Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 2001

# Aggressive Cooldown Analyses for Small Break LOCA with a Failure of SIS

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## Abstract

Thermal hydraulic analyses were performed to support the development of risk-informed design methodology using best estimate computer model, input data and assumptions. In the case of small break LOCA with a failure of the safety injection system, aggressive secondary cooldown (ASC) analyses were performed to demonstrate that ASC could be accomplished with advanced conceptual designs. In addition, the rapid depressurization analyses using the safety depressurization system were performed to depressurize the primary pressure below shutdown cooling pump shut-off head.

The RELAP5/MOD3 code was used to perform the small break LOCA analyses and KNGR/System 80+ database as the basic input. It was verified that aggressive secondary cooldown could be accomplished with one SIT using 100 $^{o}$F/hr cooldown rate at 15 minutes without exceeding the safety limit. For the rapid depressurization using SDS valve, it was demonstrated that the rapid depressurization could be successfully accomplished with one SDS valve opening at 30 minutes without the use of SIT.

## 1. Introduction

One of the objectives of the risk-informed assessment (RIA) project as identified in Ref. 1 is to develop a risk-informed design process, which integrates three key elements; the design and analysis process, the risk-informed regulatory process, and the risk assessment process. The efficacy of the RIA design method was in part demonstrated by identifying “risk-informed” design changes for the System 80+ Standard Design and evaluating the impact of these changes by using the PSA models for the design changes. Advanced conceptual systems, which consist of an advanced Emergency Core Cooling System (ECCS) and advanced secondary heat removal system, were defined and the risk-informed design process was exercised to identify and evaluate potential risk-informed design methods. The detailed functions, configurations, operations of advanced conceptual systems are described in Ref. 2.

In the existing regulatory framework, the capabilities of mitigation systems should be demonstrated deterministically with conservative assumptions and margins prescribed in the model. Because of their arbitrary and intentional inaccuracies, these conservative estimates prevent designers from quantifying the actual safety margin or safety capability. In the RIA design method, best estimate analyses are used as a means to estimate the capability of plant systems that are used to mitigate the consequences of given initiating events. In addition, the use of best estimate assumptions in the analyses is expected to enable appropriate decision making by designers and analysts using PSA success criteria for achieving a desired low level of core damage frequency. The best estimate analysis for the RIA methodology development mainly focused on the quantification of the success criteria defined in the PSA models for selected design changes. That is, the success criteria are determined based on the thermal hydraulic analysis results.

In this paper, small break LOCA analyses with a failure of SIS system were performed to establish the timing for aggressive cooldown and depressurization using secondary side cooling for the advanced conceptual system. In addition, the rapid depressurization analyses using the safety depressurization system were performed to depressurize the primary pressure below shutdown cooling pump shut-off head.

## 2. Best Estimate LOCA Analysis

### 2.1 Nodalization

The nodalization of the advanced conceptual system contains sufficient detail to allow the RELAP5/MOD3 input model to be applied to broad range of LOCAs. The nodalization of the reactor vessel and external coolant loops containing the steam generator is presented in Figure 1. Coolant from the four cold legs enters the vessel annulus while the hot leg fluid exits the upper plenum into the two hot legs. The four direct vessel injection (DVI) lines are attached to the reactor vessel at four locations just above the elevation of the four cold leg connections. The DVI lines carry emergency core cooling (ECC) injection flow from the two SITs and two HPSI pumps into the upper annulus of the reactor vessel. The shutdown cooling pumps can also inject the coolant from IRWST into the RCS through the DVI lines by manual operation during an event. The primary coolant loops contain two steam generators, two hot legs, four cold legs, four reactor coolant pumps (RCPs), and pressurizer. For each steam generator, the main feedwater system consists of two main feedwater injection lines that inject directly into the secondary side (economizer section). A third injection line provides main feedwater into the upper shell side of the steam generator (downcomer section) with a capacity of 10% of the total feedwater flow. Auxiliary feedwater (or emergency feedwater) enters the secondary side through the downcomer section.

The RELAP5/MOD3 (Ref. 4) input deck for the advanced conceptual system was obtained by modifying the System 80+ input deck (Ref. 5). For the small break LOCA analysis with a single failure in the SIS, the reactor core is modeled as pipe components having two parallel flow channels, a hot channel for one hot assembly with peak power and an average channel for the other fuel assemblies. Each core channel has 20 volumes with equal axial length for the active core region. Since core uncovery is expected in the LOCA analysis of the advanced conceptual system, 20 volumes provide the best simulation capability for accurately replicating the power distribution for highly skewed axial shapes. Cross flow junctions are modeled to connect the two core channels. The heat release from the fuel rod to the fluid in these channels is calculated by modeling an average rod and a hot rod. A hot rod represents the highest power rod in the core, which is used to determine the peak cladding temperature (PCT). In addition, System 80+ basic input models were updated to reflect improvements of the advanced conceptual ECCS and secondary heat removal systems.

### 2.2 Assumptions and Initial Conditions

Basic assumptions and initial conditions pertinent to the analyses are listed in Table 1. In the licensing evaluation model which conforms to the requirements in 10CFR50.46 and Appendix K, the core decay heat generation rate is based on the 1973 ANS standard plus an additional 20%. In the current analyses, which use best estimate assumptions and input data, the core decay heat generation rate is based on the 1973 ANS model without any additional uncertainty. For the hot rod used for determining the PCT, the peak power and its location are the important parameters. In this analysis, top-skewed axial shape is used for conservatism. In this analysis, 100% of nominal RCS flow, nominal reactor coolant temperatures, nominal pressurizer pressure, nominal steam generator water level and pressure are assumed. In addition, nominal volume, pressure, and temperature of SIT are chosen as input for realistic calculations at nominal conditions.

## 3. LOCA Analysis Results

Small break LOCA analyses with a failure of SIS system were performed to establish the timing for aggressive cooldown and depressurization using secondary side cooling for the advanced conceptual system. In addition, the rapid depressurization analyses using the safety depressurization system were performed to depressurize the primary pressure below shutdown cooling pump shut-off head. In these analyses, a 0.03 $ft^2$ break size was assumed. The small LOCA analyses (with 0.03 $ft^2$ hot leg and cold leg breaks) (Refs. 2 and 3) were performed to set a break-point between small LOCA and medium LOCA by demonstrating that this break is large enough to remove energy. Keeping the core covered with fluid limits the likelihood of fuel damage during a small LOCA because the associated heat transfer coefficients are sufficient to remove stored and decay heat without the occurrence of excessive cladding temperatures. In Ref.2, it was verified that no core melt occurred by showing core coverage during 2 hours using 1 HPSI with 4 DVI injection point and no secondary heat removal.

### 3.1 Aggressive Secondary Cooldown Analysis

For the small break LOCA with a failure of the HPSI, the SCS can be used to provide injection for the RCS inventory control if the primary system can be depressurized below the SCS pump shut-off head before core damage begins. Depressurization of the primary system is achieved by aggressively cooling the primary system using the secondary heat removal system. Analyses for System 80+ (Ref. 3) have shown that if the aggressive cooldown using the secondary system is initiated within 10 minutes of small LOCA, the SCS can successfully provide RCS inventory control.

At 15 minutes, an aggressive cooldown was initiated with 100 $^{o}$F per hour (or 75 $^{o}$F per hour) by opening an ADV on each steam generator and delivering the emergency feedwater to both steam generators. SIT injection from the one SIT was credited when the RCS pressure dropped below 615.7 psia. To establish SCS injection following a successful aggressive cooldown, the SCS pumps must be manually aligned to the IRWST, the suction and discharge valves must be opened and the pump must be manually started. It was assumed that the SCS pumps could begin to inject when the RCS pressure reached 285.1 psia.

Table 2 shows the summary of aggressive secondary cooldown analysis results. Figures 2 through 13 present the results of the aggressive secondary cooldown for the 0.03 $ft^2$ break in the RCS discharge leg with the 100 $^oF$/hr. cooldown rate and one SIT. As the RCS continues to depressurize, low pressurizer pressure signal of 1825 psia is reached at about 50 seconds, tripping the plant and causing the core power to quickly decrease to the decay heat region for the duration of the event as shown in Figures 2 and 3. It is assumed that two RCPs are tripped at reactor trip with the remaining two RCPs assumed to be tripped at 15 minutes according to the emergency operating procedure. As shown in the Figures 3 and 11, the RCS pressure reaches 285.1 psia at about 6520 seconds. At this point, SCS injection can begin and inventory control is restored. Collapsed water level in the core and downcomer are shown in Figure 4. Figure 7 shows the void distributions in the core.

Figures 8, 9 and 13 show that the decrease of total RCS liquid mass was stopped by SIT injection at about 3795 seconds and this total RCS liquid mass was increased by shutdown cooling injection at about 6500 seconds. Figure 10 shows that the maximum cladding temperatures were maintained below the safety limit (2200 $^oF$). It was verified that an aggressive secondary cooldown with RCS injection by SCS pumps and resultant RCS inventory control could be accomplished with the 100 $^oF$/hr. cooldown rate and one SIT. With 75 $^oF$/hr. cooldown rate, an aggressive secondary cooldown and RCS inventory control could not be successfully accomplished. In the case of 75 $^oF$/hr cooldown rate, the maximum cladding temperature exceeded the PCT safety limit of 2200 $^oF$.

### 3.2 Rapid Depressurization Analysis Using SDS

The SDS was designed to provide a manual means of rapidly depressurizing the reactor coolant system for the highly unlikely event of a total loss of feedwater (Ref. 6). One of the SDS functions is to provide a manual means of quickly depressurizing the RCS when normal and emergency feedwater are unavailable for an extended time and to remove core decay heat through the steam generator. This function is achieved via remote manual operator control. The SDS consists of two separate 6-inch piping pathways that discharge to the IRWST. Each pathway is attached to a 6-inch nozzle on the pressurizer and has two motor-operated valves in series (one gate valve and one globe valve). There is a rupture disk at the end of each SDS line to prevent valve leakage into the IRWST during normal reactor operation.

Additional analysis was performed by crediting the SDS for depressurization of the RCS to permit the use of the SCS pumps for injection. SDS was used to depressurize the RCS instead of the secondary system in this case. The SDS valves were assumed to have a 30 second opening dead time and a 30 second stroke time for the isolation valve. In this analysis, the rapid depressurization analyses using the SDS were performed to demonstrate that depressurization of the primary pressure below shutdown cooling pump shut-off head can be achieved, thereby allowing safety injection by the SCS pumps

At 30 minutes, a rapid depressurization was initiated by opening one SDS (or two SDS) valve without secondary cooling. SIT injection was not credited when the RCS pressure dropped below 615.7 psia. It was assumed that the SCS pumps could begin to inject when the RCS pressure reached 285.1 psia. Table 3 shows the summary of rapid depressuriation analysis results. Figures 14 through 24 present the results of the 0.03 $ft^2$ break in the RCS discharge leg with one SDS valve opening at 30 minutes without SITs. As the RCS continues to depressurize, a low pressurizer pressure signal at 1825 psia is generated at about 50 seconds, tripping the plant and causing the core power to quickly decrease to the decay heat region as shown in the Figures 14 and 15. It is assumed that two RCPs are tripped at reactor trip with the remaining two RCPs assumed to be tripped at 30 minutes. RCS pressure rapidly falls following the opening of one SDS valve at 30 minutes as shown in Figure 15. RCS pressure then rises when the bleed valve discharge changes from pure steam to low quality two phase as shown in Figures 15 and 23. Collapsed water level in the core and downcomer are shown in Figure 16. Figure 19 shows the void distributions in the core. RCS pressure reaches 285.1 psia at about 2310 seconds. SCS injection can begin at this point and inventory control is restored as shown in Figures 20 and 23. Figure 21 shows that the maximum peak cladding temperature (1265 $^{o}$F) was maintained below the safety limit.

## 4. Conclusions

For small break LOCAs with a failure of the HPSI, the SCS can be used to provide safety injection for inventory control if the primary system can be depressurized below the SCS pump shutoff head before the core damage begins. It was verified that aggressive secondary cooldown at 15 minutes could be accomplished with one SIT using 100 $^{o}$F/hr. cooldown rate without exceeding the safety limit. For the rapid depressurization scheme using the SDS valve, it was demonstrated that rapid depressurization could be successfully accomplished with only one SDS valve opening at 30 minutes and without the use of the SIT.

## 5. References

1. Westinghouse, “NERI Risk-Informed Assessment of Regulatory and Design Requirements for Future Power Plants,” RISK-G-007-2000, August 2000.
2. S. G. Chi, et. al., “Development of Risk-Informed Design Methodology, ” Proc. KNS Autumn Mtg., 2001.
3. CESSAR Design Certification, Amendment M, “Small Break LOCA,” Section 19.4.3.1.3, March, 1993.
4. NUREG/CR-5535, “RELAP5/MOD3 Code Manual (Draft),” June 1990.
5. L.W. Ward, “System 80+ RELAP5/MOD3 Input Deck,” INEL-94/0247, December 1994.
6. S. J. Park, “Total Loss of Feedwater Event Analysis for UCN 3&4,” KAERI/TR-673/96, 1996.

Table 1. General System Parameters and Initial Conditions for LOCA Analysis

| Quantity | Values |
|---|---|
| Core Power Level | 3992 MWt (102% of Nominal) |
| Average Linear Heat Generation Rate | 5.6 kw/ft |
| Peak Linear Heat Generation Rate (PLHGR) | 15.0 kw/ft |
| Gap Conductance at PLHGR | 2123 Btu/hr-ft$^2$-$^o$F |
| Fuel Centerline Temperature at PLHGR | 3638 $^o$F |
| Fuel Average Temperature at PLHGR | 2239 $^o$F |
| Hot Rod Gas Pressure | 1061 psia |
| Moderator Temperature Coefficient | 0.0 x10$^{-4}$ Delta k/k-$^o$F |
| Initial RCS Flow Rate | 165.8x10$^6$ lbm/hr |
| Initial Core Flow Rate | 160.8x10$^6$ lbm/hr |
| Initial RCS Pressure | 2250 psia |
| Initial Reactor Vessel Inlet Temperature | 555.8 $^o$F |
| Initial Reactor Vessel Outlet Temperature | 615 $^o$F |
| Low Pressurizer Pressure Reactor Trip Setpoint | 1825 psia |
| SIAS Setpoint on Low Pressurizer Pressure | 1825 psia |
| SIT Gas Pressure | 615.7 psia |

Table 2. Analysis Results of Aggressive Secondary Cooldown

| Case | Operator Action Time (Min.) | Cooldown Rate ($^o$F/Hr.) | No. of SIT | Criteria Met? (Yes/No) |
|---|---|---|---|---|
| 1 | 15 | 75 | 0 | No |
| 2 | 15 | 100 | 0 | No |
| 3 | 15 | 75 | 1 | No |
| 4 | 15 | 100 | 1 | Yes |
| 5 | 15 | 75 | 2 | No |
| 6 | 15 | 100 | 2 | Yes |

Assumptions : 1) Small LOCA with Cold Leg Break, 2) No HPSI, 3) 1 AFW/SG and 1 ADV/SG
4) SCS Injection at 285.1 psia

Note : Peak Cladding Temperature < 2200 $^o$F is used as the criteria.

Table 3. Analysis Results of Rapid Depressurization Using SDS

| Case | No. of SDS | No. of SIT | Criteria Met? (Yes/No) |
|---|---|---|---|
| 1 | 1 | 0 | Yes |
| 2 | 1 | 1 | Yes |
| 3 | 1 | 2 | Yes |
| 4 | 2 | 0 | Yes |
| 5 | 2 | 1 | Yes |
| 6 | 2 | 2 | Yes |

Assumptions : 1) Small LOCA with Cold Leg Break, 2) No HPSI, 3) Operator Action Time : 15 Miniutes
4) SCS Injection at 285.1 psia, 5) Credit of SDS

Note : Peak Cladding Temperature < 2200 $^{o}$F is used as the criteria.

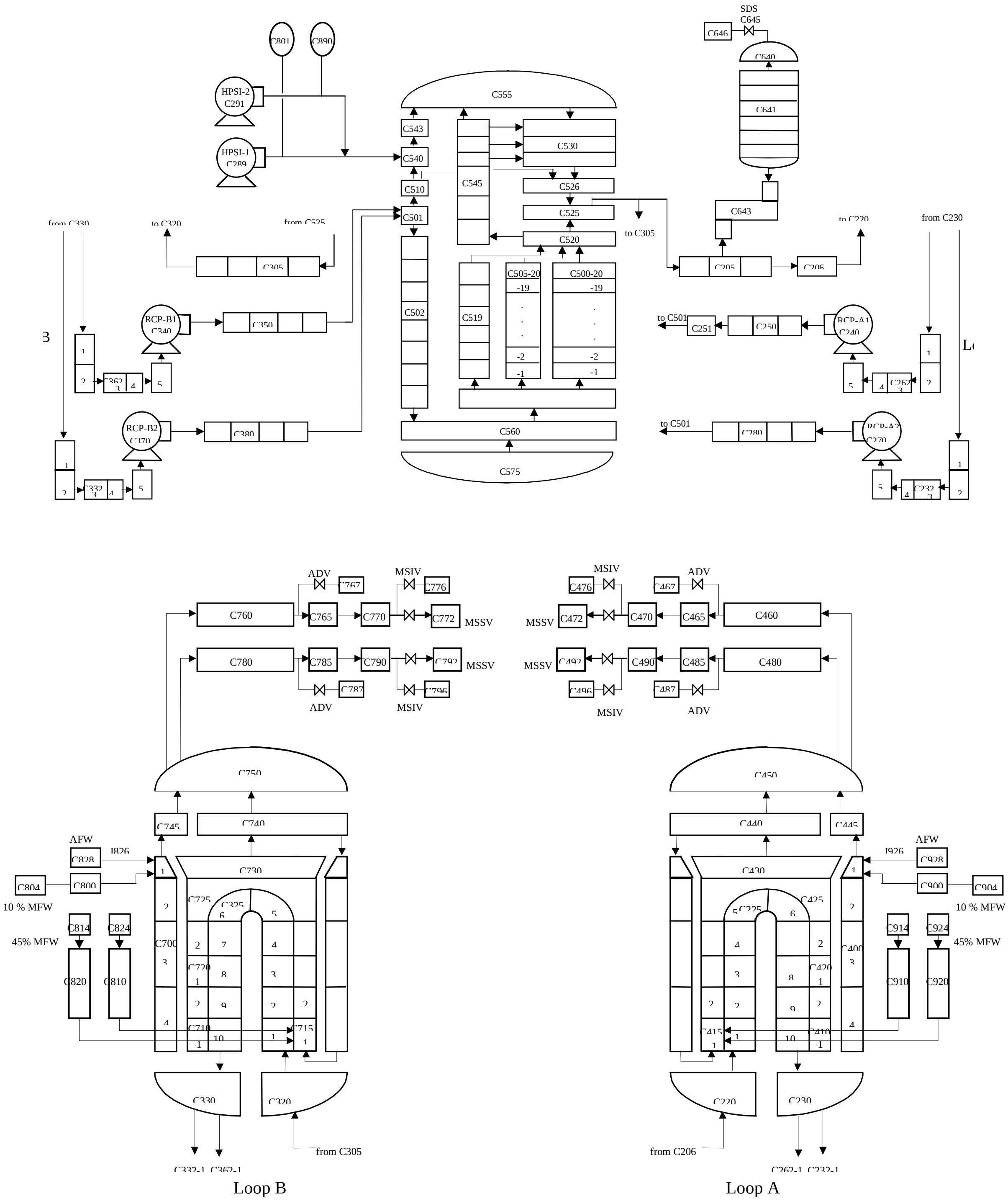


Figure 1 Nodalization of Advanced Conceptual Design for LOCA Analysis

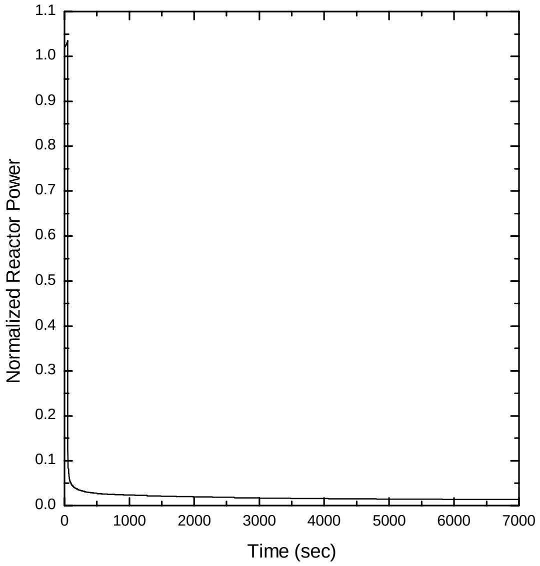


Figure 2 Normalized Reactor Power (ASC)

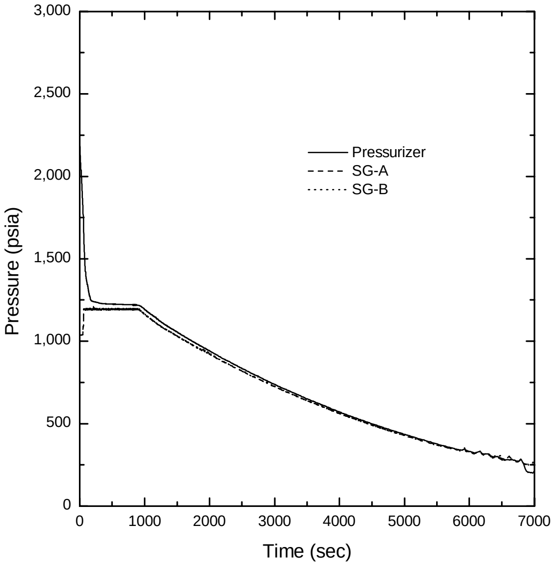


Figure 3 Pressurizer and Steam Generator Pressures (ASC)

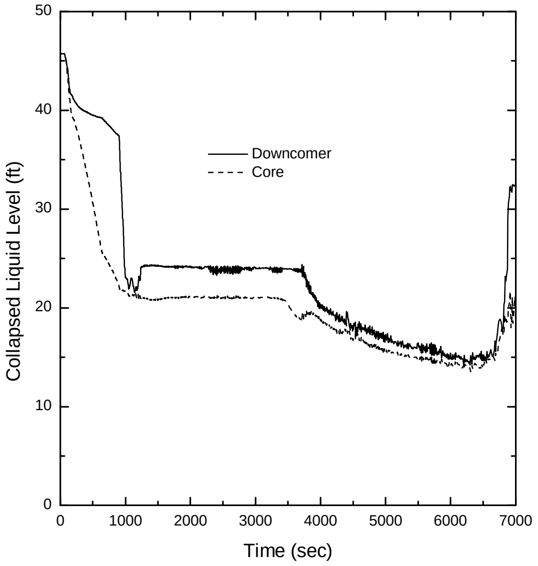


Figure 4 Core and Downcomer Collapsed Liquid Levels (ASC)

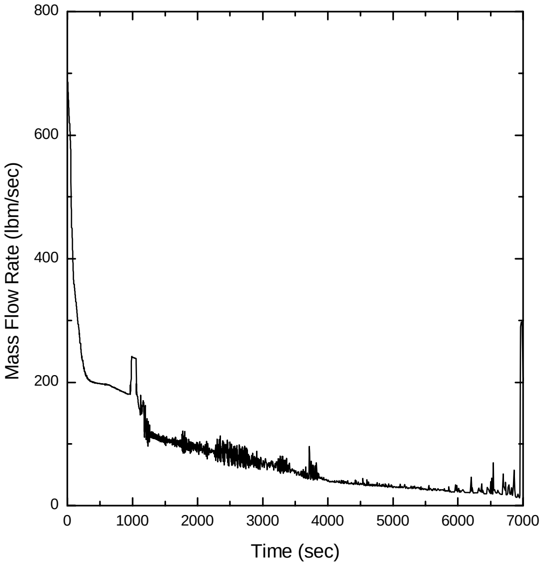


Figure 5 Break Mass Flow Rate (ASC)

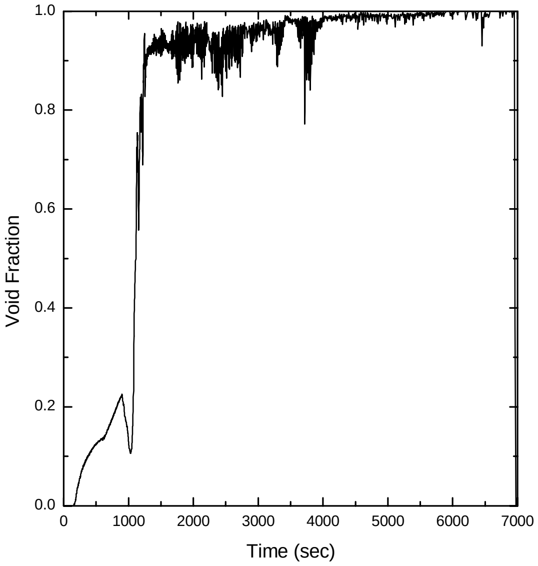


Figure 6    Break Path Void Fraction (ASC)

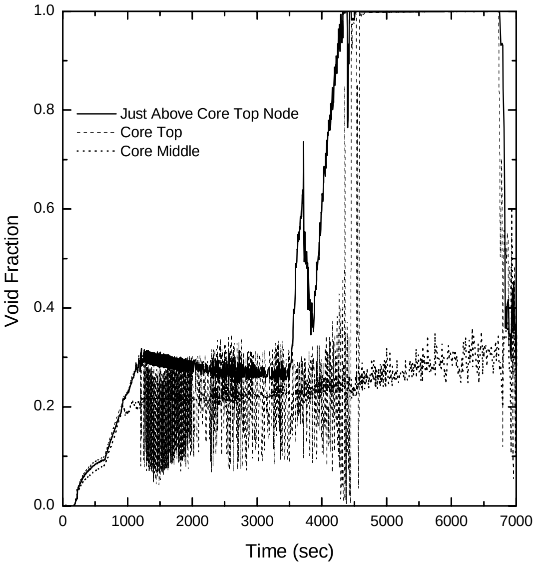


Figure 7 Void Distribution at Core (ASC)

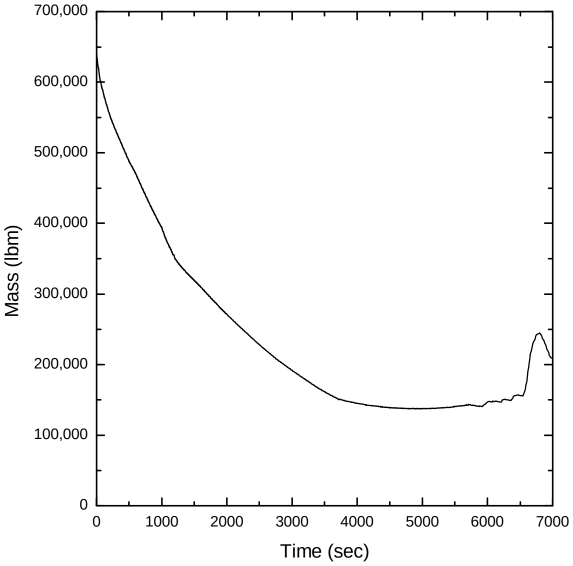


Figure 8    Total RCS Liquid Mass (ASC)

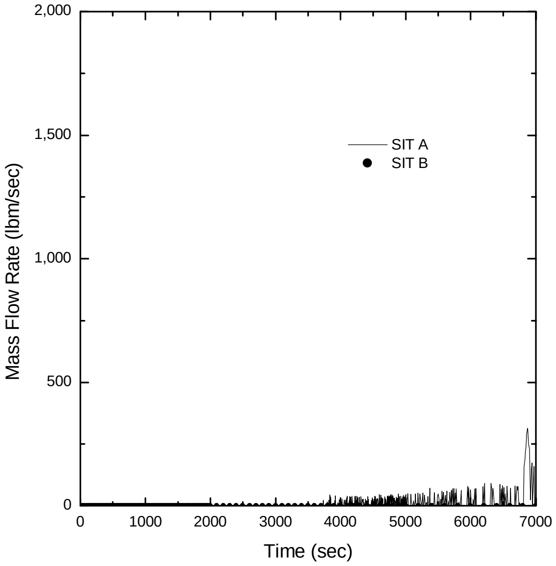


Figure 9    SIT Mass Flow Rate (ASC)

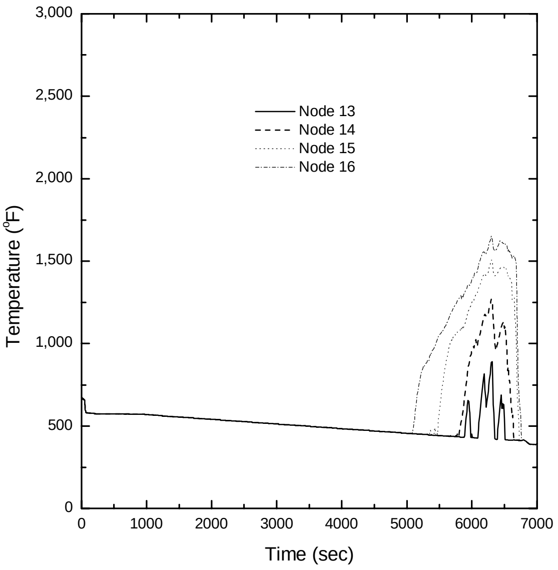


Figure 10　Hot Rod Cladding Temperature (ASC)

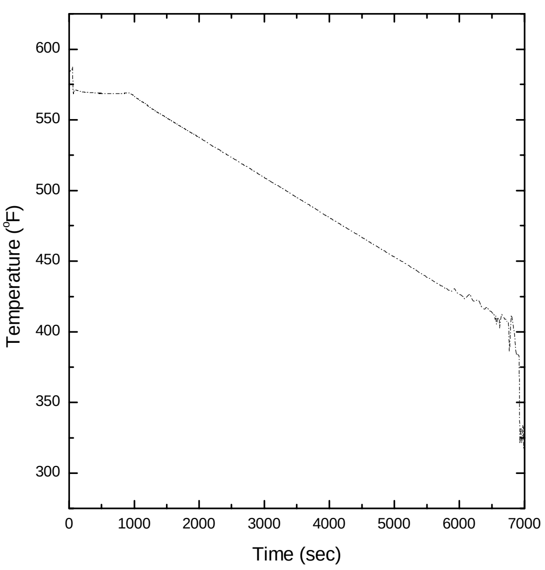


Figure 11　Average RCS temperature (ASC)

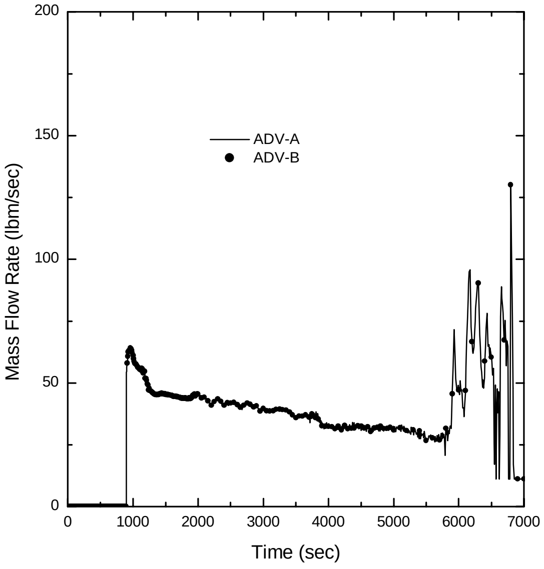


Figure 12　ADV Mass Flowrate (ASC)

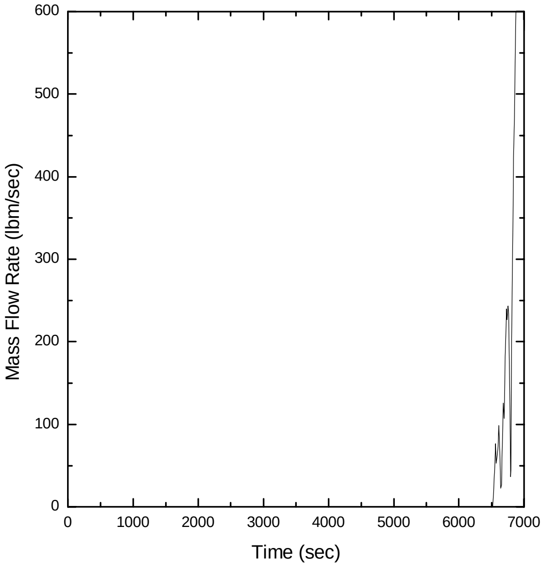


Figure 13　Mass Flowrate of Shutdown Cooling Injection (ASC)

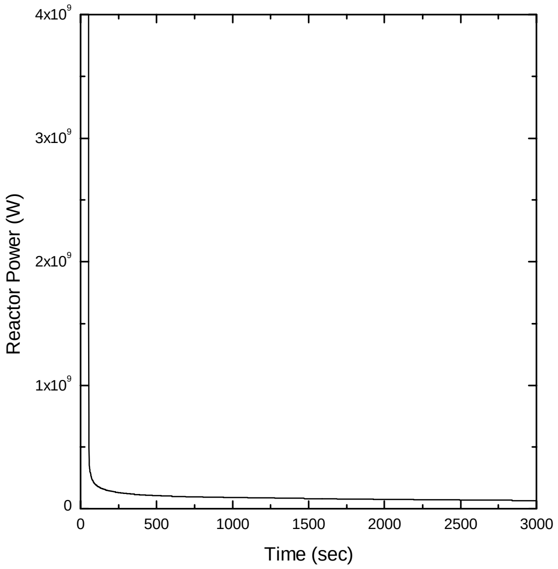


Figure 14 Normalized Reactor Power (SDS)

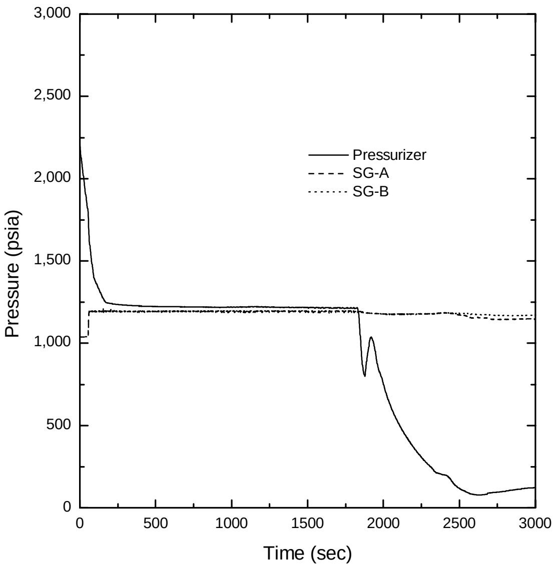


Figure 15 Pressurizer and Steam Generator Pressures (SDS)

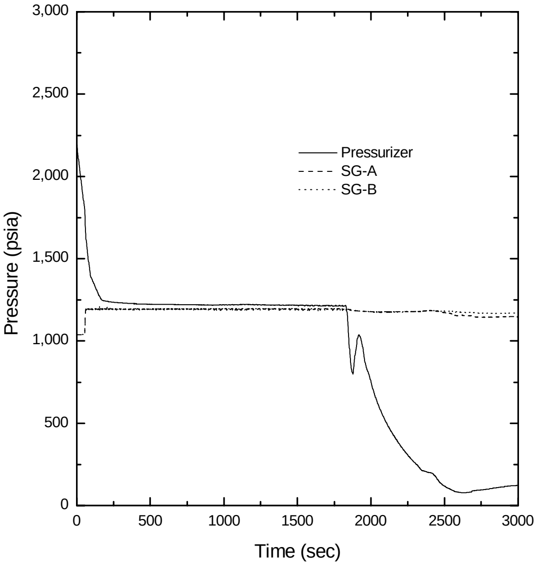


Figure 16 Core and Downcomer Collapsed Liquid Level (SDS)

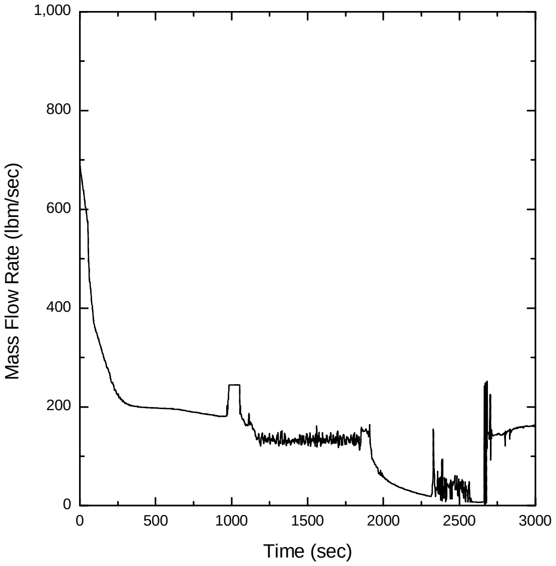


Figure 17 Break Mass Flow Rate (SDS)

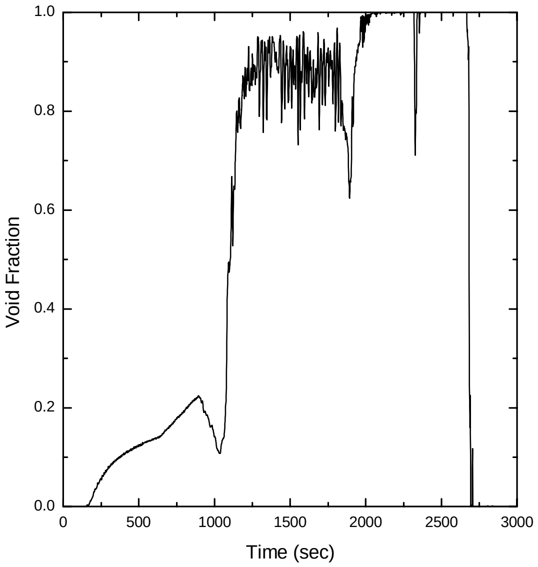


Figure 18 Break Path Void Fraction (SDS)

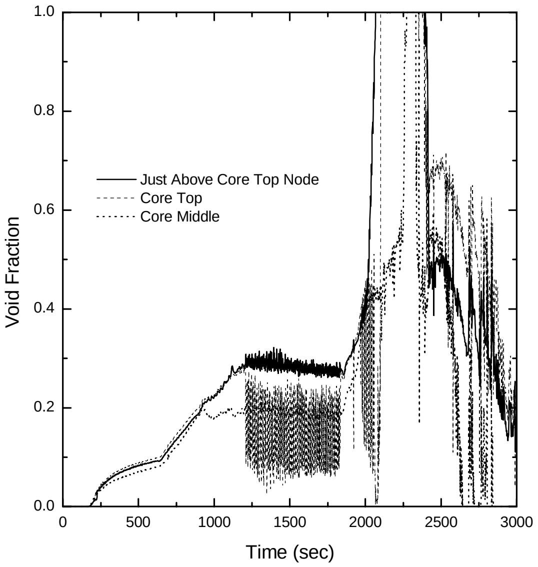


Figure 19 Void Distribution at Core (SDS)

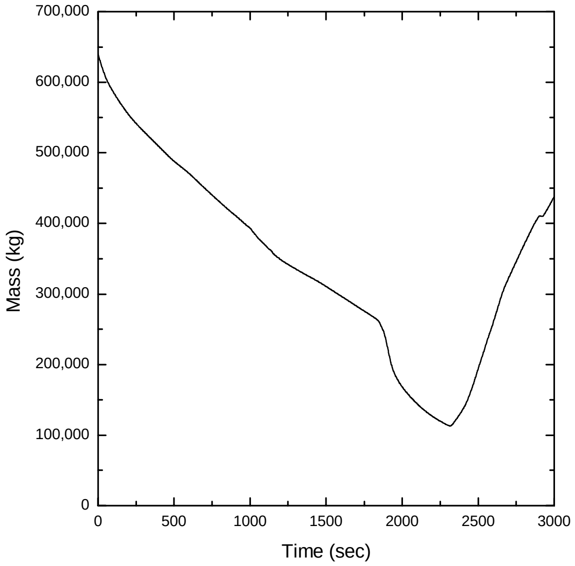


Figure 20 Total RCS Liquid Mass (SDS)

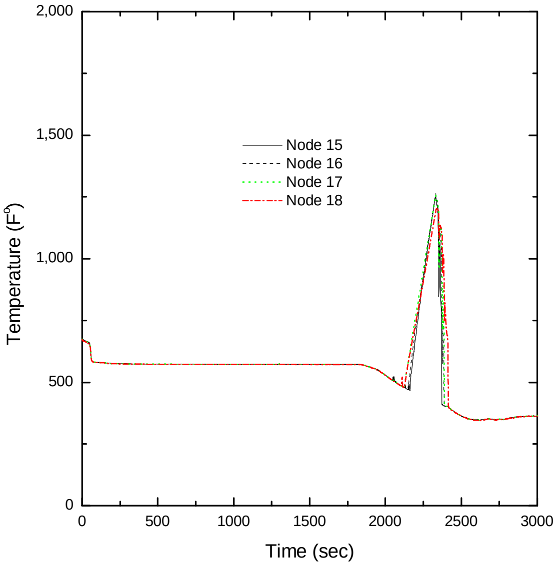
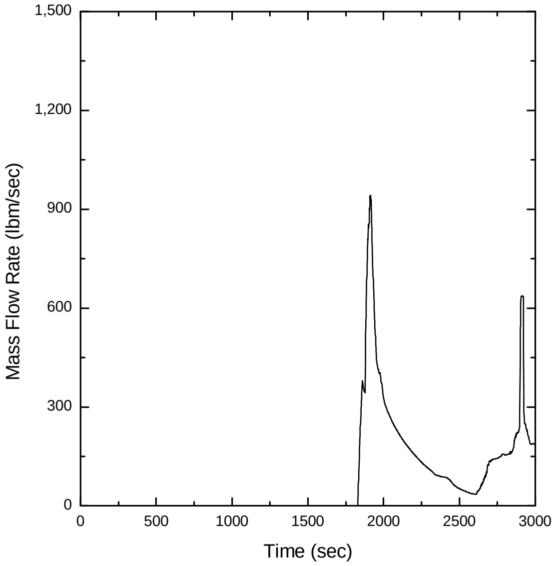


Figure 21 Hot Rod Cladding Temperatures (SDS)



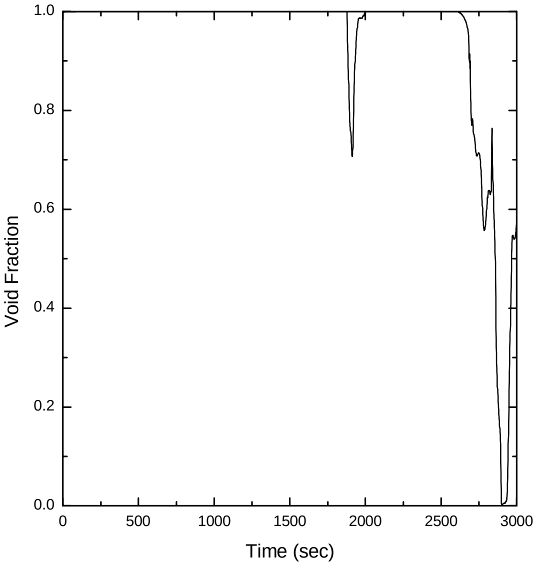


Figure 22　Mass Flowrate of SDS (SDS)

Figure 23　Void Fraction of SDS Flow

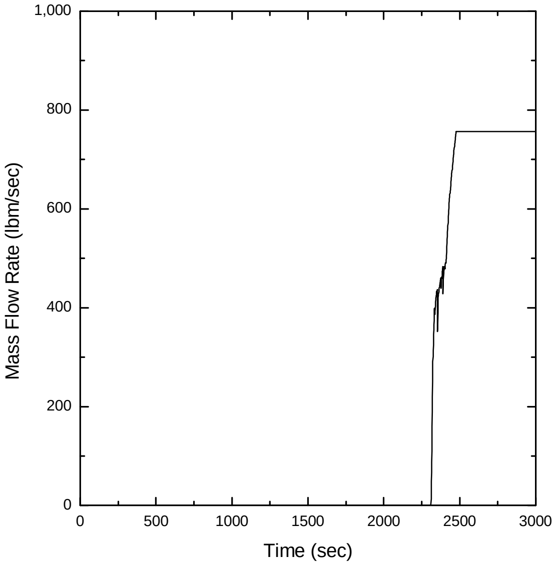


Figure 24　Mass Flow of Shutdown Cooling Injection (SDS)