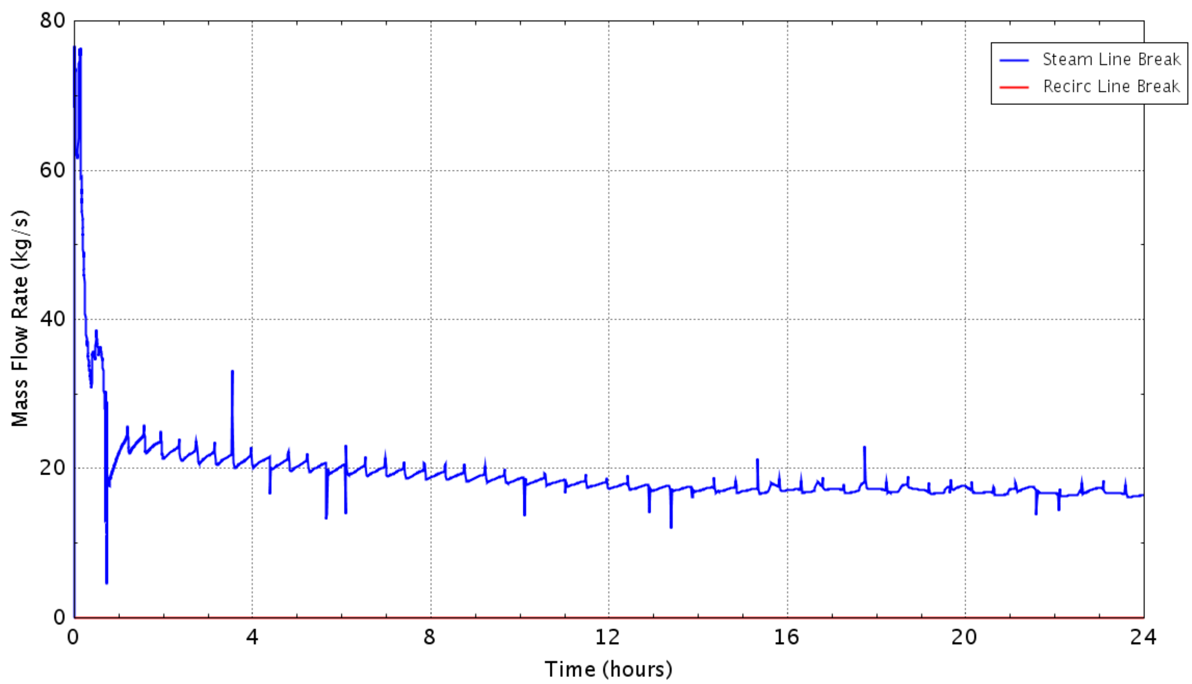

Figure C - 437 Flow rate of the break in the steamline/recirculation line

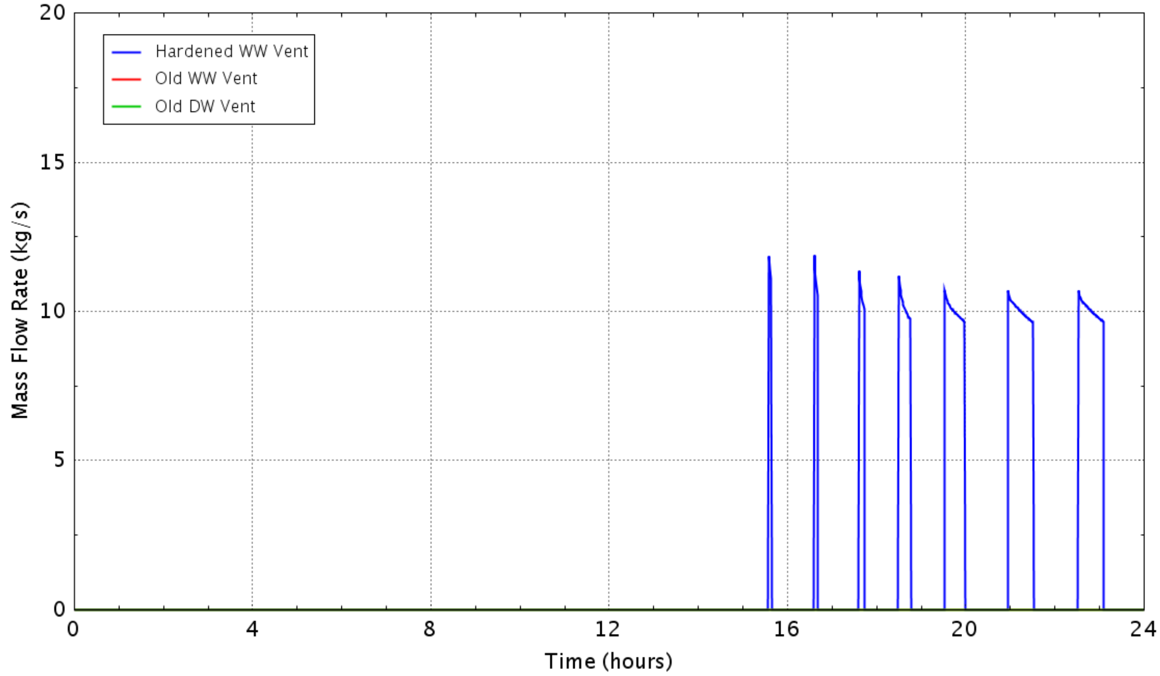

Figure C - 438 Flow rate of the containment vents

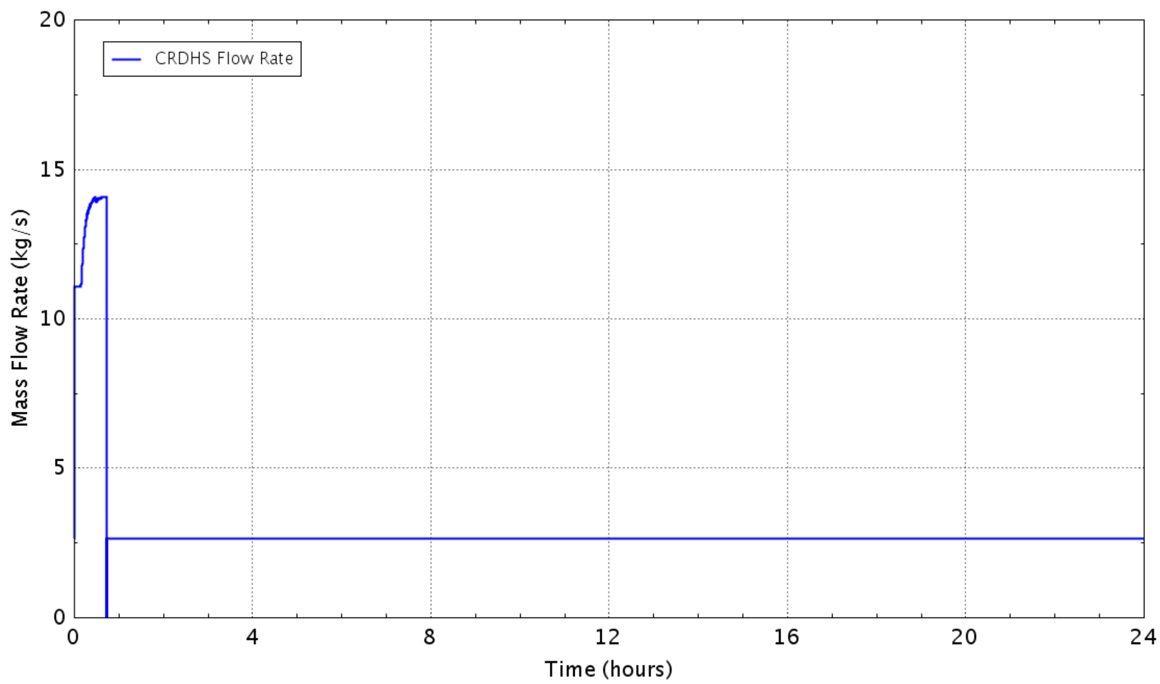

Figure C - 439 Flow rate of the control rod drive hydraulic system

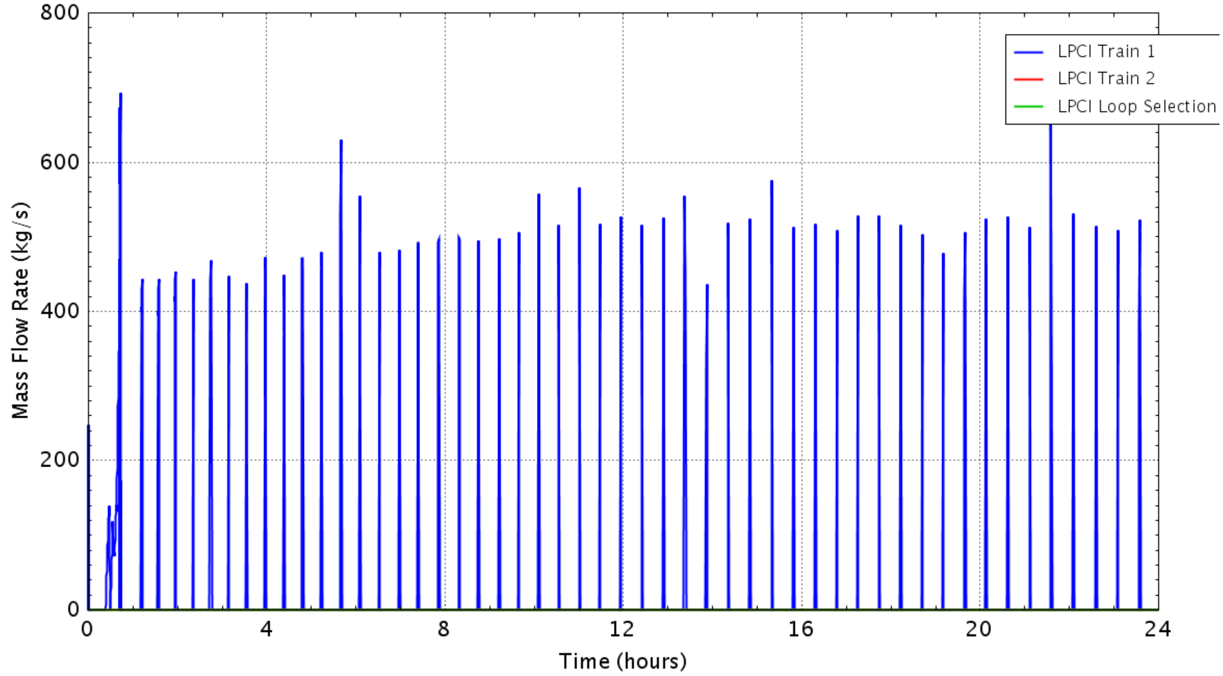

Figure C - 440 Flow rate of the LPCI pump

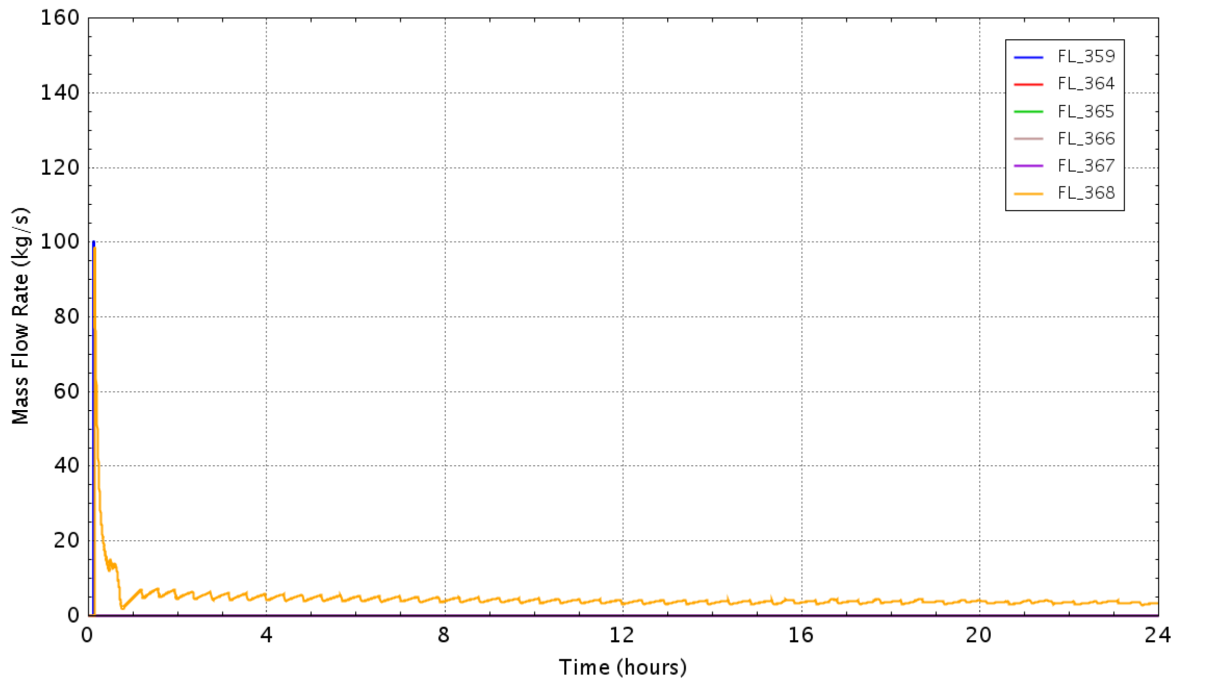

Figure C - 441 Flow rate of the SRVs

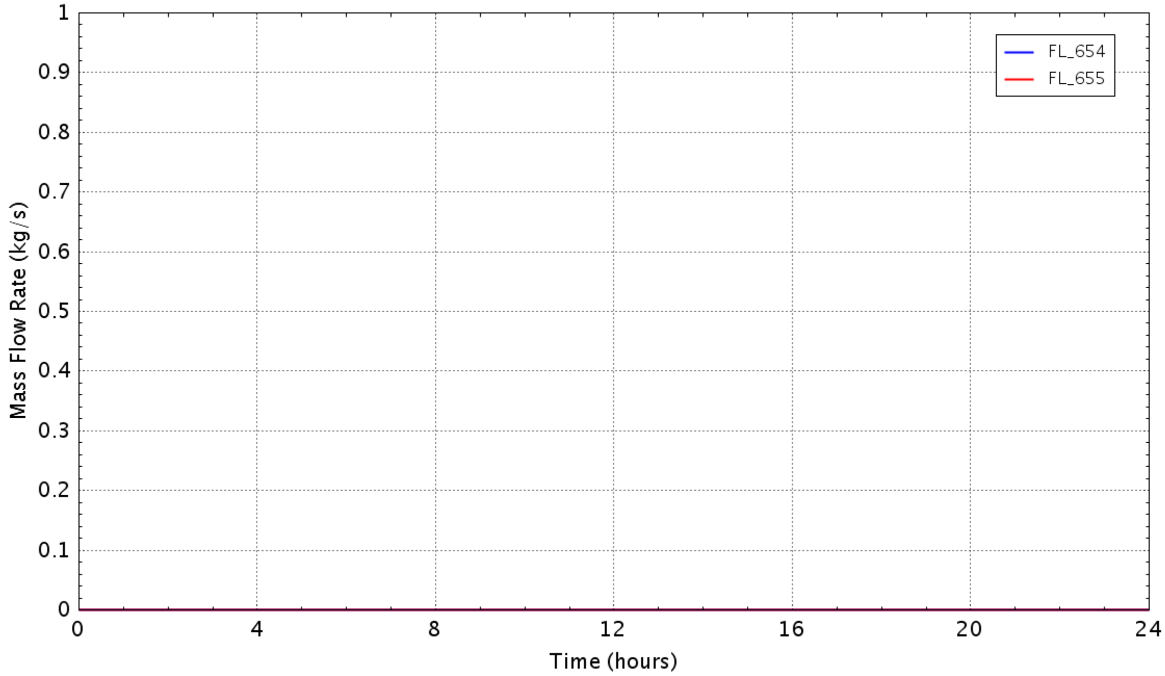

Figure C - 442 Flow rate of the wetwell cooling system

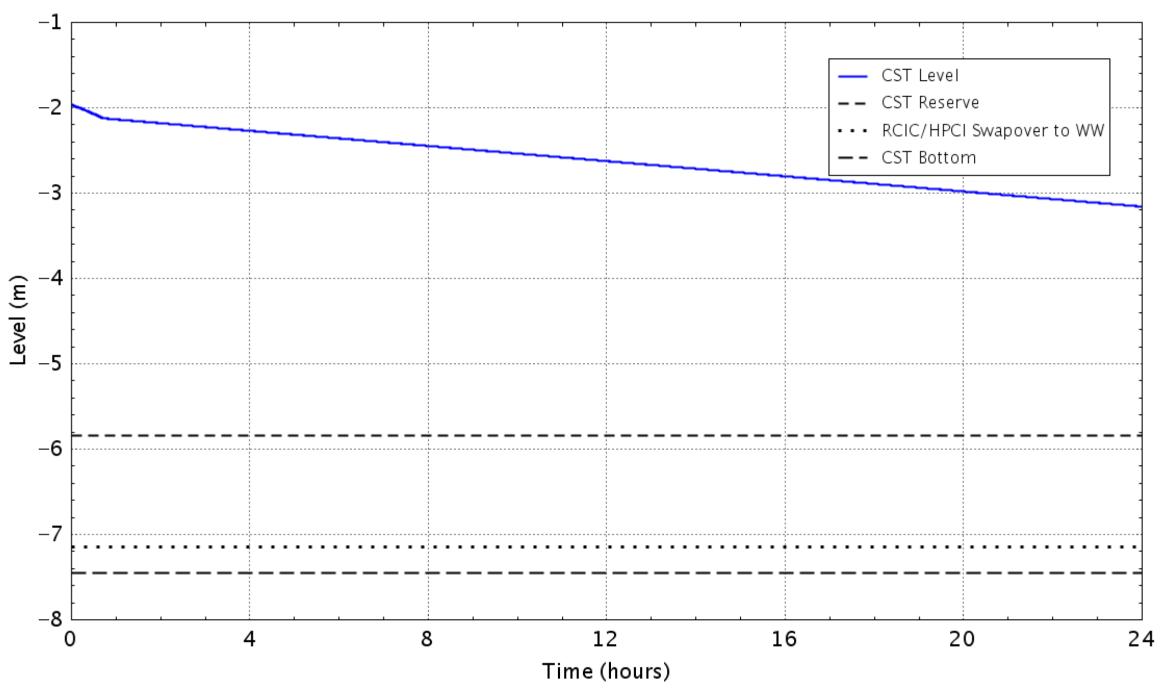

Figure C - 443 Water level in the CST

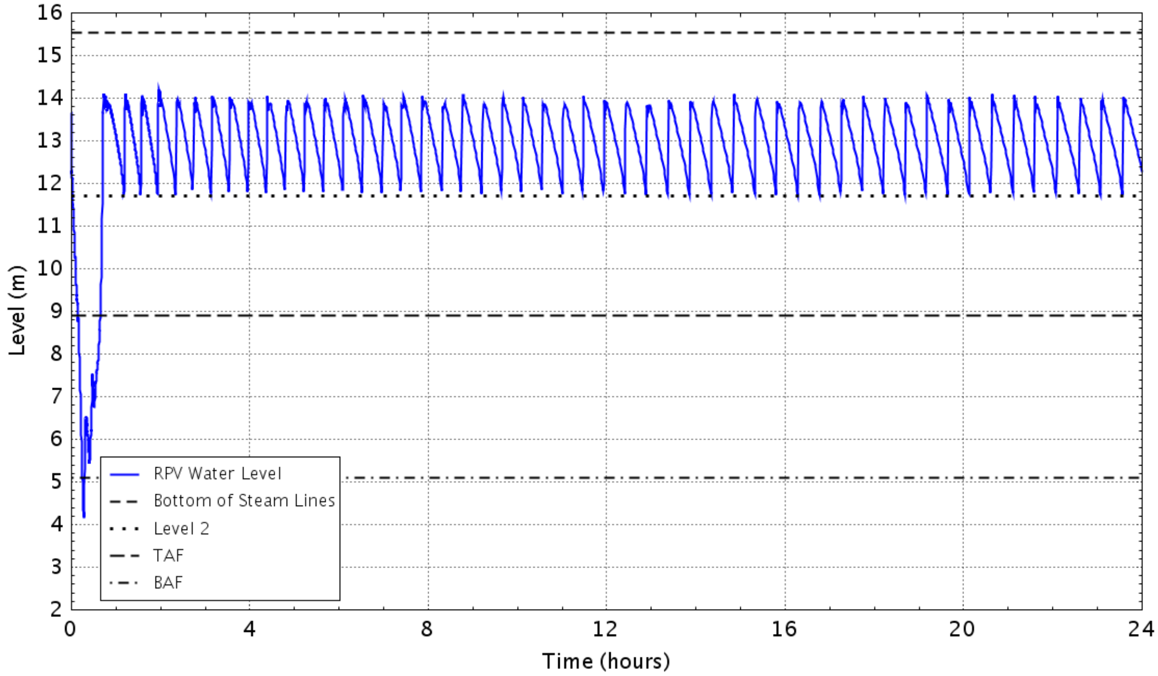

Figure C - 444 RPV Downcomer water level

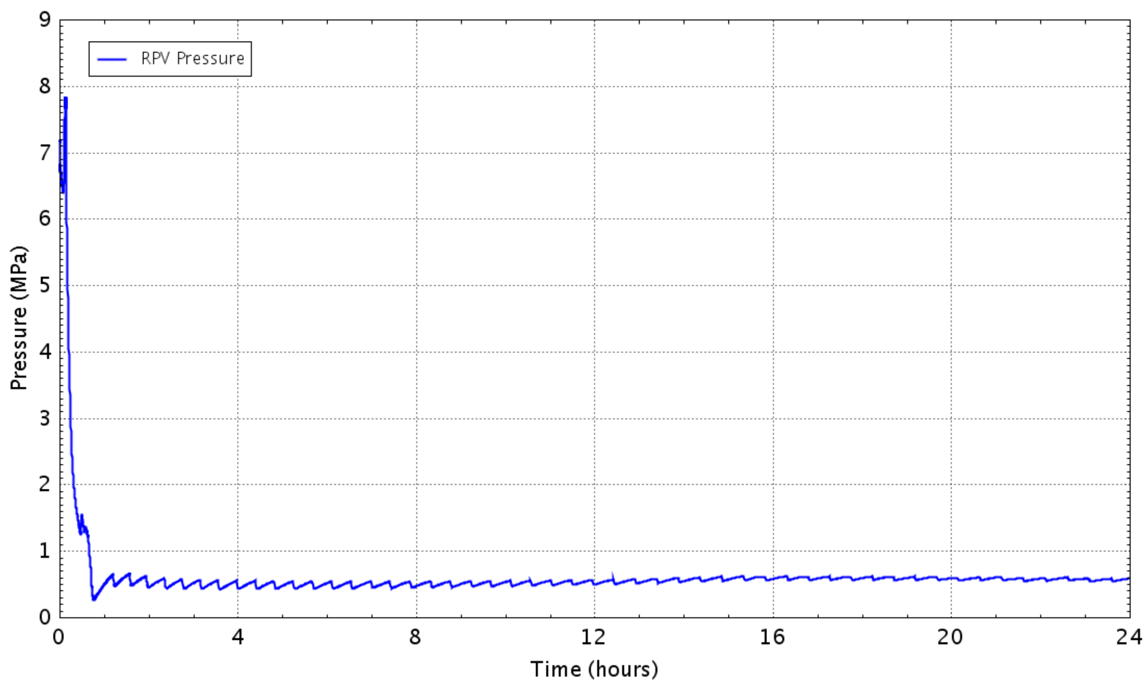

Figure C - 445 Pressure in the RPV

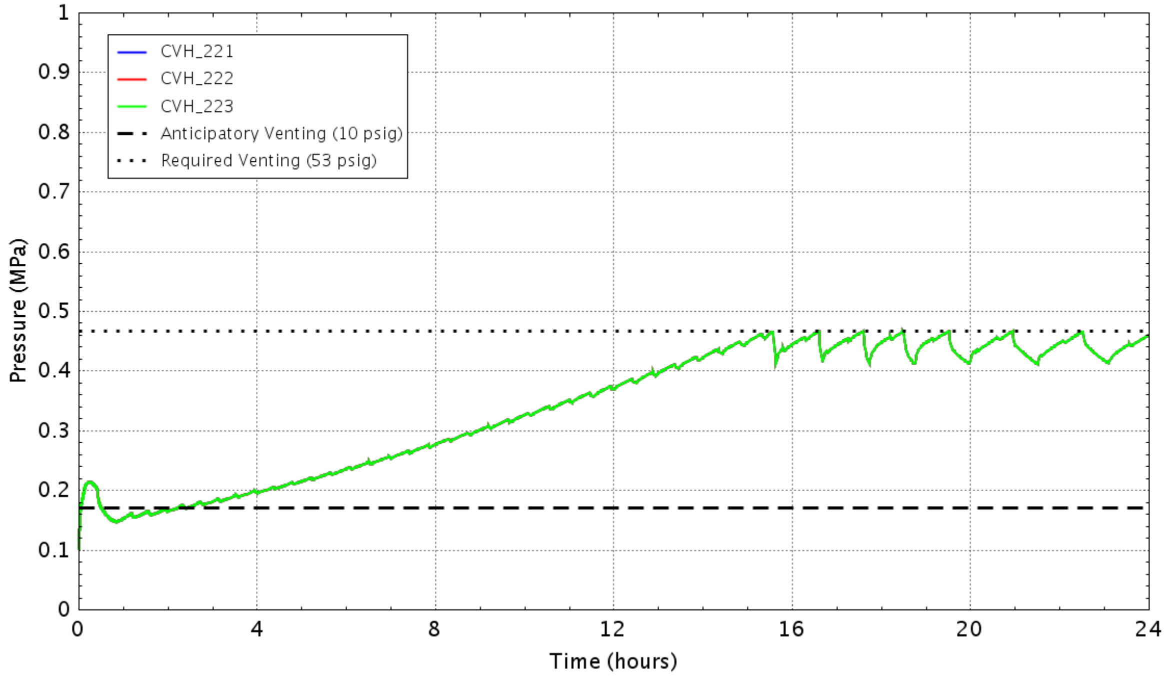

Figure C - 446 Pressure in the wetwell

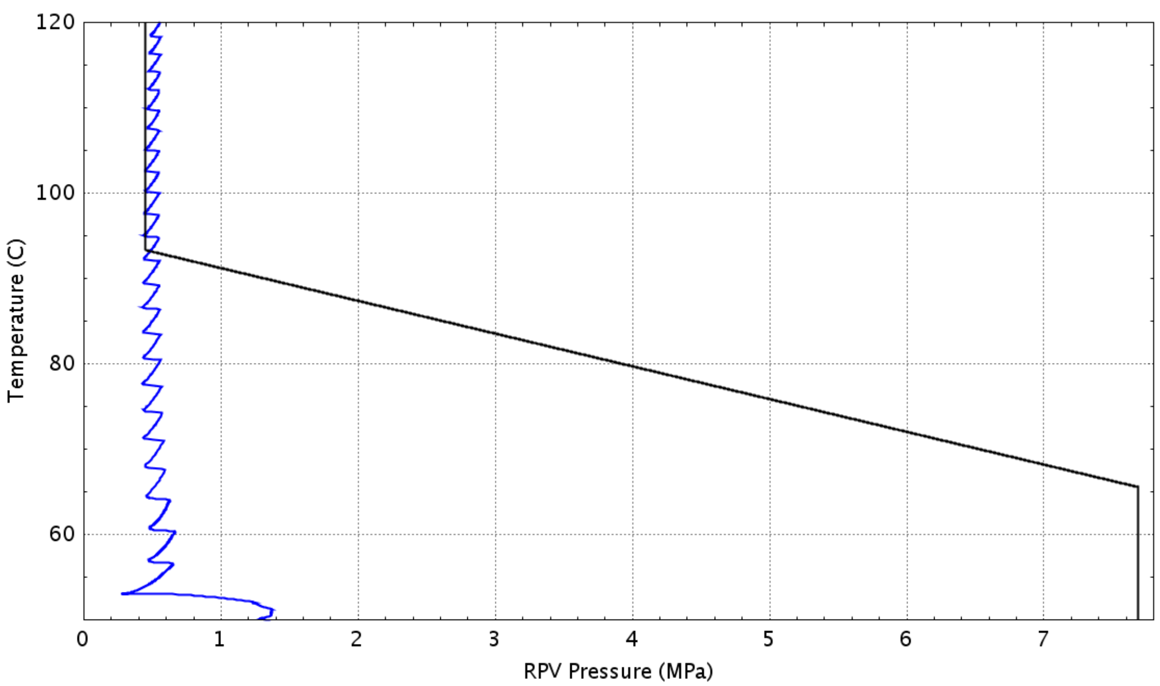

Figure C - 447 Plant status relative to the HCL curve (Graph 4 of the EOPs)

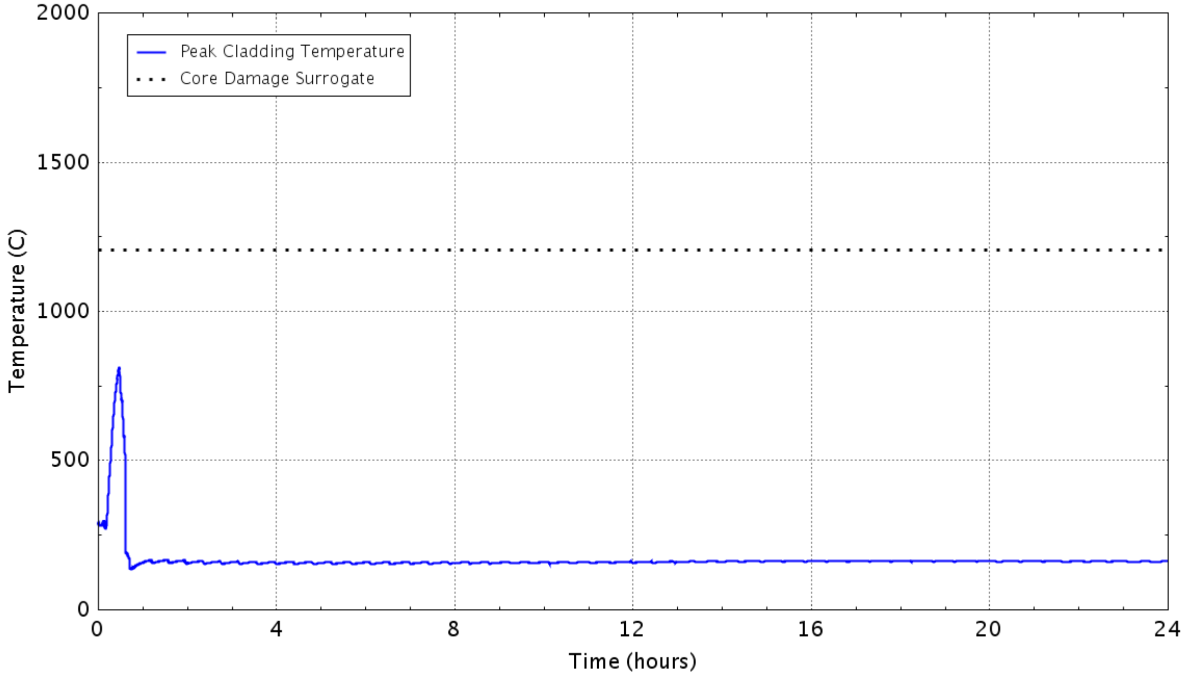

Figure C - 448 Peak temperature of the fuel cladding as a function of time

C.3.10 Case 24a: Sensitivity to SLOCA-25 Case 24 withNominal CRDHS Injection

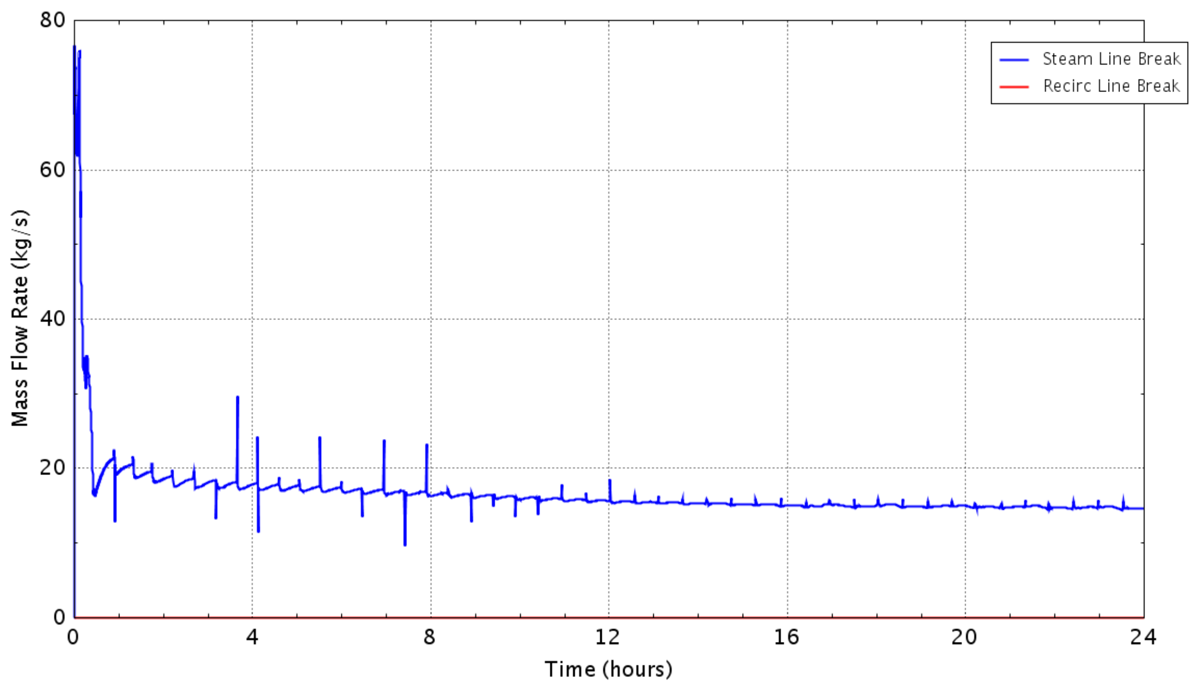

Figure C - 449 Flow rate of the break in the steamline/recirculation line

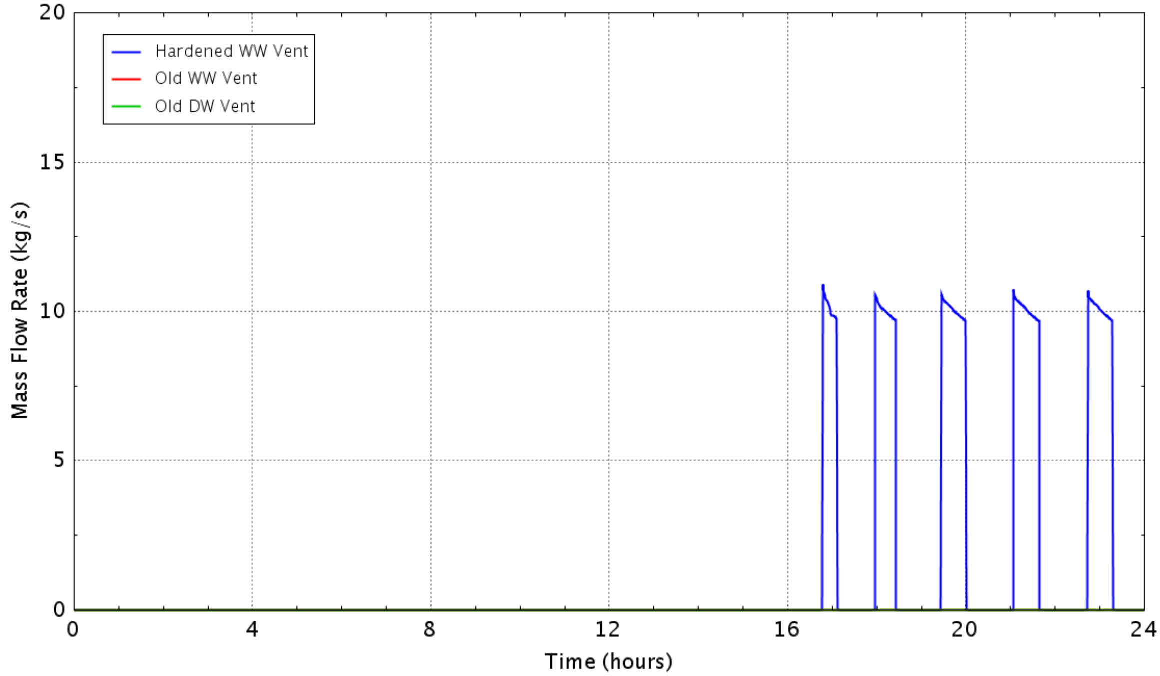

Figure C - 450 Flow rate of the containment vents

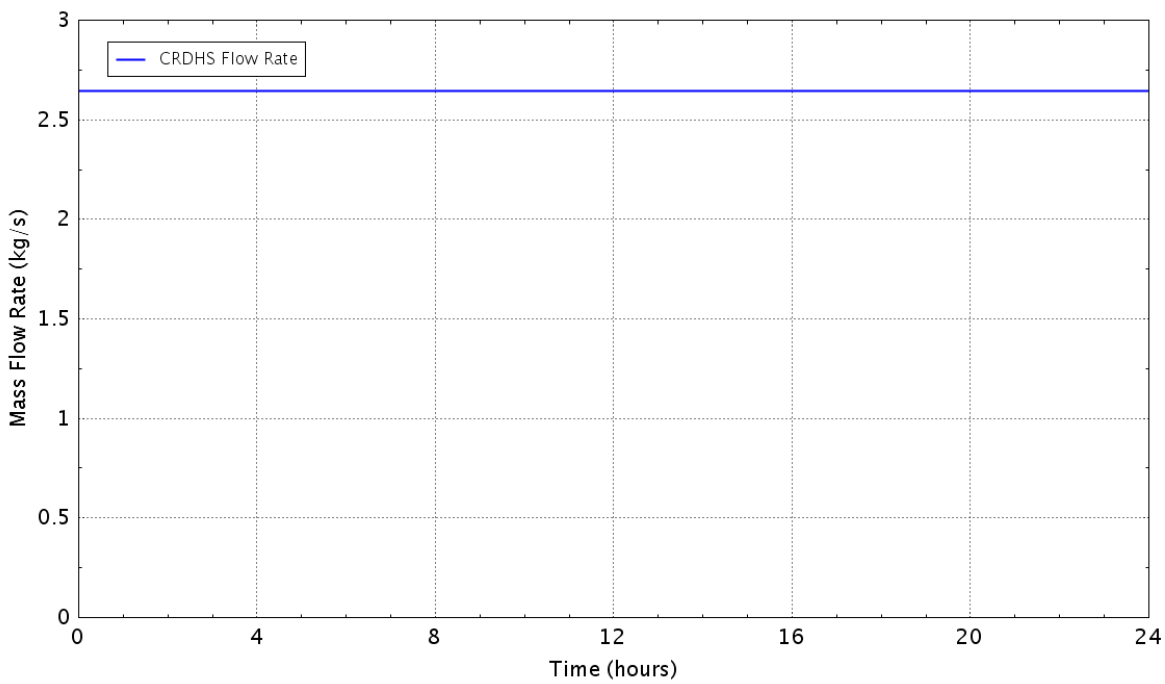

Figure C - 451 Flow rate of the control rod drive hydraulic system

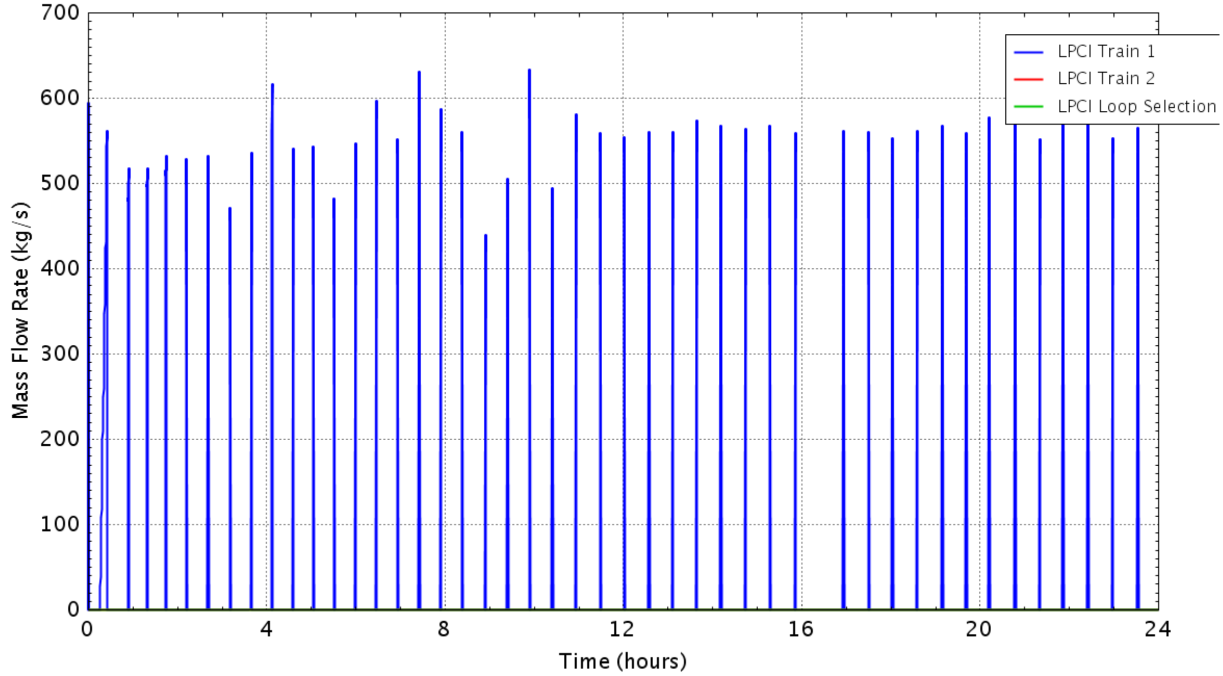

Figure C - 452 Flow rate of the LPCI pump

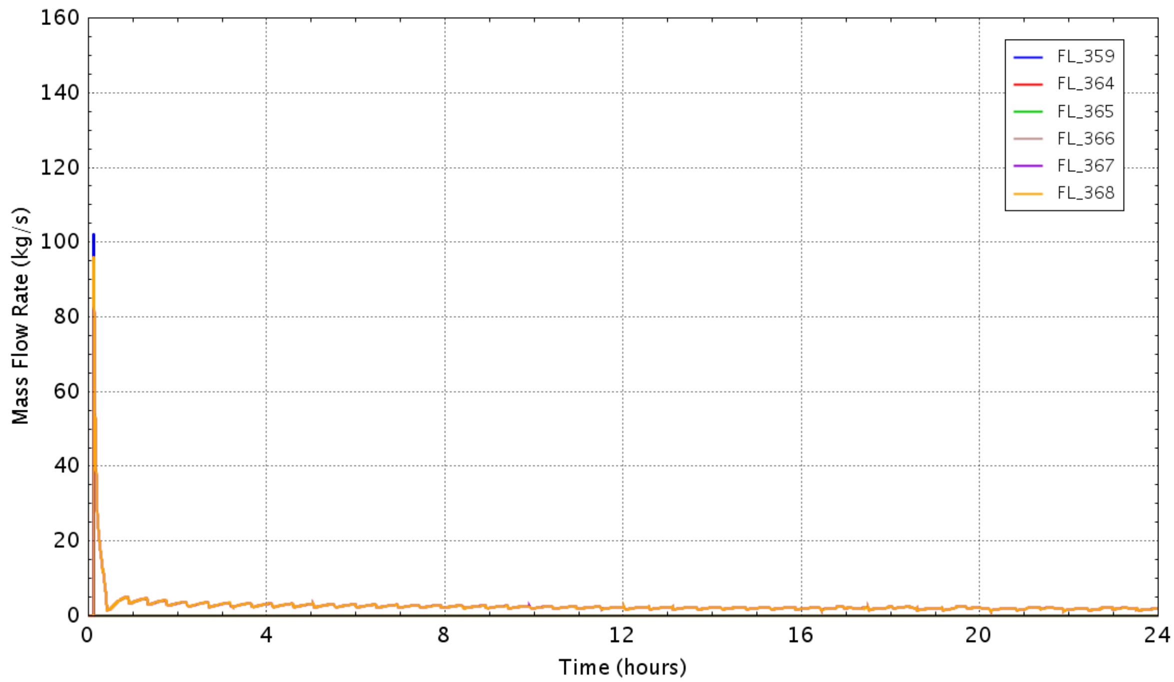

Figure C - 453 Flow rate of the SRVs

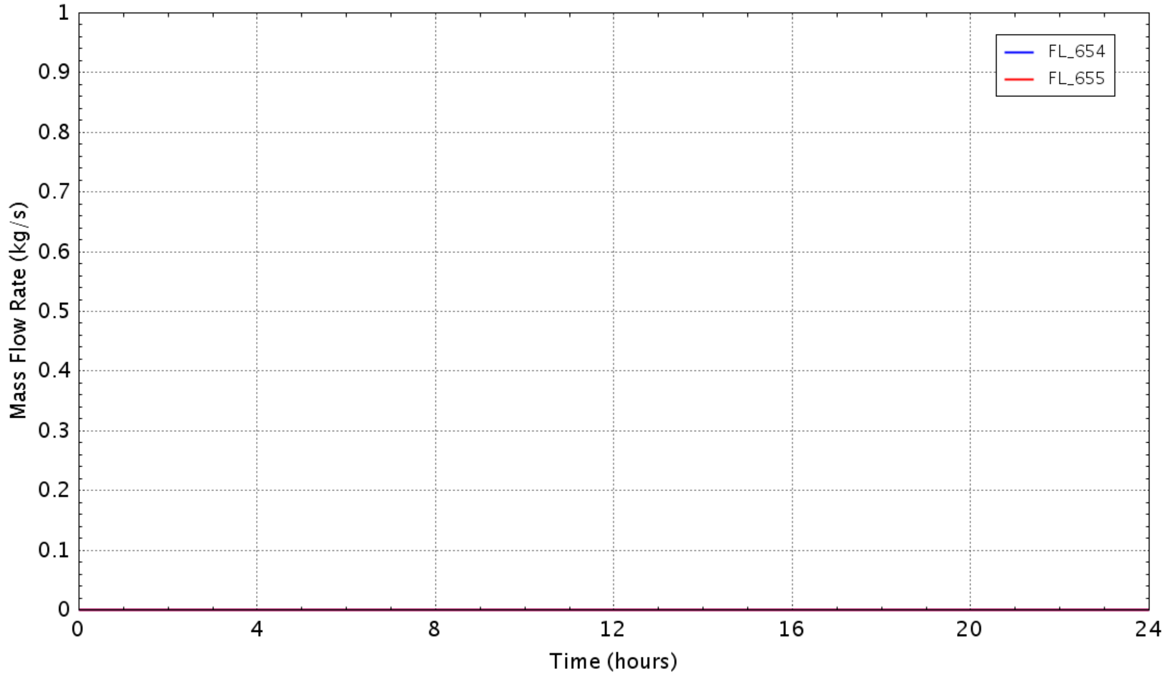

Figure C - 454 Flow rate of the wetwell cooling system

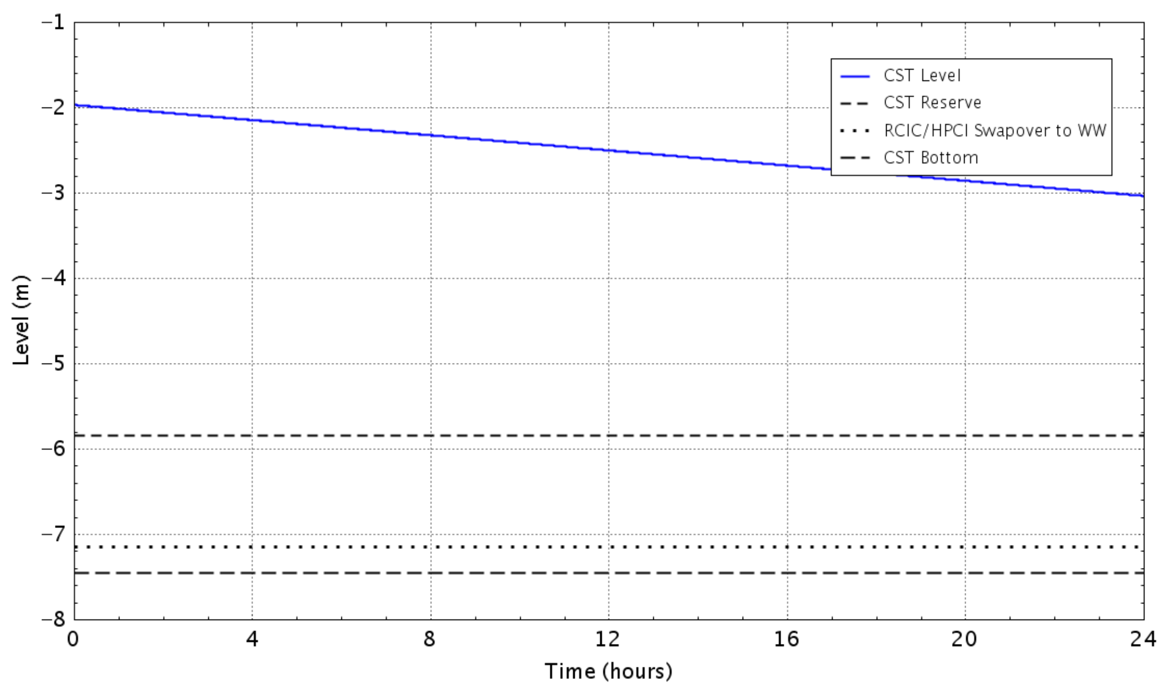

Figure C - 455 Water level in the CST

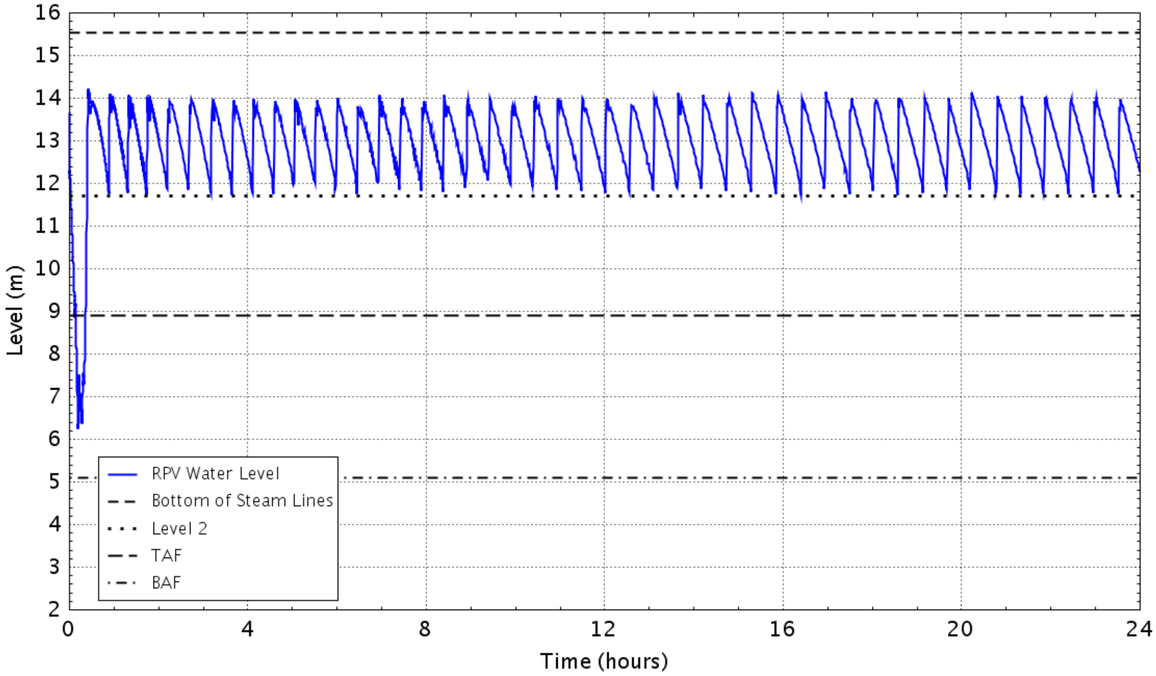

Figure C - 456   RPV Downcomer water level

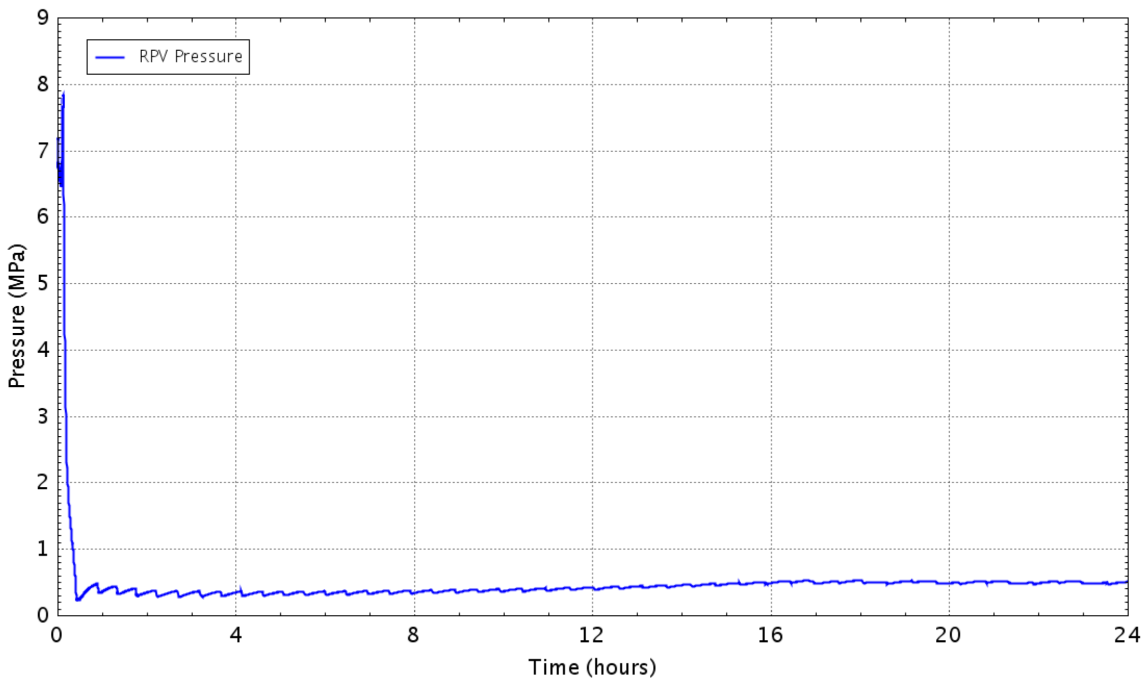

Figure C - 457 Pressure in the RPV

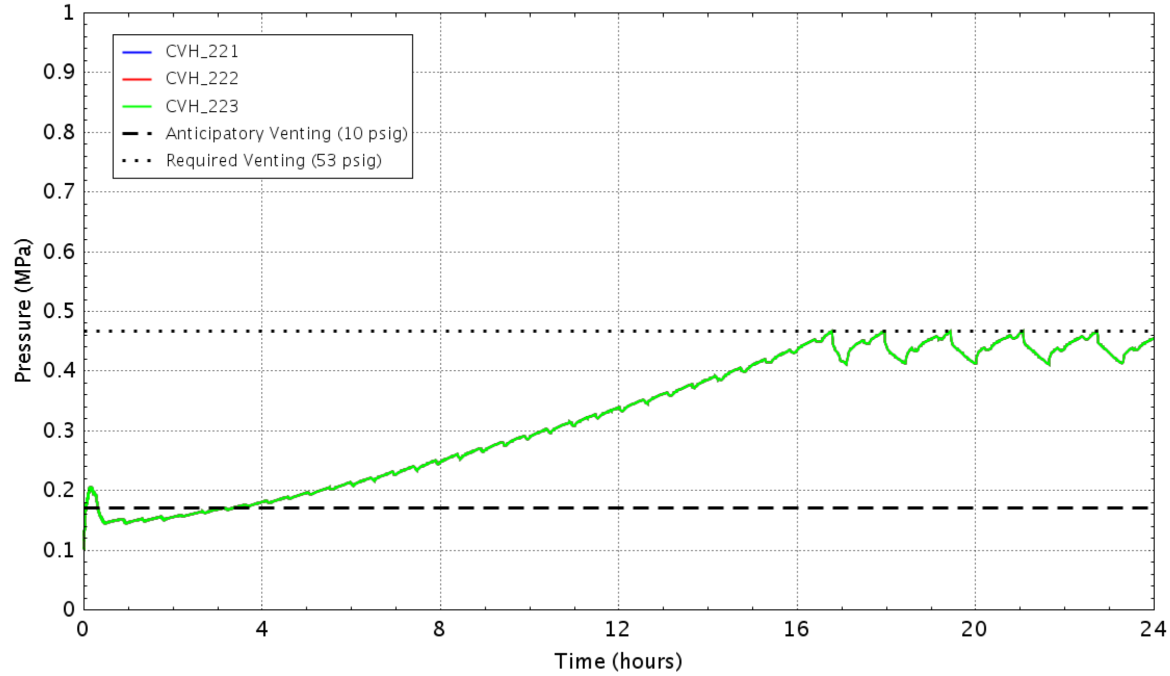

Figure C - 458 Pressure in the wetwell

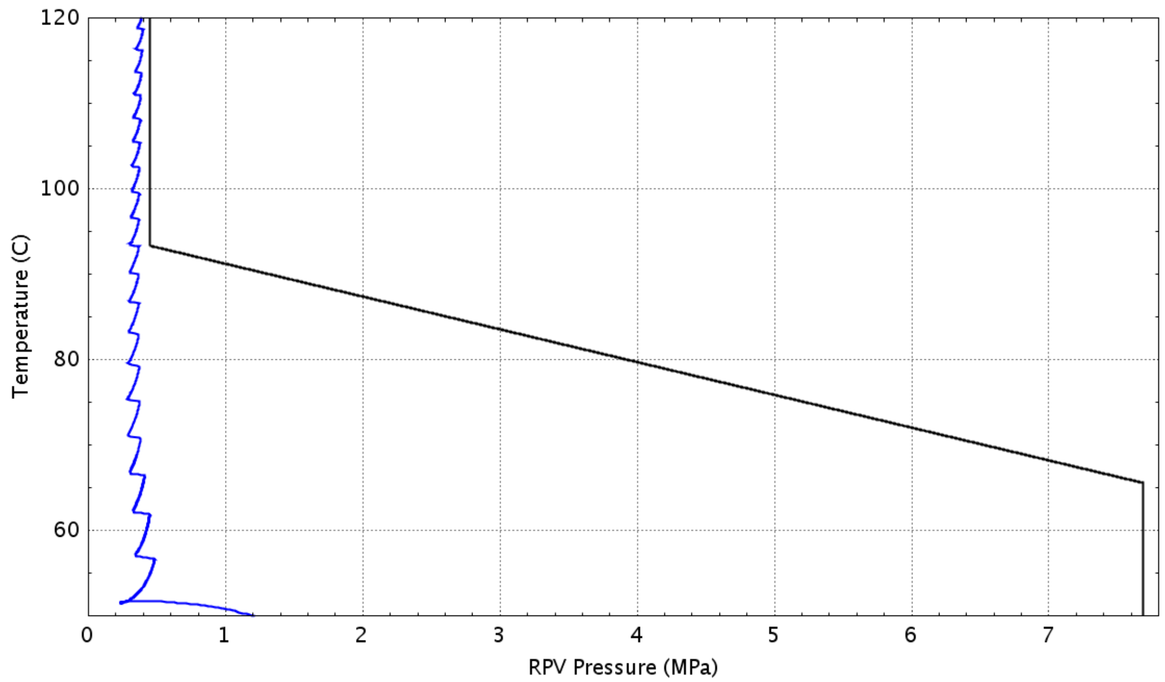

Figure C - 459 Plant status relative to the HCL curve (Graph 4 of the EOPs)

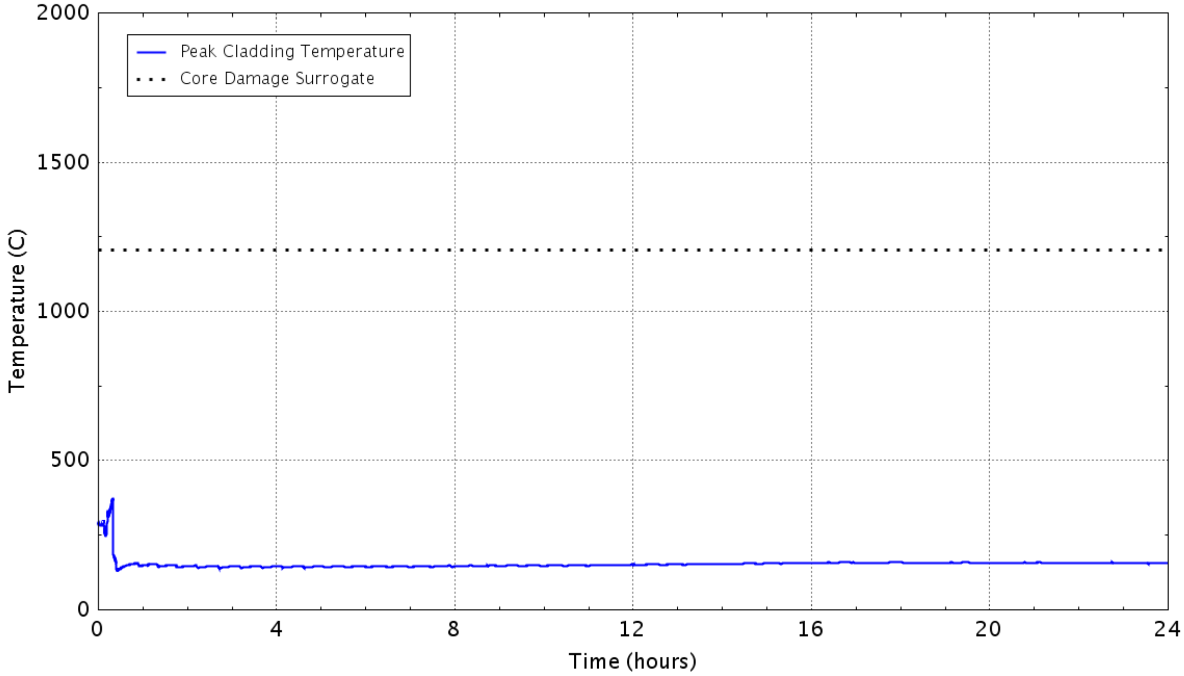

Figure C - 460 Peak temperature of the fuel cladding as a function of time

C.3.11 Case 24b: Sensitivity to SLOCA-25 Case 24 withLow-Pressure Injection Provided by Core Spray Rather Than LPCI

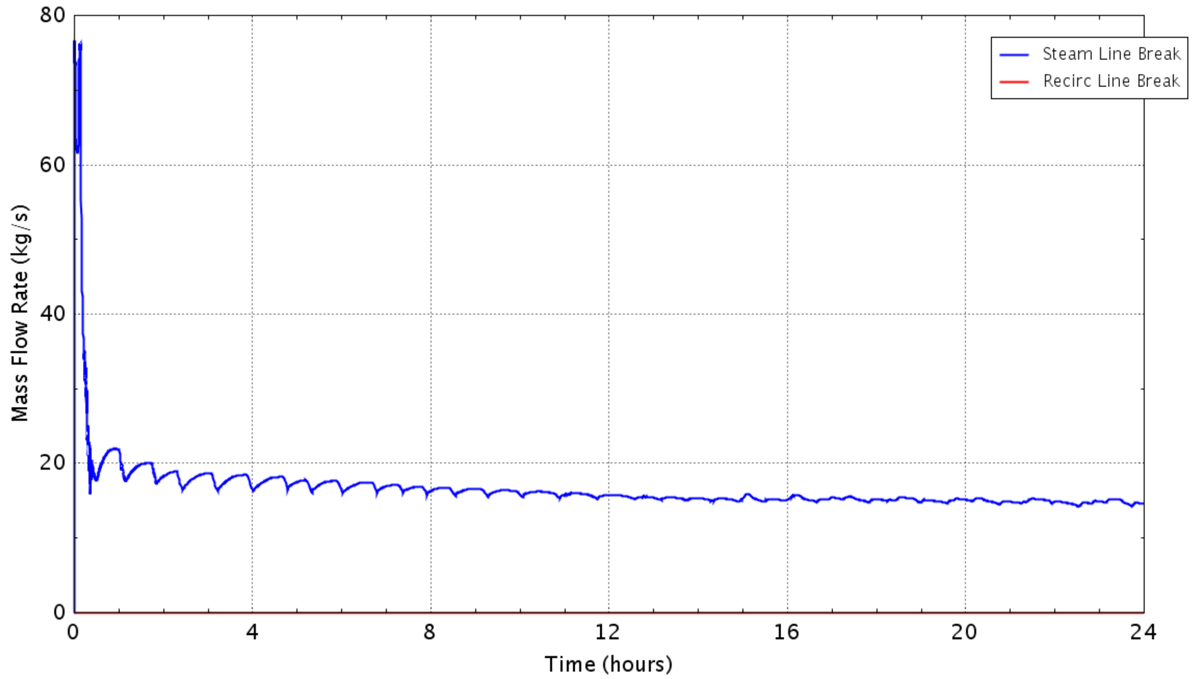

Figure C - 461 Flow rate of the break in the steamline/recirculation line

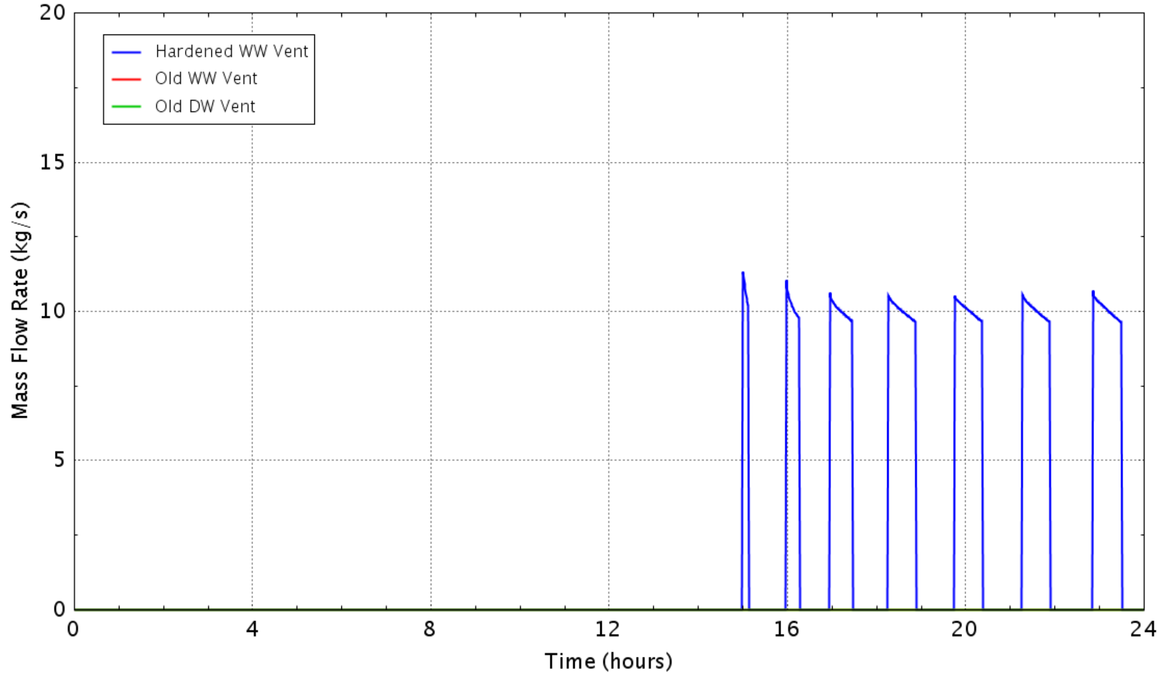

Figure C - 462 Flow rate of the containment vents

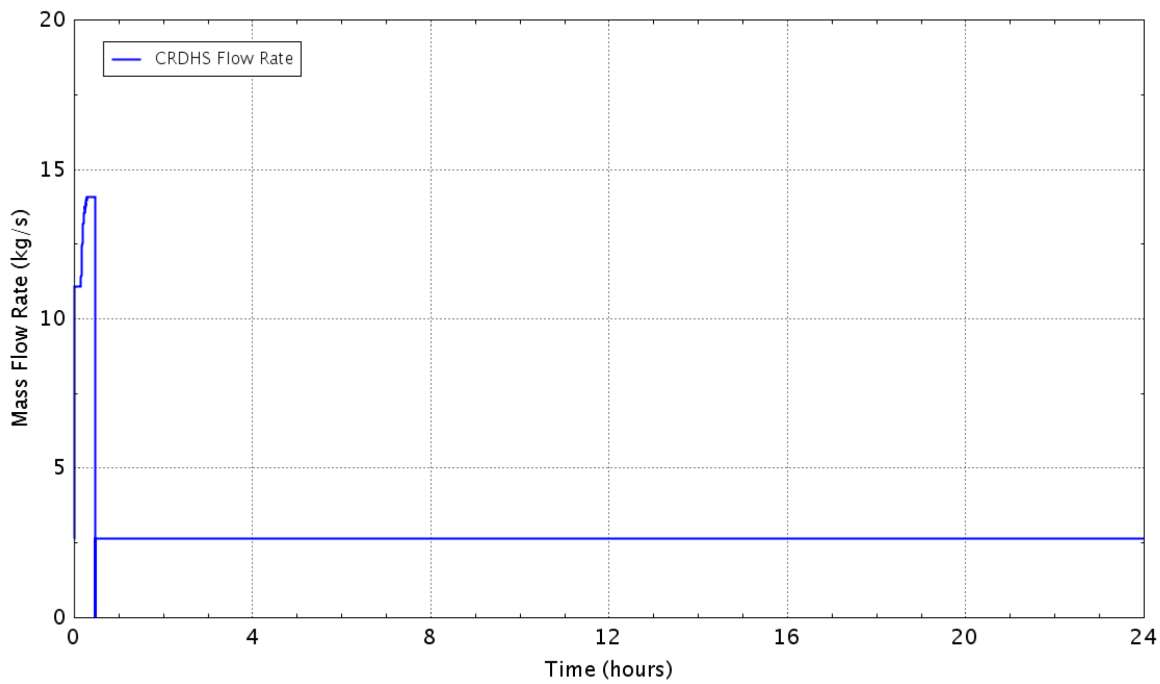

Figure C - 463 Flow rate of the control rod drive hydraulic system

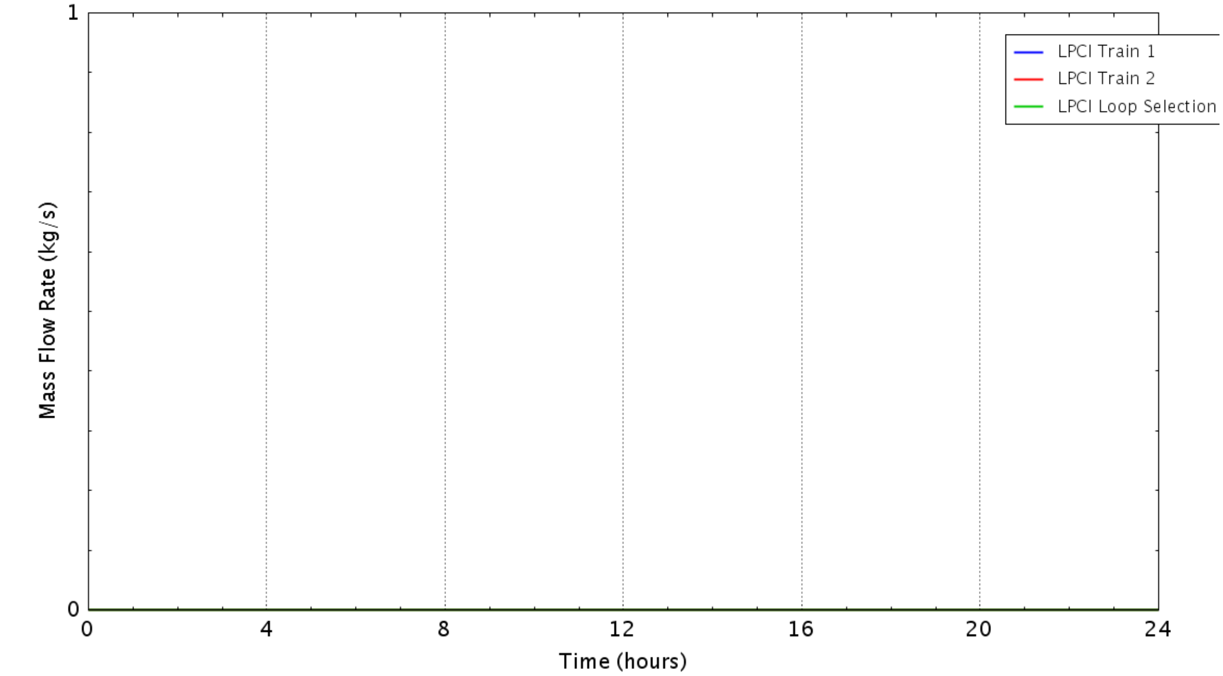

Figure C - 464 Flow rate of the LPCI pump

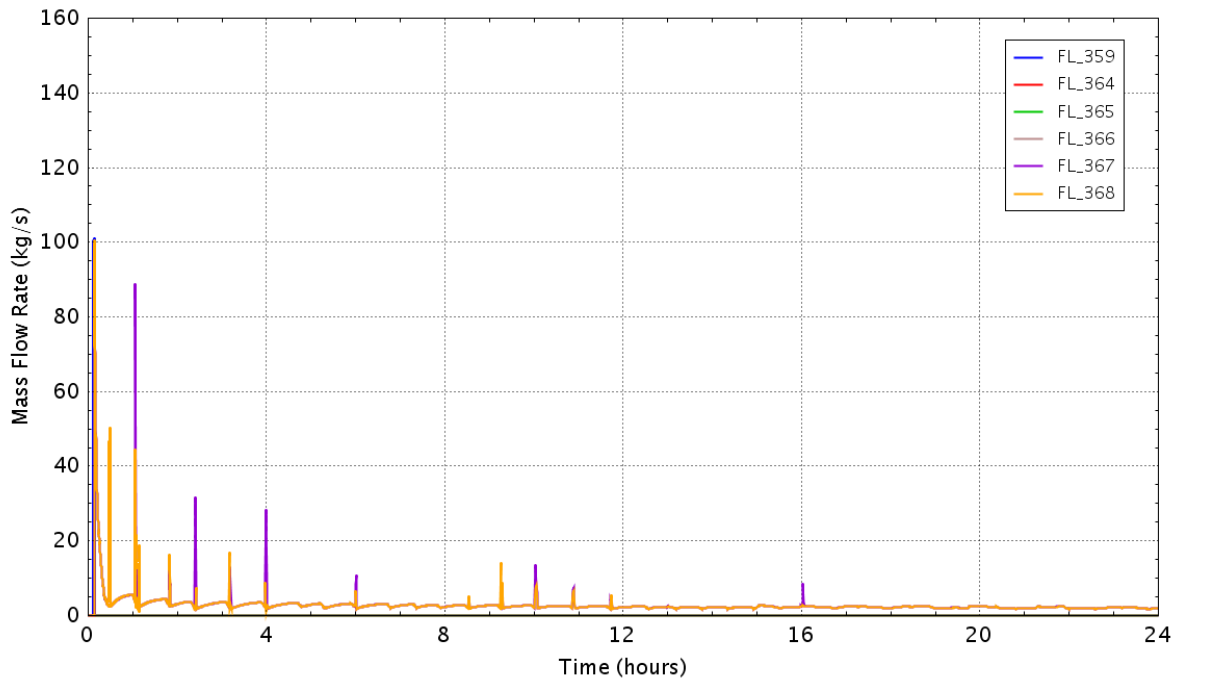

Figure C - 465 Flow rate of the SRVs

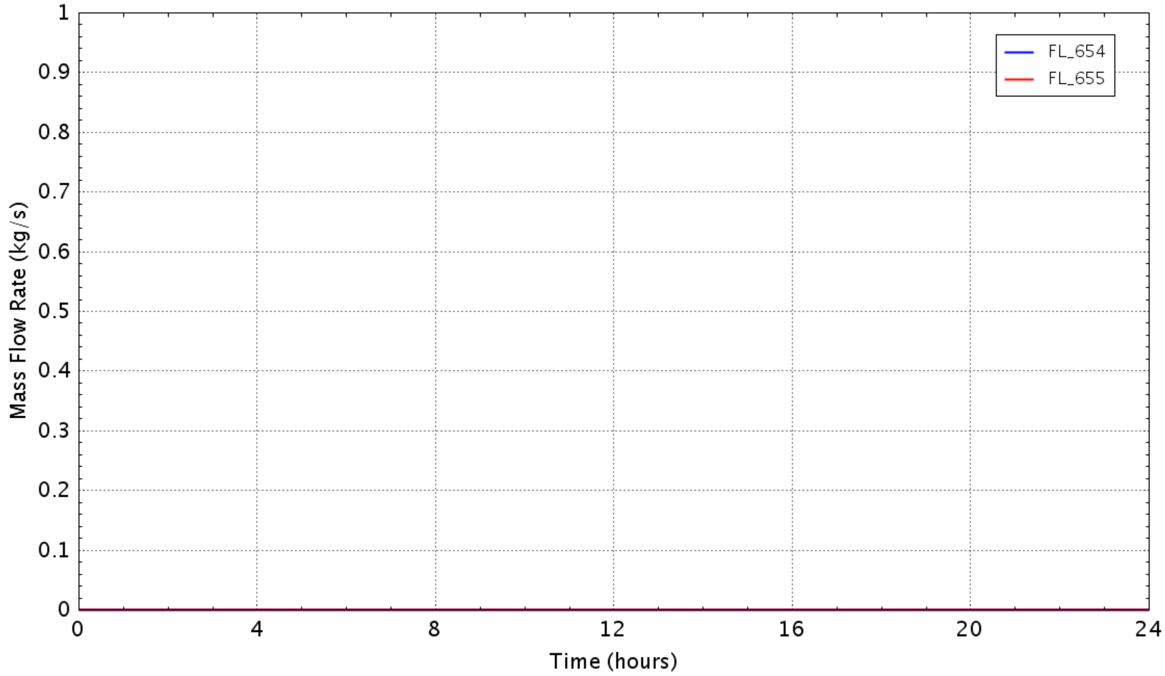

Figure C - 466 Flow rate of the wetwell cooling system

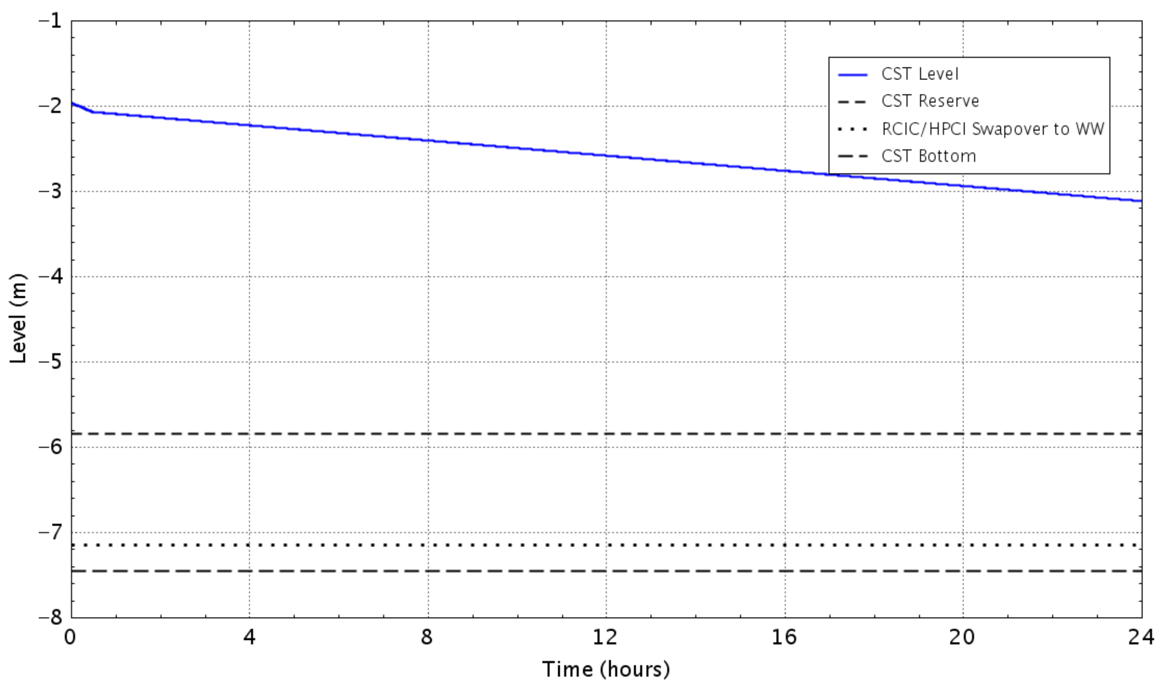

Figure C - 467 Water level in the CST

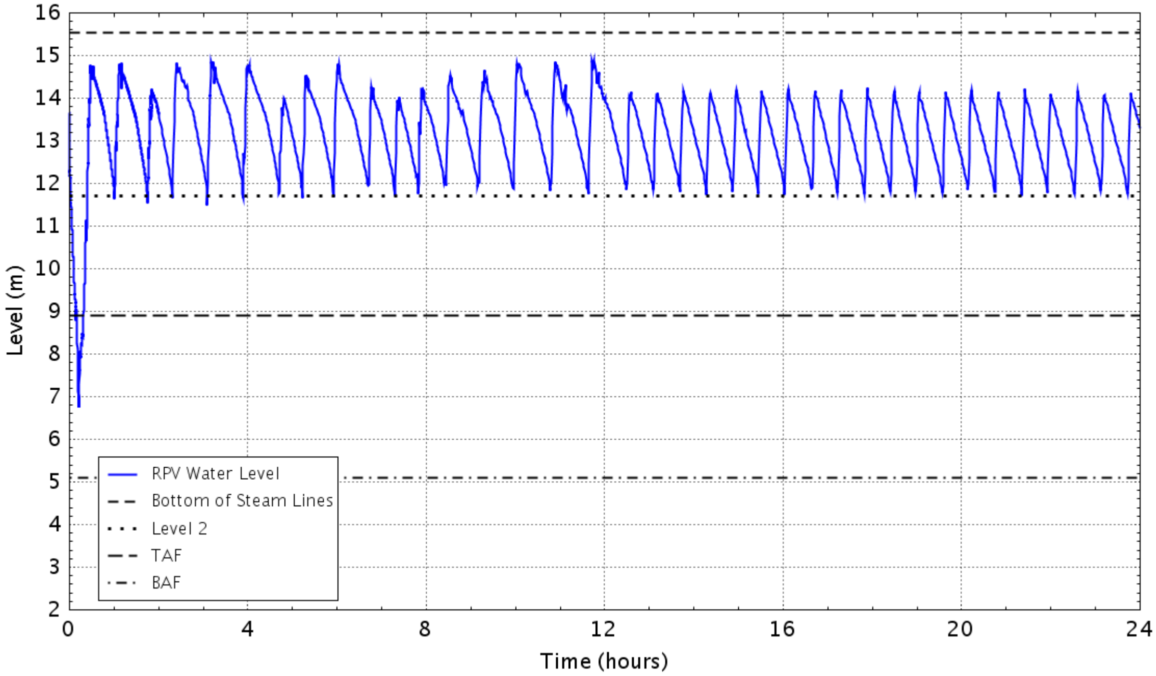

Figure C - 468 RPV Downcomer water level

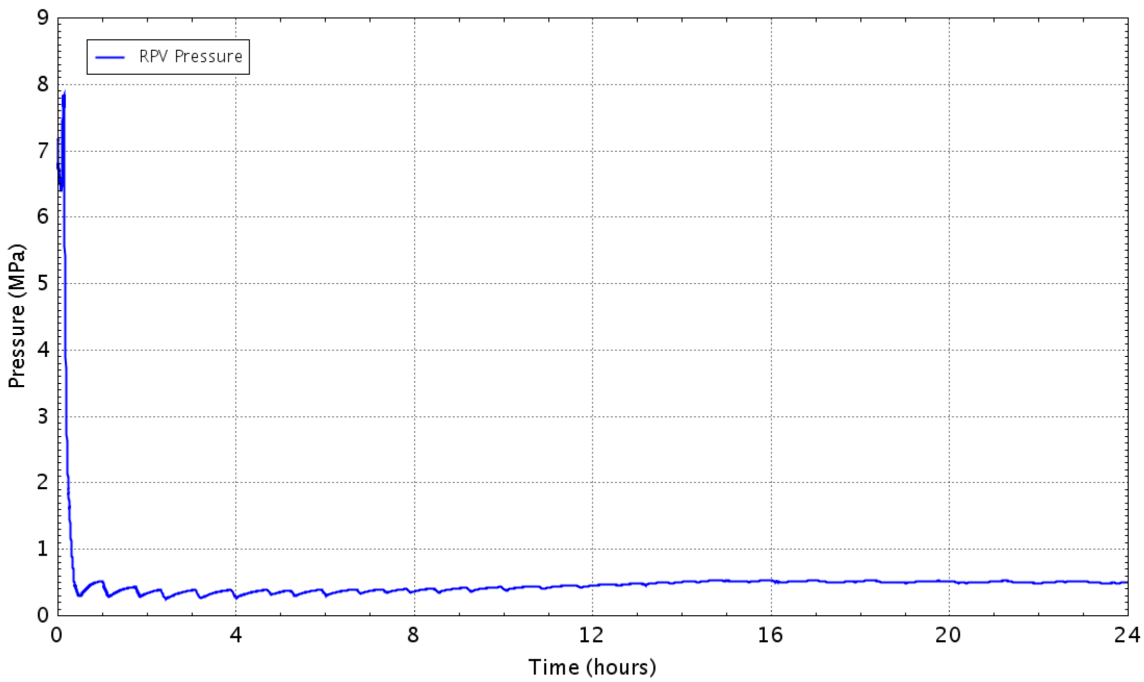

Figure C - 469 Pressure in the RPV

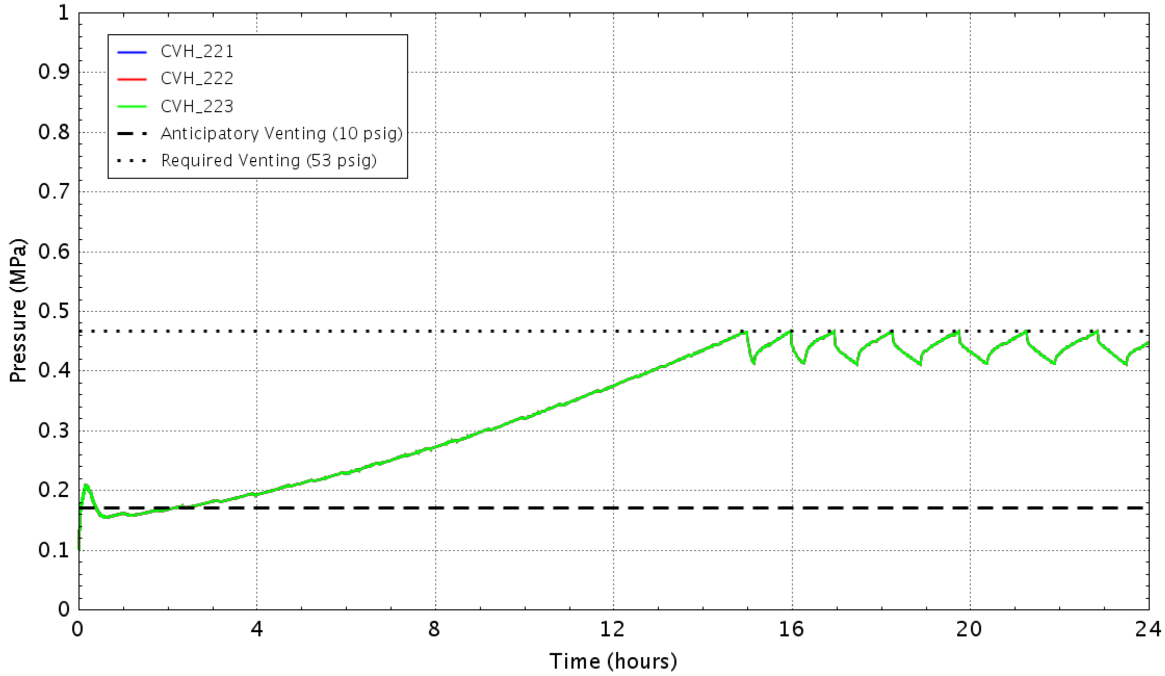

Figure C - 470 Pressure in the wetwell

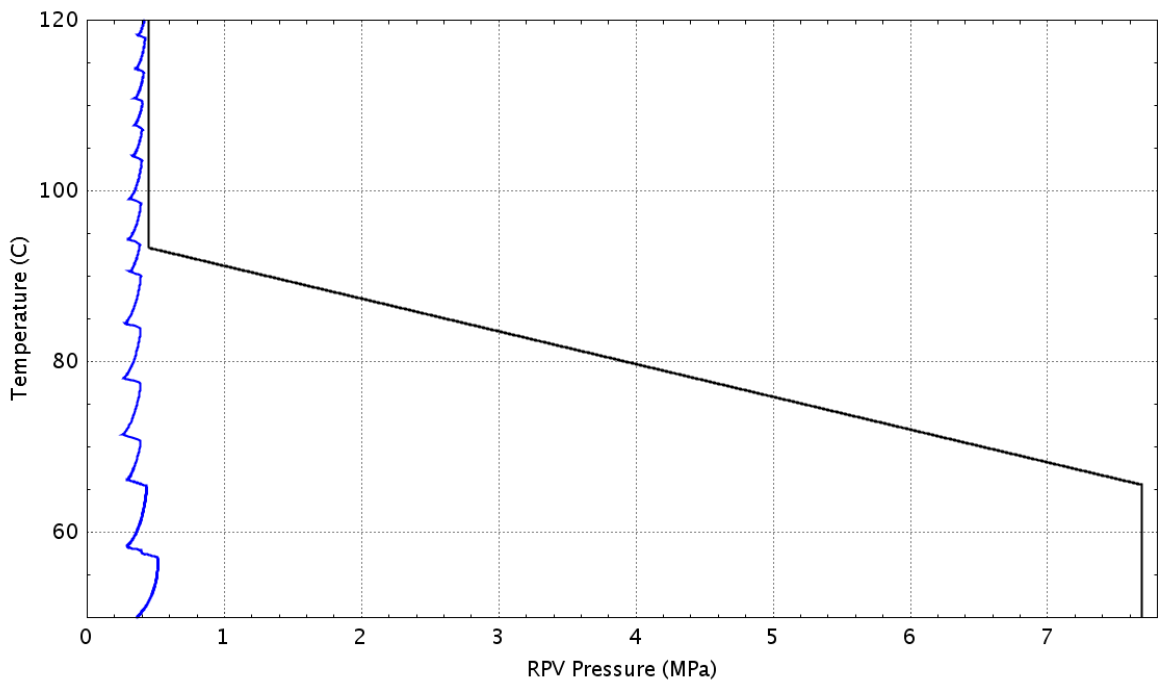

Figure C - 471 Plant status relative to the HCL curve (Graph 4 of the EOPs)

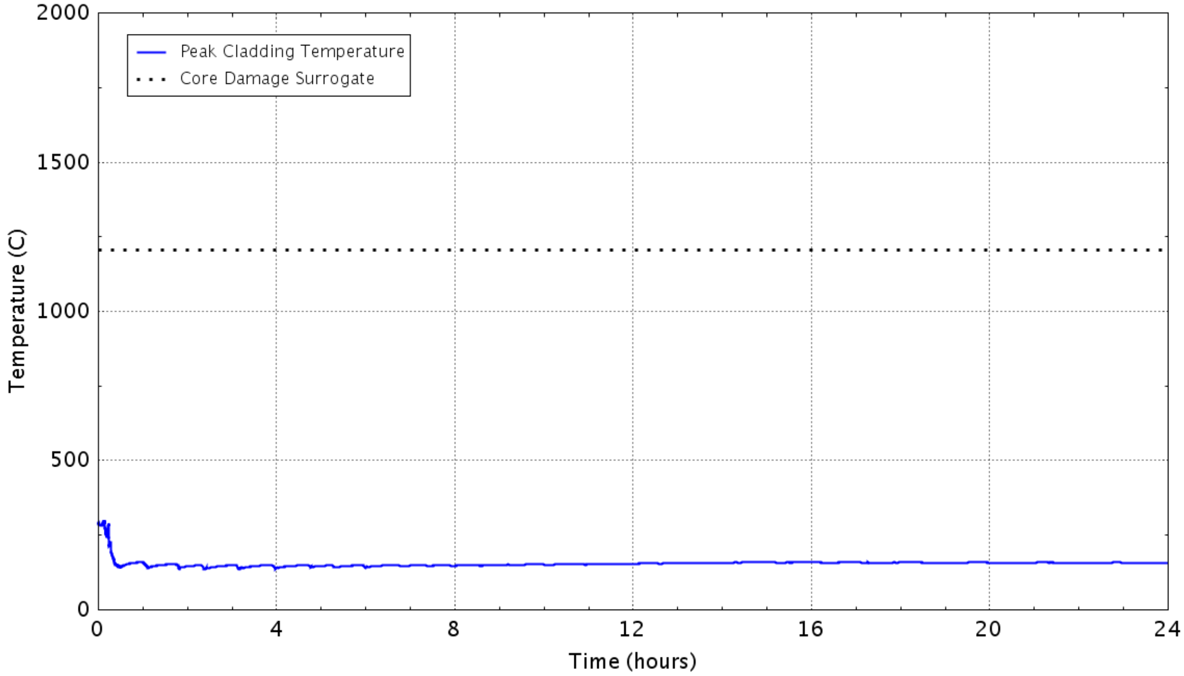

Figure C - 472 Peak temperature of the fuel cladding as a function of time

C.3.12 Case 24c: Sensitivity to SLOCA-25 Case 24 with Automatic Initiation of ADS

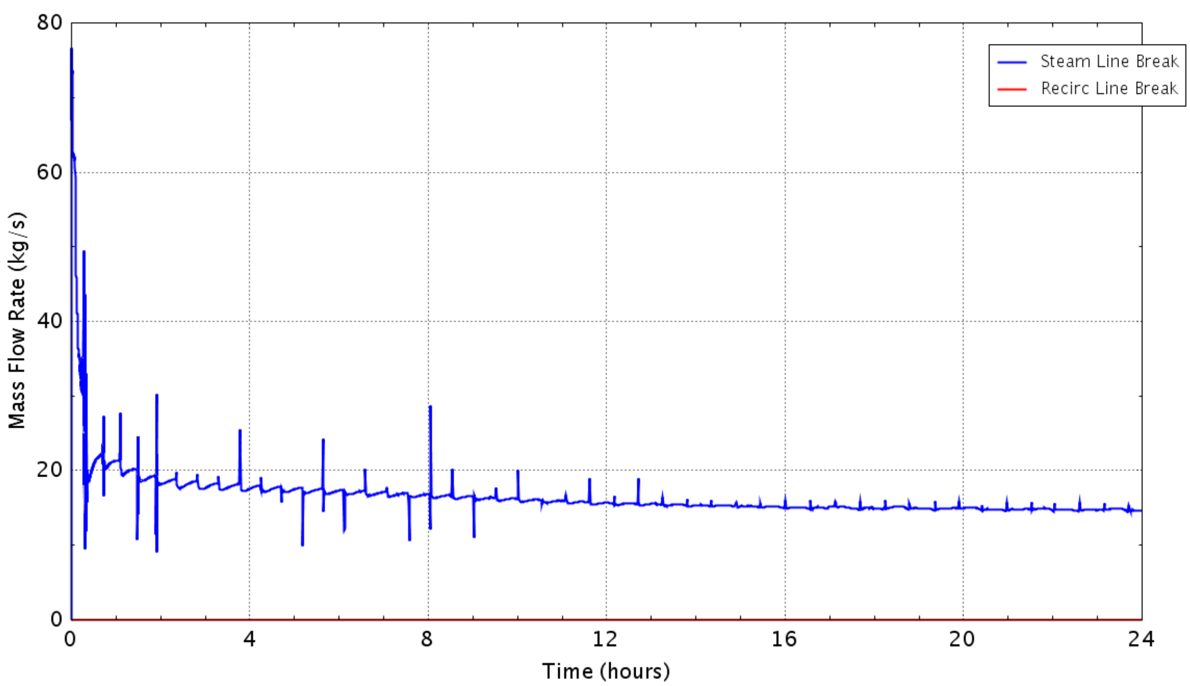

Figure C - 473 Flow rate of the break in the steamline/recirculation line

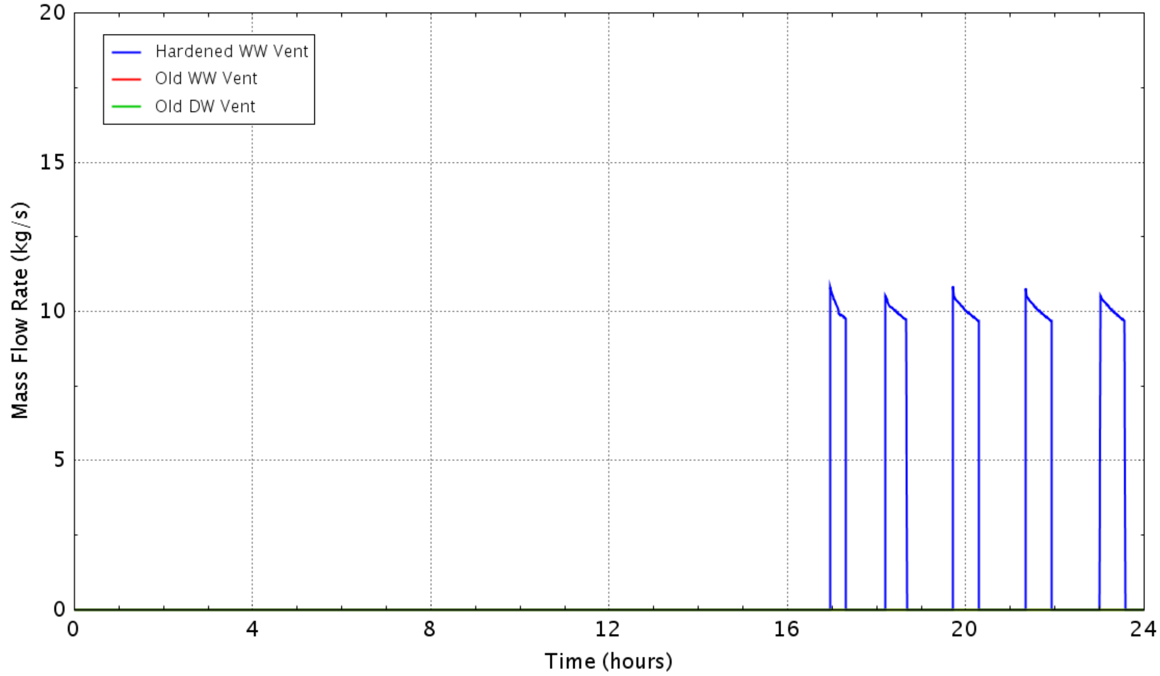

Figure C - 474 Flow rate of the containment vents

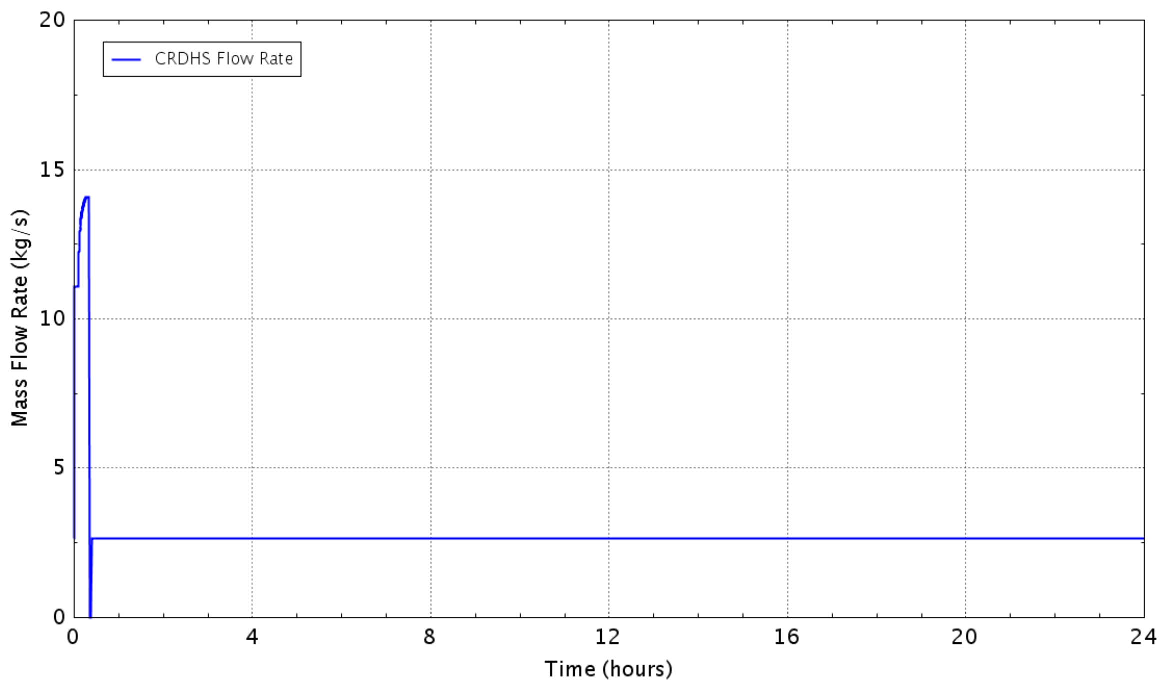

Figure C - 475 Flow rate of the control rod drive hydraulic system

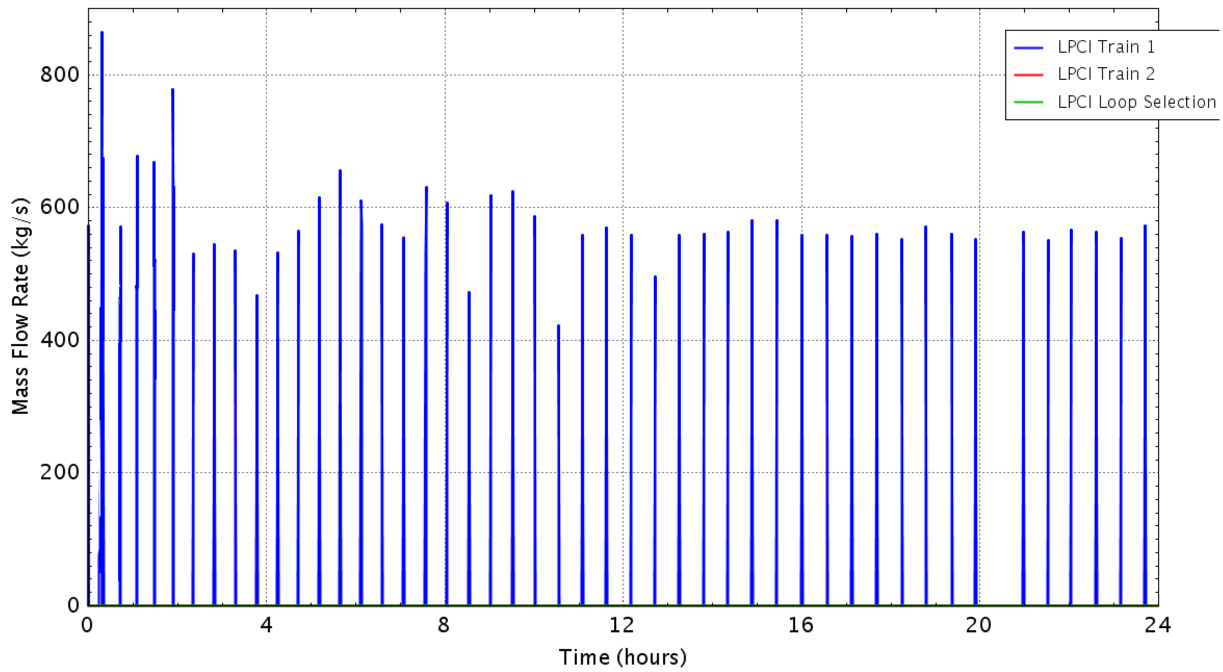

Figure C - 476 Flow rate of the LPCI pump

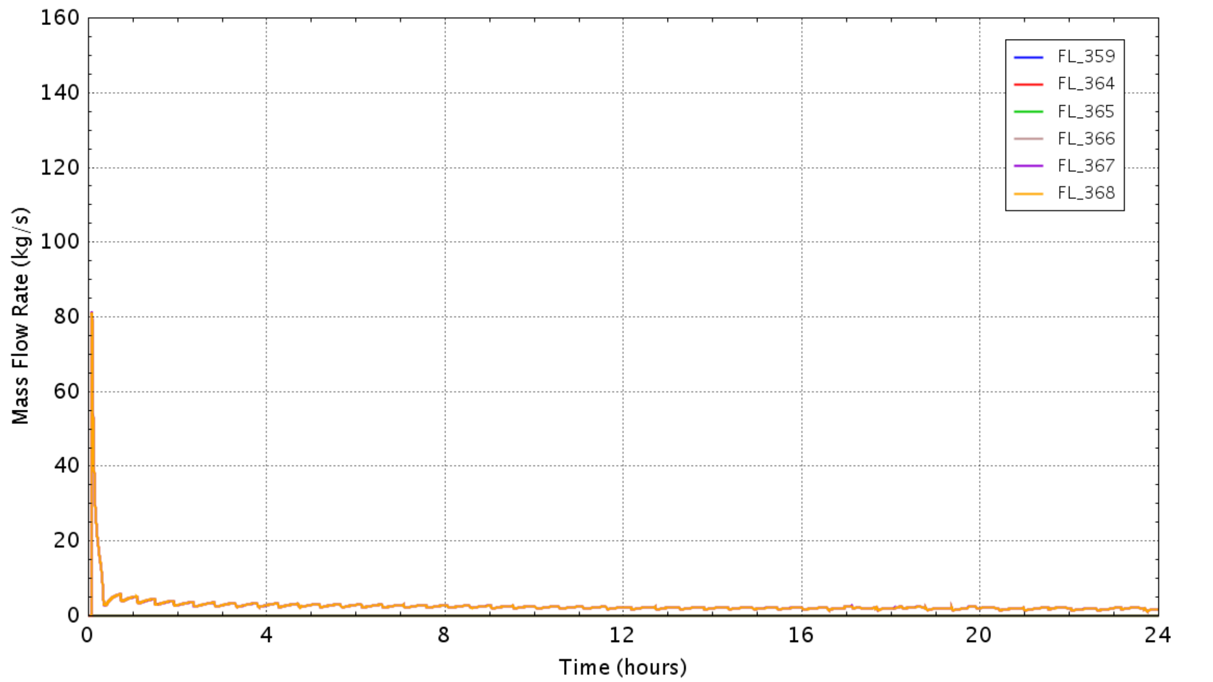

Figure C - 477 Flow rate of the SRVs

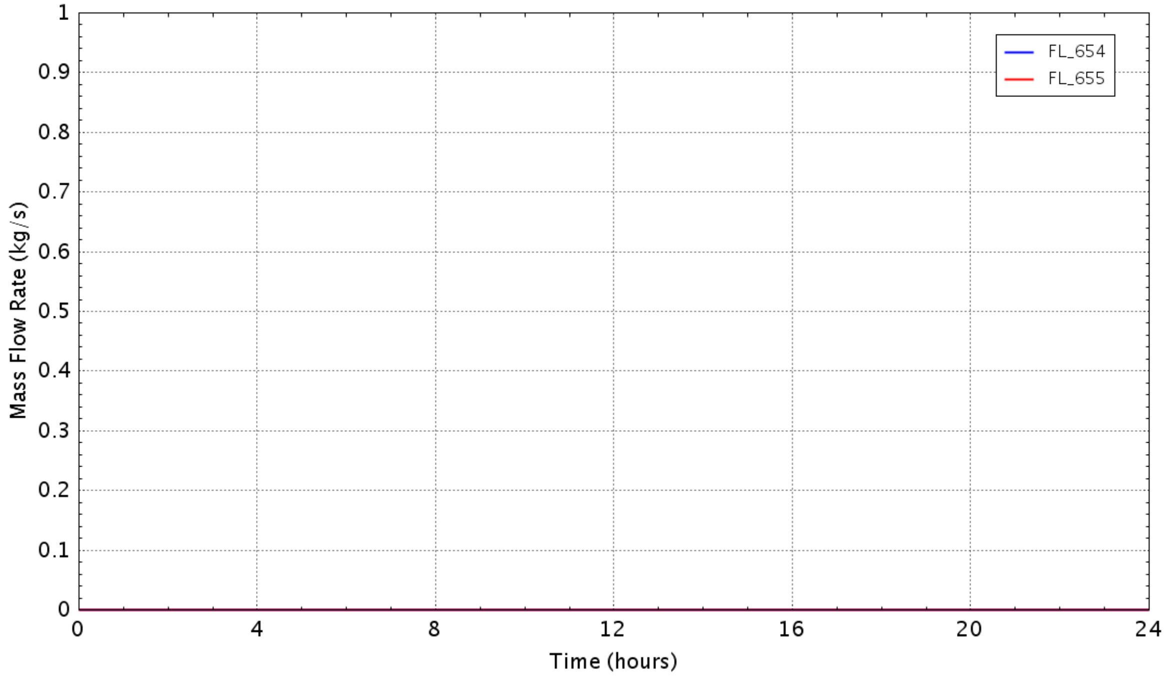

Figure C - 478 Flow rate of the wetwell cooling system

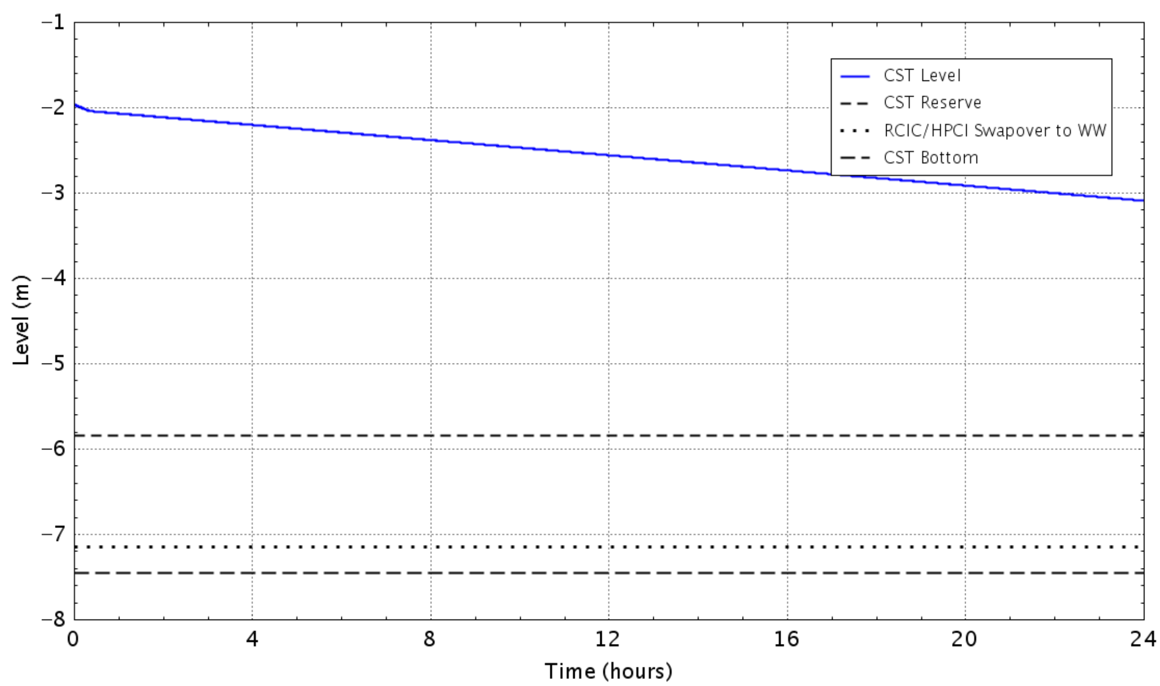

Figure C - 479 Water level in the CST

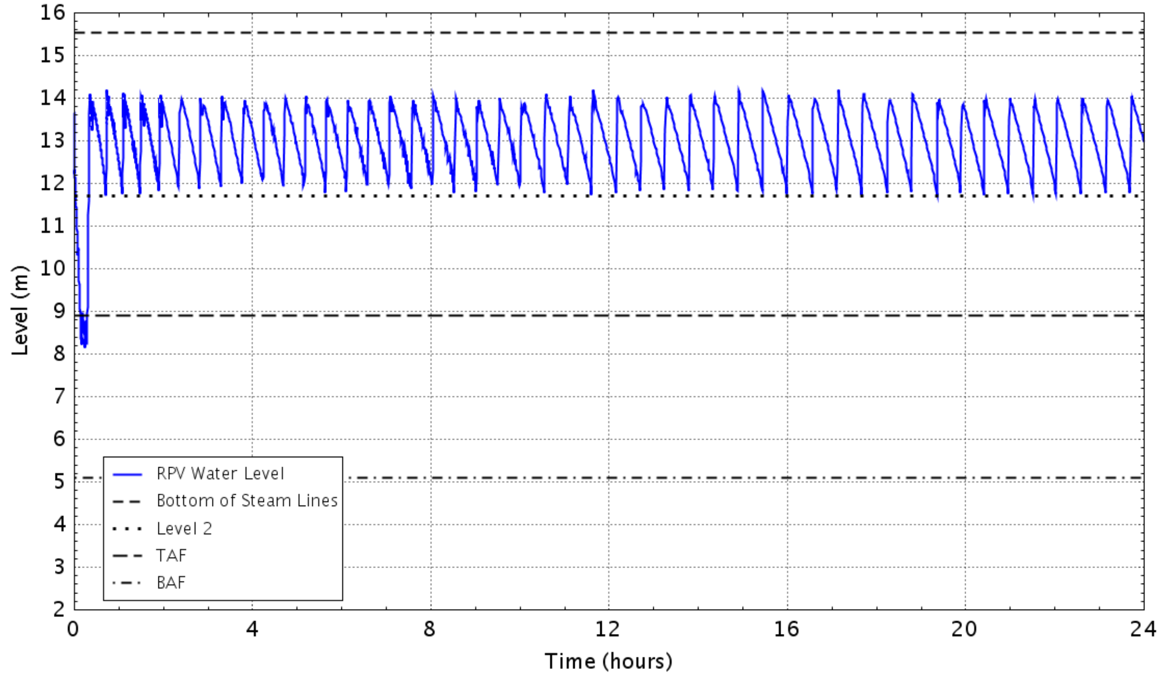

Figure C - 480 RPV Downcomer water level

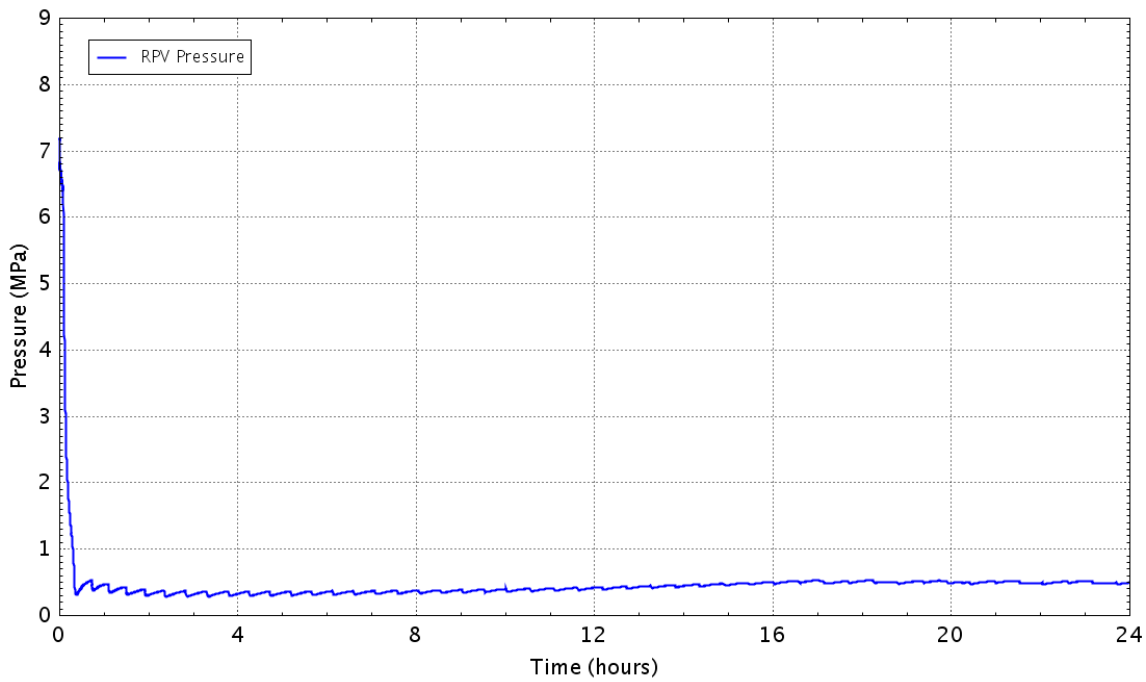

Figure C - 481 Pressure in the RPV

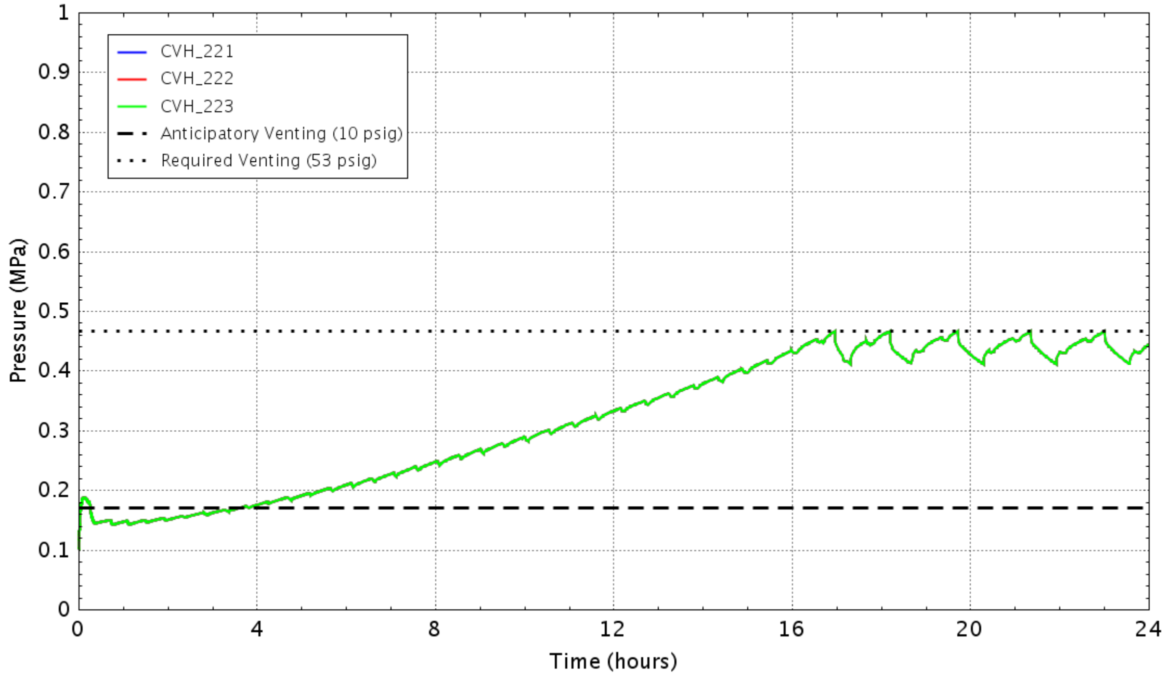

Figure C - 482   Pressure in the wetwell

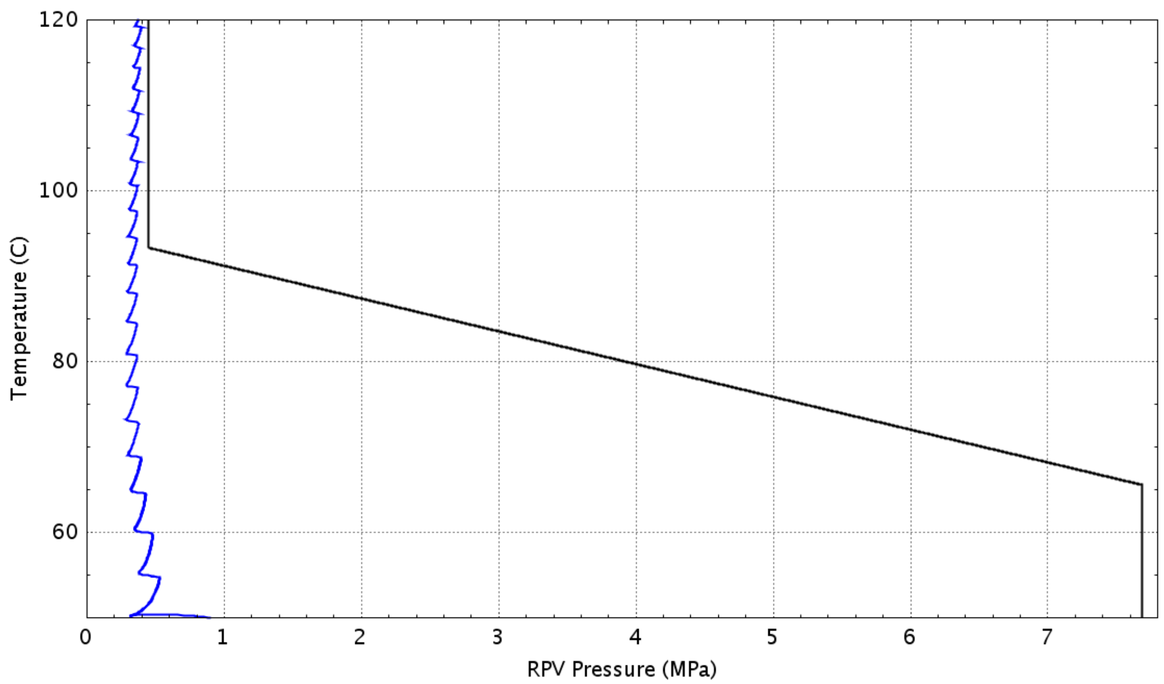

Figure C - 483   Plant status relative to the HCL curve (Graph 4 of the EOPs)

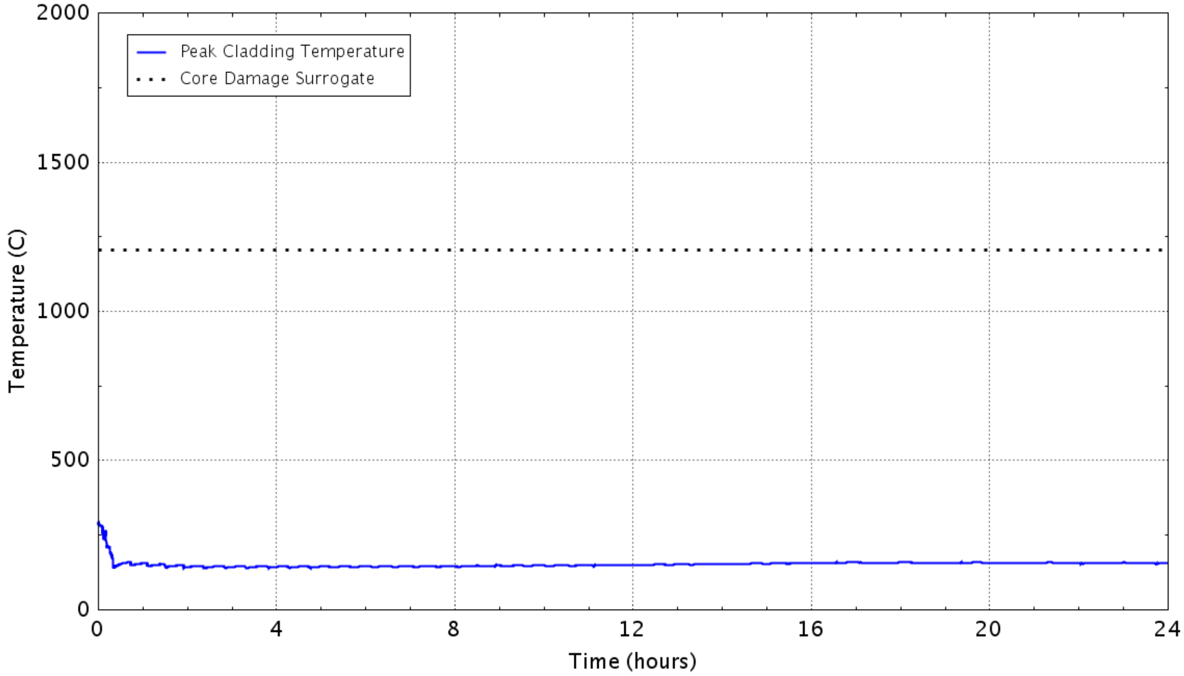

Figure C - 484 Peak temperature of the fuel cladding as a function of time

C.3.13 Case 24d: Sensitivity to SLOCA-25 Case 24 with Nominal Recirculation Pump Seal Leakage

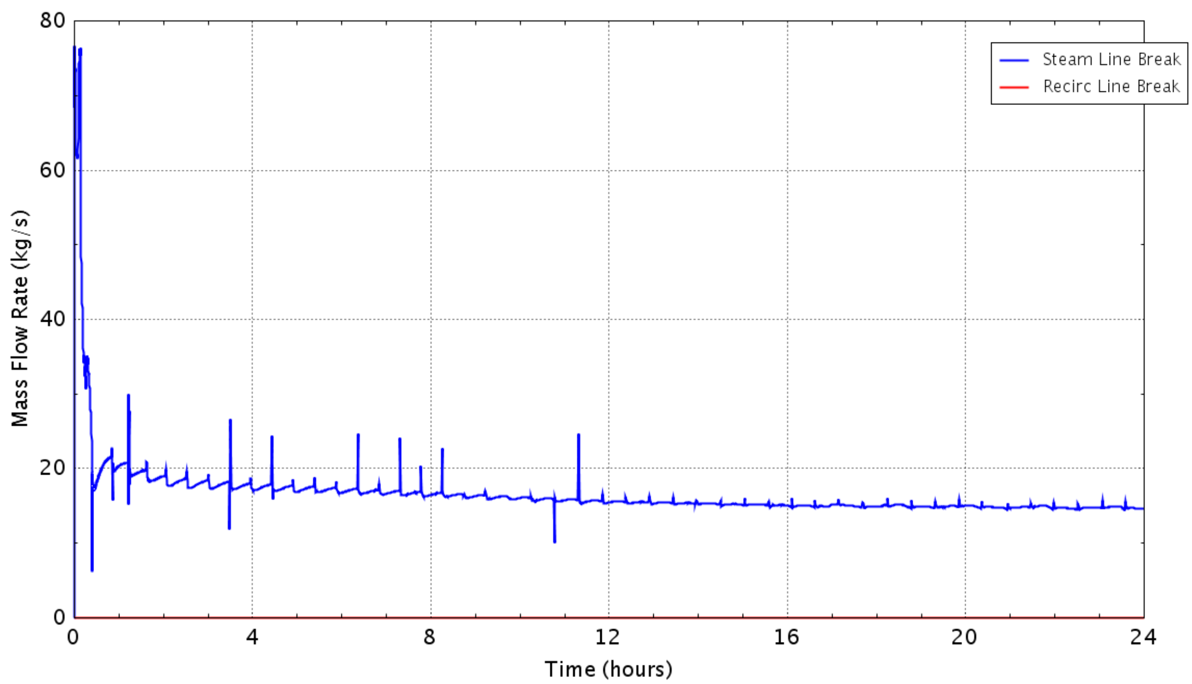

Figure C - 485 Flow rate of the break in the steamline/recirculation line

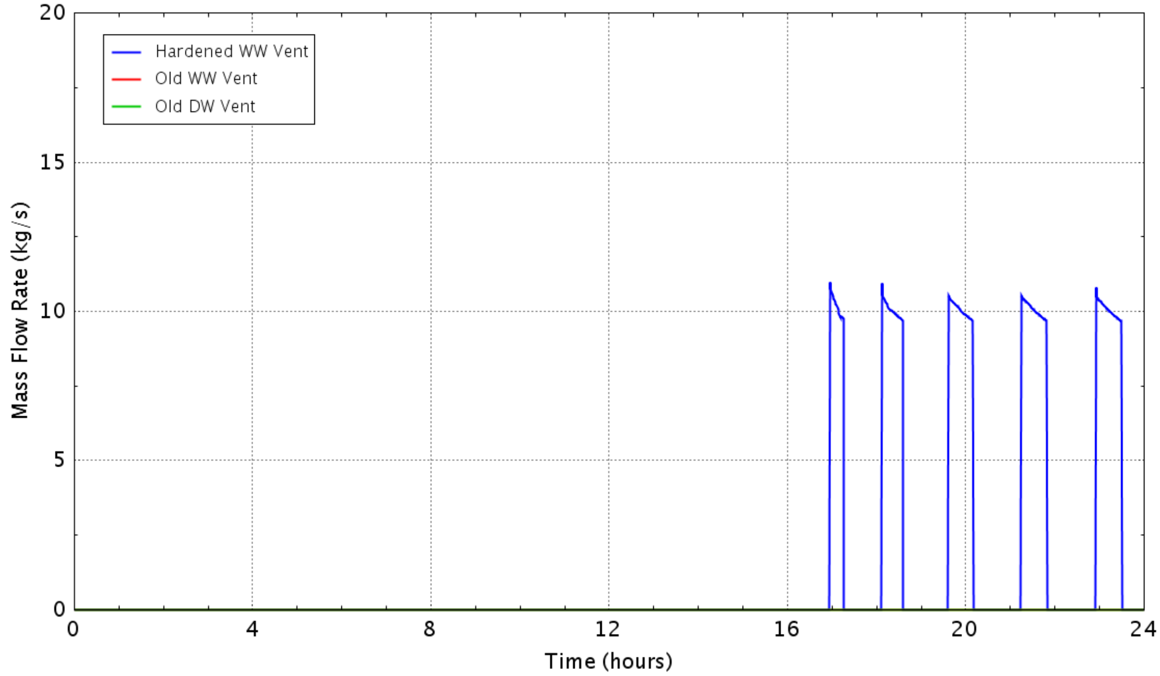

Figure C - 486   Flow rate of the containment vents

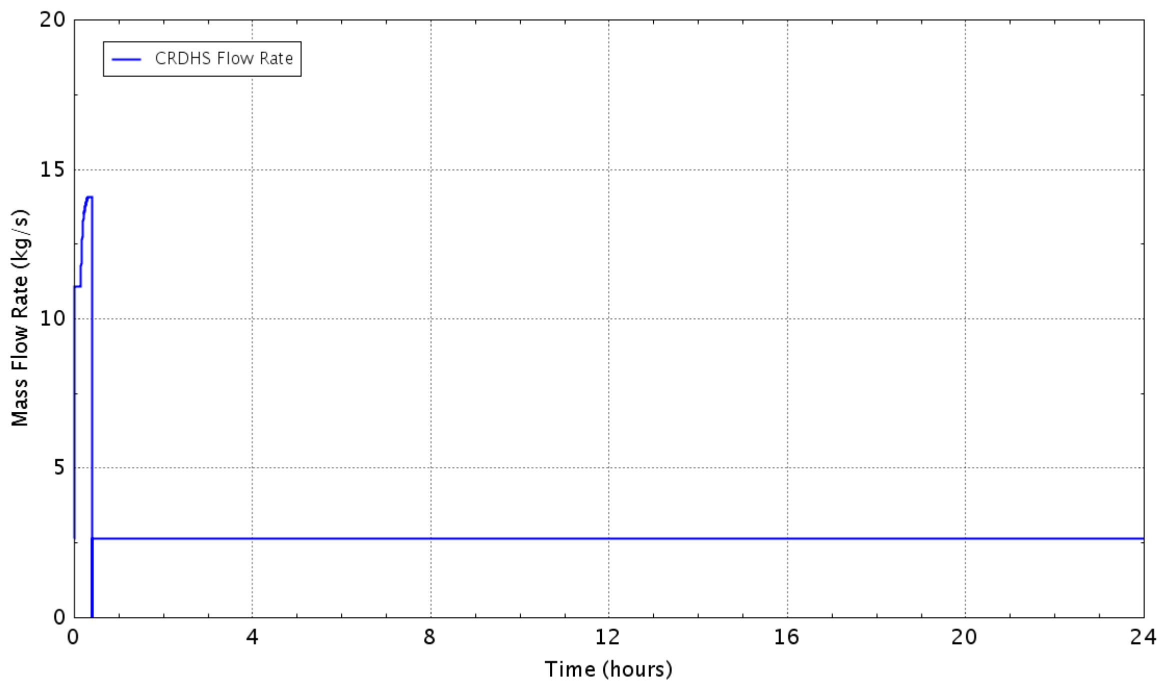

Figure C - 487   Flow rate of the control rod drive hydraulic system

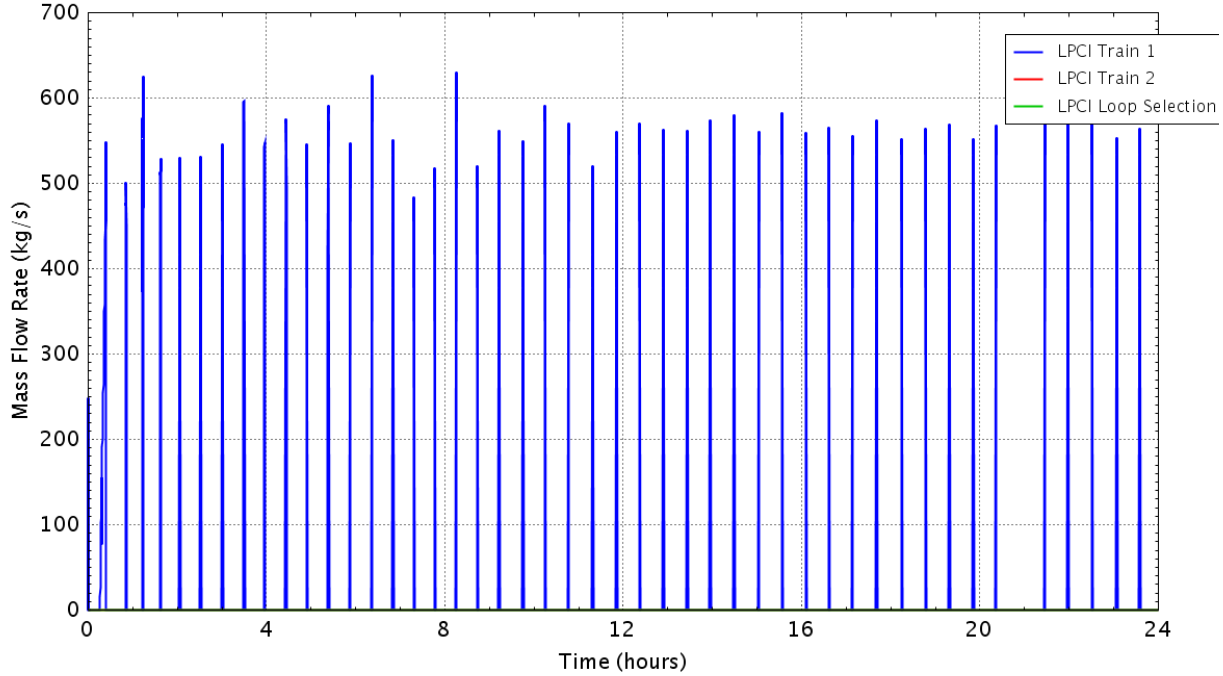

Figure C - 488   Flow rate of the LPCI pump

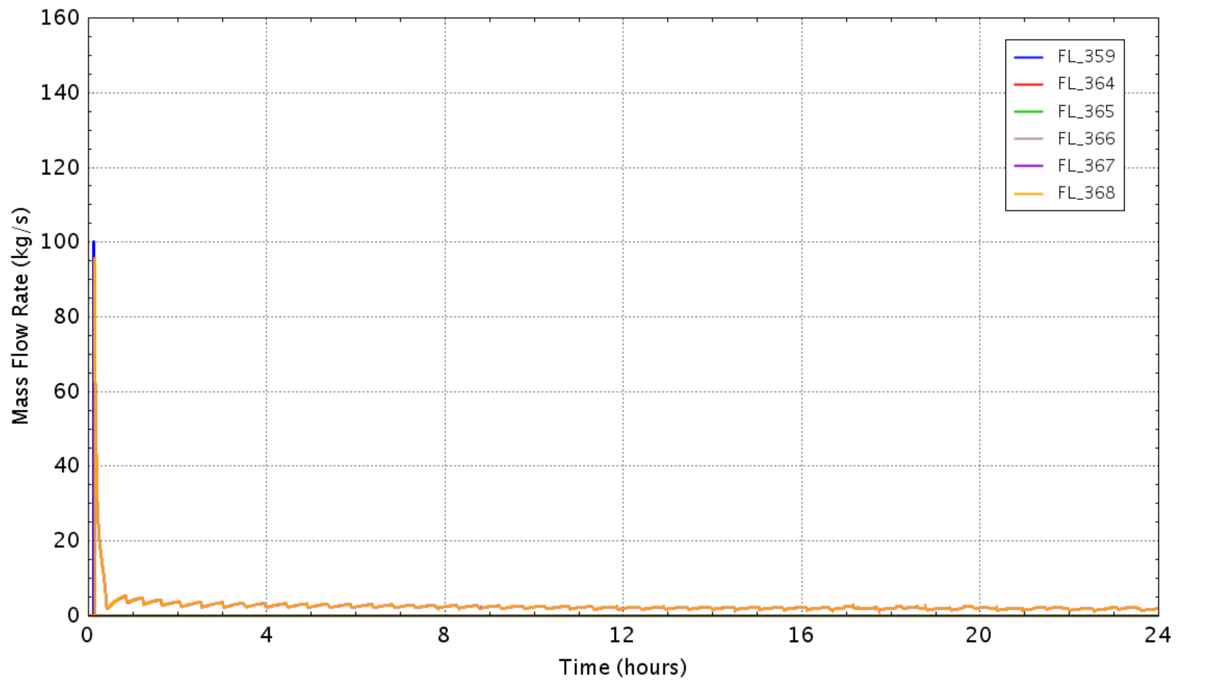

Figure C - 489   Flow rate of the SRVs

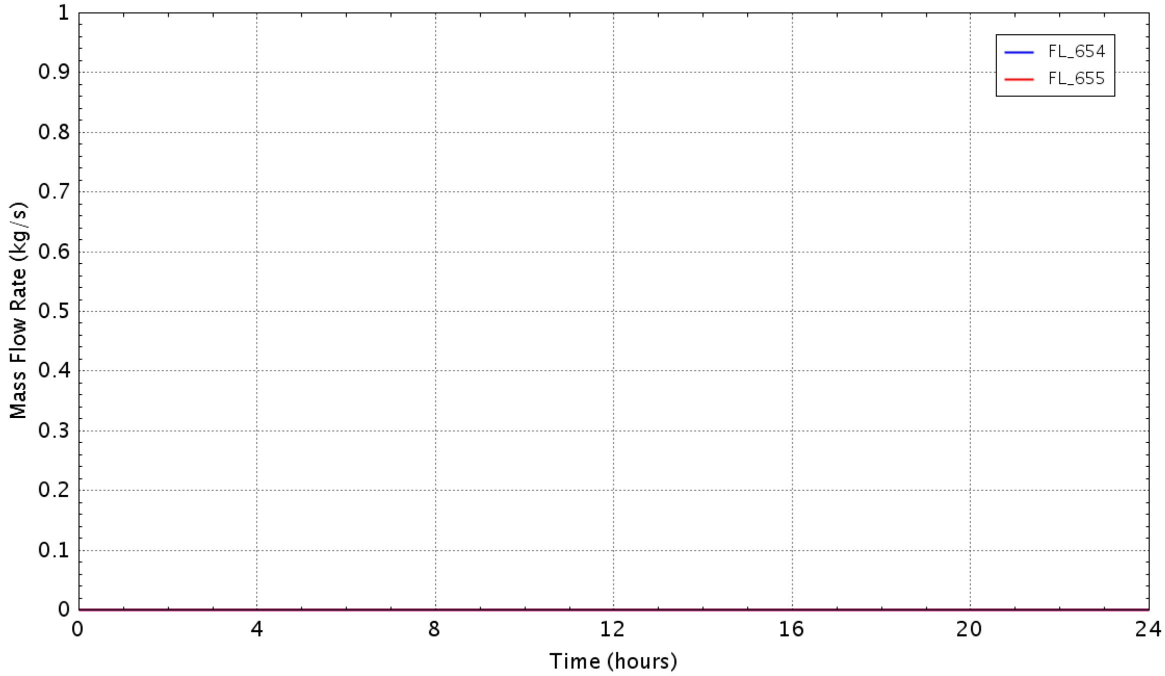

Figure C - 490 Flow rate of the wetwell cooling system

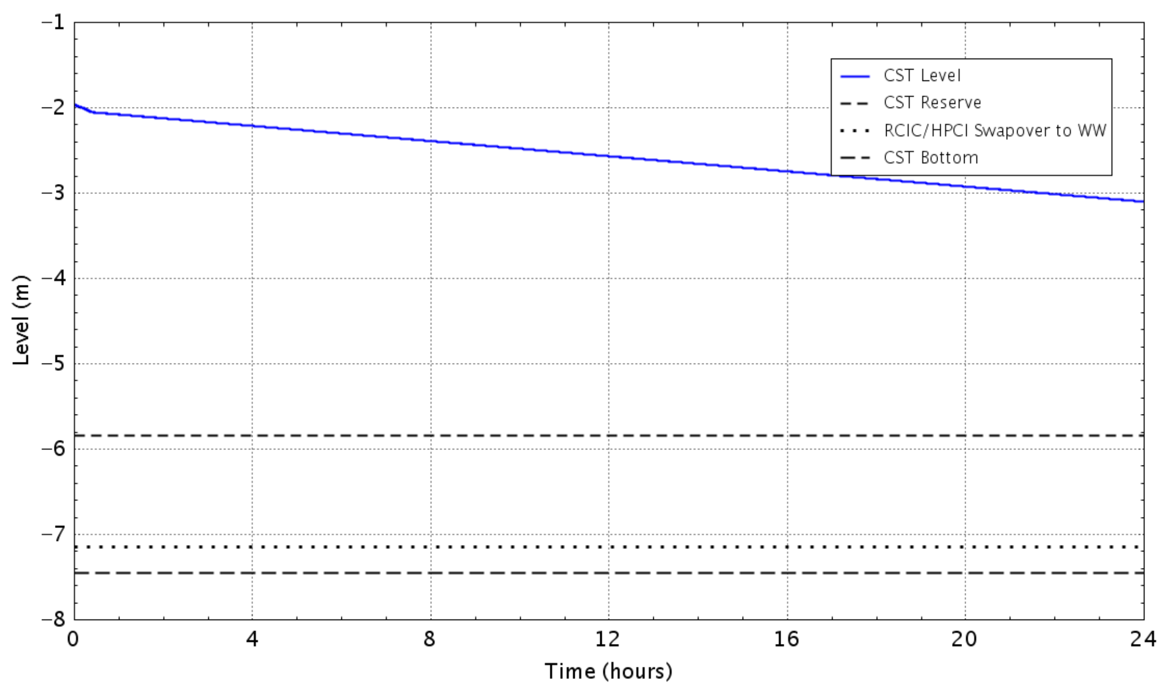

Figure C - 491 Water level in the CST

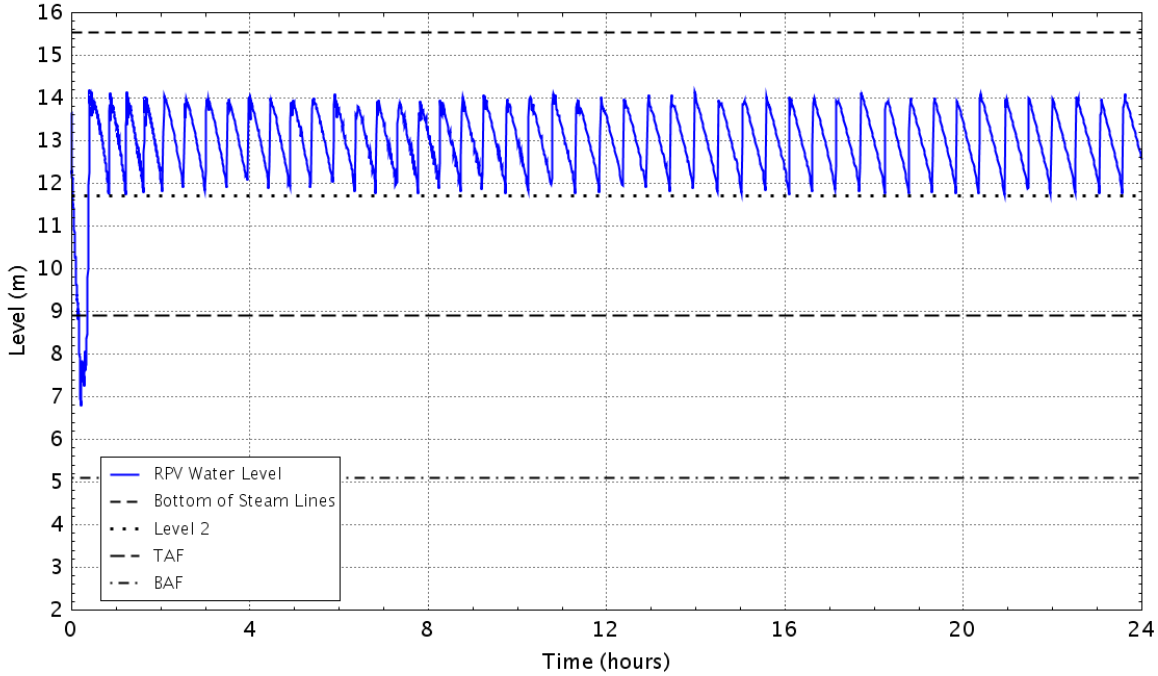

Figure C - 492 RPV Downcomer water level

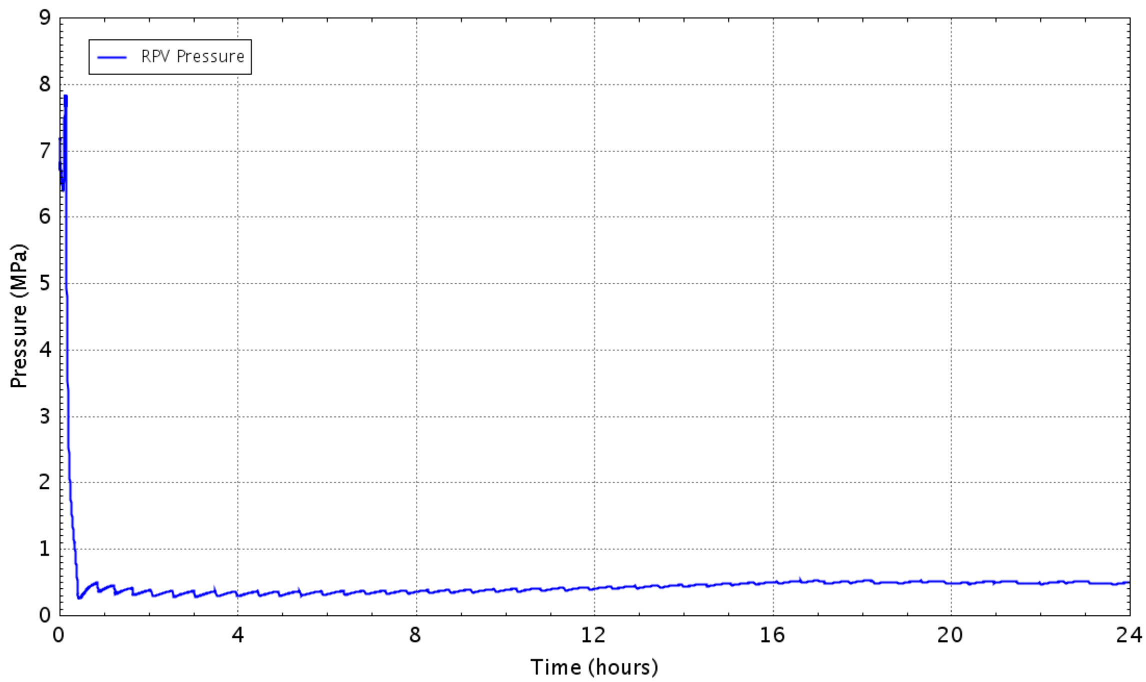

Figure C - 493   Pressure in the RPV

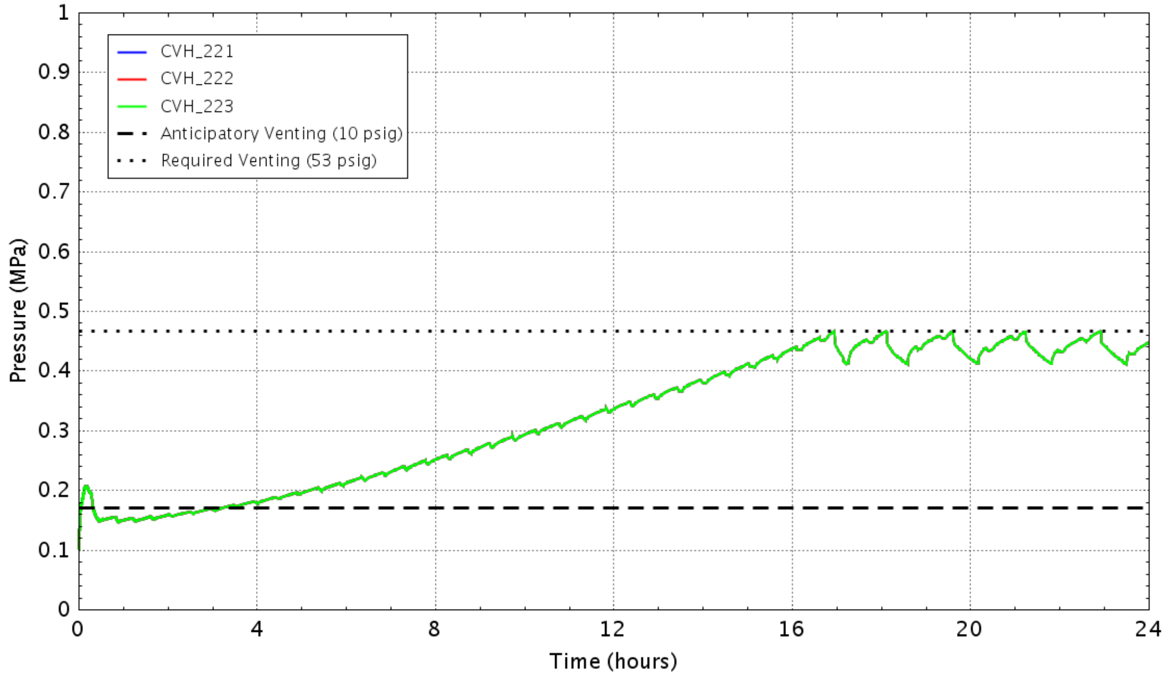

Figure C - 494 Pressure in the wetwell

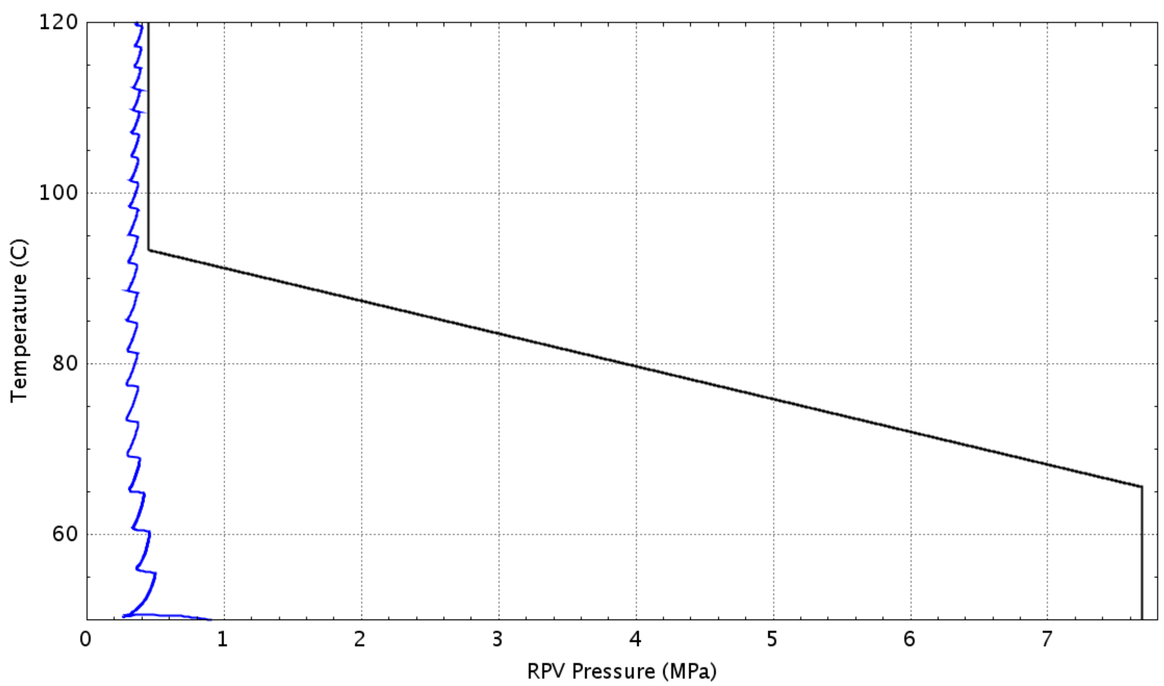

Figure C - 495 Plant status relative to the HCL curve (Graph 4 of the EOPs)

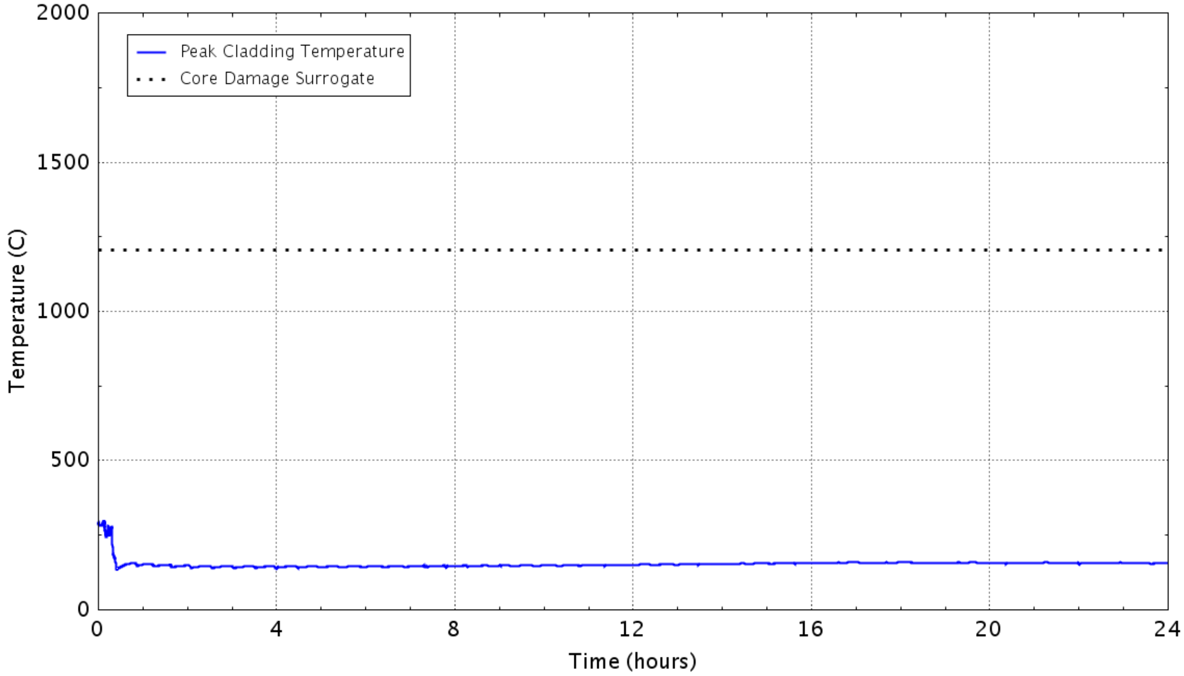

Figure C - 496 Peak temperature of the fuel cladding as a function of time

C.3.14 Case 24e: Sensitivity to SLOCA-25 Case 24 with Break Sizeand Location Exchanged

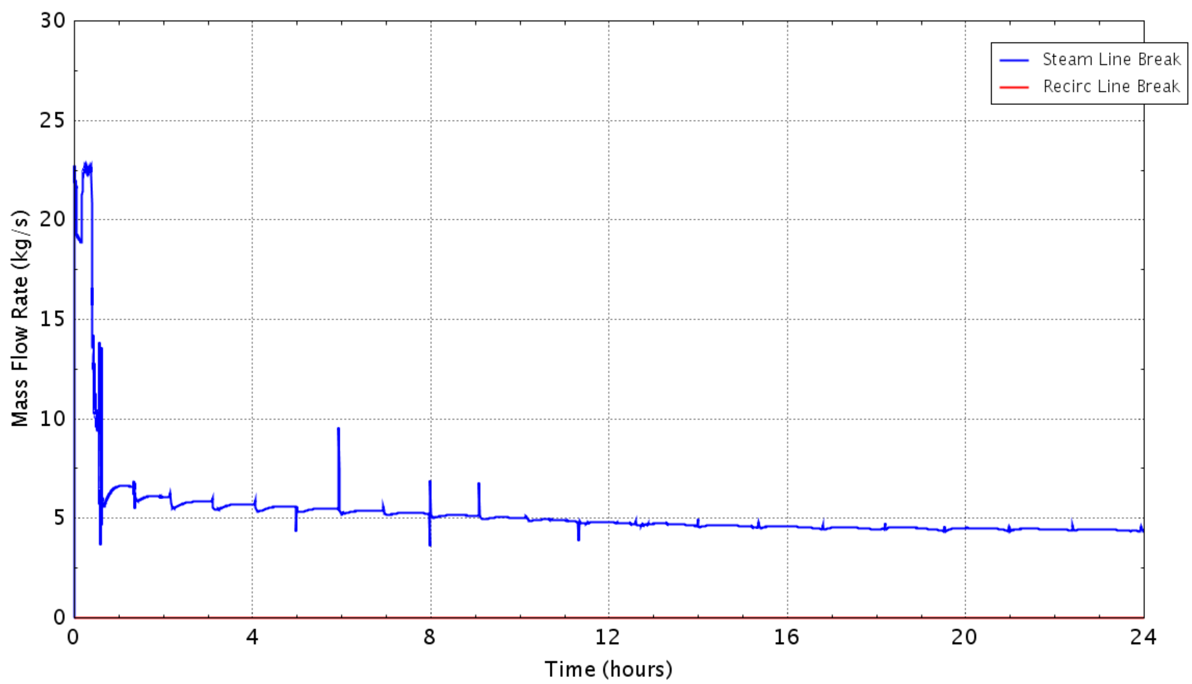

Figure C - 497 Flow rate of the break in the steamline/recirculation line

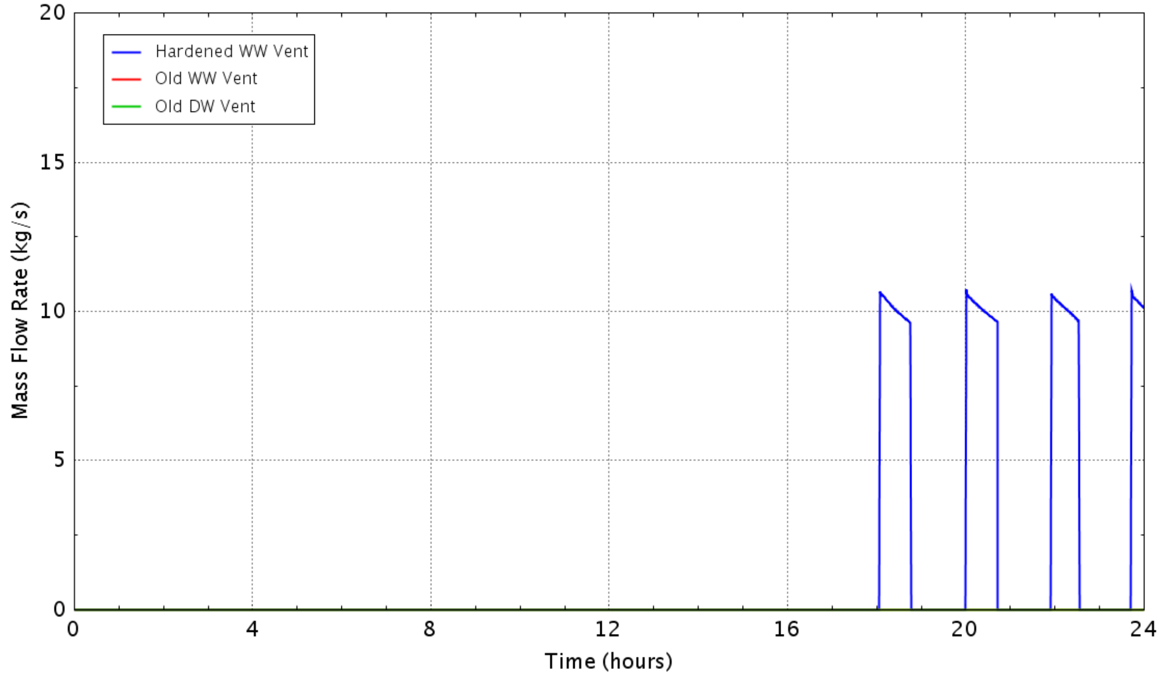

Figure C - 498 Flow rate of the containment vents

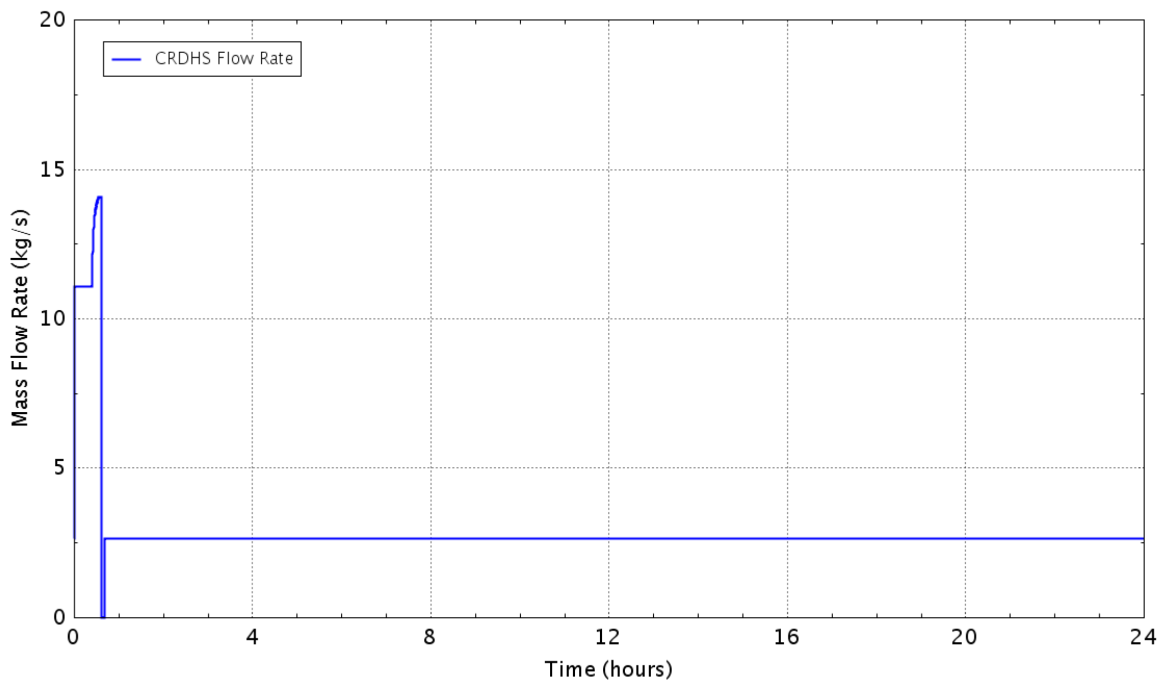

Figure C - 499 Flow rate of the control rod drive hydraulic system

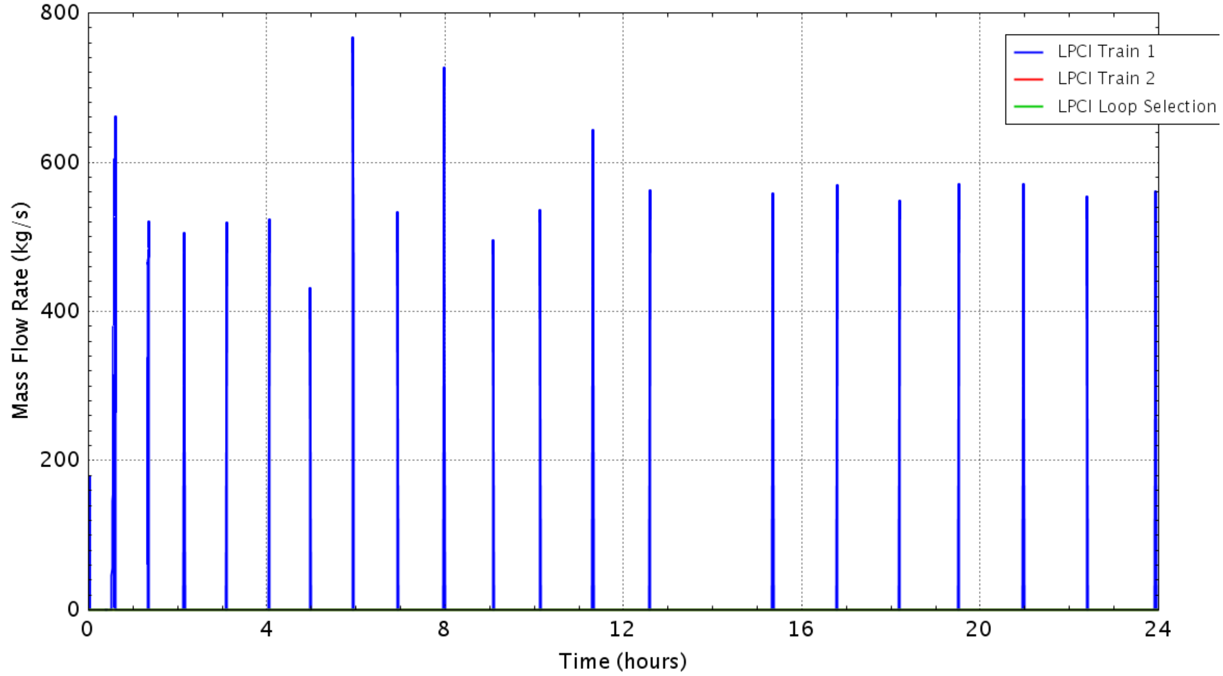

Figure C - 500 Flow rate of the LPCI pump

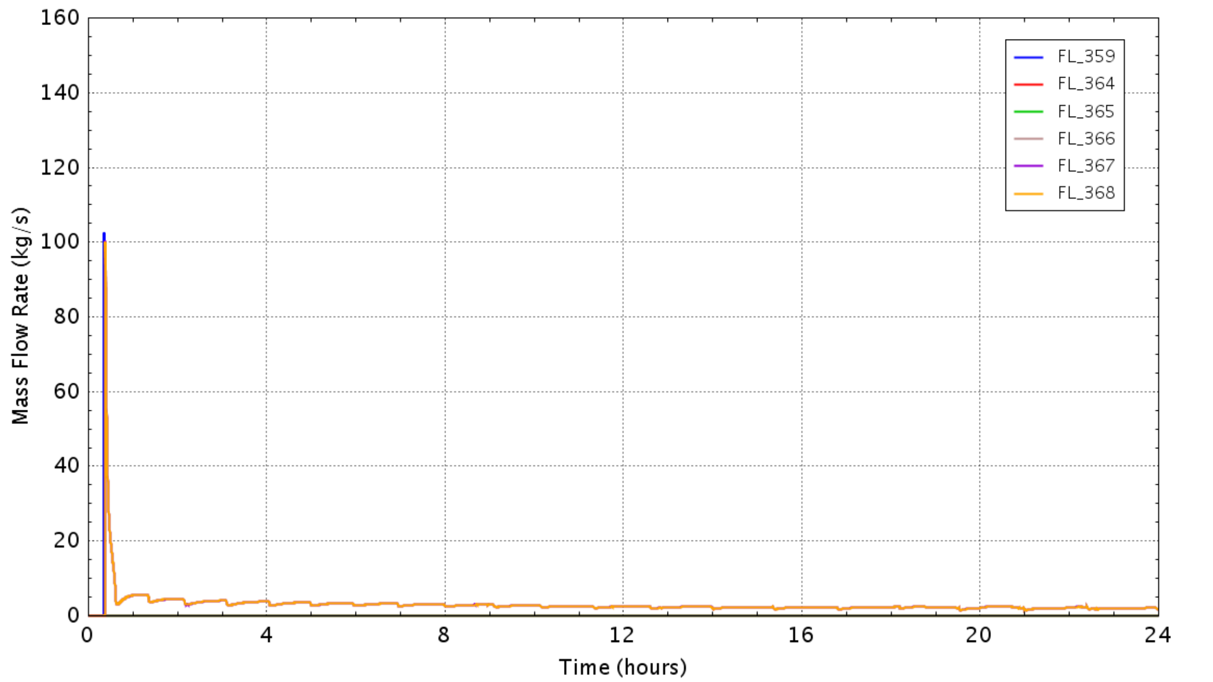

Figure C - 501 Flow rate of the SRVs

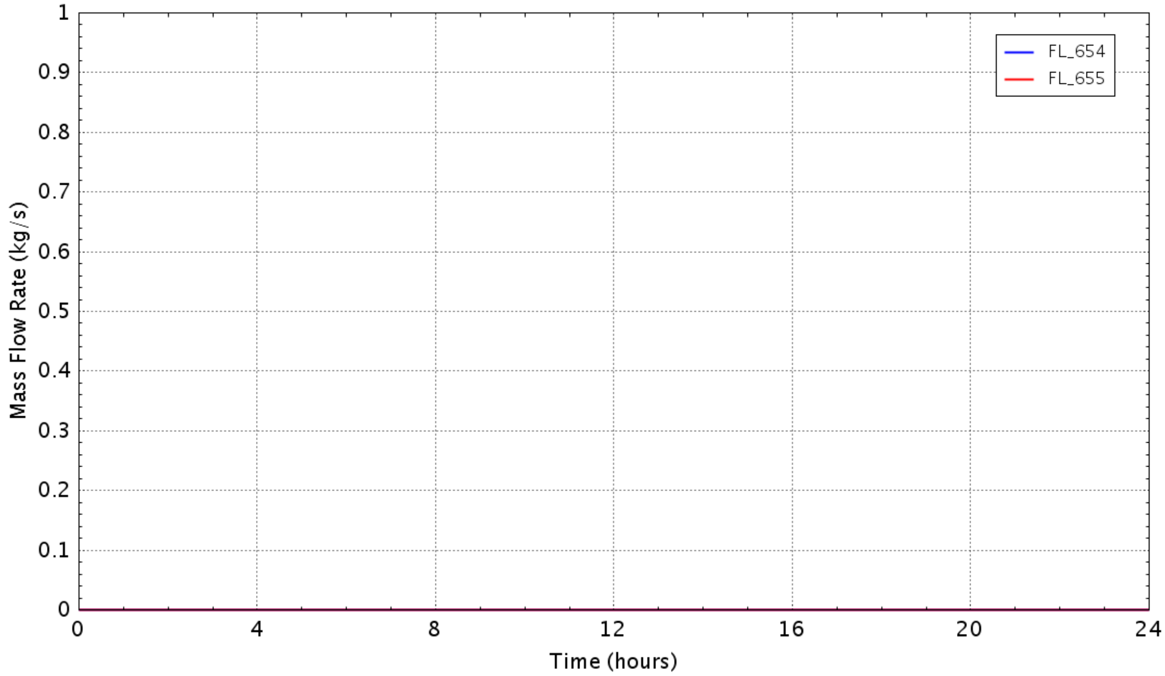

Figure C - 502   Flow rate of the wetwell cooling system

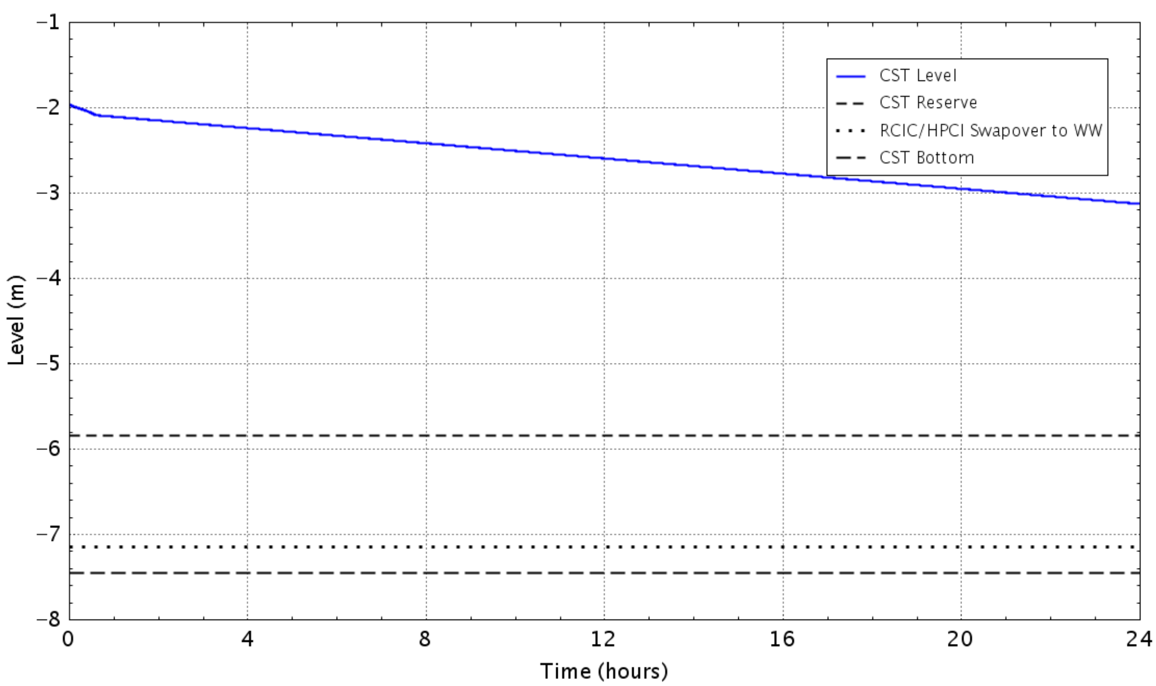

Figure C - 503   Water level in the CST

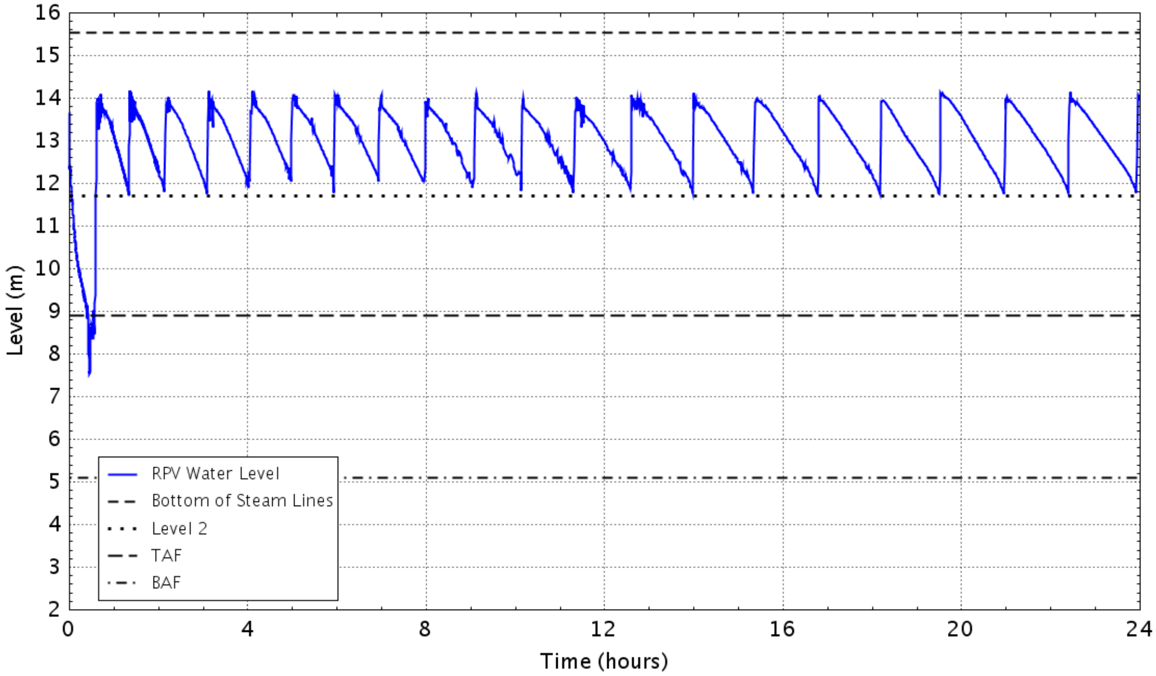

Figure C - 504 RPV Downcomer water level

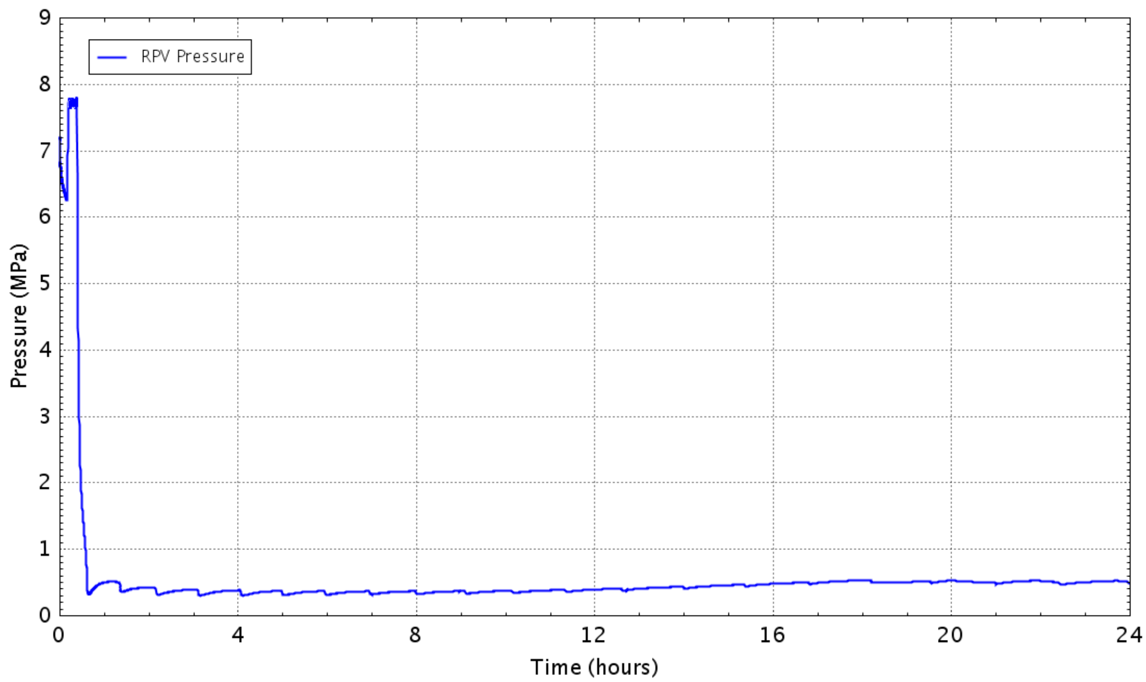

Figure C - 505 Pressure in the RPV

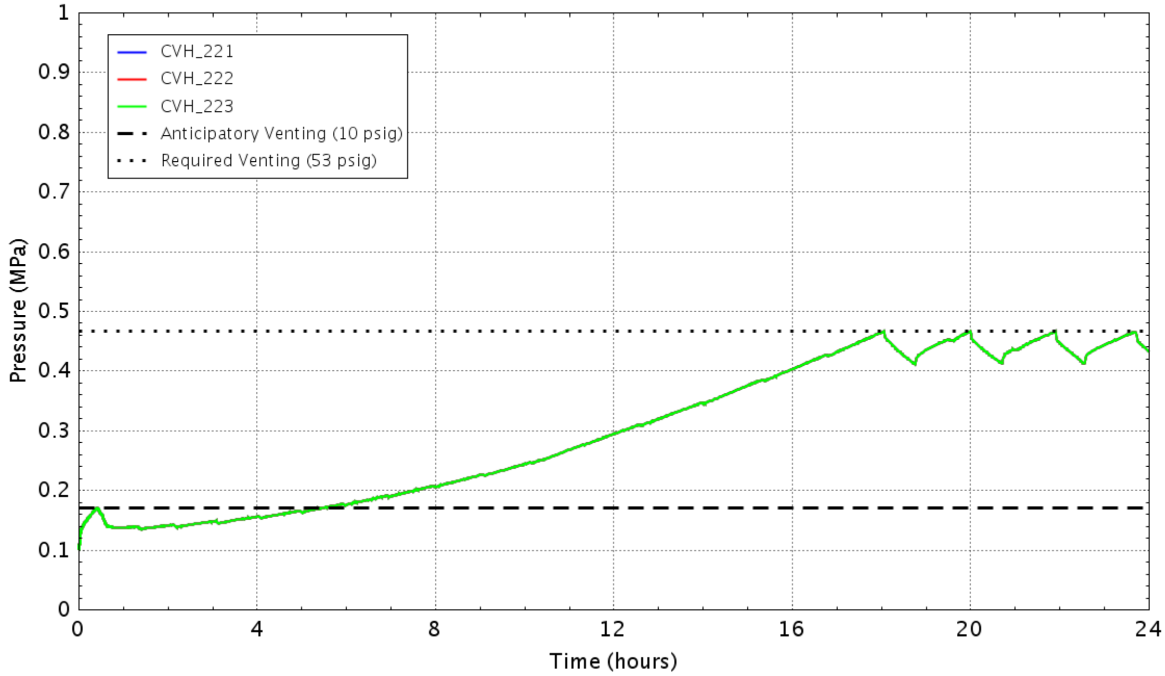

Figure C - 506 Pressure in the wetwell

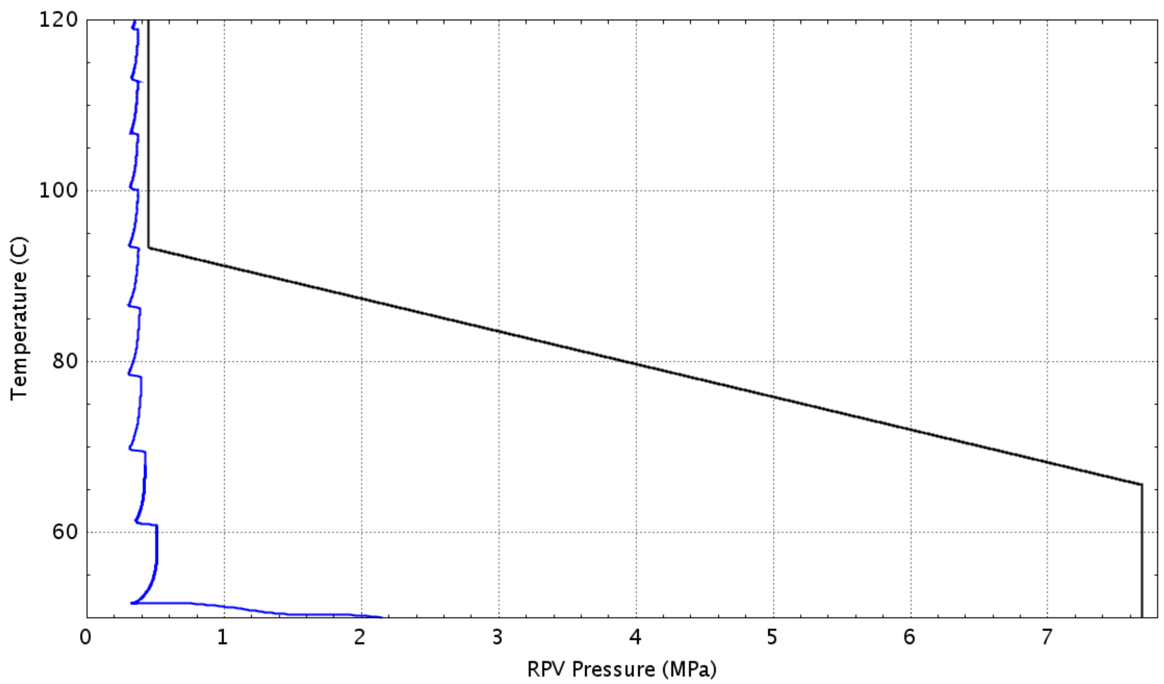

Figure C - 507 Plant status relative to the HCL curve (Graph 4 of the EOPs)

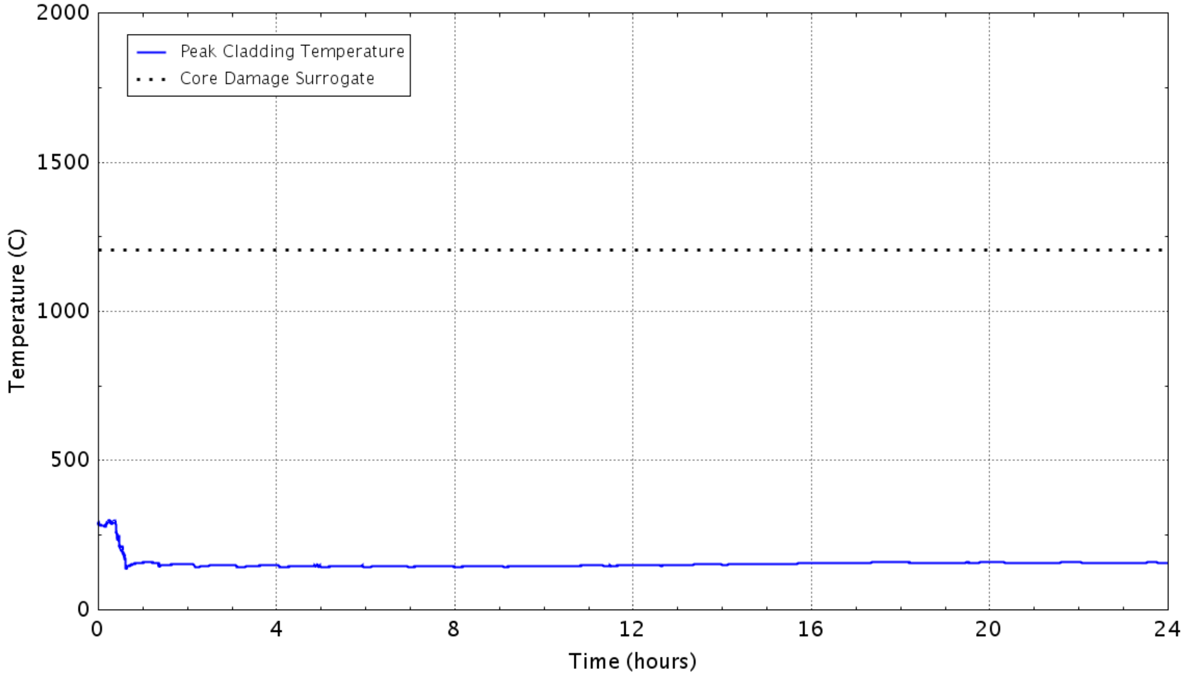

Figure C - 508 Peak temperature of the fuel cladding as a function of time

C.3.15 Case 26a: Sensitivity to SLOCA-25 Case 26 withNominal CRDHS Injection

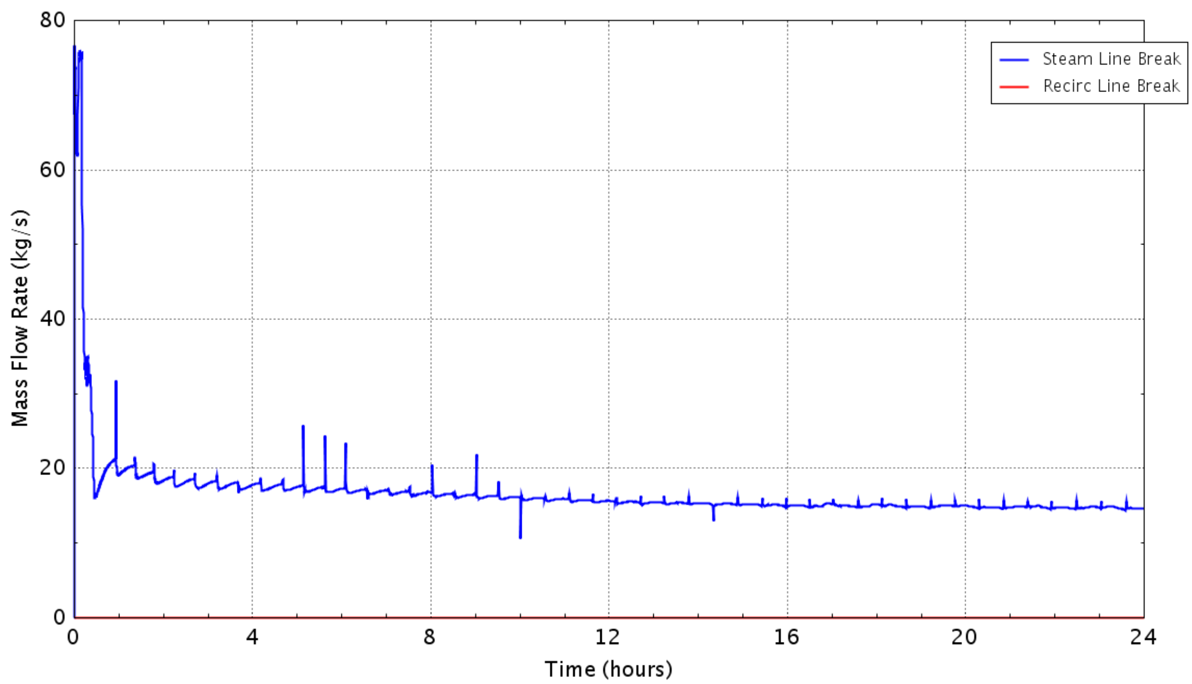

Figure C - 509 Flow rate of the break in the steamline/recirculation line

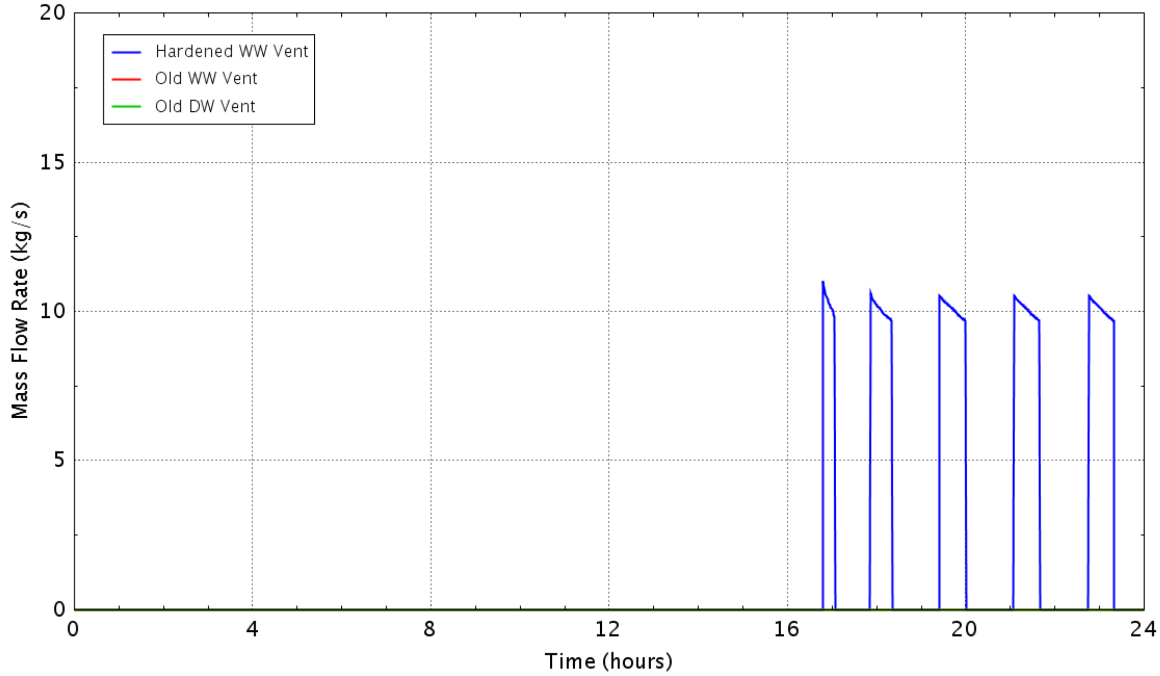

Figure C - 510 Flow rate of the containment vents

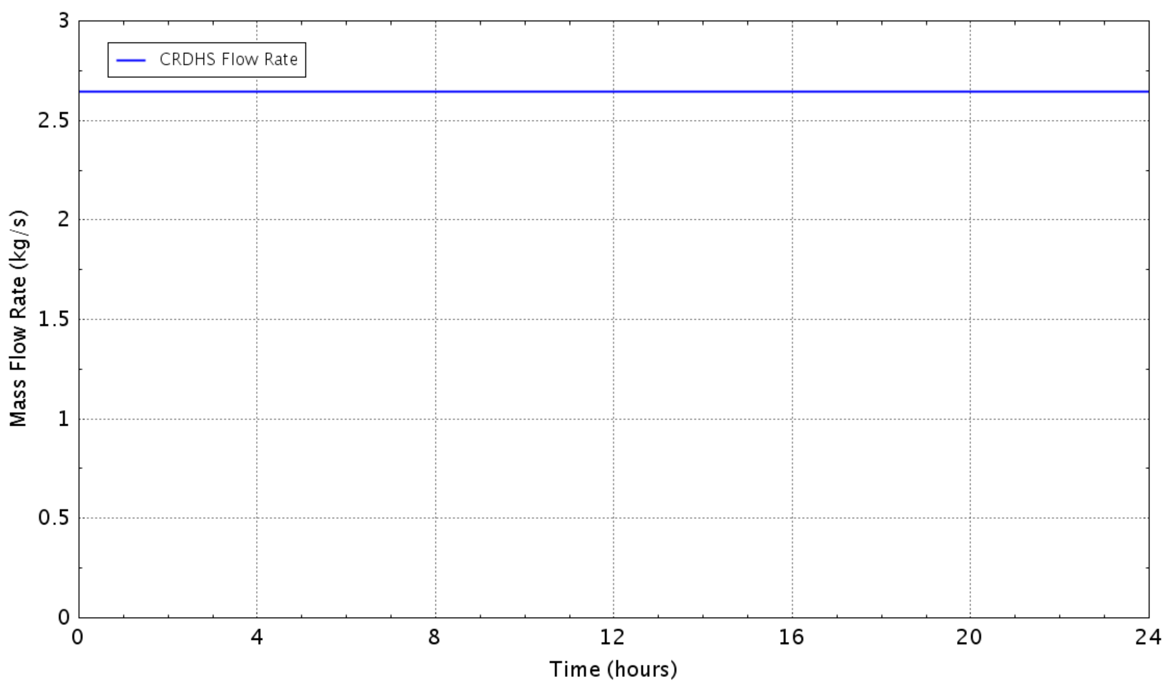

Figure C - 511 Flow rate of the control rod drive hydraulic system

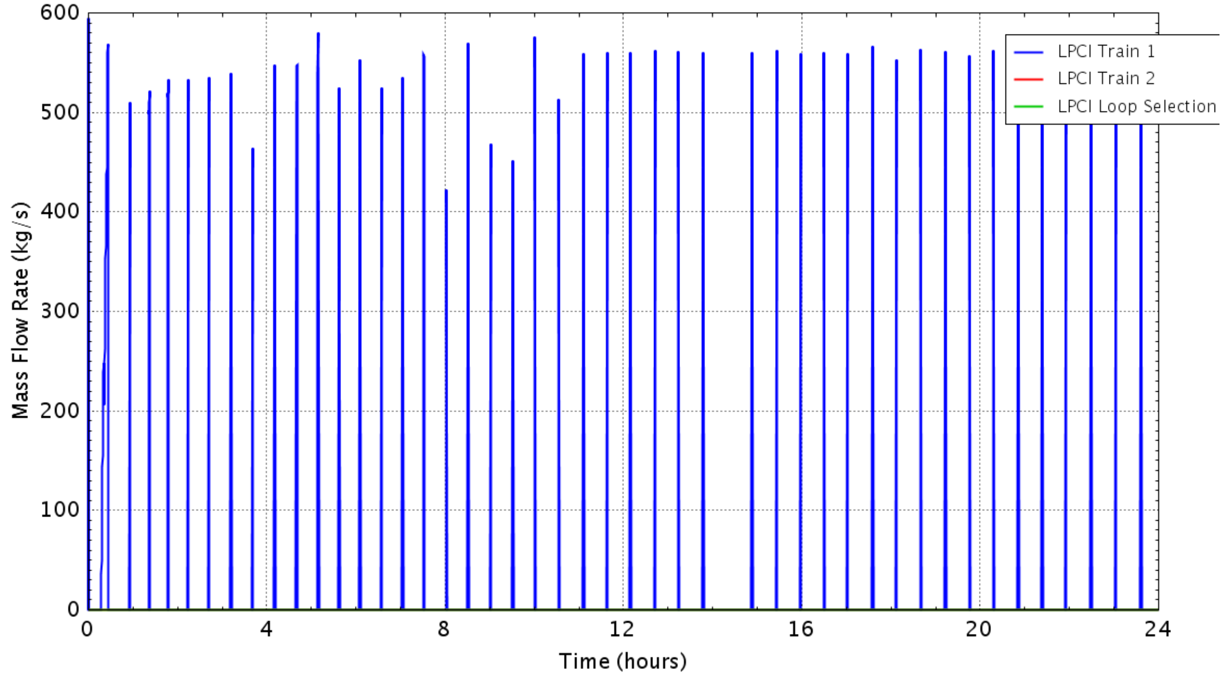

Figure C - 512 Flow rate of the LPCI pump

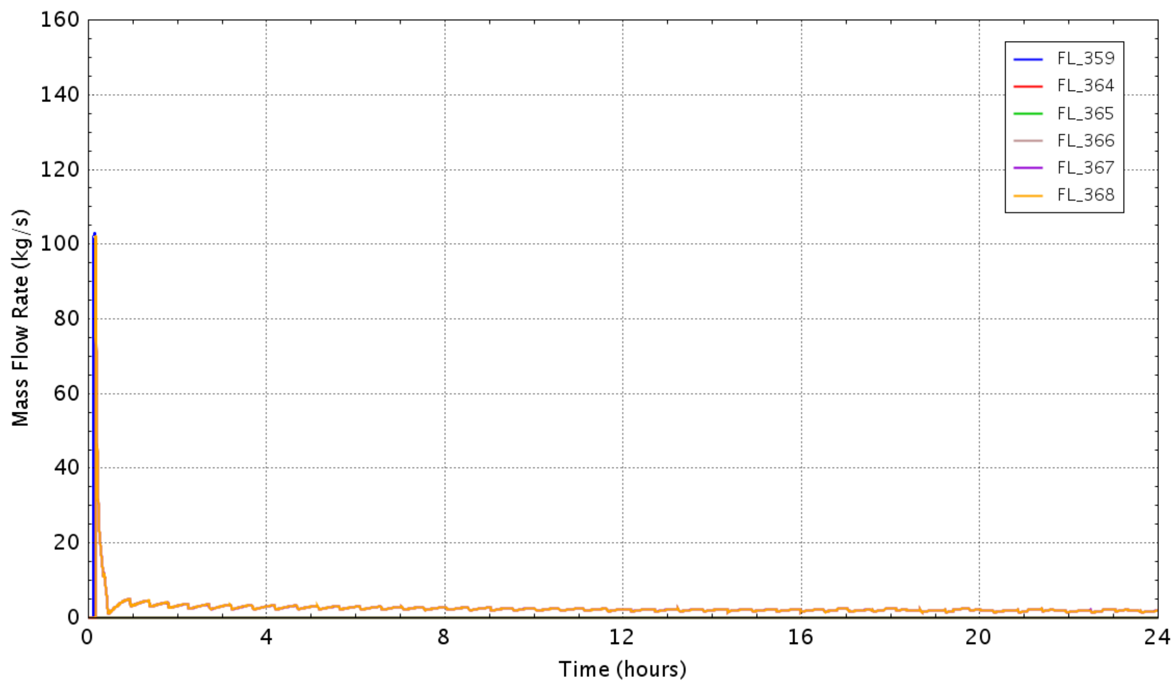

Figure C - 513 Flow rate of the SRVs

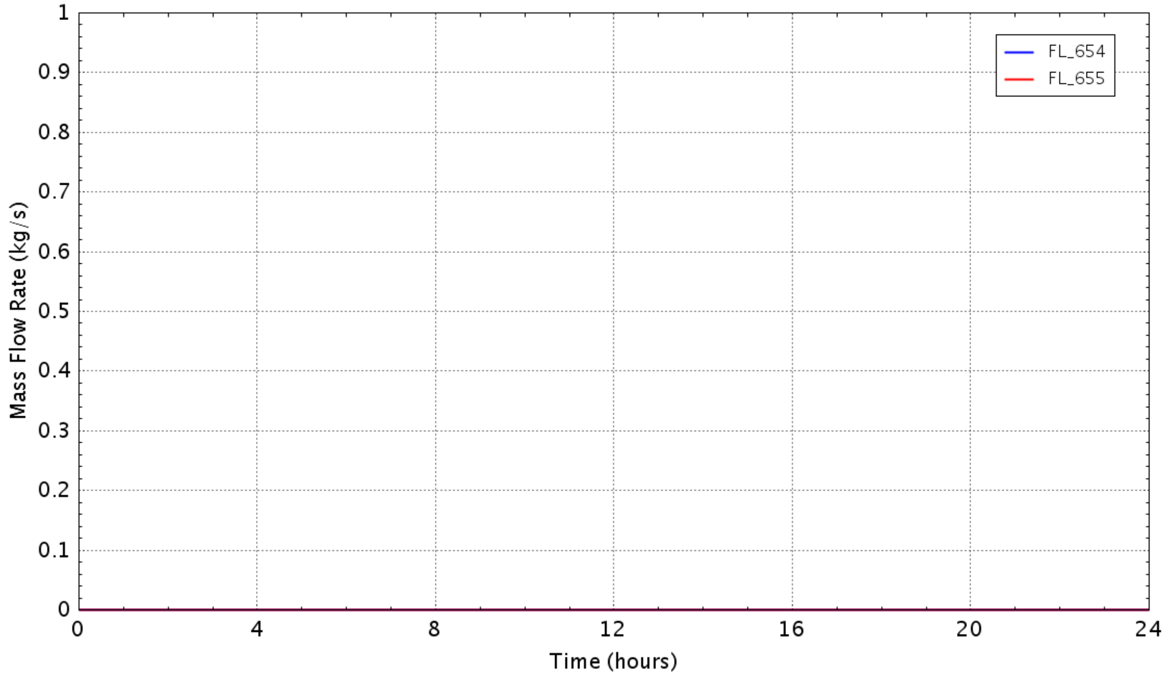

Figure C - 514 Flow rate of the wetwell cooling system

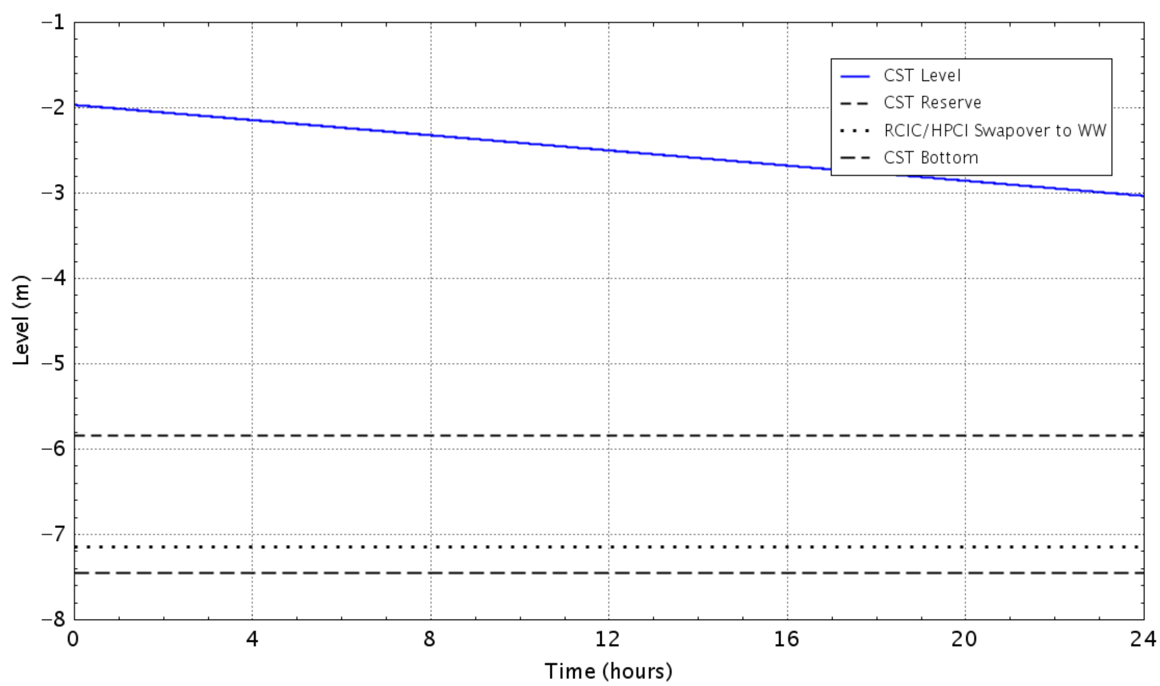

Figure C - 515 Water level in the CST

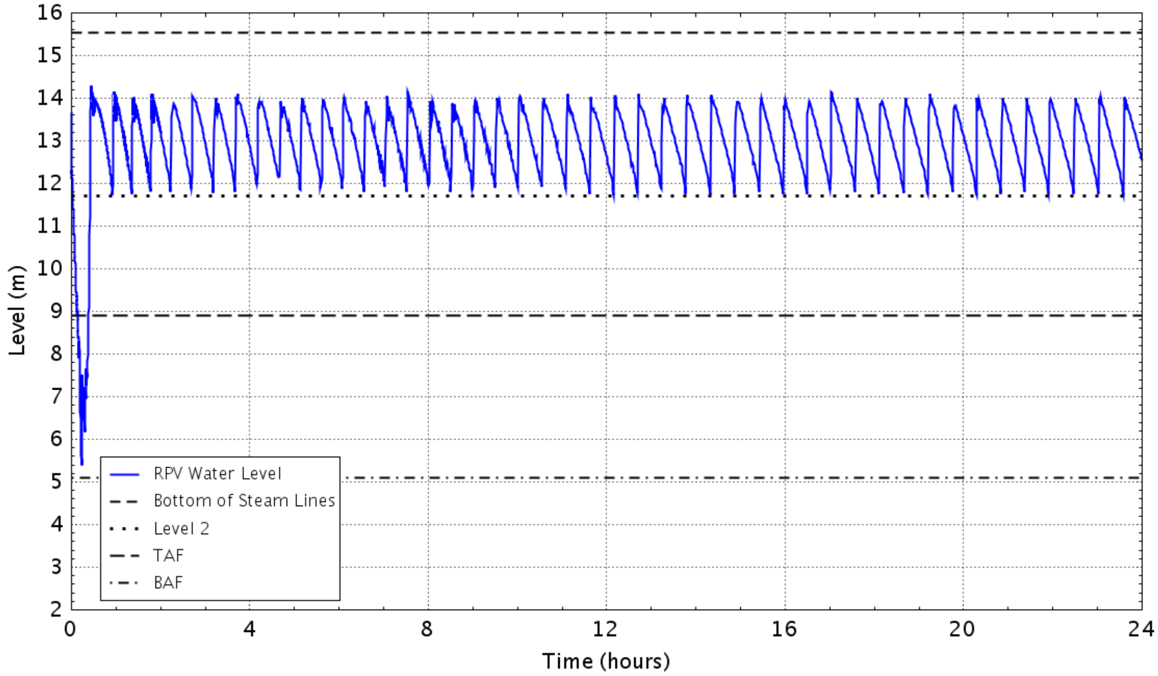

Figure C - 516 RPV Downcomer water level

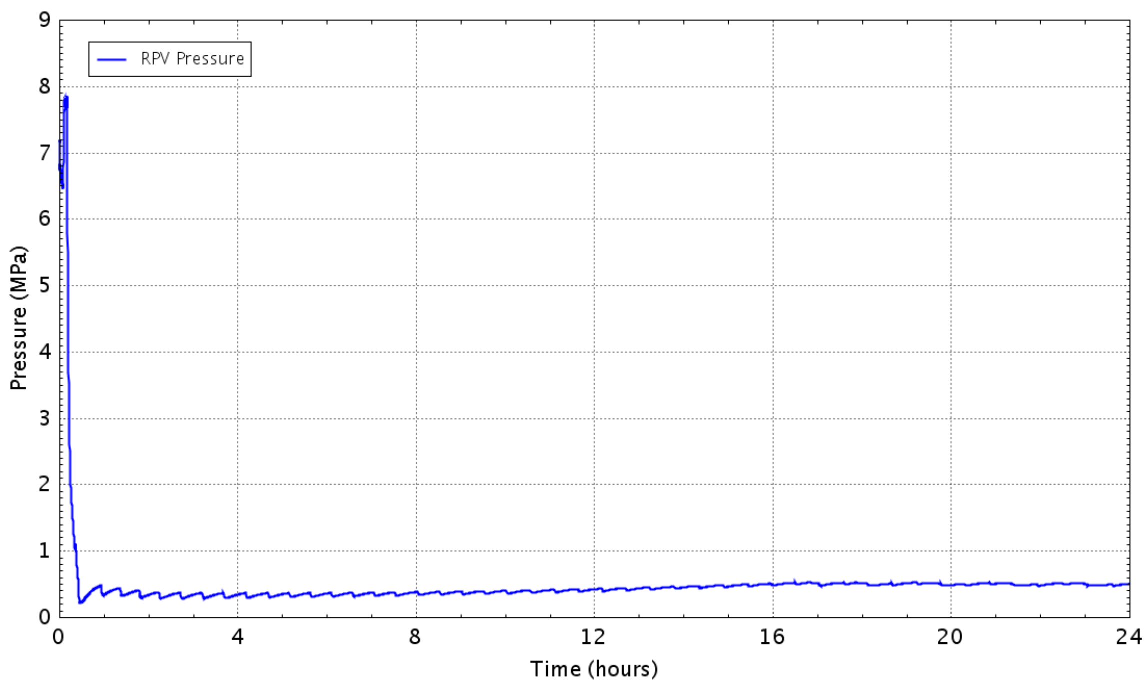

Figure C - 517 Pressure in the RPV

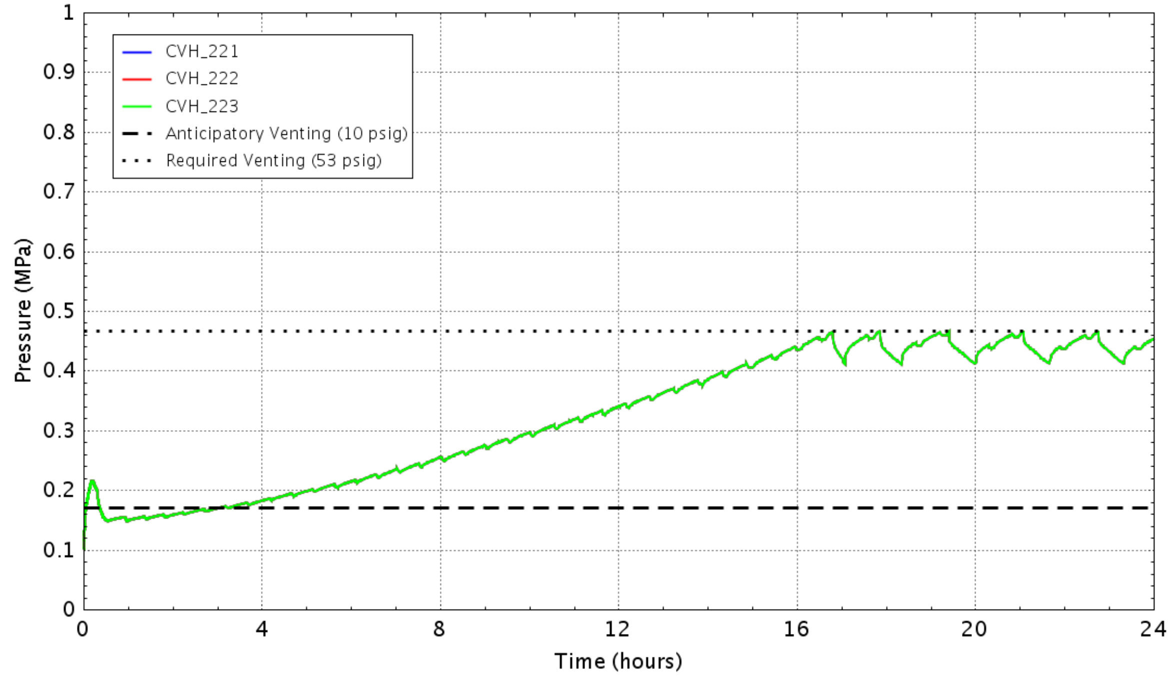

Figure C - 518 Pressure in the wetwell

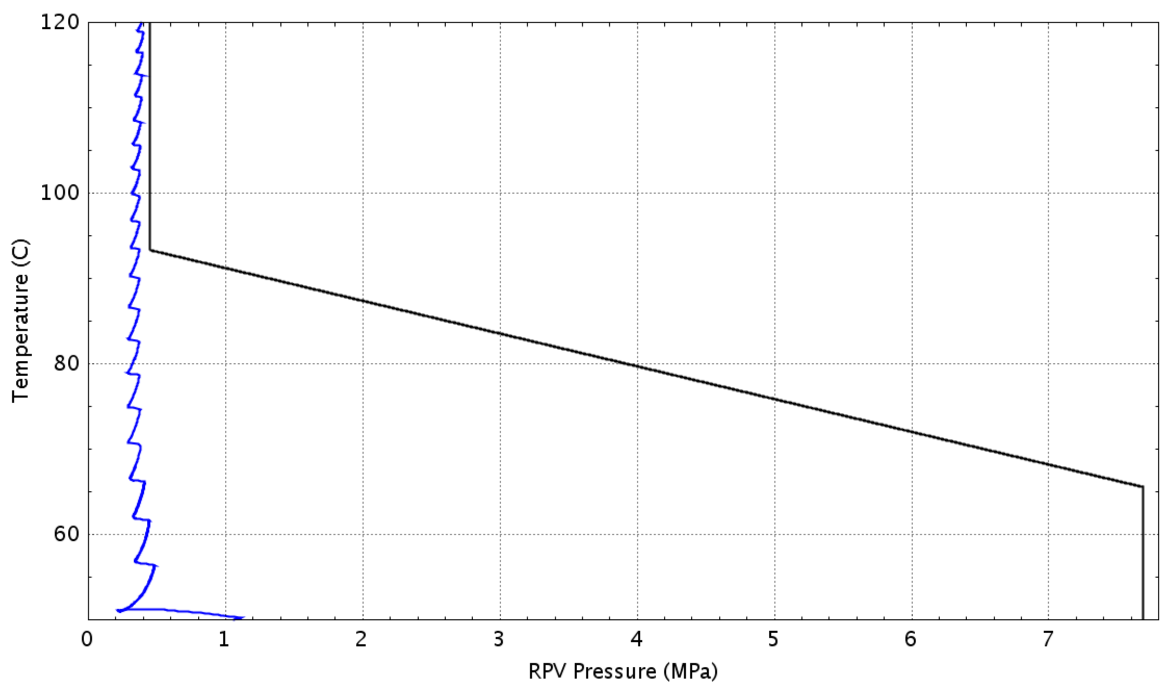

Figure C - 519 Plant status relative to the HCL curve (Graph 4 of the EOPs)

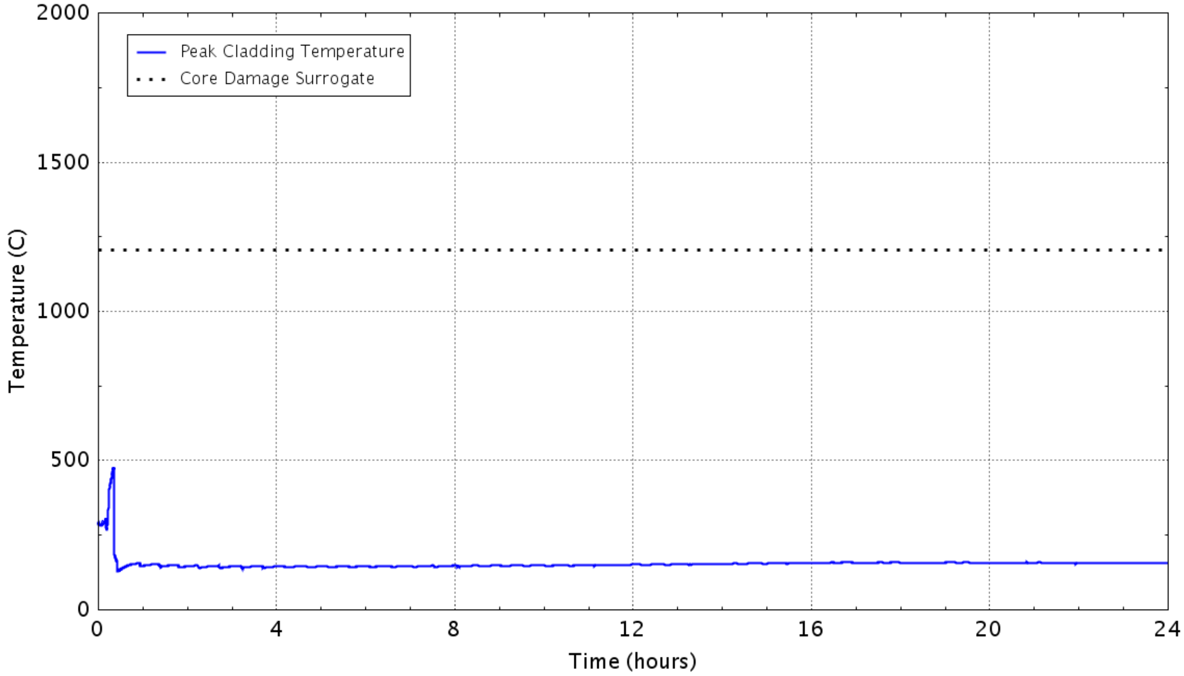

Figure C - 520 Peak temperature of the fuel cladding as a function of time

C.3.16 Case 26b: Sensitivity to SLOCA-25 Case 26 with Low-Pressure Injection Provided by Core Spray Rather Than LPCI

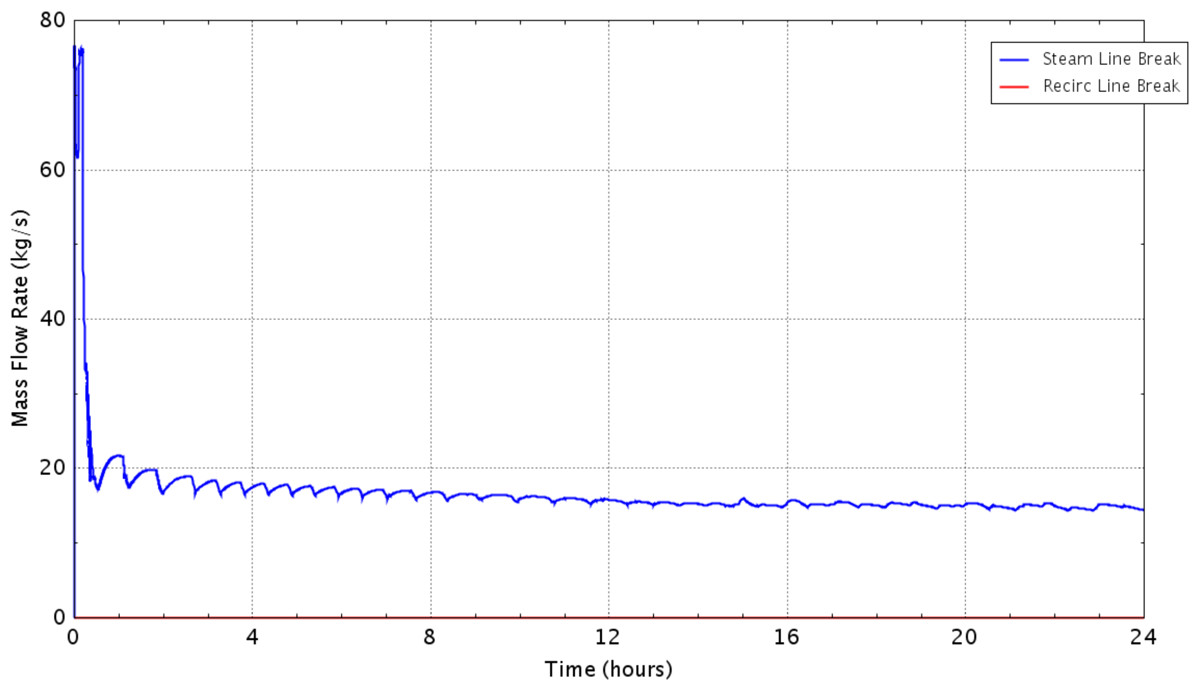

Figure C - 521 Flow rate of the break in the steamline/recirculation line

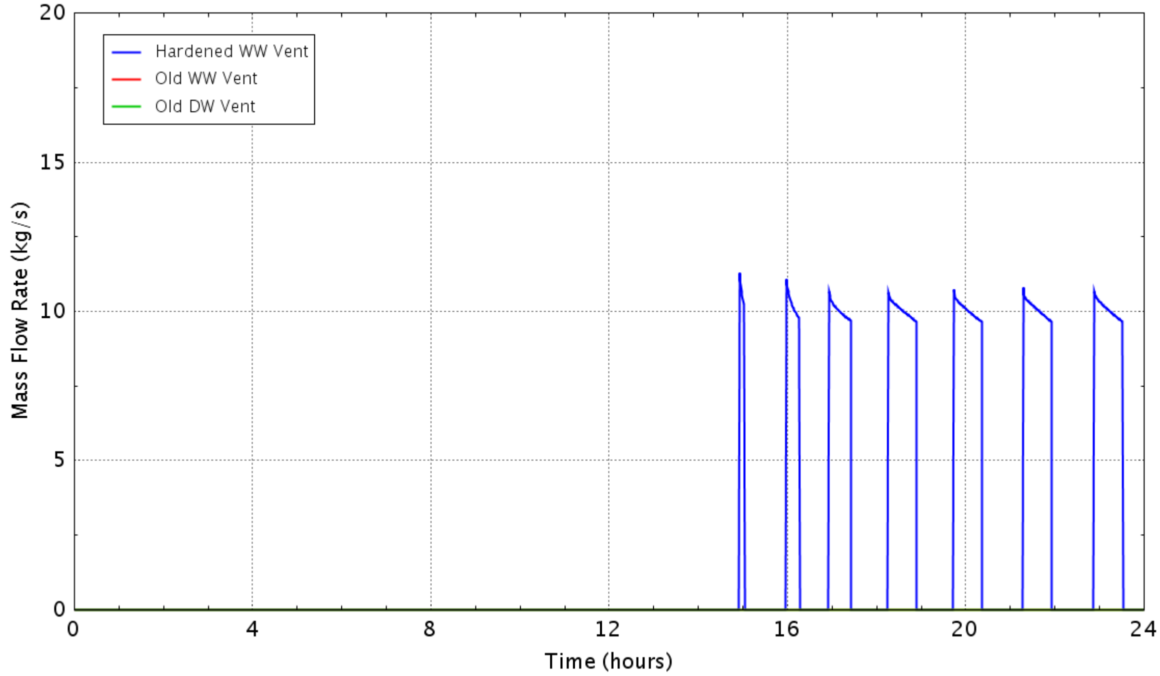

Figure C - 522 Flow rate of the containment vents

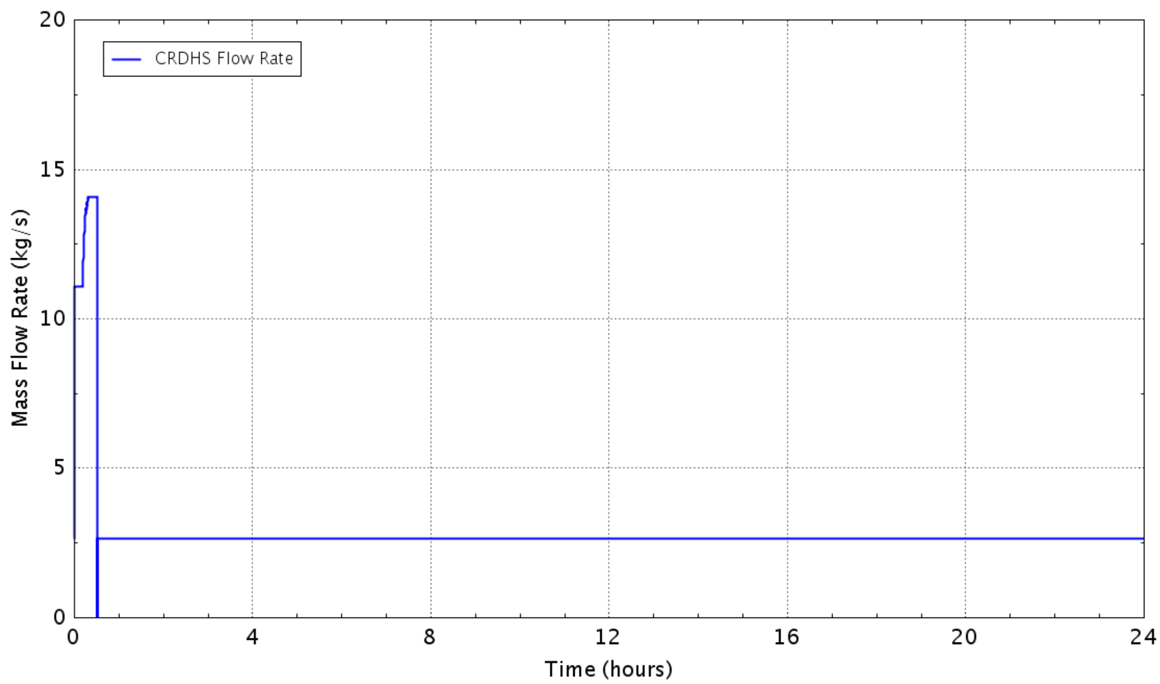

Figure C - 523 Flow rate of the control rod drive hydraulic system

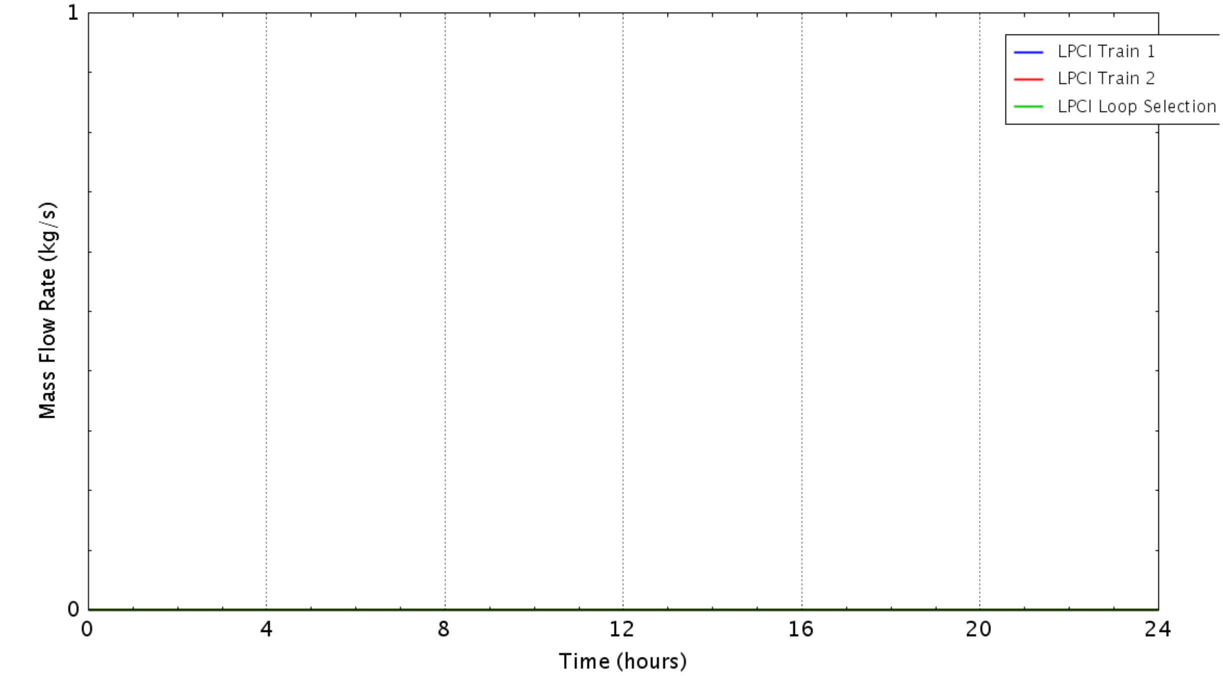

Figure C - 524   Flow rate of the LPCI pump

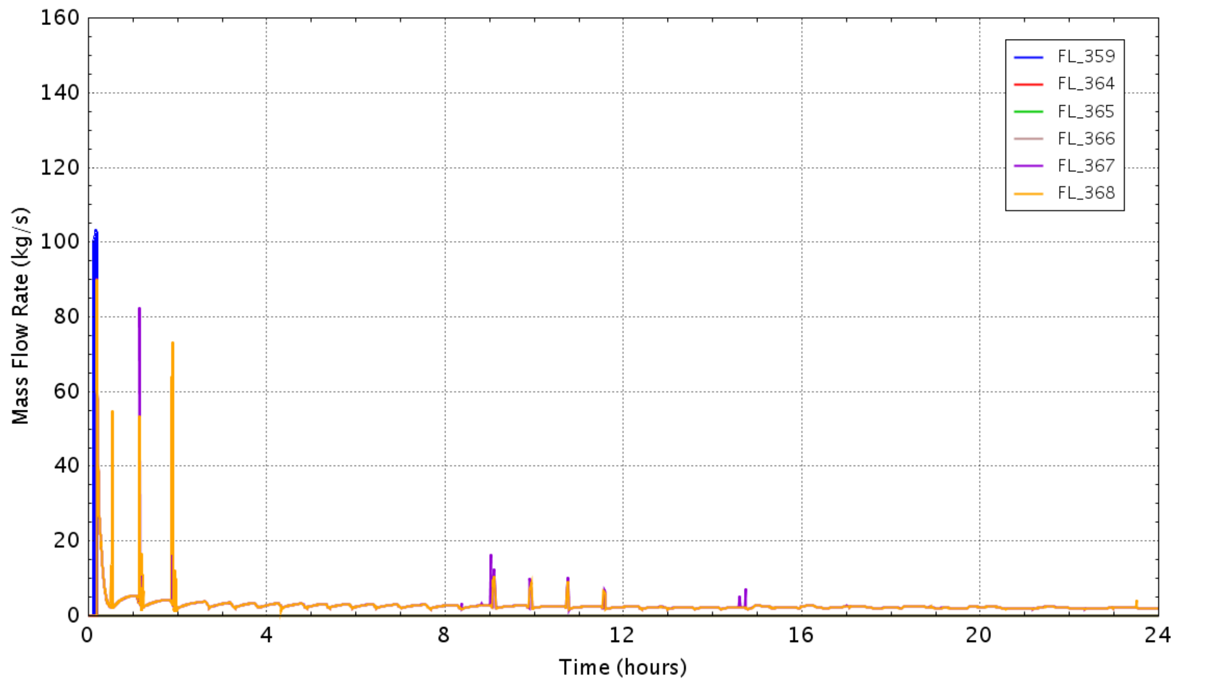

Figure C - 525   Flow rate of the SRVs

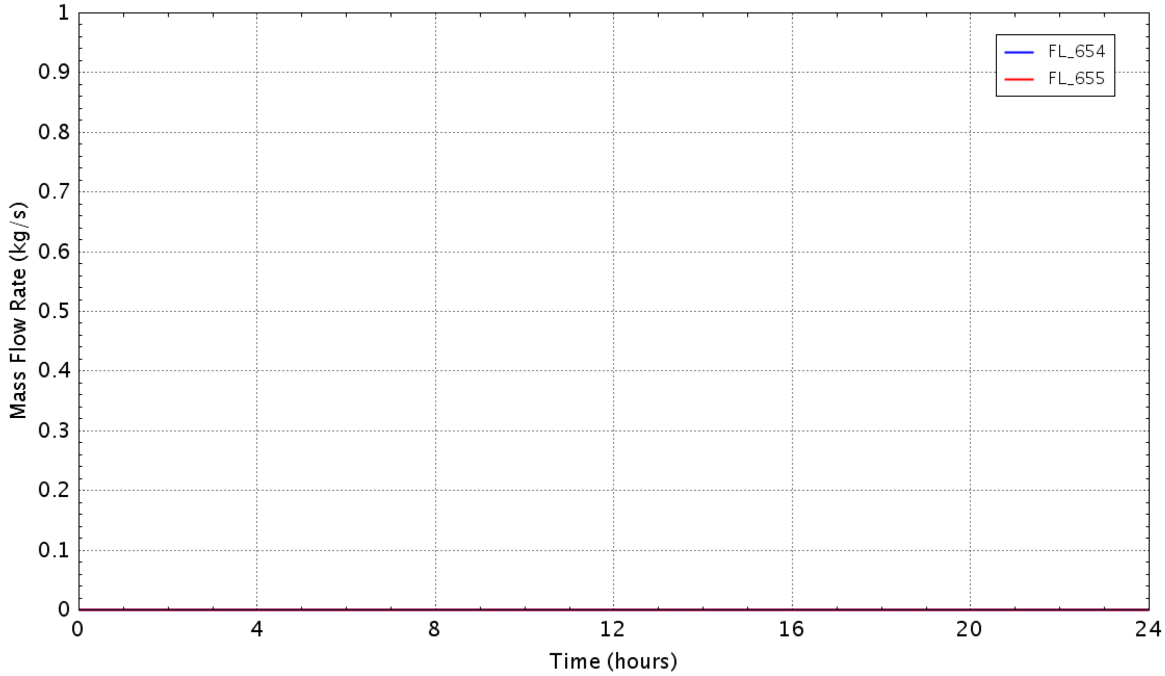

Figure C - 526   Flow rate of the wetwell cooling system

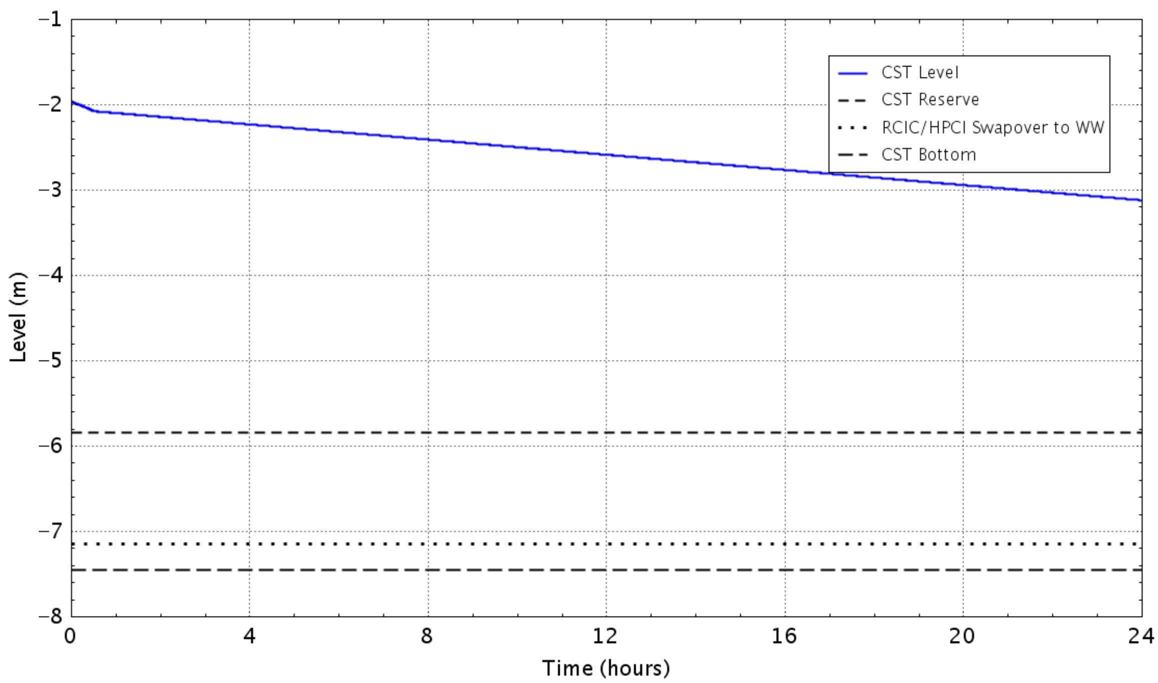

Figure C - 527   Water level in the CST

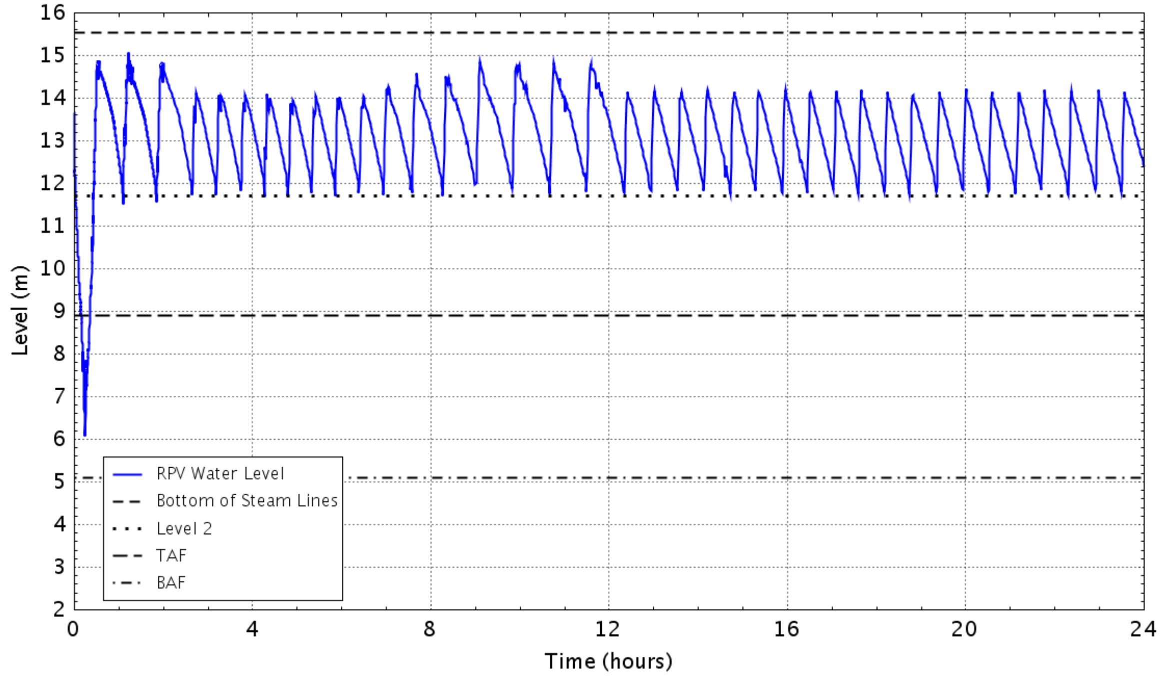

Figure C - 528 RPV Downcomer water level

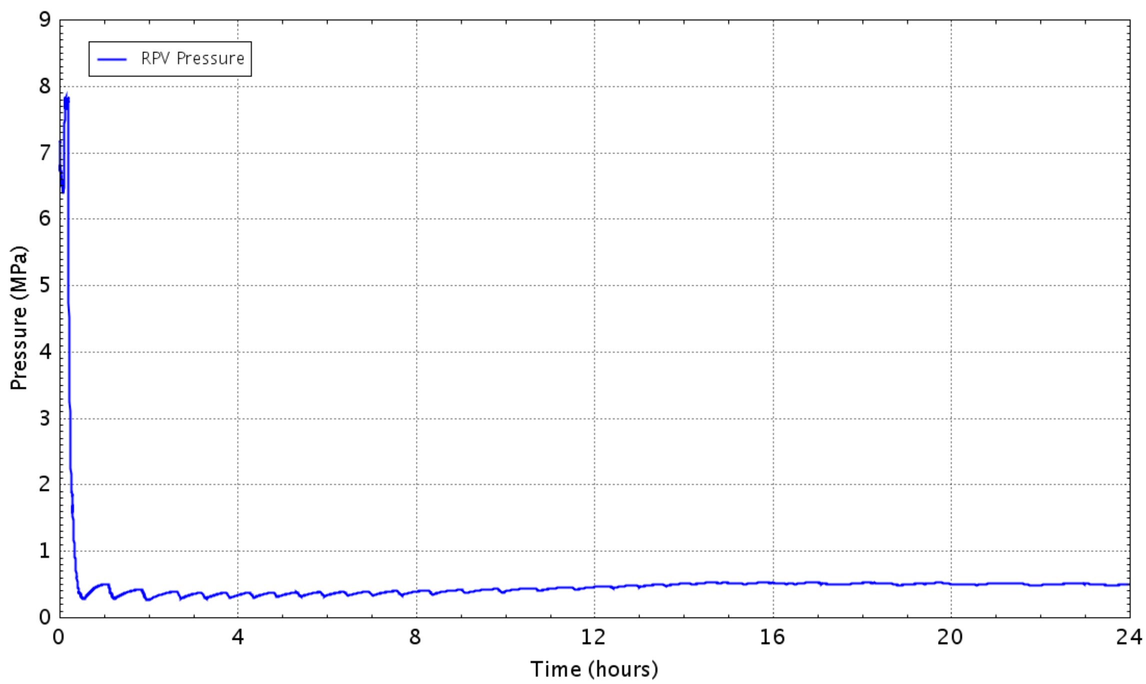

Figure C - 529 Pressure in the RPV

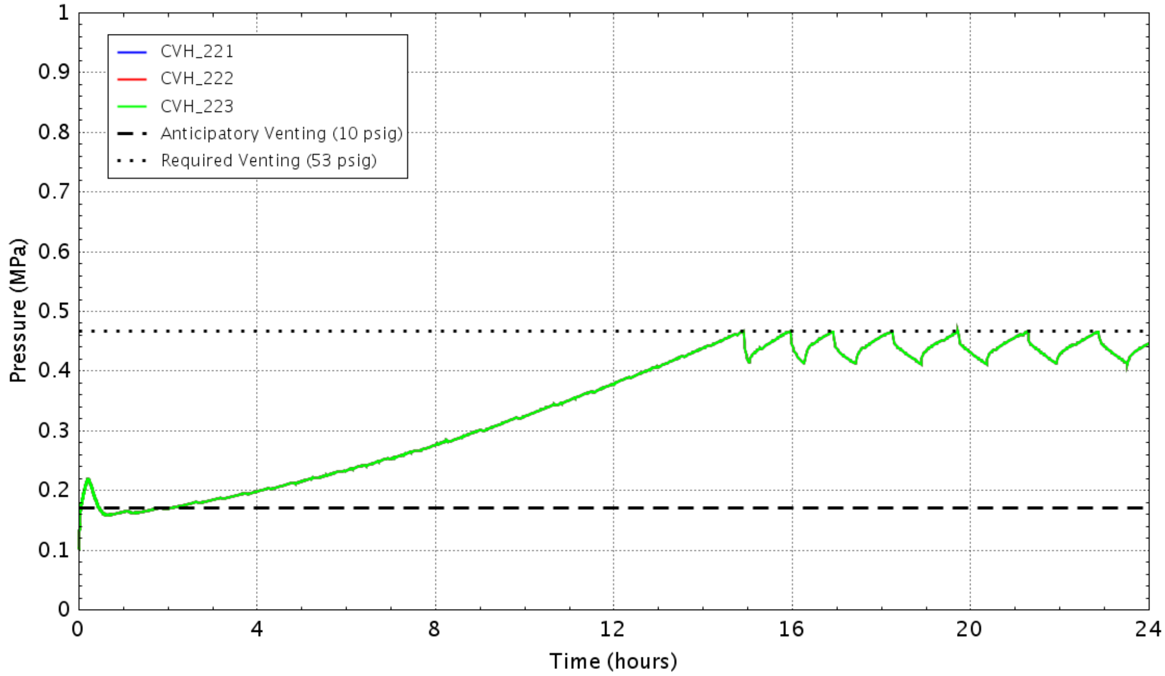

Figure C - 530 Pressure in the wetwell

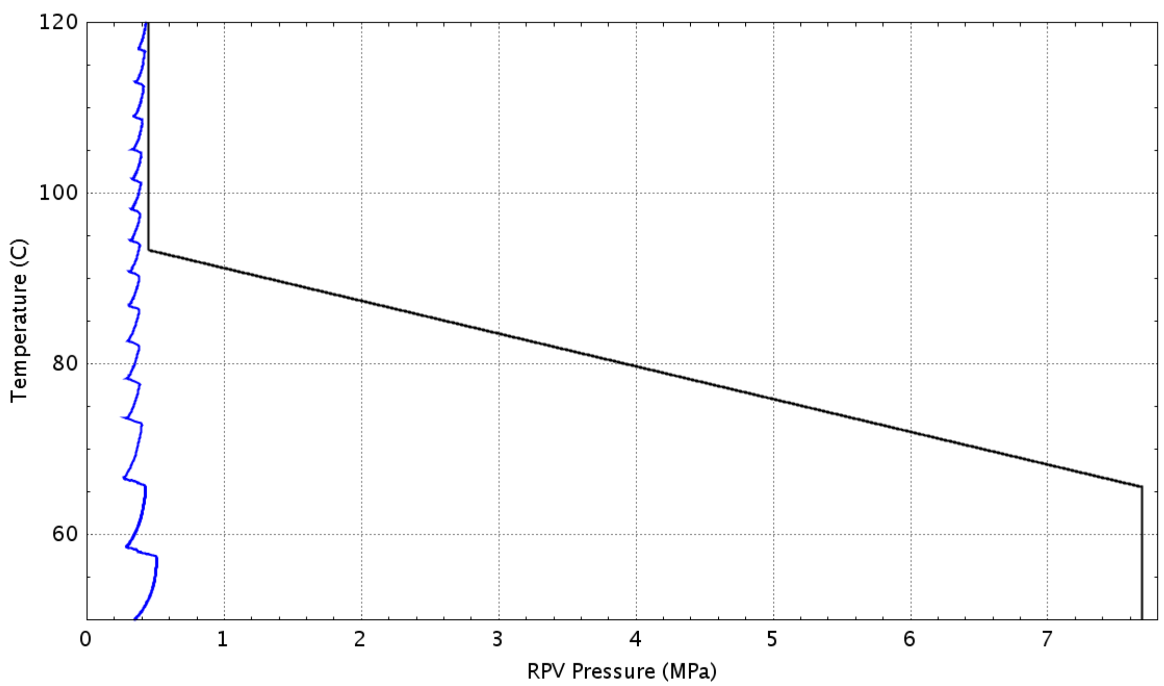

Figure C - 531 Plant status relative to the HCL curve (Graph 4 of the EOPs)

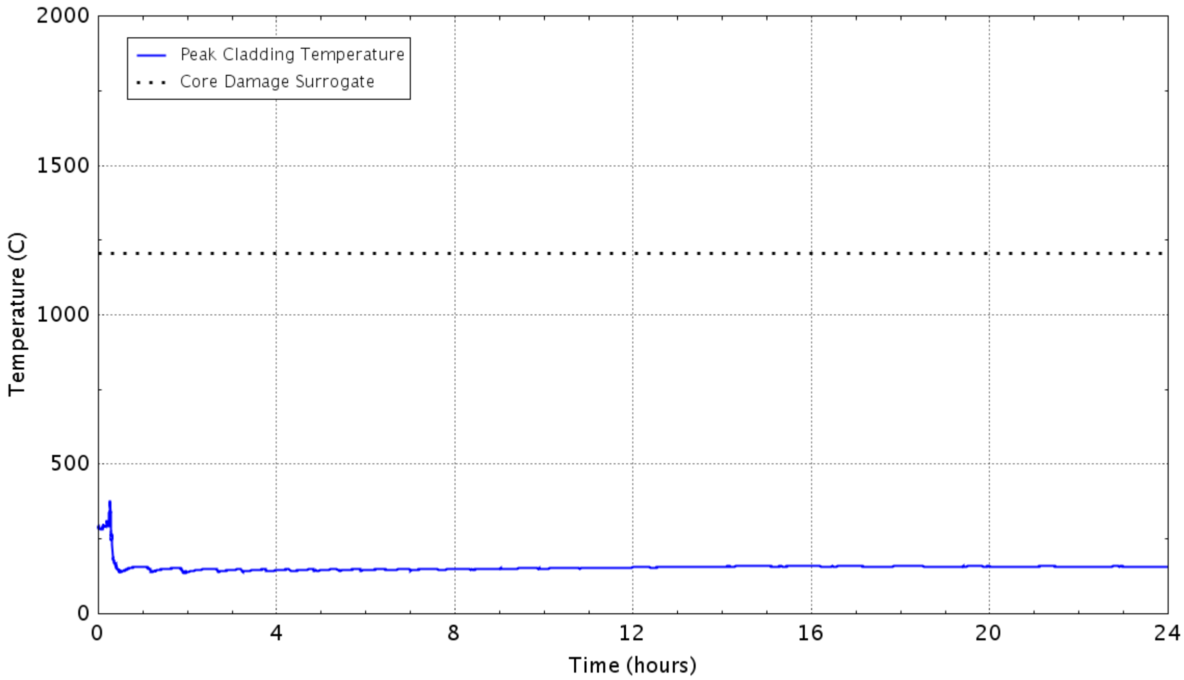

Figure C - 532   Peak temperature of the fuel cladding as a function of time

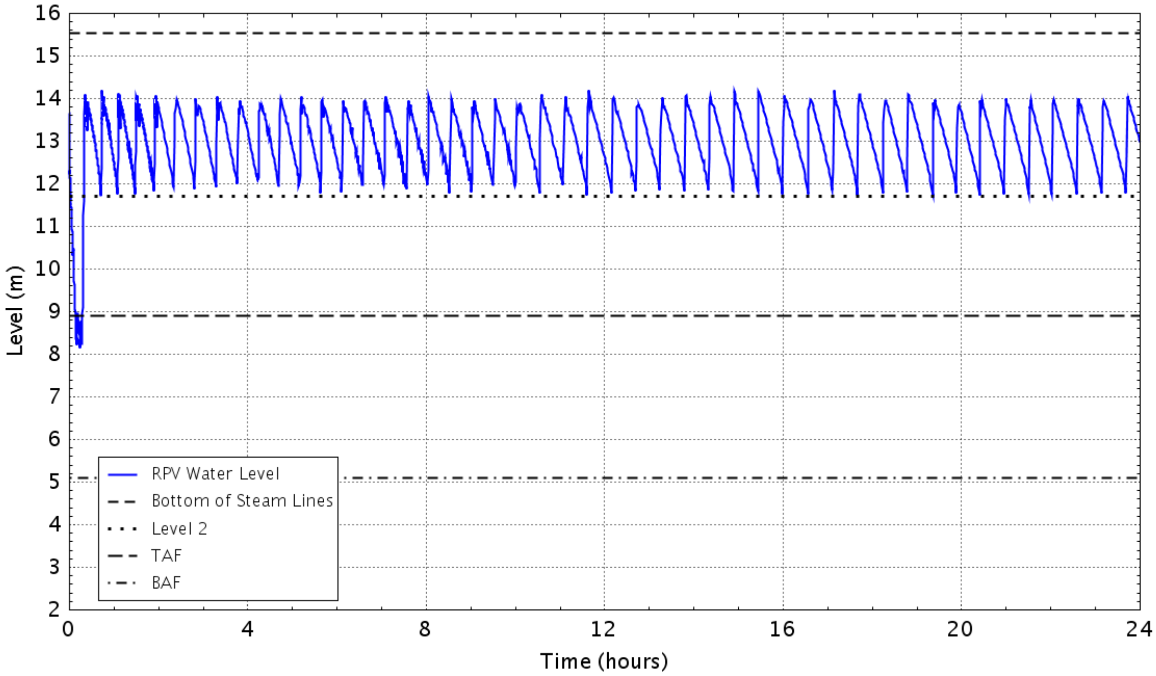

Figure C - 533 RPV Downcomer water level

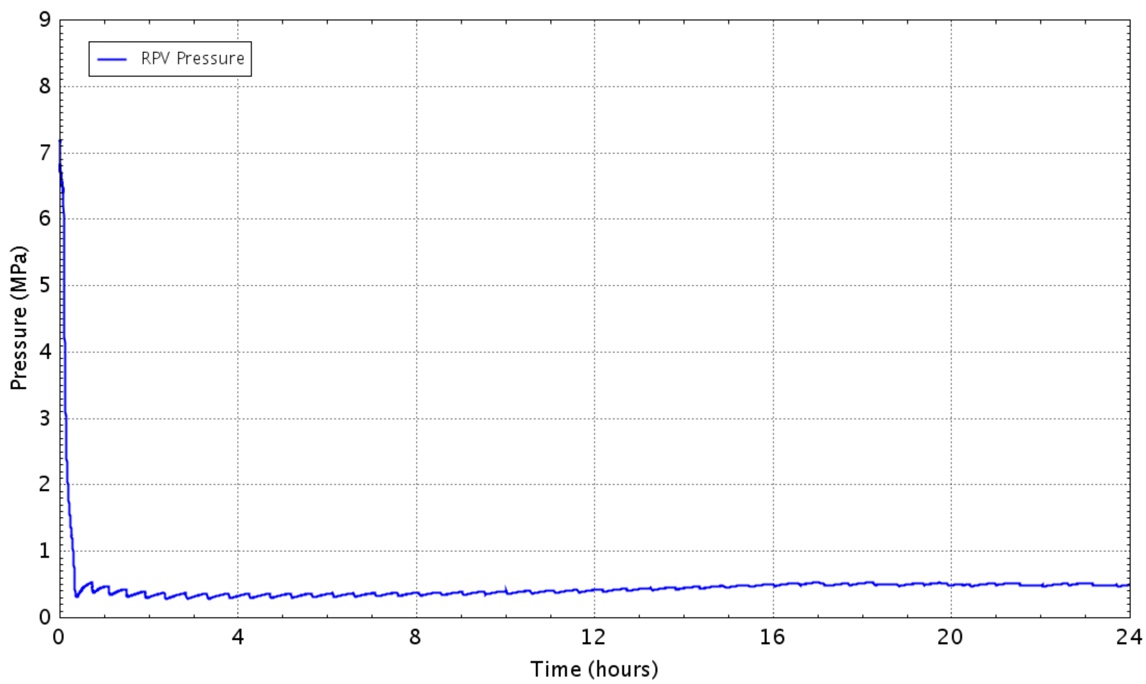

Figure C - 534 Pressure in the RPV

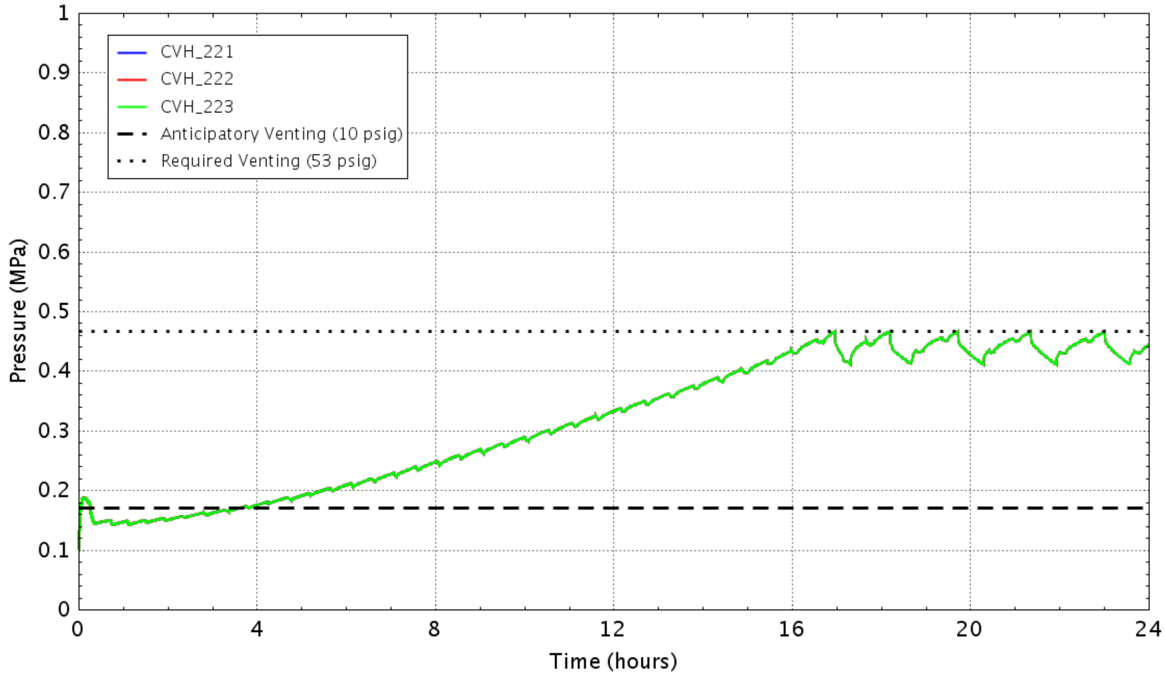

Figure C - 535 Pressure in the wetwell

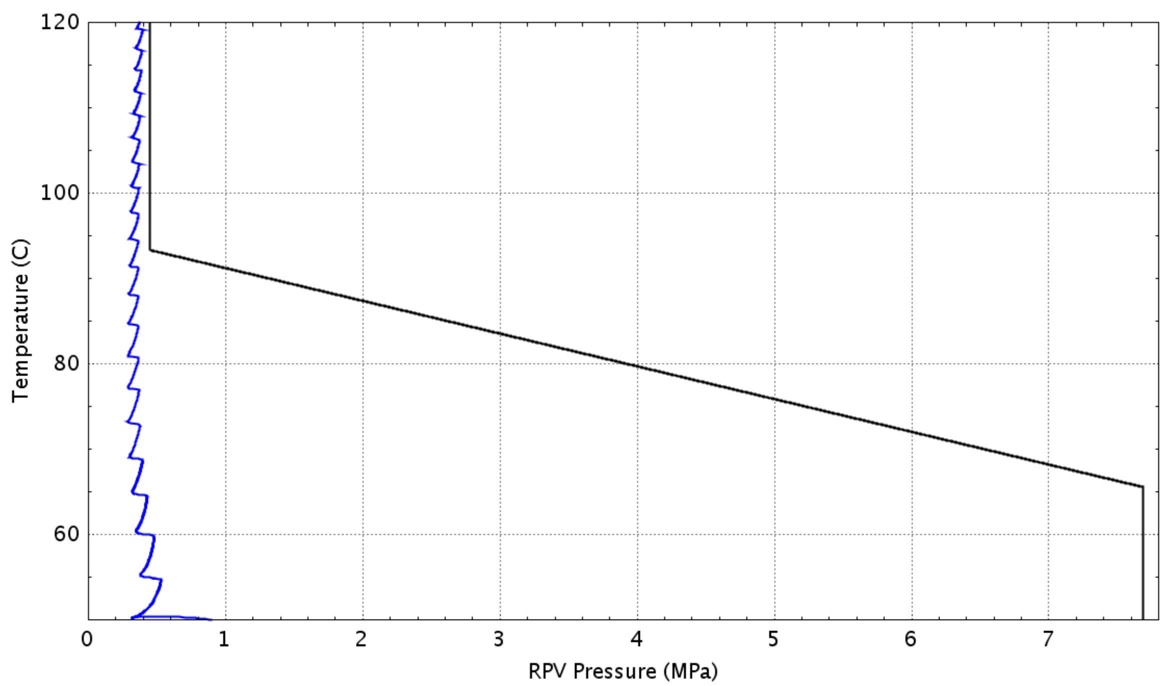

Figure C - 536 Plant status relative to the HCL curve (Graph 4 of the EOPs)

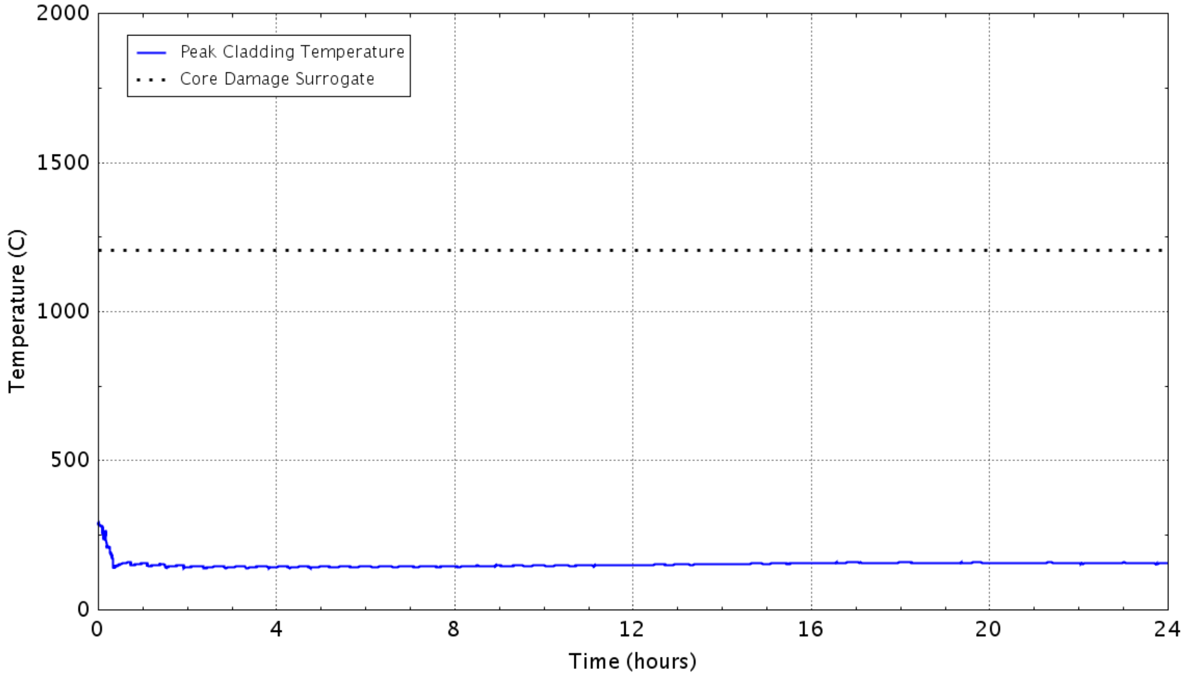

Figure C - 537 Peak temperature of the fuel cladding as a function of time

C.3.13 Case 24d: Sensitivity to SLOCA-25 Case 24 with Nominal Recirculation Pump Seal Leakage

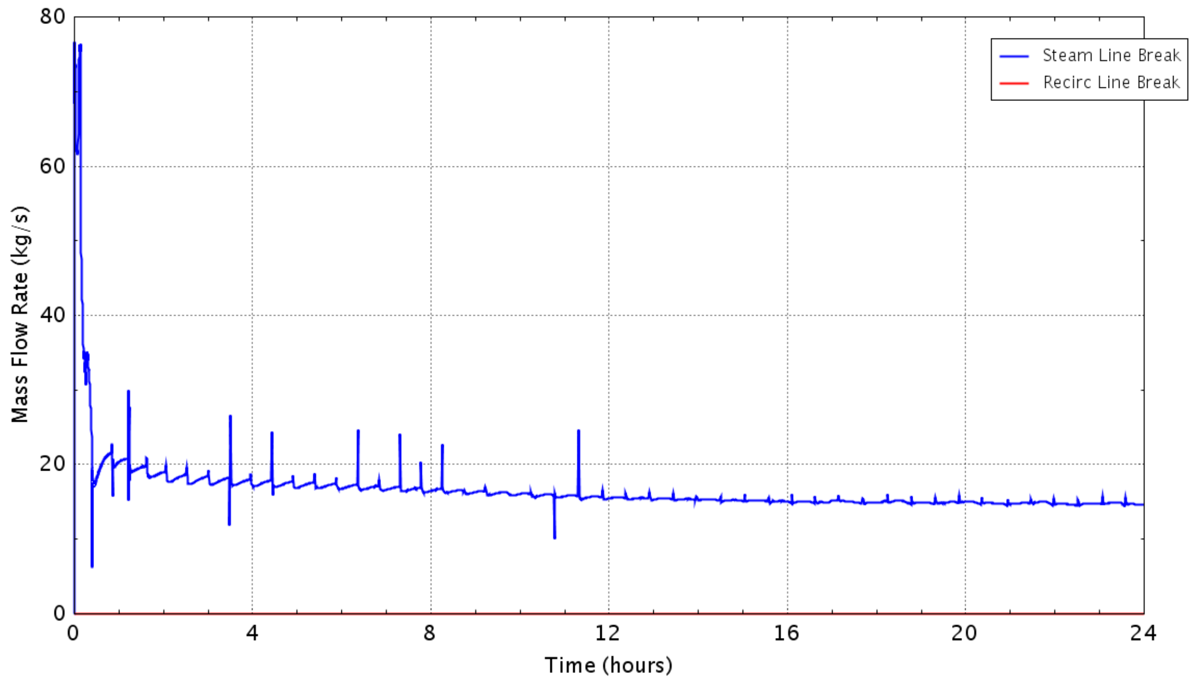

Figure C - 538 Flow rate of the break in the steamline/recirculation line

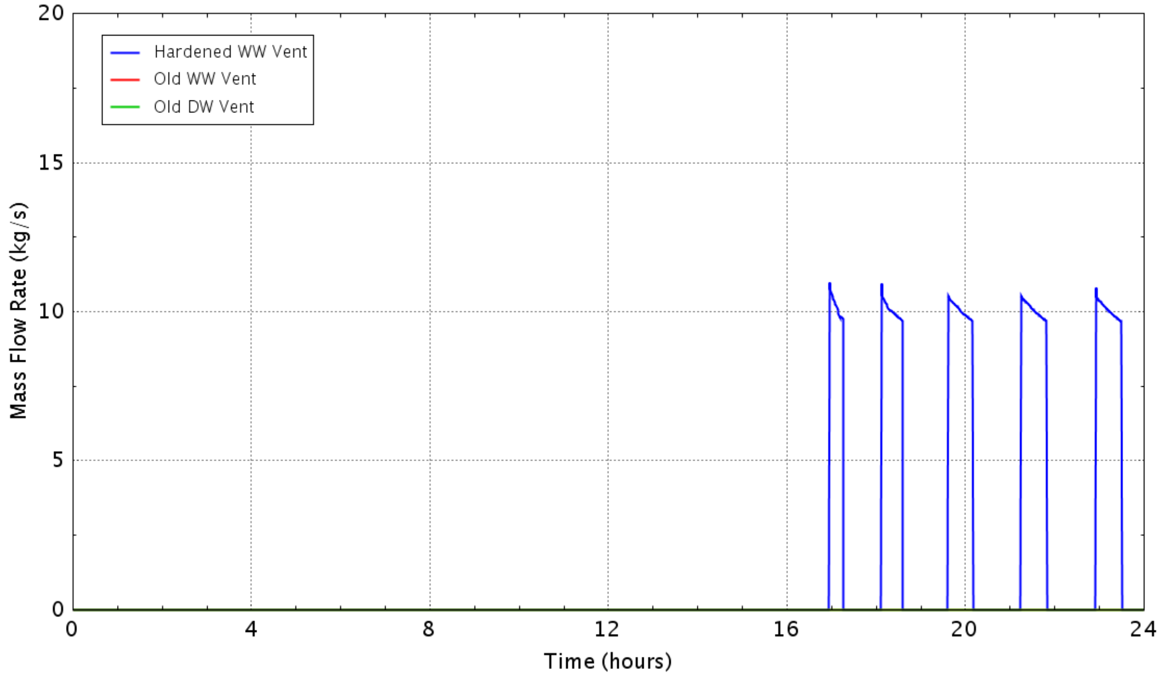

Figure C - 539 Flow rate of the containment vents

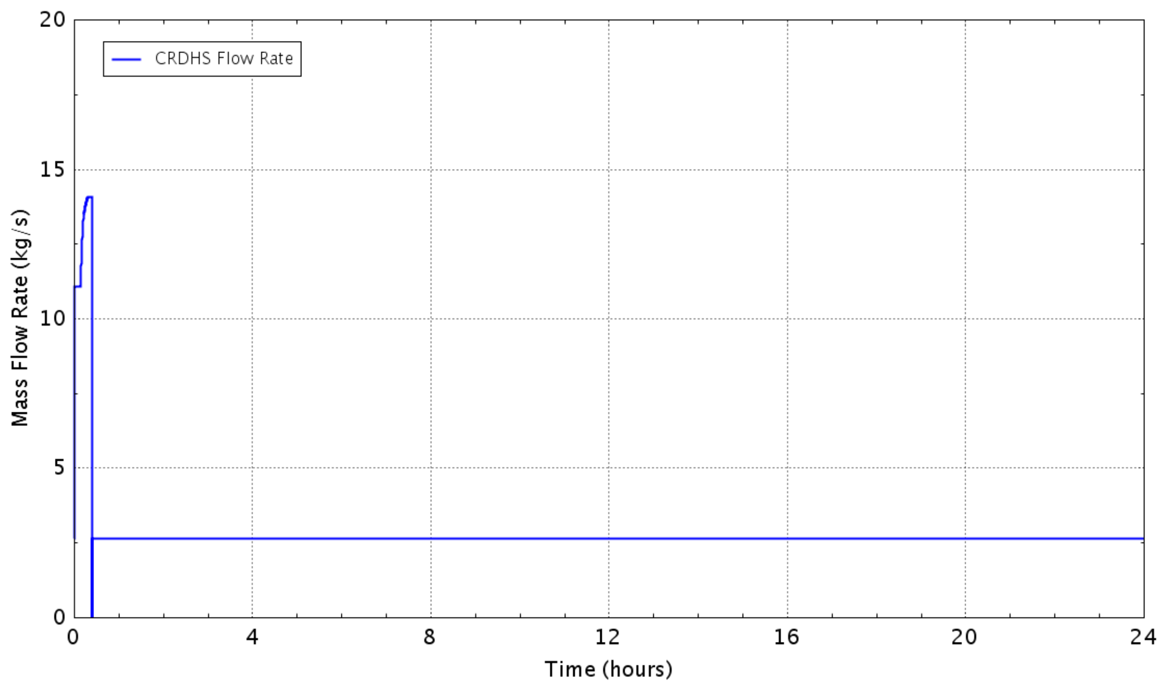

Figure C - 540 Flow rate of the control rod drive hydraulic system

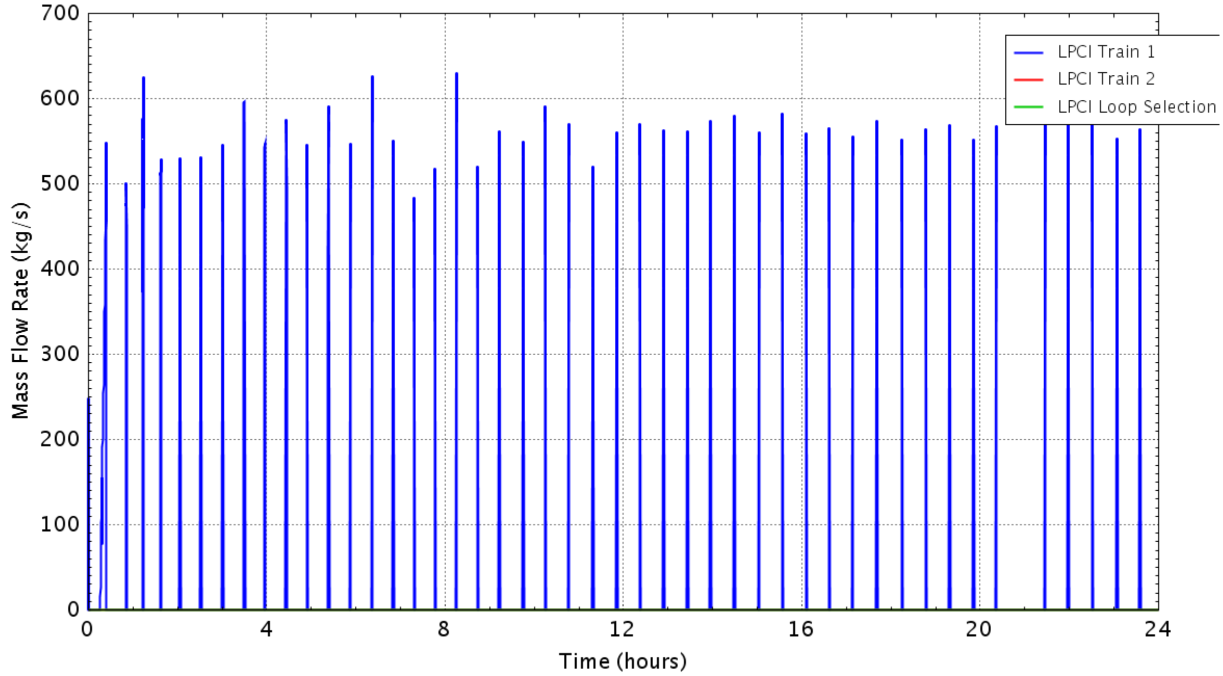

Figure C - 541 Flow rate of the LPCI pump

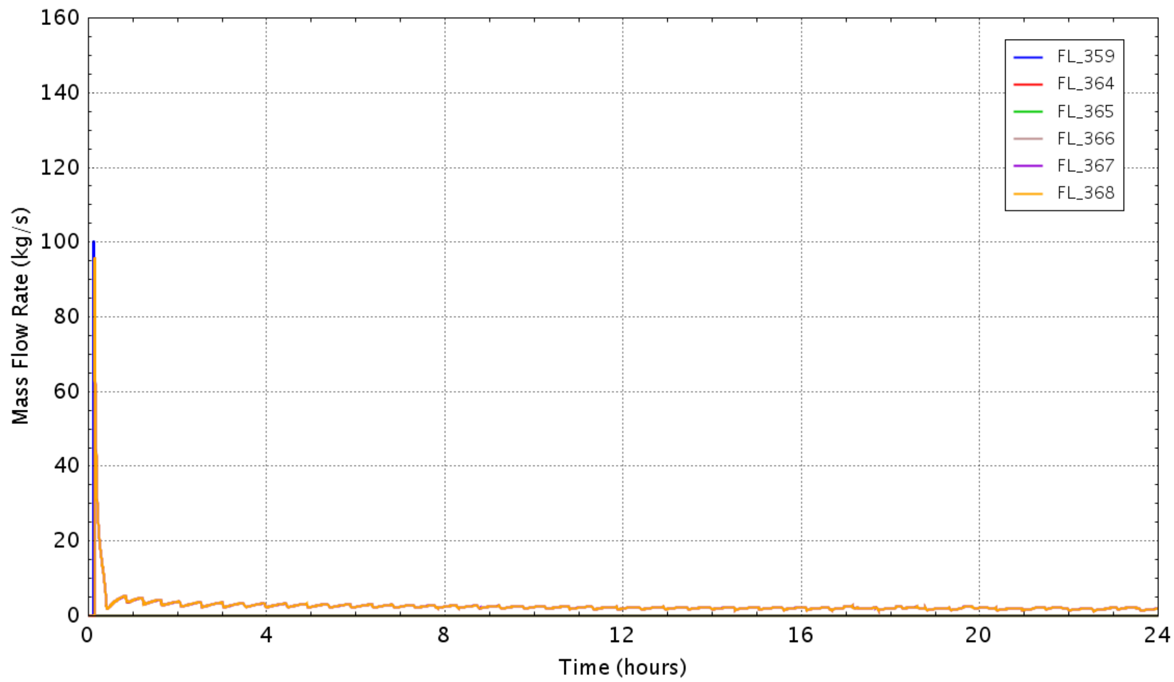

Figure C – 542 Flow rate of the SRVs

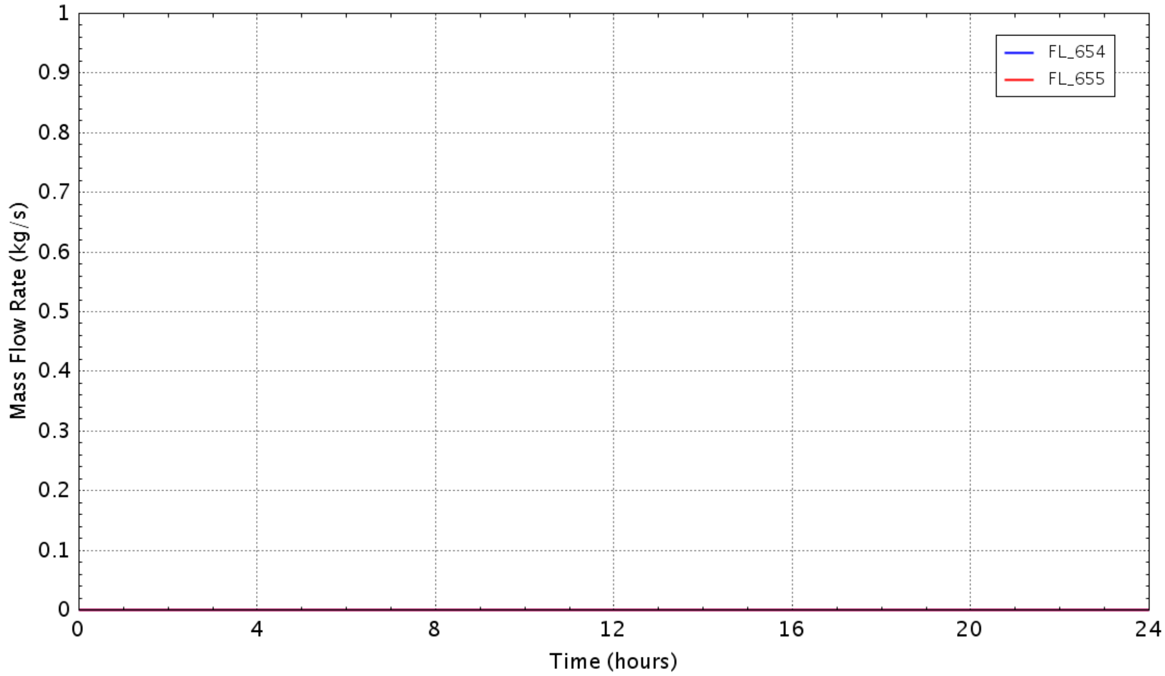

Figure C - 543   Flow rate of the wetwell cooling system

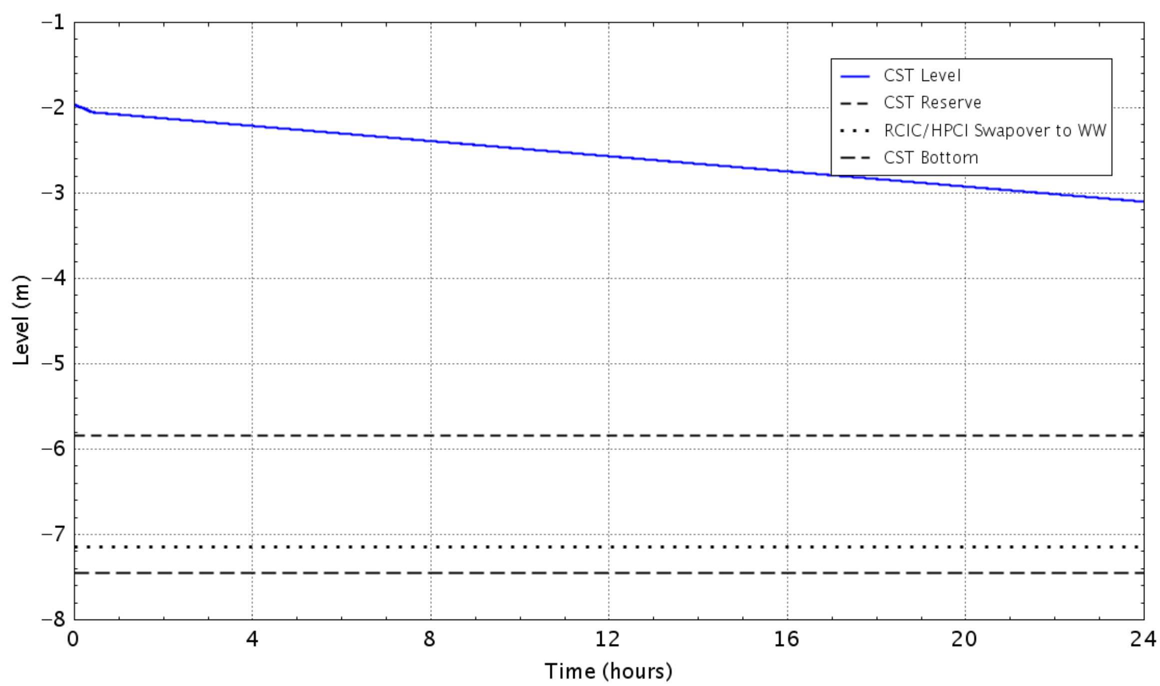

Figure C - 544   Water level in the CST

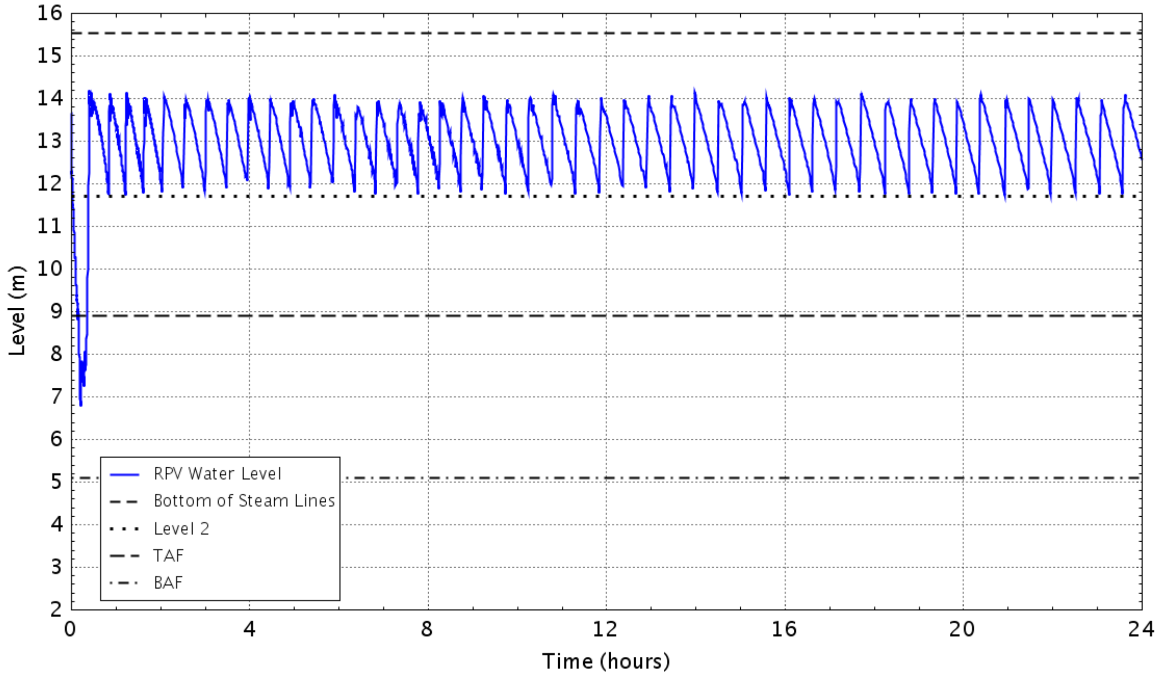

Figure C - 545 RPV Downcomer water level

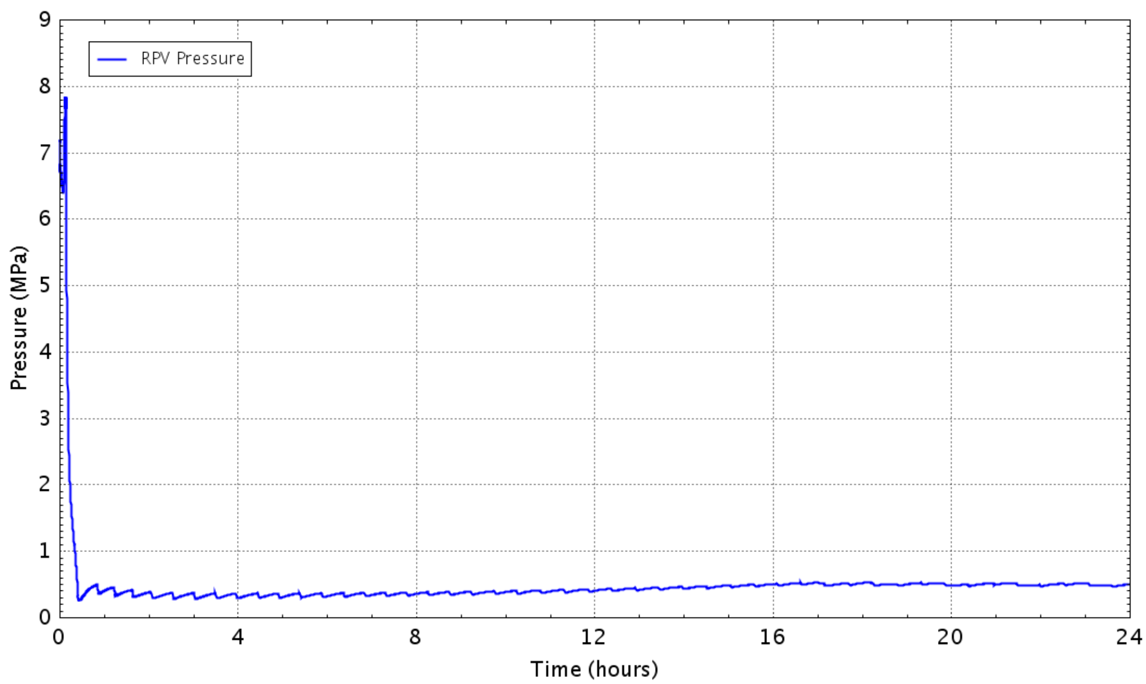

Figure C - 546 Pressure in the RPV

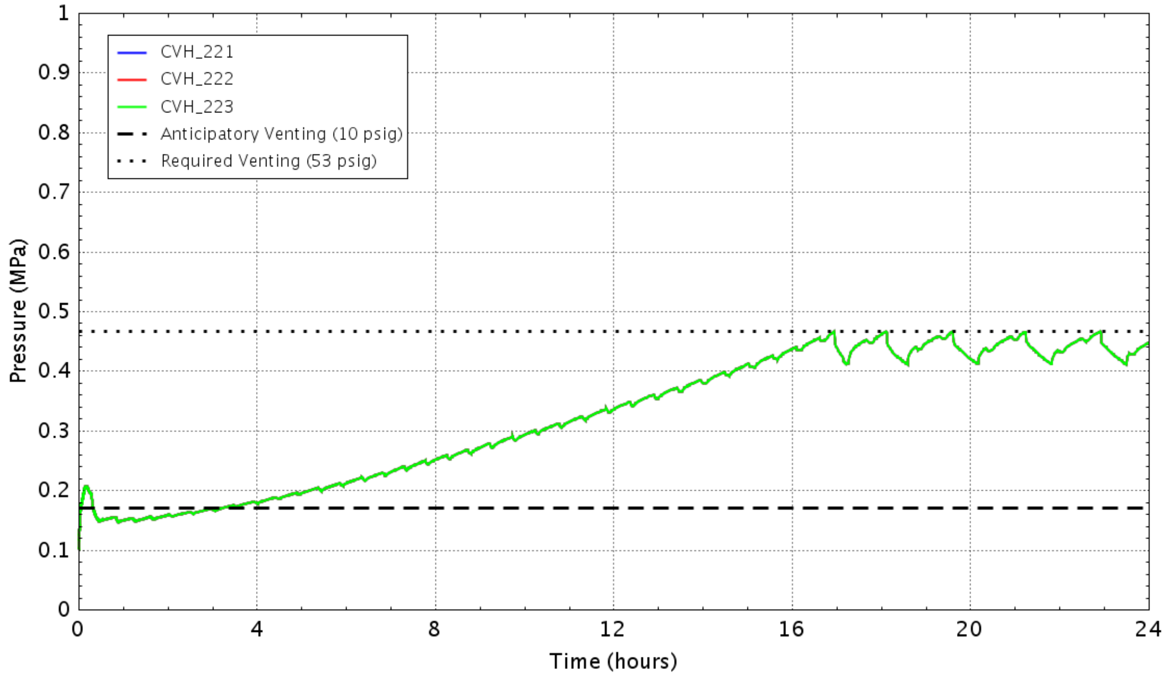

Figure C - 547   Pressure in the wetwell

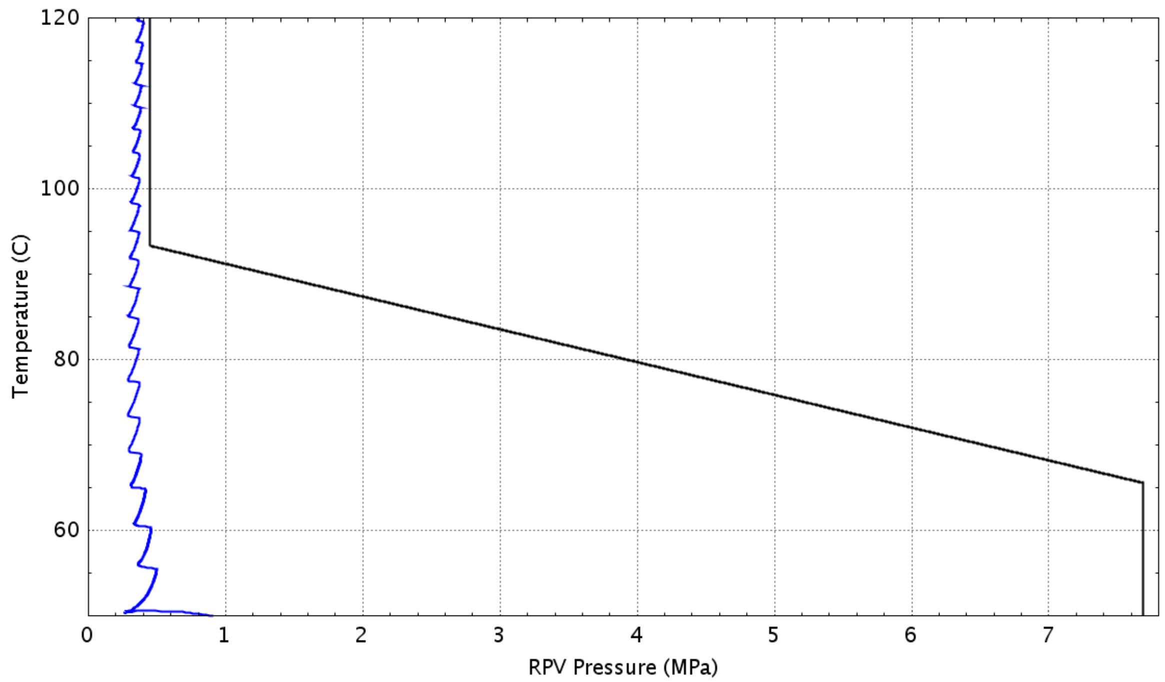

Figure C - 548   Plant status relative to the HCL curve (Graph 4 of the EOPs)

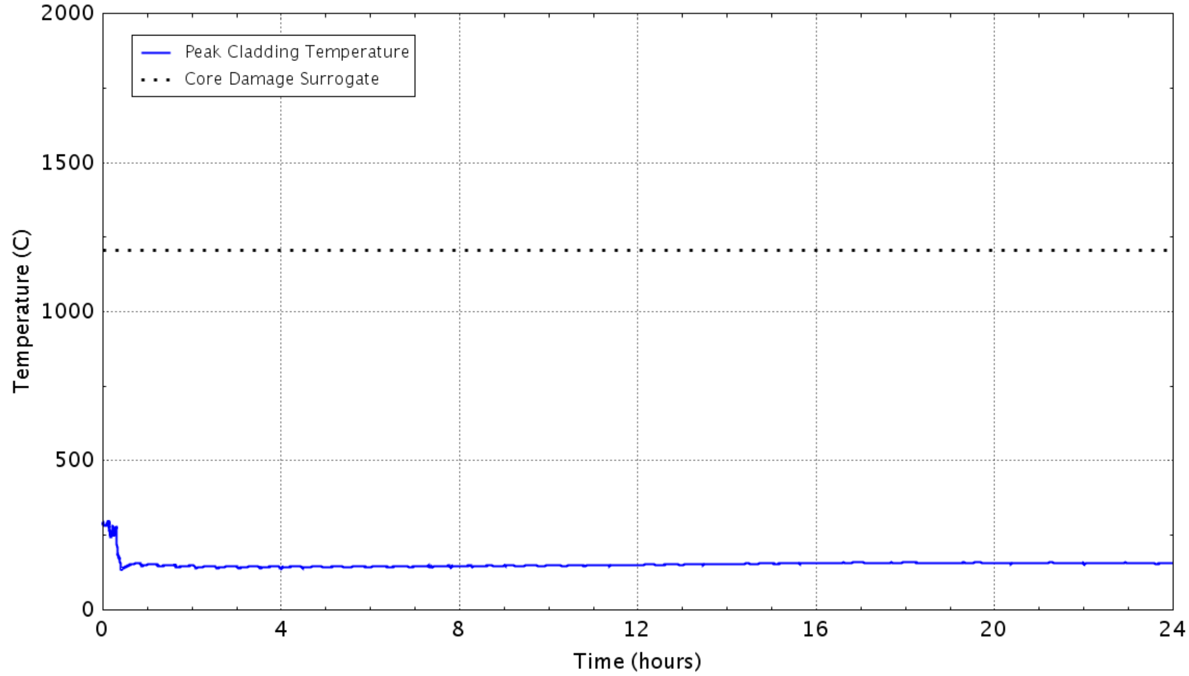

Figure C – 549 **Peak temperature of the fuel cladding as a function of time**

C.3.14 Case 24e: Sensitivity to SLOCA-25 Case 24 with Break Size and Location Exchanged

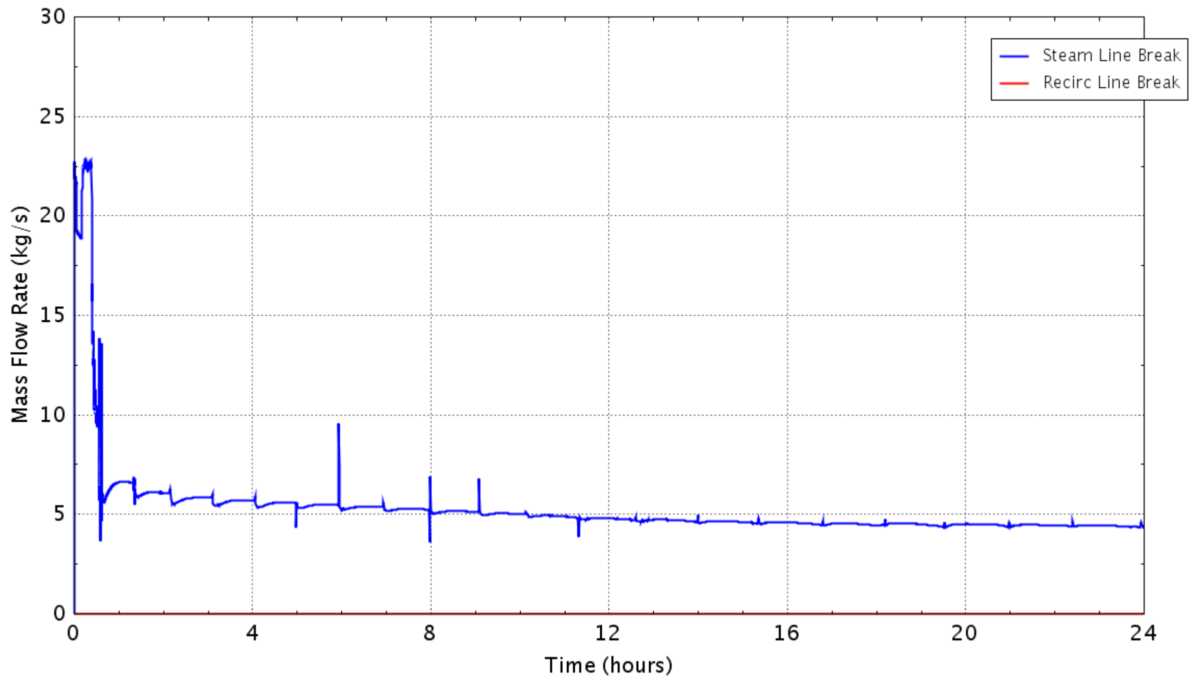

Figure C - 550 Flow rate of the break in the steamline/recirculation line

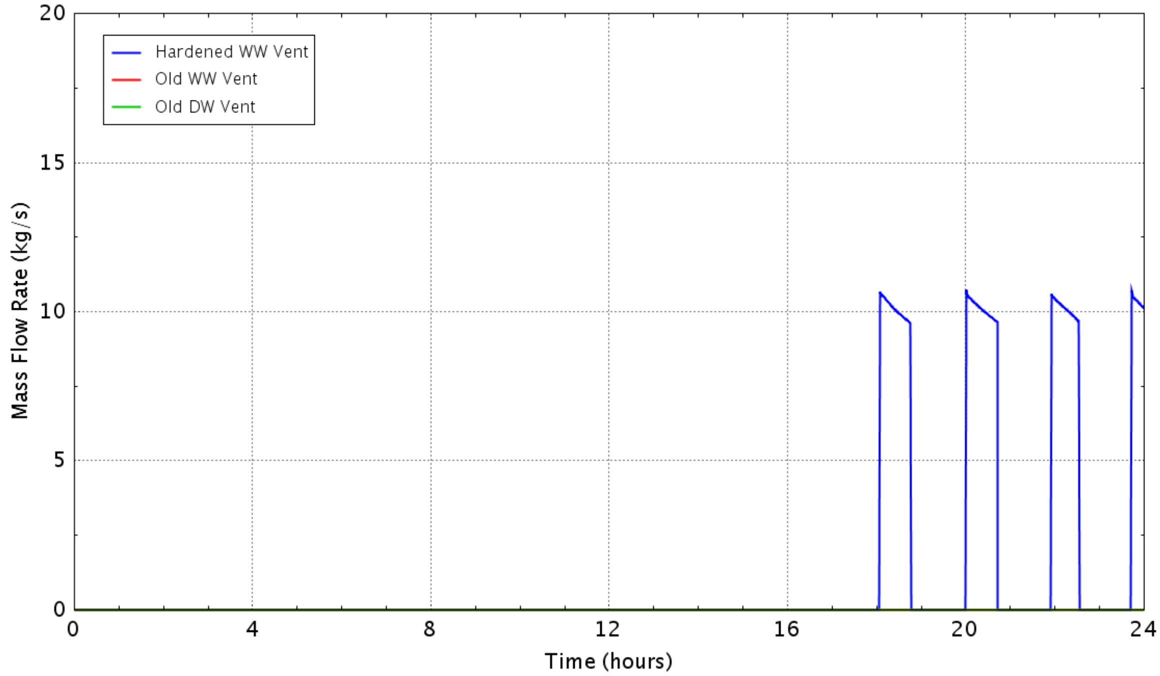

Figure C - 551 Flow rate of the containment vents

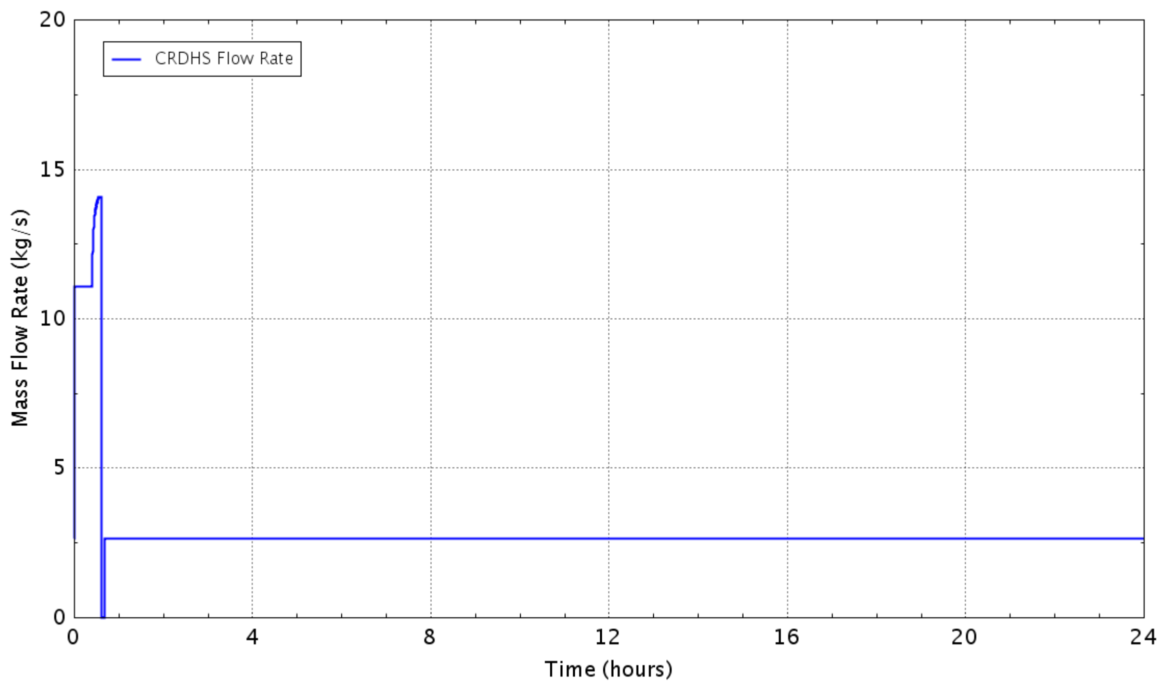

Figure C - 552 Flow rate of the control rod drive hydraulic system

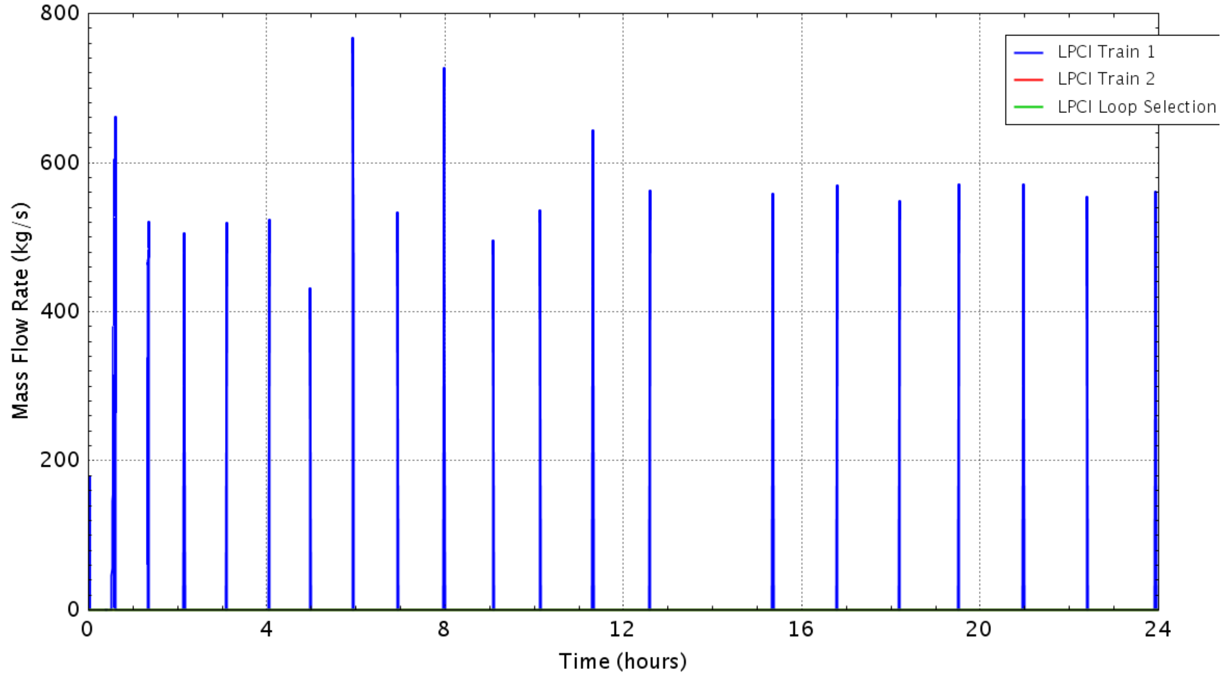

Figure C - 553 Flow rate of the LPCI pump

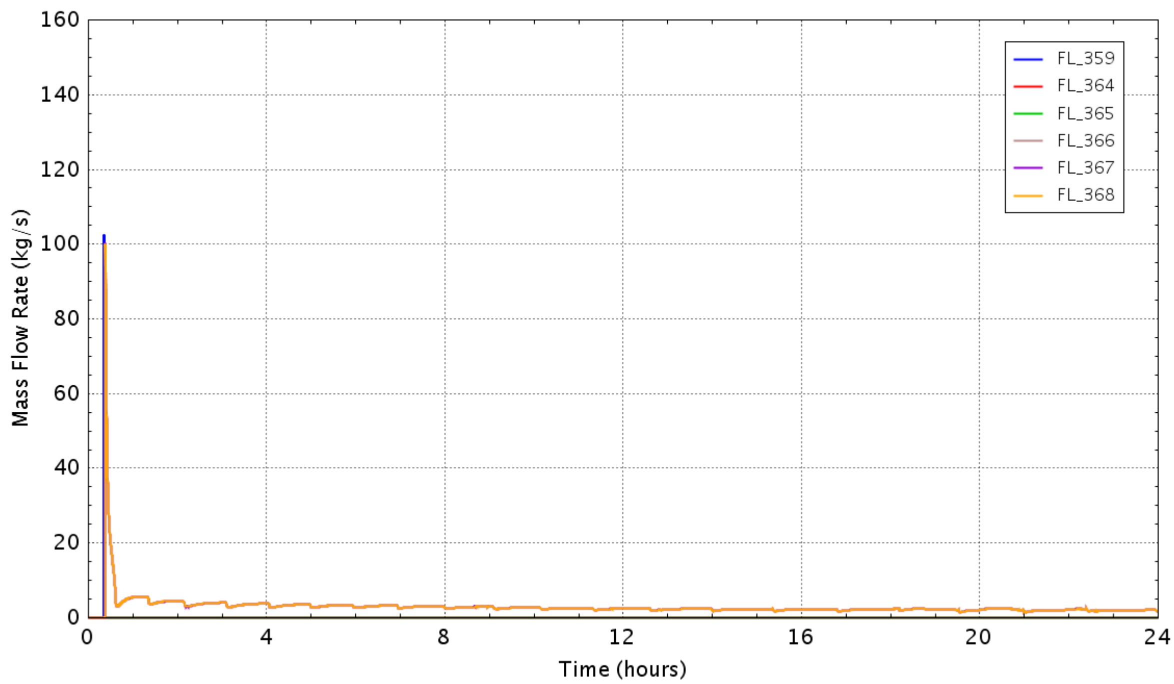

Figure C - 554 Flow rate of the SRVs

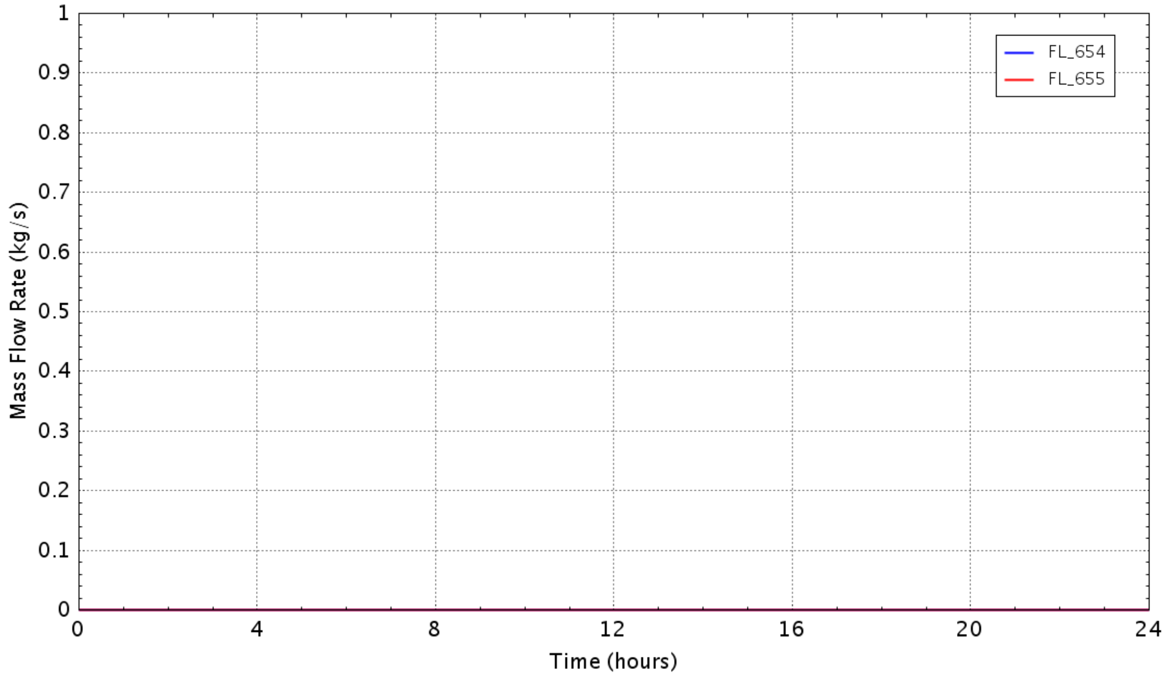

Figure C - 555 Flow rate of the wetwell cooling system

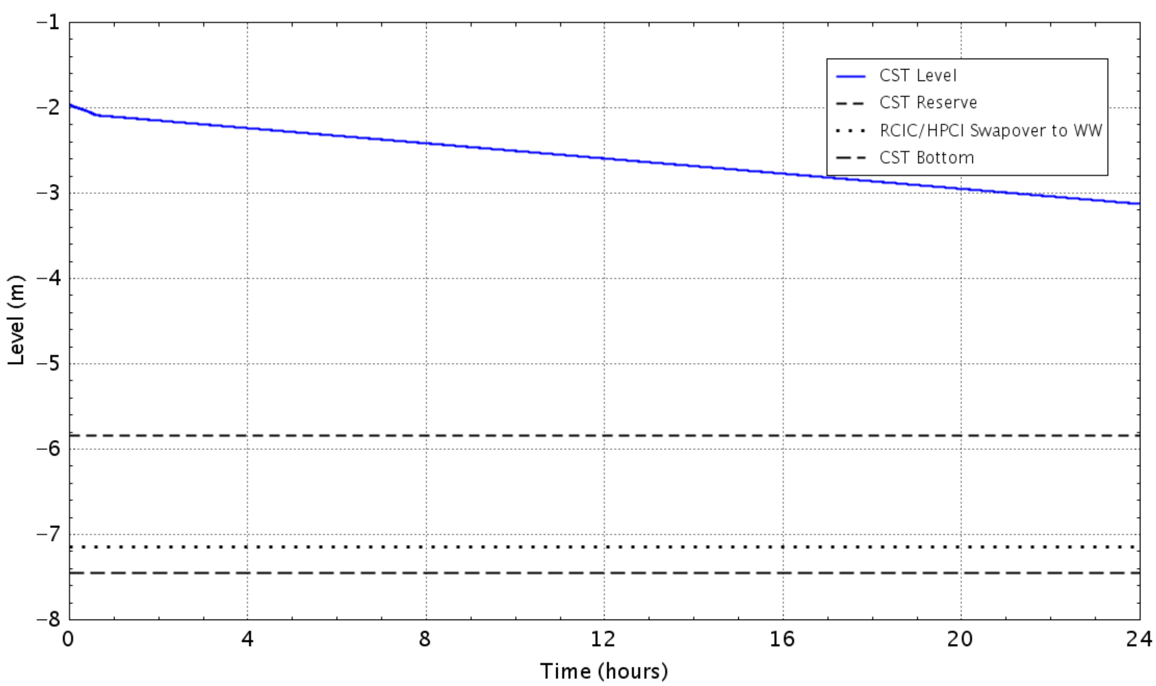

Figure C - 556 Water level in the CST

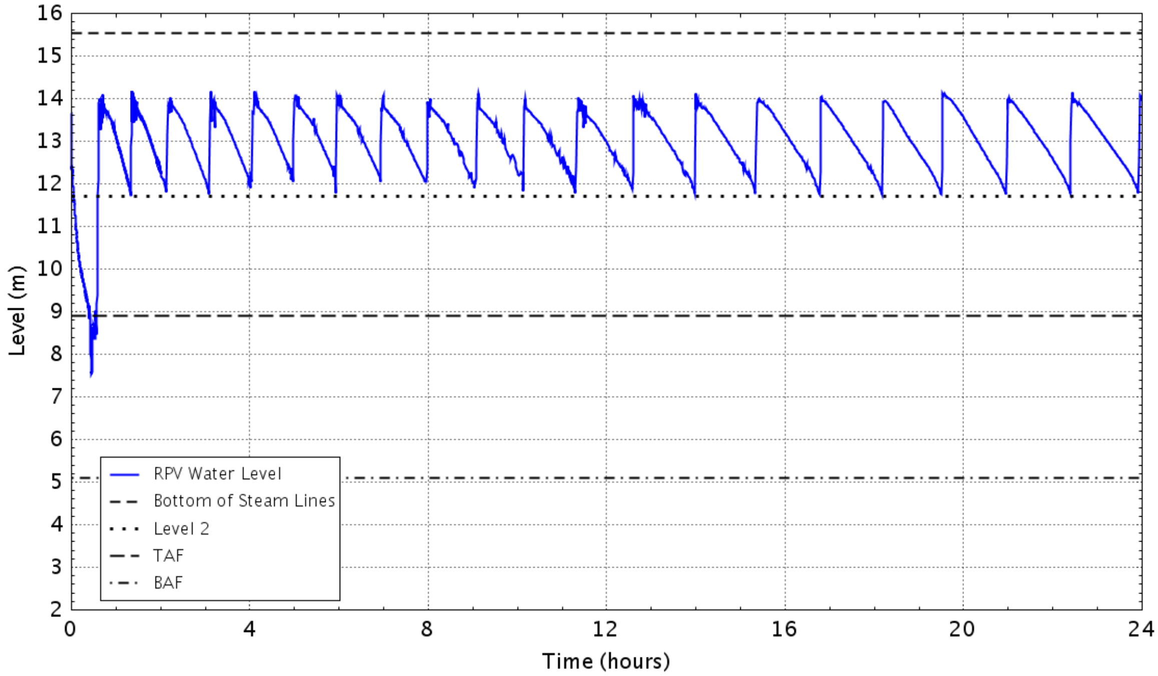

Figure C - 557 RPV Downcomer water level

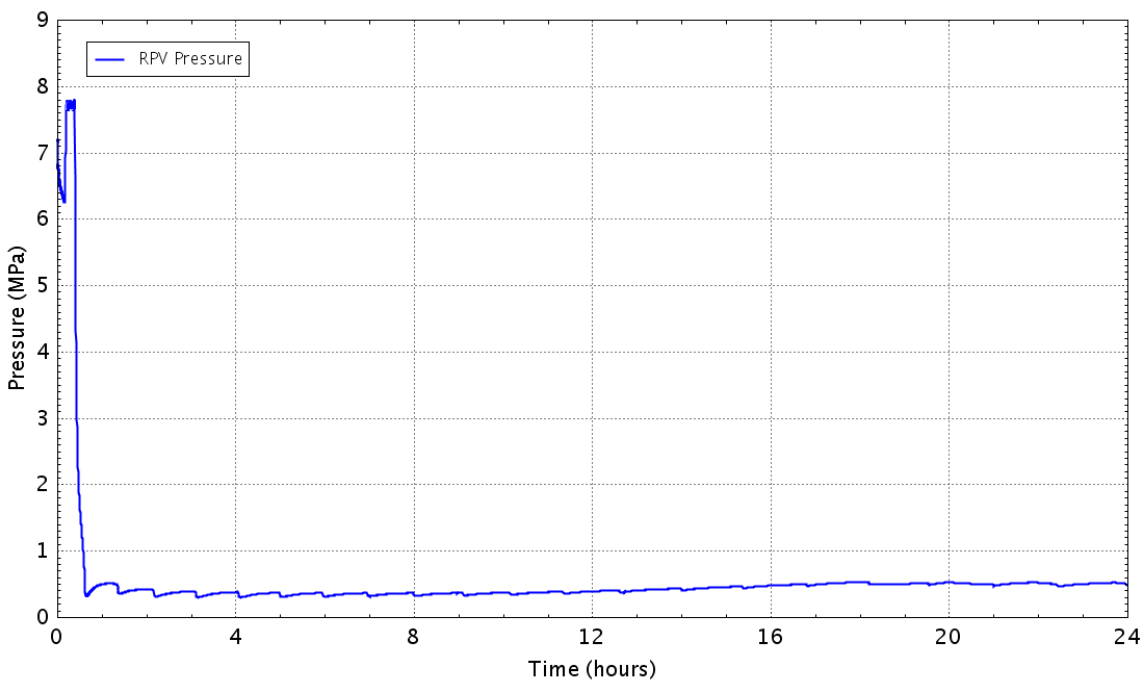

Figure C - 558 Pressure in the RPV

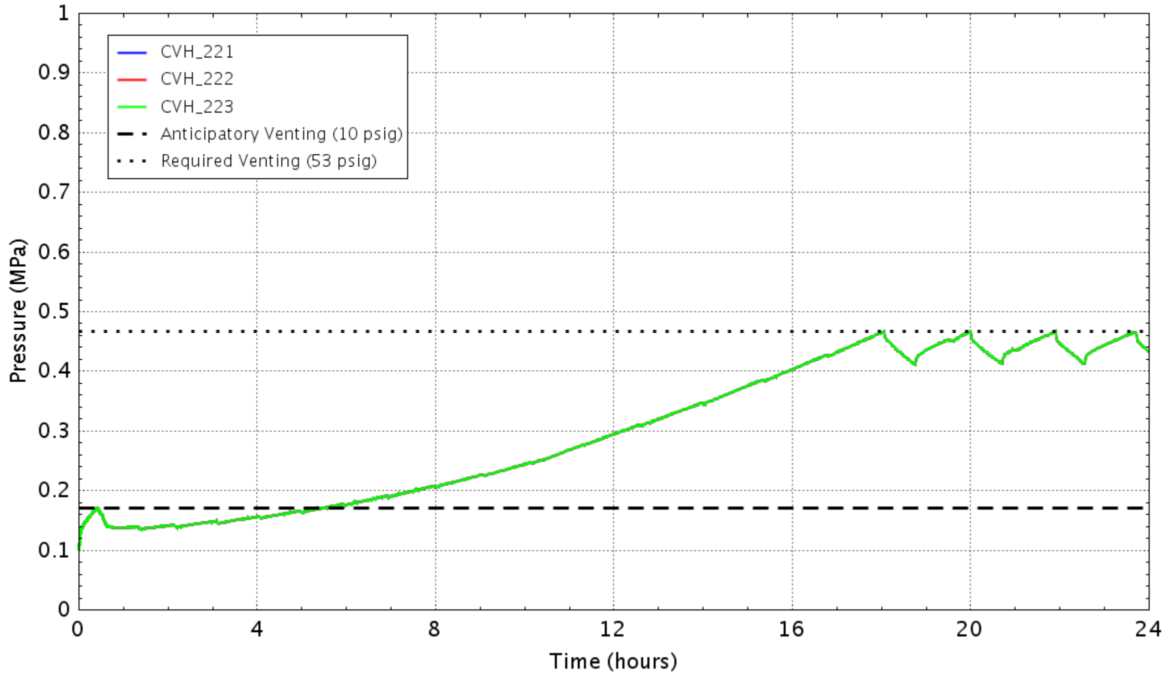

Figure C - 559 Pressure in the wetwell

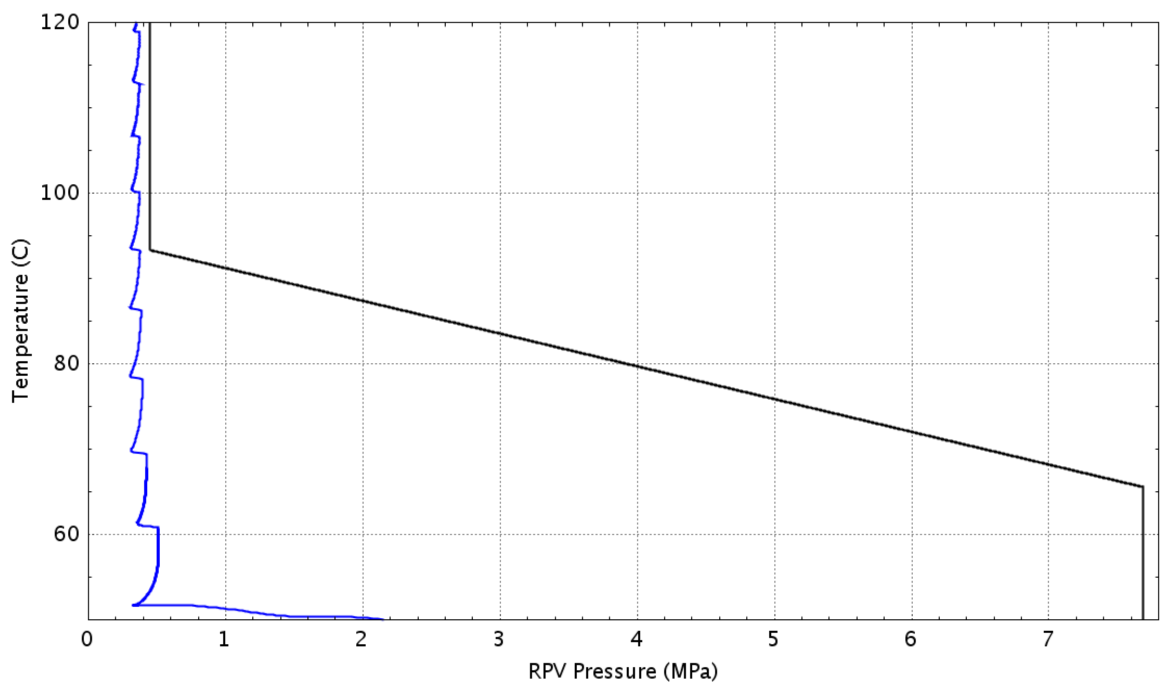

Figure C - 560 Plant status relative to the HCL curve (Graph 4 of the EOPs)

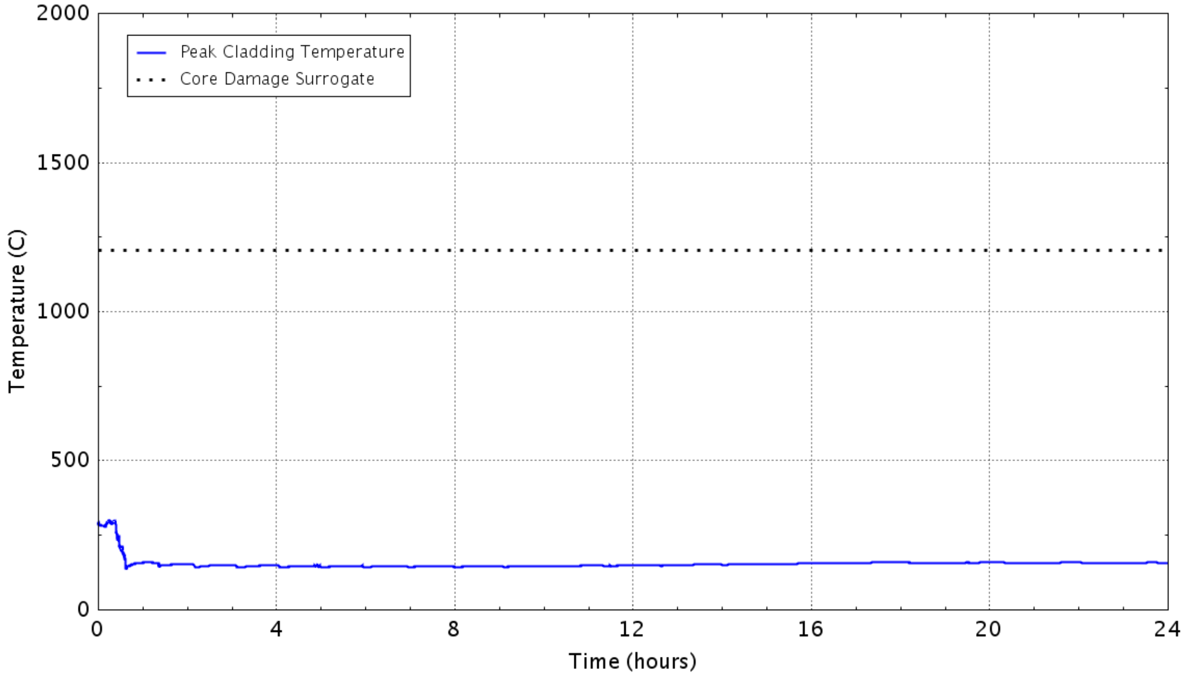

Figure C - 561 Peak temperature of the fuel cladding as a function of time

C.3.15 Case 26a: Sensitivity to SLOCA-25 Case 26 with NominalCRDHS Injection

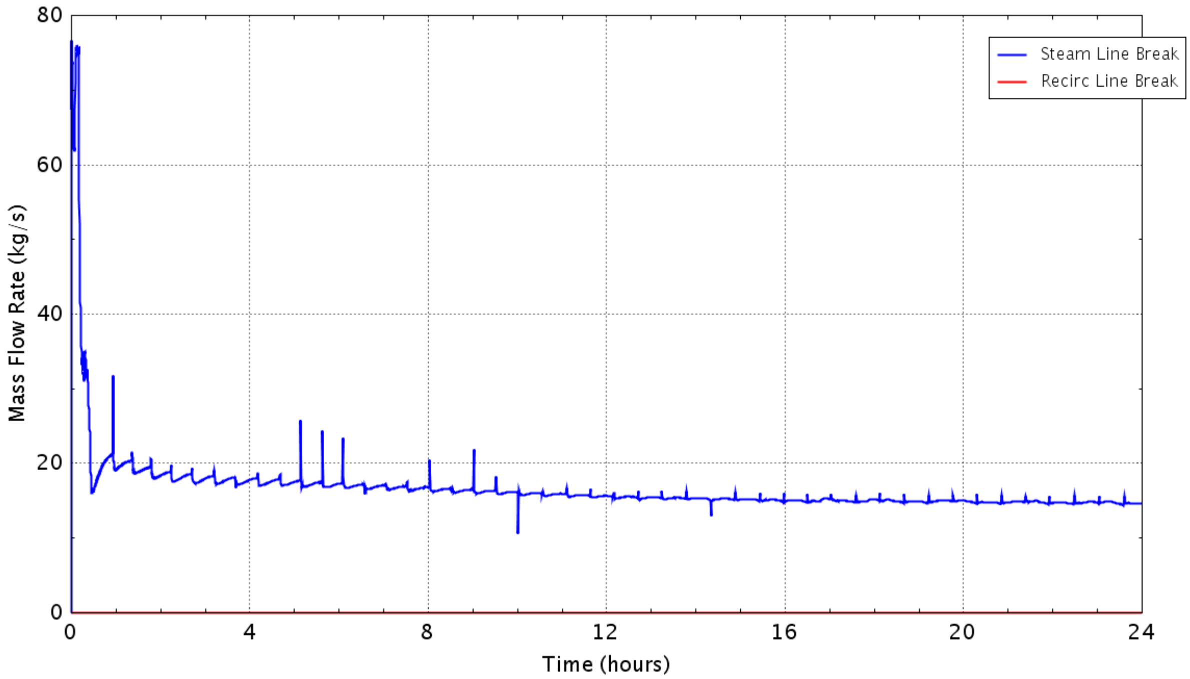

Figure C - 562 Flow rate of the break in the steamline/recirculation line

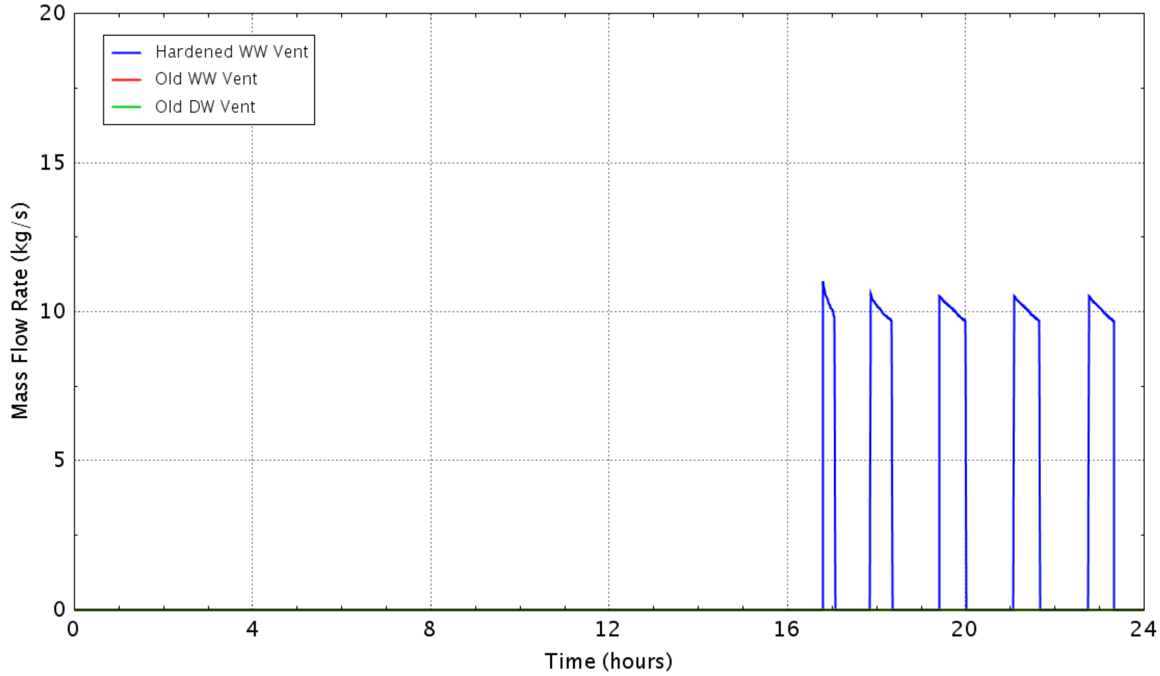

Figure C - 563 Flow rate of the containment vents

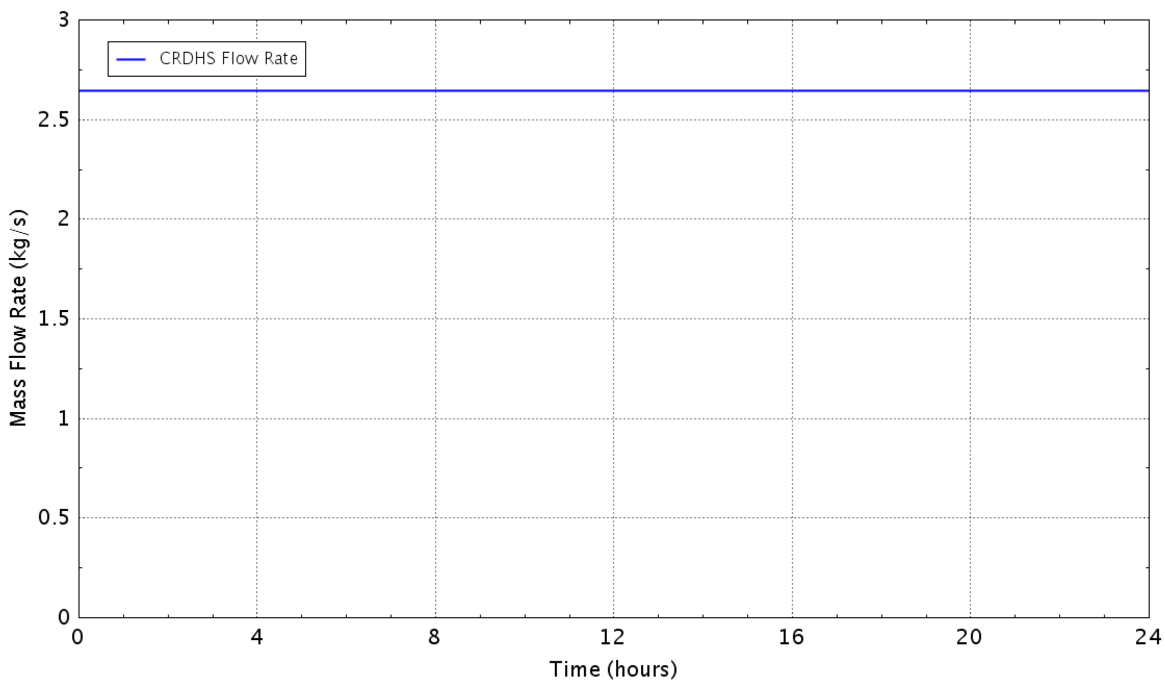

Figure C - 564 Flow rate of the control rod drive hydraulic system

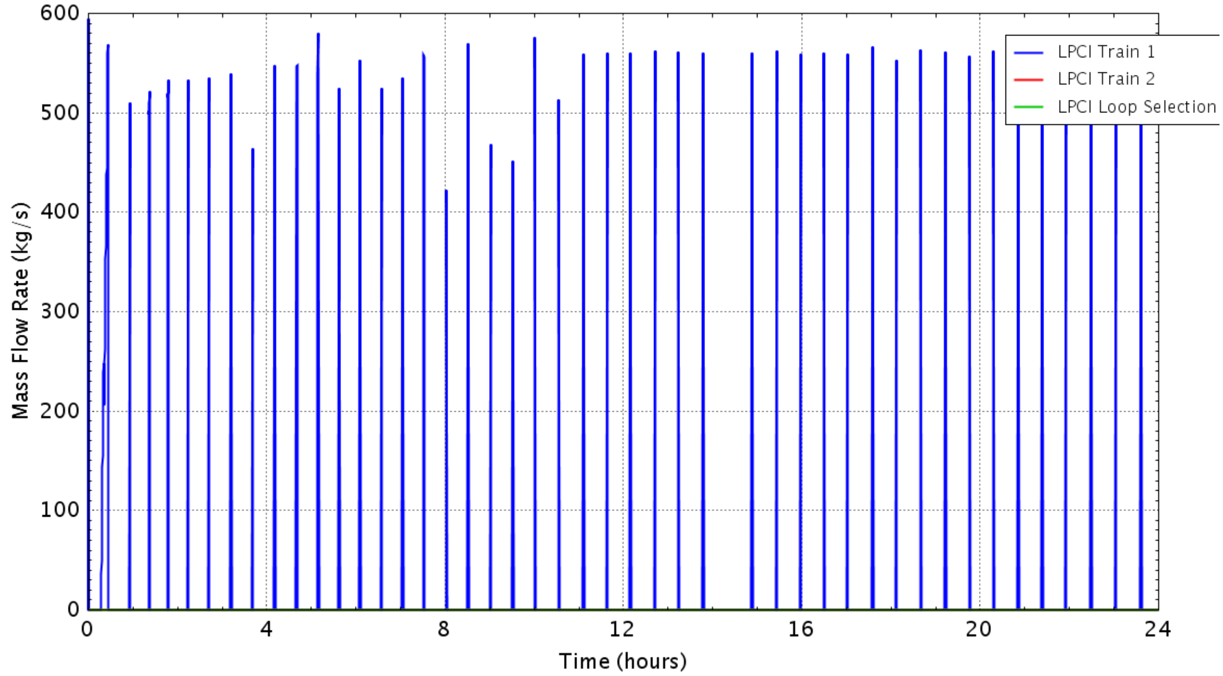

Figure C - 565 Flow rate of the LPCI pump

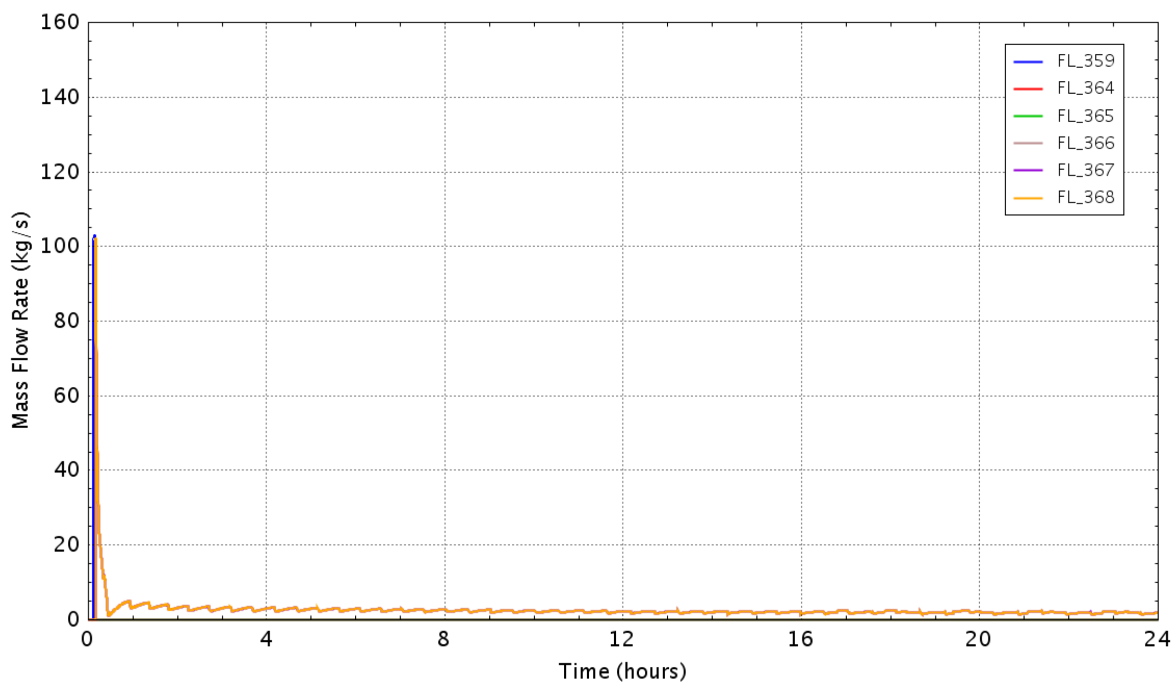

Figure C - 566 Flow rate of the SRVs

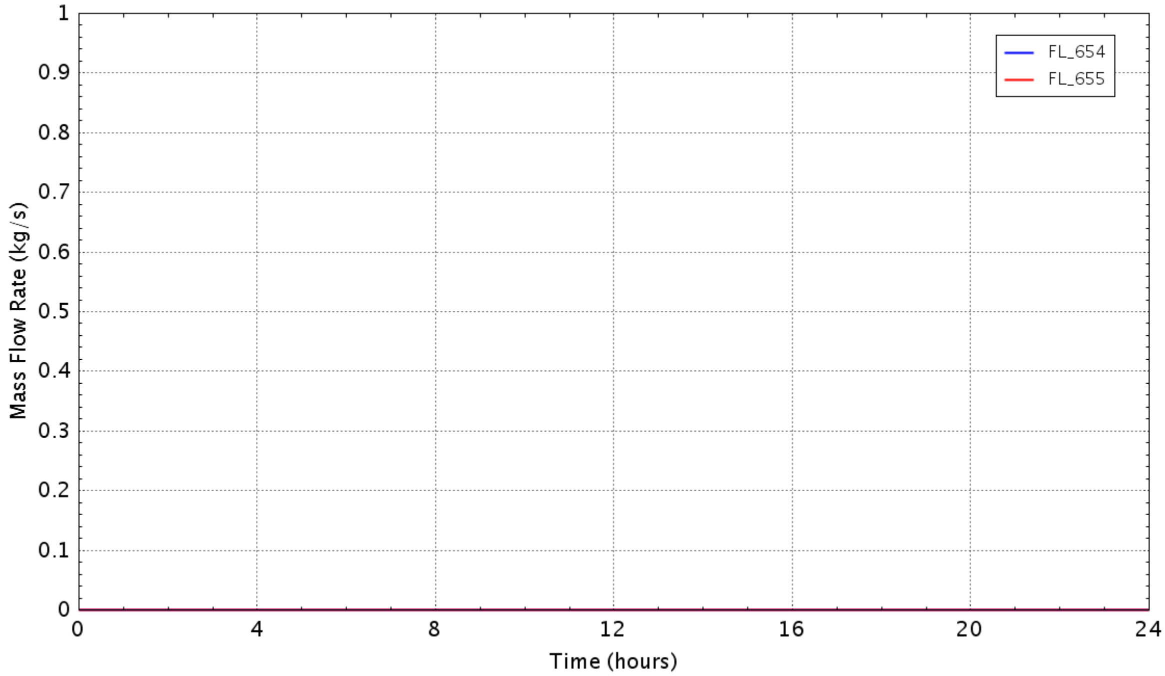

Figure C - 567 Flow rate of the wetwell cooling system

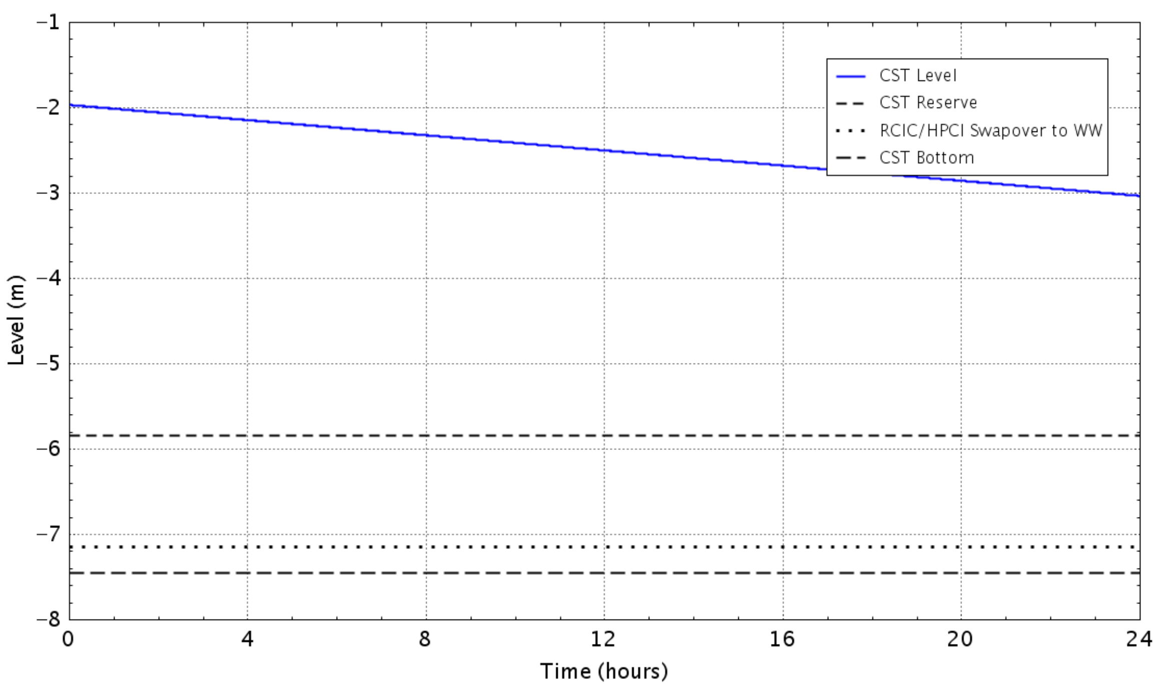

Figure C - 568 Water level in the CST

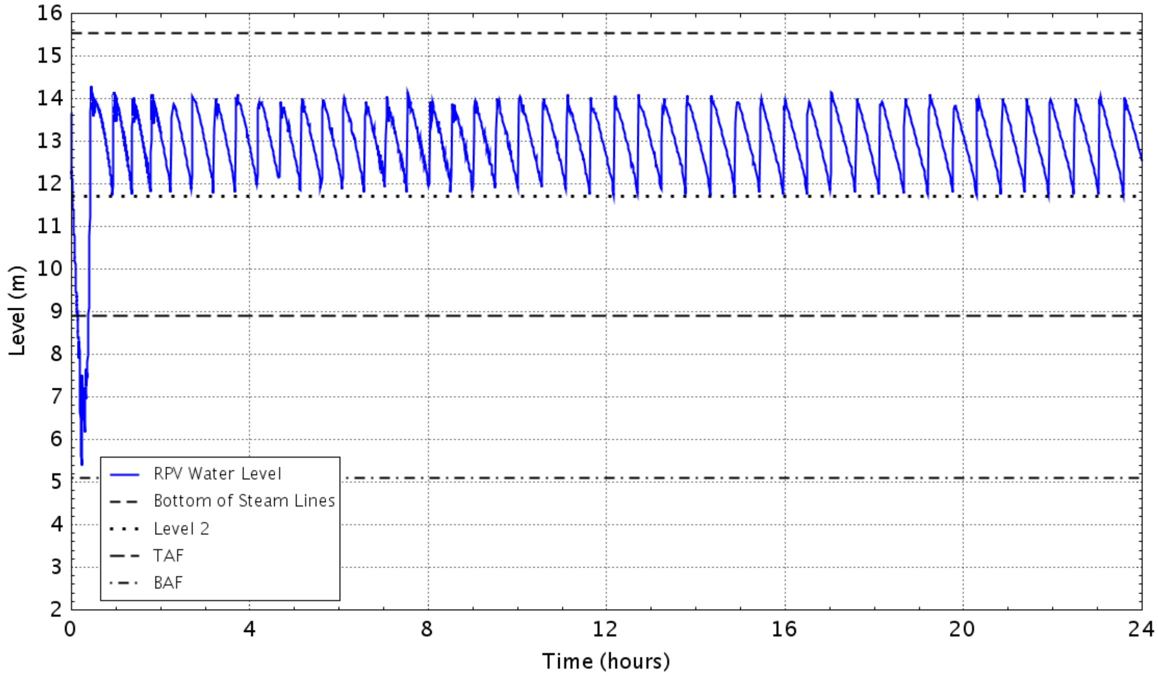

Figure C - 569 RPV Downcomer water level

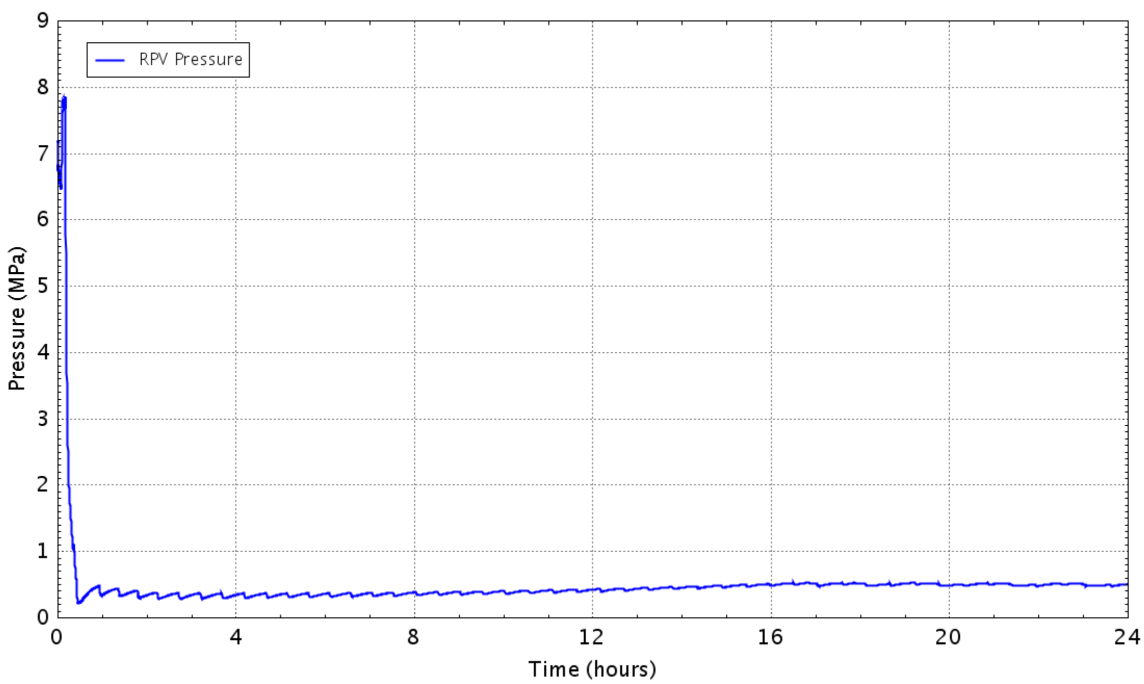

Figure C - 570 Pressure in the RPV

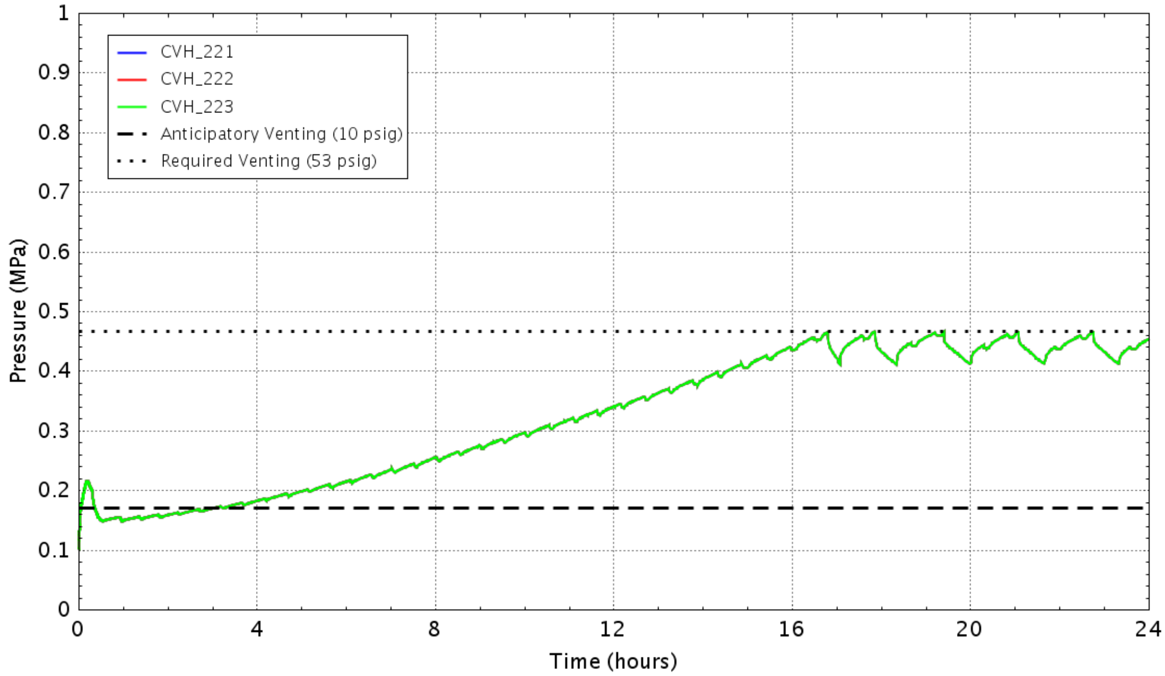

Figure C - 571 Pressure in the wetwell

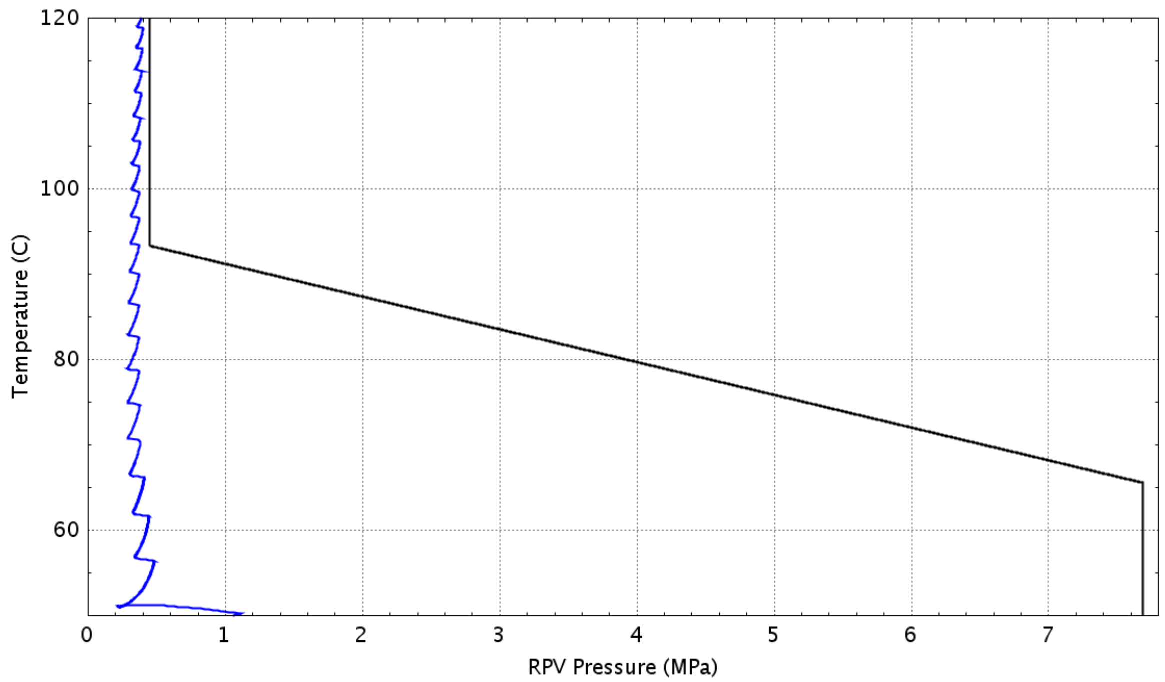

Figure C - 572 Plant status relative to the HCL curve (Graph 4 of the EOPs)

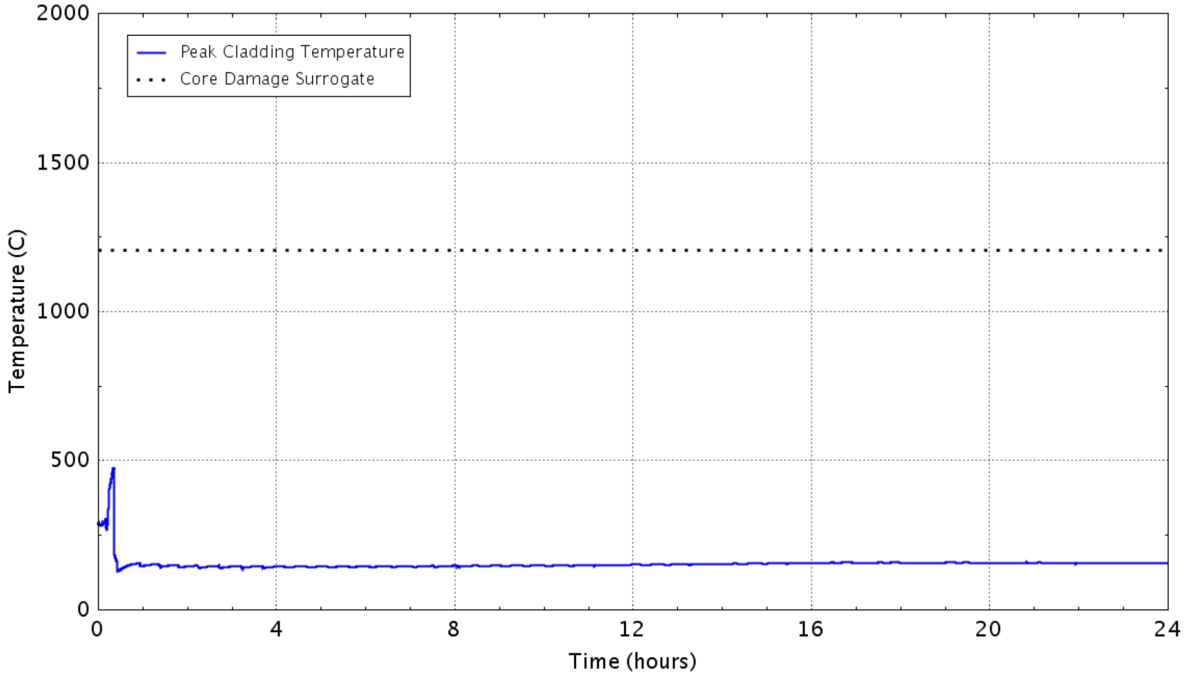

Figure C - 573   Peak temperature of the fuel cladding as a function of time

C.3.16 Case 26b: Sensitivity to SLOCA-25 Case 26 with Low-Pressure Injection Provided by Core Spray Rather Than LPCI

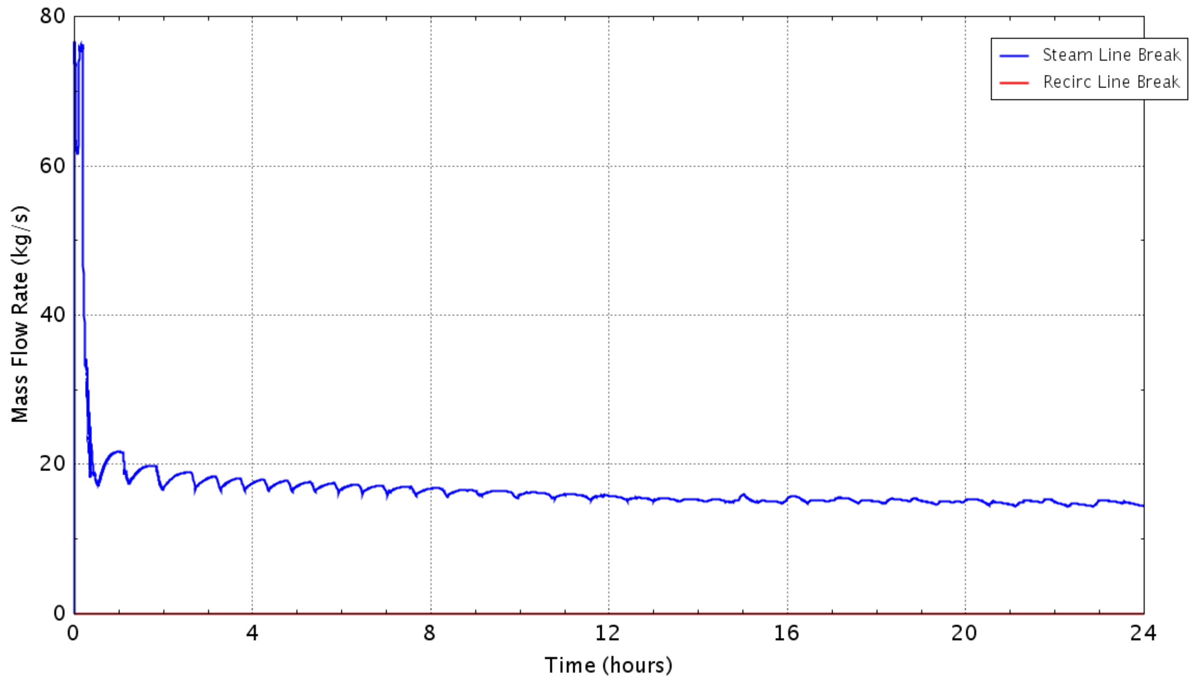

Figure C - 574 Flow rate of the break in the steamline/recirculation line

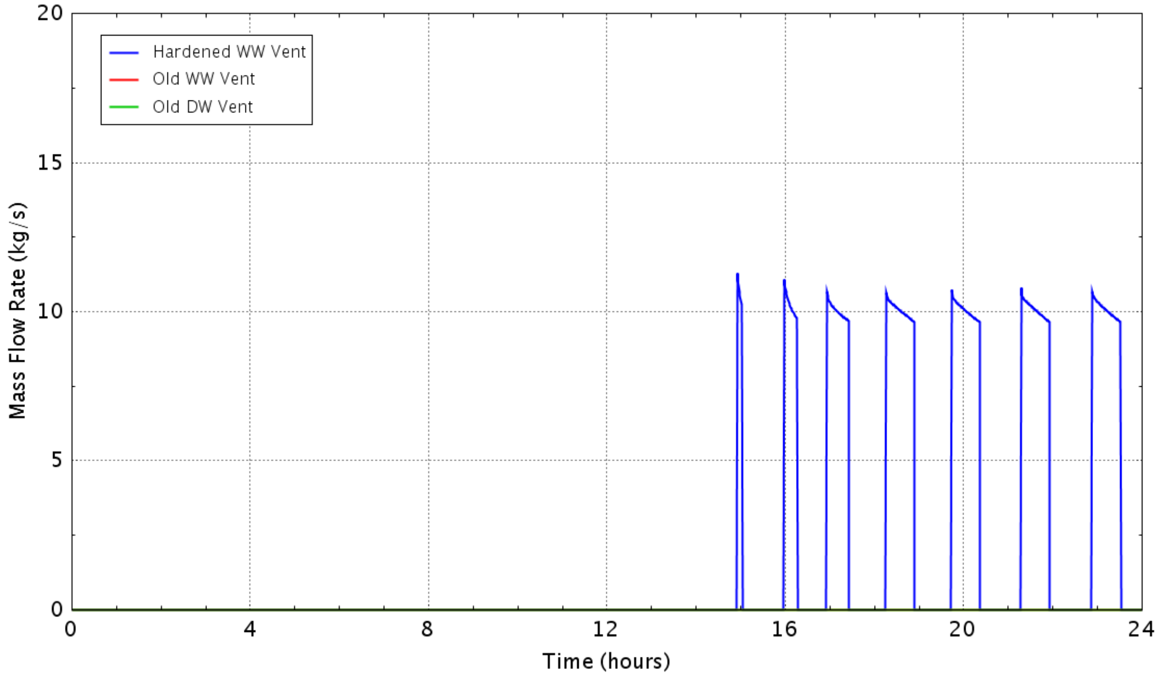

Figure C - 575 Flow rate of the containment vents

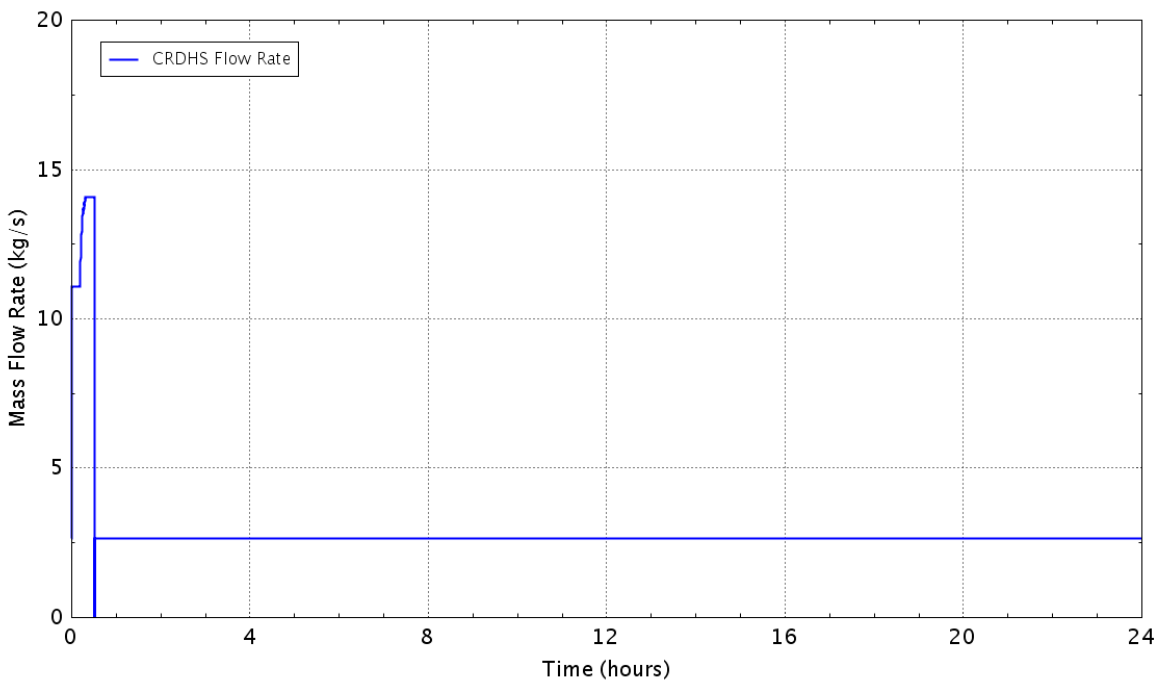

Figure C - 576 Flow rate of the control rod drive hydraulic system

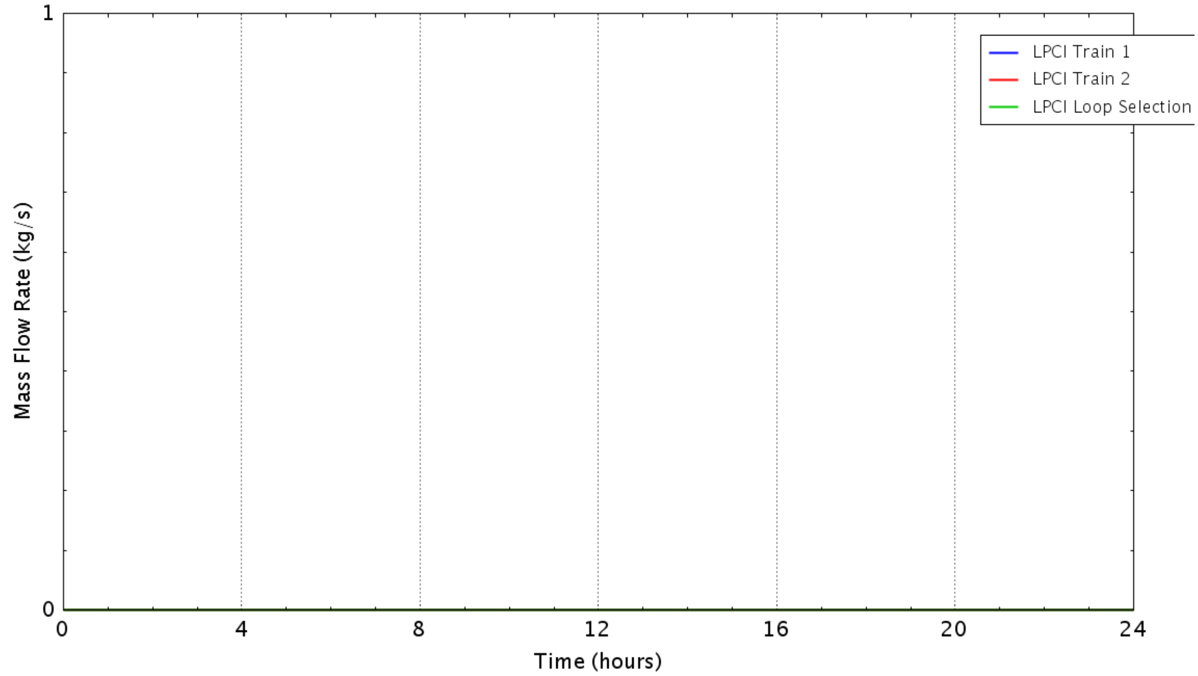

Figure C - 577 Flow rate of the LPCI pump

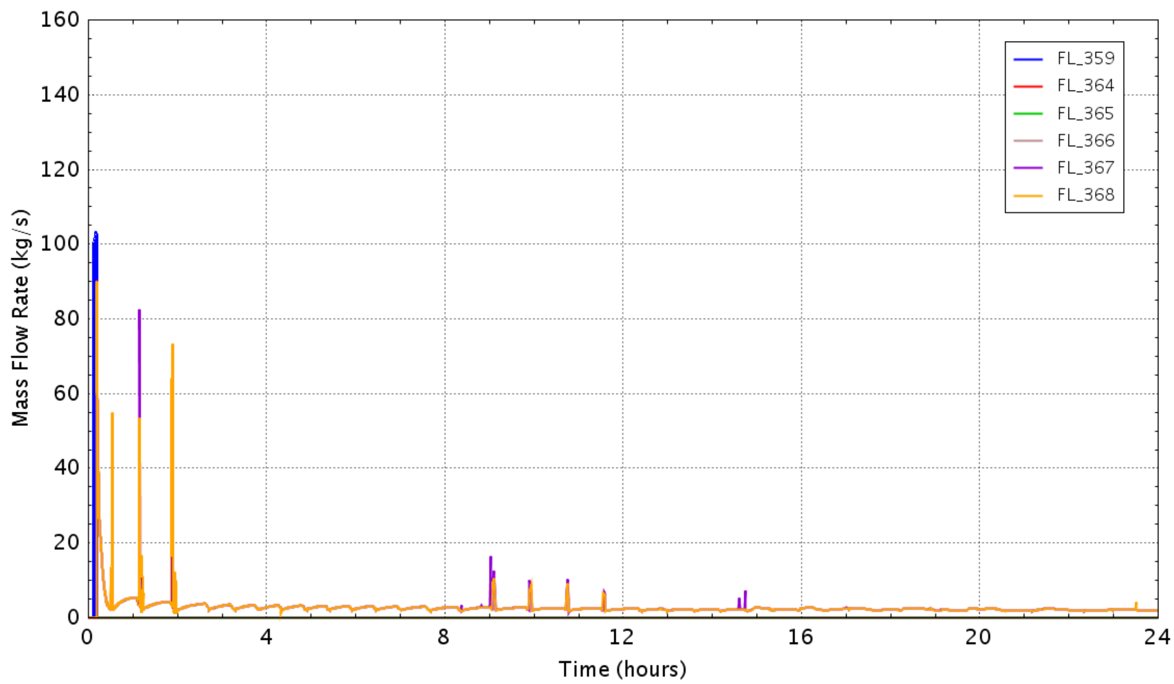

Figure C - 578 Flow rate of the SRVs

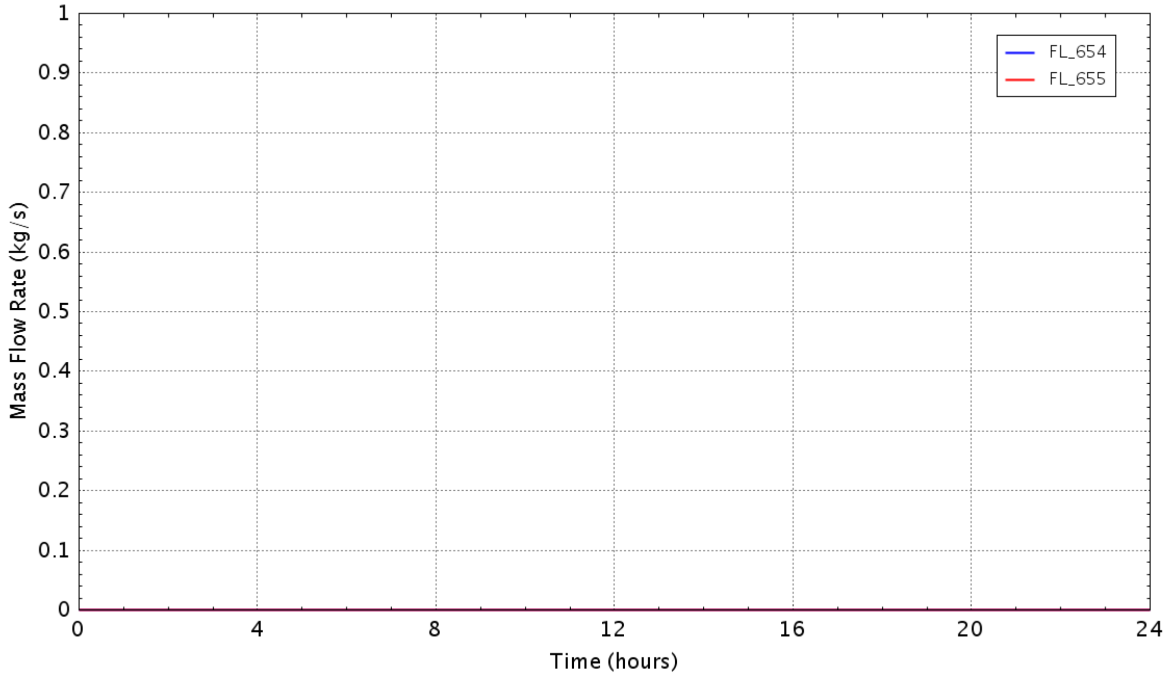

Figure C - 579 Flow rate of the wetwell cooling system

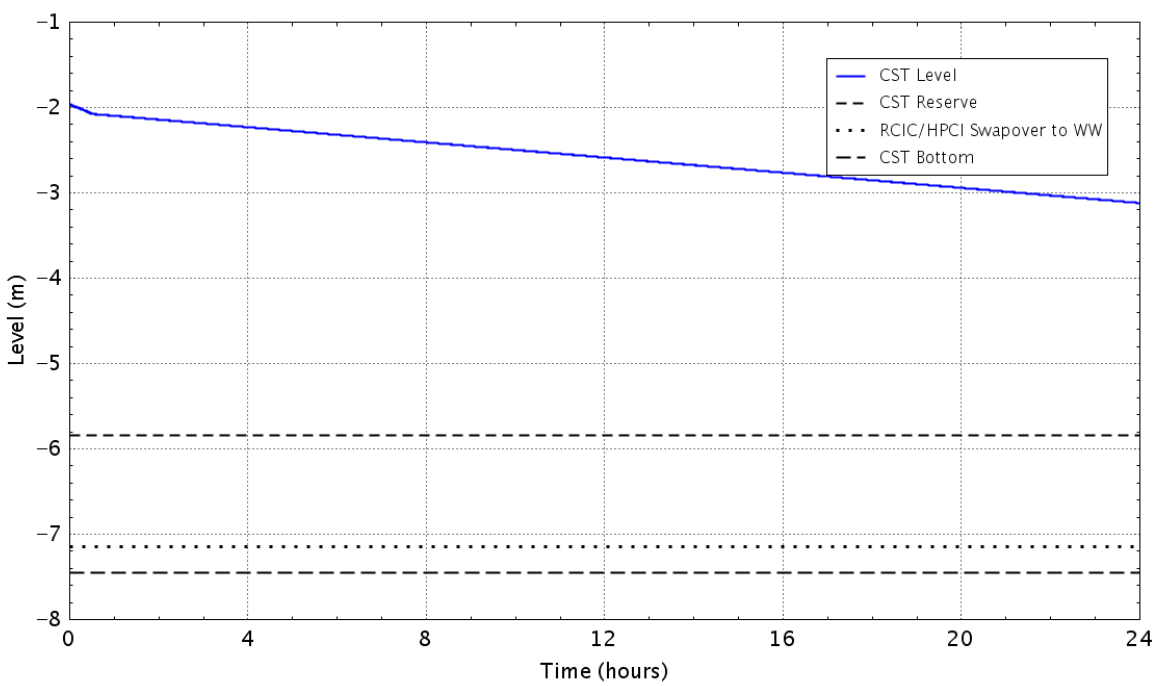

Figure C - 580 Water level in the CST

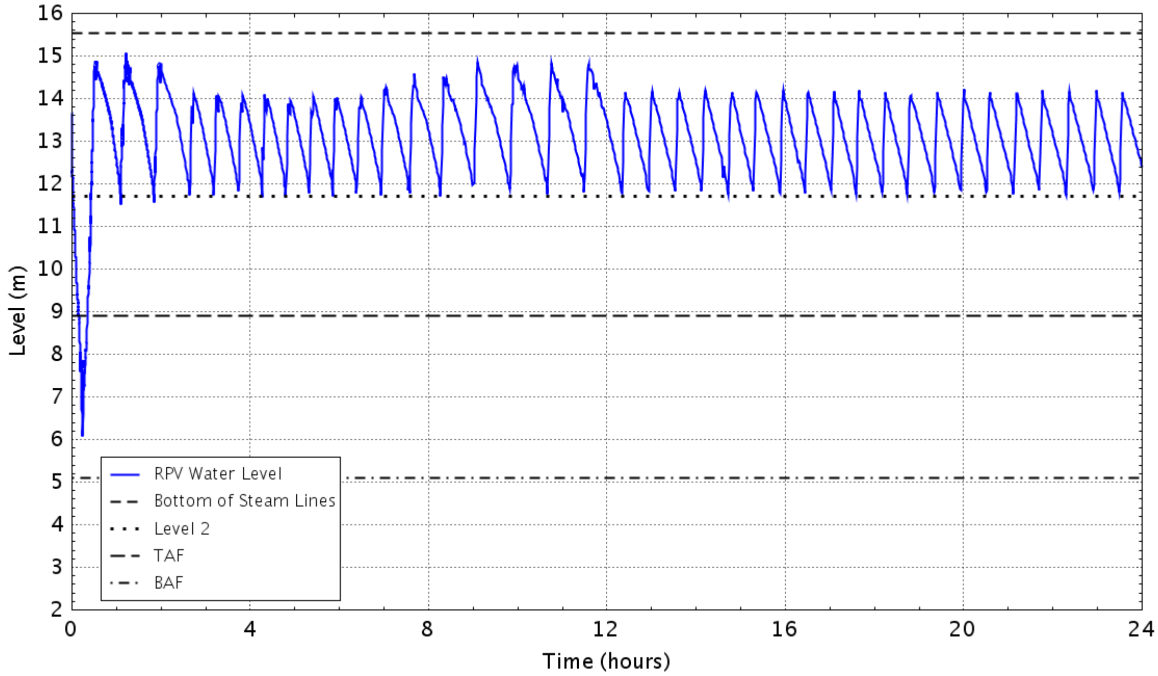

Figure C - 581 RPV Downcomer water level

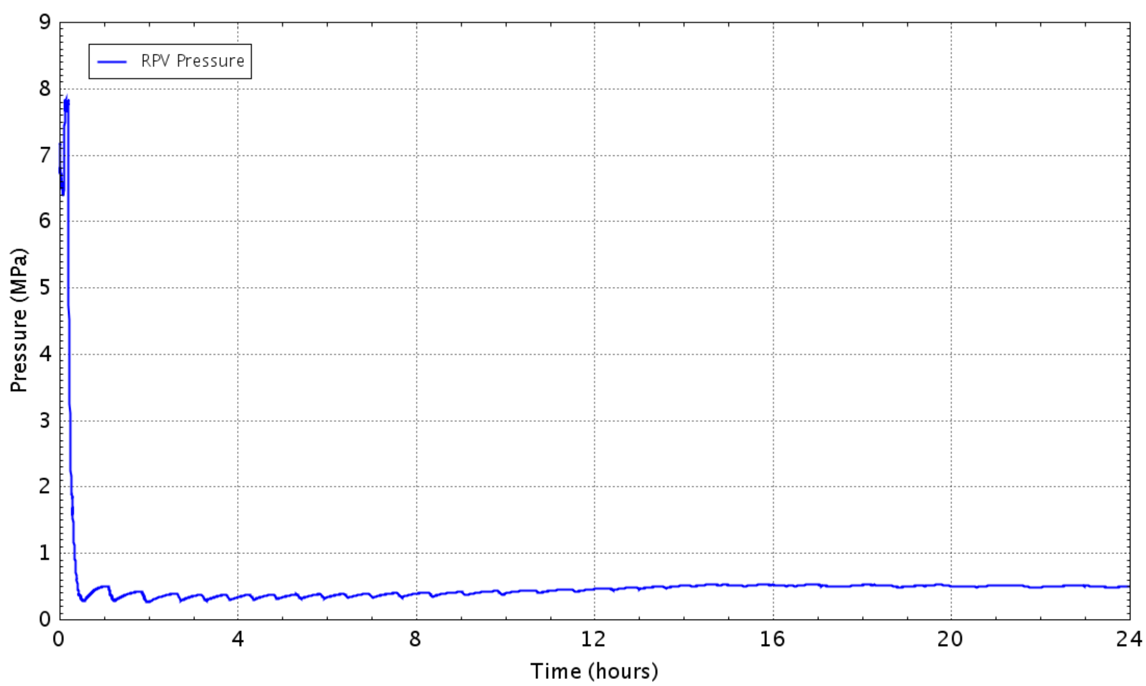

Figure C - 582 Pressure in the RPV

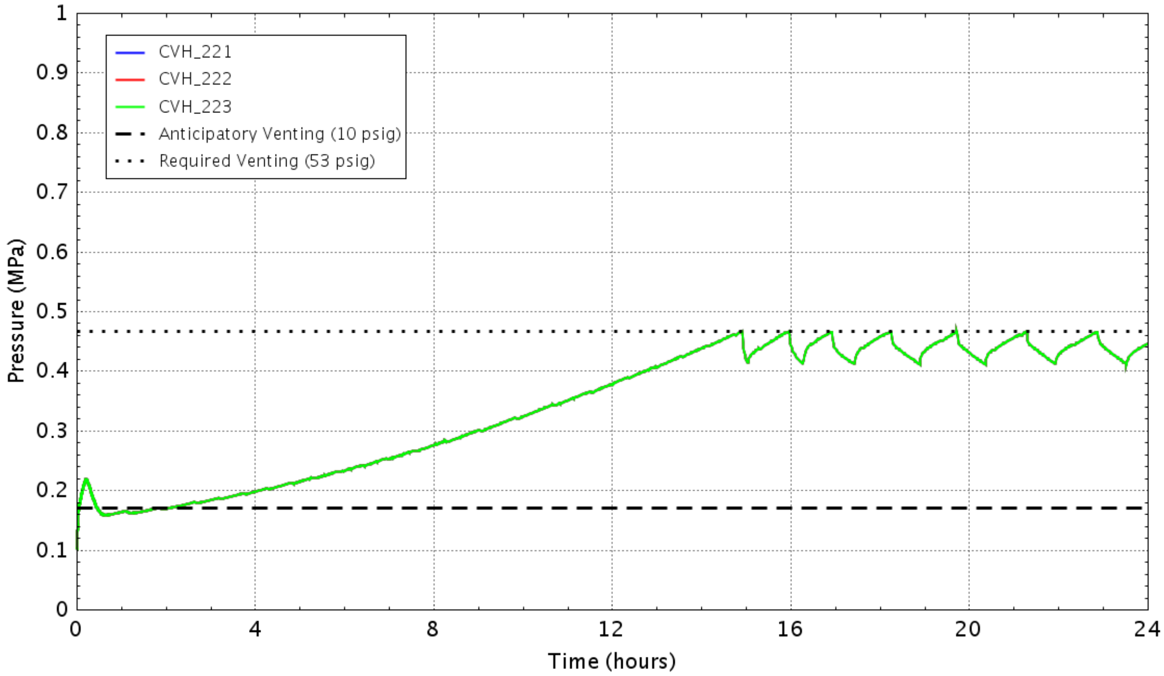

Figure C - 583 Pressure in the wetwell

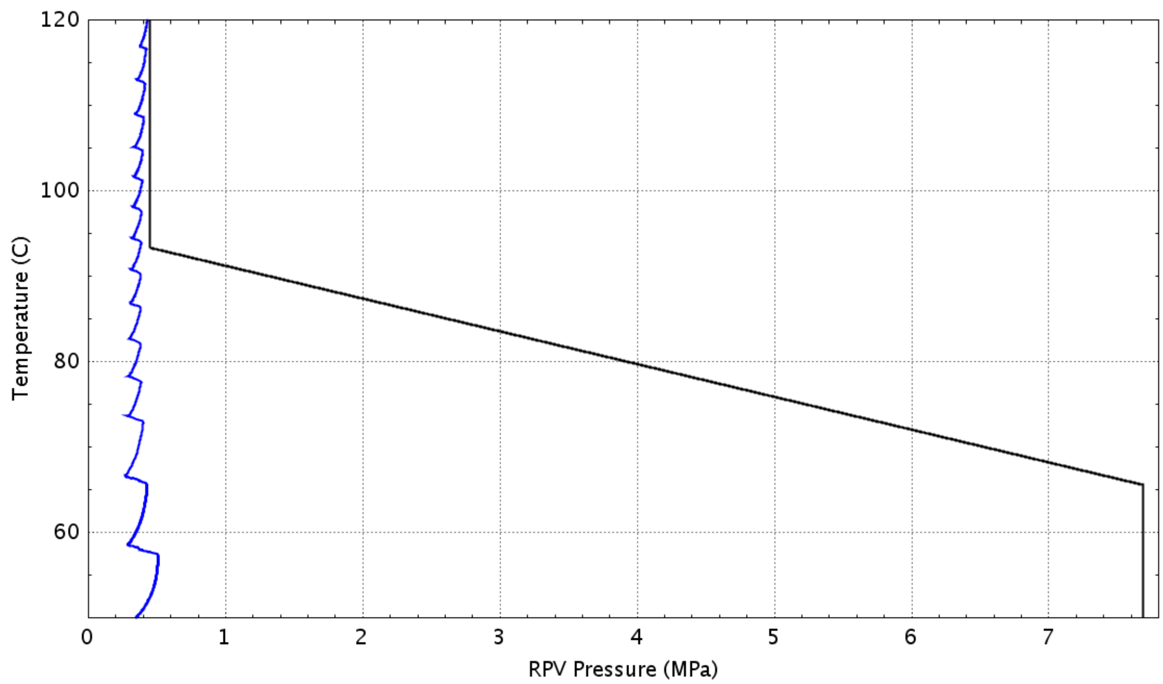

Figure C - 584 Plant status relative to the HCL curve (Graph 4 of the EOPs)

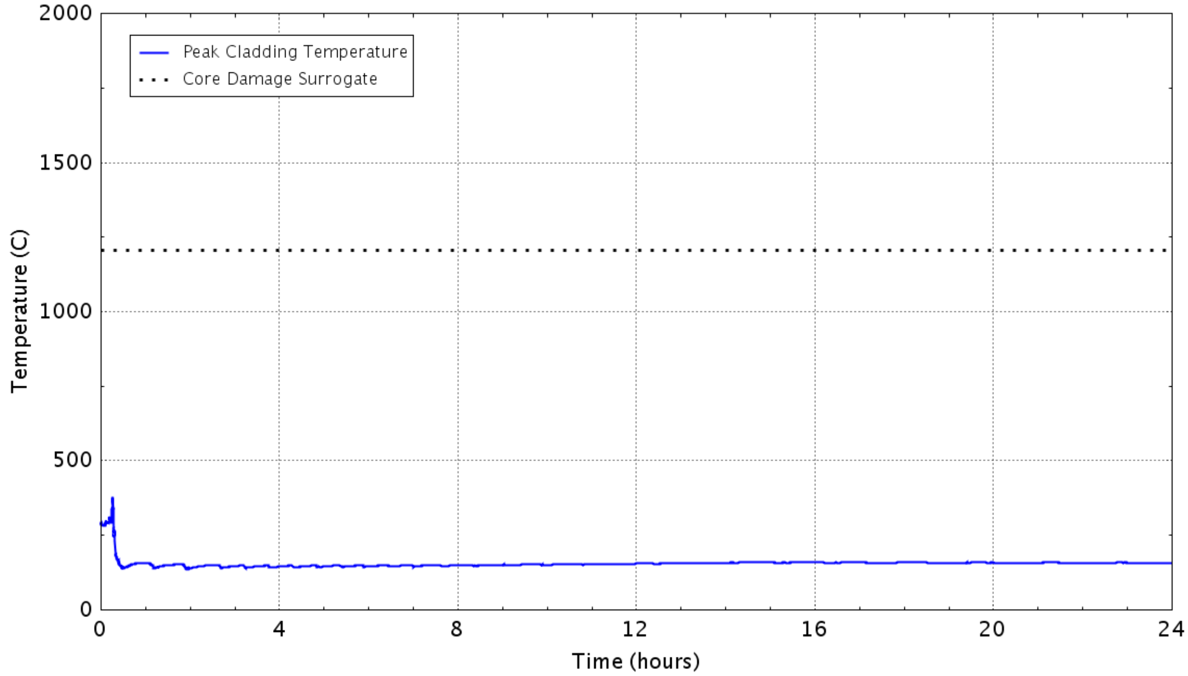

Figure C - 585 Peak temperature of the fuel cladding as a function of time

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10. SUPPLEMENTARY NOTES

S. Dennis

11. ABSTRACT (200 words or less)

This report extends the work documented in NUREG-2187, "Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Byron Unit 1," issued January 2016, to the Duane Arnold Energy Center. Its purpose is to produce an additional set of best estimate thermal-hydraulic calculations that can be used to confirm or enhance specific success criteria for system performance and operator timing found in the agency's probabilistic risk assessment tools. Along with enhancing the technical basis for the agency's independent standardized plant analysis risk (SPAR) models, these calculations are expected to be a useful reference to model end users for specific regulatoryapplications.

This report first describes major assumptions used in this study. It then describes the major plant characteristics for the Duane Arnold Energy Center, in addition to the MELCOR model used to represent the plant. Finally, the report presents the results of MELCOR calculations for selected initiators and compares these results to SPAR success criteria, the licensee's success criteria, or other generic studies.

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