A BORON TRANSPORT SIMULATION USING RETRAN-03 CONTROL SYSTEM MODELS FOR ANTICIPATED TRANSIENT WITHOUT SCRAM (ATWS) EVENT

by

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* Original work was performed for Gulf States Utilities at River Bend Station

ABSTRACT

This paper is being presented at the Specialist Meeting on Boron Dilution Reactivity Transient. The meeting is being held on October 18, 19 and 20 in State College, PA.

This paper presents the results of Anticipated Transient Without Scram (ATWS) analyses performed for River Bend Station (RBS) in 1987. RBS is a Boiling Water Reactor/6 (BWR/6) with 624 fuel assemblies and an inside reactor vessel diameter of approximately 218 inches. During postulated ATWS events, important operator actions and system design considerations, among other things, include: (1) stand pipe lower plenum injection effectiveness, (2) water level control, (3) enrichment of Boron-10, (4) ability to maintain adequate suppression pool temperature within the limits based on heat capacity considerations, and (5) ability to maintain and achieve the cold shutdown conditions. This work considers the first four items for RBS ATWS analysis by incorporating a new boron transport model in the RBS RETRAN model that represents a more realistic analysis based on local mass balance of the boron between each volume and its adjacent neighboring volumes.

The boron transport model assumes that the boron flow at each junction is proportional to the junction liquid flow and the associated boron concentration from which the junction emanates. Control system models in the RETRAN program were used as building blocks for the boron transport model. RETRAN03-PRE34 version with a hardwired modification performed by Energy Incorporated (EI) to treat boron absorption was used for this work. This approach builds upon the work by C. G. Metloch et al, "A Methodology for the Calculation of Boron Concentration in Boiling Water Reactors," presented at the Third International RETRAN Meeting[5]. This study extends Metloch's work to a complete plant ATWS analysis including water level reduction, one-dimensional kinetics and thermal-hydraulic feedback. Many of the complications introduced by the ATWS computer simulation make this study challenging and unique. In addition, the following features were included in the new boron transport model reported in this paper:

1) Implicit Solution Scheme
2) Boron Mass Balance Tracking
3) Flow Reversal Situation

The overall results based on the new boron transport model indicate that with 65% enrichment of B-10, and water level controlled at TAF+5ft and TAF+10ft, the suppression pool temperature can be maintained within heat capacity temperature limit of the suppression pool.

The use of 65% B-10 enrichment provided significant cost savings compared with using 90% enrichment. Initial ATWS analyses indicated that a 90% enrichment would be required to attain the specified goals. With more refinement in the boron tracking models, a significant reduction in cost was achieved. In addition, the use of 65% B-10 enrichment eliminates the need of heat tracing on the SLCS. The RBS ATWS analysis also provided confidence that maintaining water level at TAF+5ft is sufficient to shut down the reactor avoids unnecessary actions to use Automatic Depressurization System (ADS).

ACKNOWLEDGMENTS

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Section 1

PURPOSE

Emergency Procedure Guidelines (EPGs)[1] for Anticipated Transient Without Scram (ATWS) events have undergone close scrutiny within the nuclear industry to better define the expected sequence of events and recommended operator actions This work was performed at Gulf States in 1987, in part, to support plant-specific Emergency Operating Procedures (EOPs) for ATWS scenarios The primary objectives of this work are (1) to determine if the boron delivery point which is through a stand pipe in the lower plenum (i.e., the boron is in solution as sodium pentaborate) is appropriately located to shut down the reactor in the event of a worst case ATWS, (2) to evaluate the effects of different enrichments of Boron-10 on an ATWS event and decide which enrichment level meets the basic requirements of this work, (3) to determine the merits of maintaining water levels higher than the top of active fuel (TAF) presently recommended by the BWR Owner's Group EPGs, and (4) to demonstrate the ability of standby liquid control system (SLCS) to achieve hot shutdown before suppression pool temperature exceeds Technical Specifications limits. As part of this study a new boron tracking model was developed to track the mass flow of the boron throughout the reactor vessel and keep track of the boron mass.

Because of practical constraints, this work focused only on determining whether the suppression pool temperature would stop increasing when the reactor power reaches 5% or lower. The 5% of rated power is the rated heat removal capacity of residual heat removal (RHR) system in suppression pool cooling mode.

This paper summarizes the assumptions and models used and discusses the results based on various boron tracking models.

Section 2

BACKGROUND

An Anticipated Transient Without Scram (ATWS) is an expected operational transient (such as a main steam isolation valve (MSIV) closure, a loss of feedwater, loss of condenser, or loss of offsite power) which is accompanied by a failure of the reactor trip system to shut down the reactor.

As part of the final ATWS rule, a 86 gpm Boron Injection Capability or Equivalent is required. As a result of these analyses enriched Boron-10 at 65% enrichment in nominal 9% sodium pentaborate solution is used at RBS to satisfy the 86 gpm equivalency. This design avoids the difficulty of rerouting the SLCS piping to the high pressure core spray (HPCS) lines. The enriched Boron-10 is injected into the reactor vessel lower plenum by manually initiating SLCS.

The analyzed ATWS event simulated for these evaluations is a MSIV closure from 100% power. The major tasks involved in the best-estimate analysis of several ATWS scenarios included modeling the numerous operator responses, developing the large and complex model consistent with the computer capacity, representing boron mixing in the pressure vessel, and simulating the mixing of subcooled water injected into a two-phase region.

Since these transients are numerically difficult, the prerelease version of RETRAN-03 was used to take advantage of its significantly faster computational speed than RETRAN-02.

It is noted that the work spanned more than a two-year period due to the complex and difficult decisions involved in selecting operator actions, choosing various assumptions and developing best-estimate boron tracking models.

Because the effectiveness of SLCS and the variation of water level control represent two most important aspects of mitigating ATWS scenarios, the following sections provide a basic description of the SLCS and the water level control for ATWS events.

GENERAL DESCRIPTION OF THE SLCS

The SLCS is designed to inject into the reactor a sufficient quantity of a neutron-absorbing solution (sodium pentaborate) so as to achieve reactor shutdown, independent of control rod action, under the most reactive core conditions. Some of the design parameters of the SLCS with respect to determining the amount of time required to shut down the reactor include: (1) SLCS pumping rate, (2) the neutron absorber's mixing efficiency once it is injected into the reactor vessel, and (3) weight percentage of the absorber in the SLCS solution.

The SLCS pumping rate depends on the capacity, the number of SLCS pumps used, and the piping alignment. The mixing efficiency of the boron depends on the core flow. The weight percentage of the neutron absorber (i.e. B-10) depends on the concentration of sodium pentaborate in the solution, the enrichment of the B-10, and the mass of water in the reactor pressure vessel.

The current SLCS design and specified sodium pentaborate boron enrichment was revised to comply with the ATWS rule, provide additional margin for the removal of heat tracing requirement from the RBS Technical Specifications, and provide RBS Emergency Operating Procedures (EOPs) margin for not exceeding the heat capacity temperature limit (HCTL) of the suppression pool during a worst case ATWS event.

GENERAL DISCUSSION OF WATER LEVEL REDUCTION

The core power in a BWR can be controlled by varying core flow. For example, for the worst case ATWS event, the recirculation pump trip would immediately reduce the reactor core flow and hence reduce the reactor power. Following the trip of the recirculation pumps, the reactor is in natural circulation mode. The driving head to establish natural circulation is created by the fluid density difference inside versus outside the shroud, and inside versus outside the active channels Figure 1 shows typical BWR natural circulation paths.

The two-phase fluid inside the active channel has a lower density than the water in the bypass region and outside the shroud. The natural circulation driving density head for the path including downcomer, Jet pumps and core inlet, is determined by the reactor water level, reactor power and core void fraction. Natural circulation driving head and flow in this path drop as reactor water level drops. The reduced core flow produces more voids in the core and thus further suppresses power generation. This power suppression is achieved, if needed, by manually lowering reactor water level following an ATWS.

EPGs Revision 4[1] contains a CONTINGENCY #5 for Level/Power Control In CONTINGENCY #5, lowering water level in the reactor pressure vessel to TAF is recommended if reactor power is above Average Power Range Monitoring (APRM) downscale trip setpoint (5% for River Bend) or cannot be determined. It is one of the objectives of this study to determine whether lowering water levels to higher than TAF would be sufficient to comply with heat capacity temperature limit as specified in EPGs Revision 4 and maintain adequate mixing in the lower plenum to allow boron to be circulated into the active core.

Section 3

EVALUATION

The ATWS event analyzed for this paper is a main steam isolation valve (MSIV) closure from 100% power with failure to scram. This event was determined in NED0-24222 to be the worst case ATWS. It is recognized that there are many other possible ATWS scenarios, but the worst case ATWS was used to test the various methods of controlling the ATWS event. A constraining factor in such an event is the suppression pool (SP) Heat Capacity Temperature Limit (HCTL) as prescribed by EPGs Revision 4. The SP temperature limit prescribes the temperature above which a 100% steam condensation in the SP cannot be assured during a complete blowdown of the Reactor Pressure Vessel (RPV).

Following an MSIV closure, the vessel water level decreases due to collapsing of voids. At water level 3, vessel water level setpoint setdown is initiated. When the reactor vessel pressure reaches approximately 1100 psig, recirculation pump trip occurs. Because of continuing high power, pressure of the RPV is increasing. The Safety Relief Valves (SRVs) open to allow steam into the suppression pool. The suppression pool is gradually heated up by the steam released from SRVs. The residual heat removal (RHR) system is then actuated with some time delay. In addition, the SLCS and water level control are manually initiated. The type of scenario described above was analyzed in this study by varying the following assumptions and models:

- Water level to be Controlled

  Three water levels at which the operator would maintain the reactor were analyzed Top of Active Fuel (TAF), TAF+5ft, and TAF+10ft.

- Operator Actions

  The time delays associated with the various operator actions were varied. These operator actions were injection of SLCS, reduction of water level, and initiation of RHR system suppression pool cooling mode.

- Thermal-Hydraulic Modeling

  Slight nodalization and modeling associated with injection of subcooled liquid were made to alleviate oscillation problems.

- Boron Tracking Model

  Four boron tracking models with different levels of detail and sophistication were included in the ATWS analyses using RETRAN.

REACTOR PHYSICS MODEL

The RETRAN-03 analysis of a turbine trip ATWS for the GSU River Bend plant invoked the space-time kinetics model to calculate the power responses. In the absence of a reactor scram, ultimate reactivity control is assumed to depend on Boron-10 injection into the core vessel. Thus, the cross-sections used in the analysis must also include the effects due to the presence of boron. Including such an explicit boron dependence in the cross-sections required a code modification since the standard cross-section model includes only coolant density and fuel temperature dependencies. For the River Bend ATWS analysis, the basic cross-section set was developed with no boron present and a correction to the absorption cross-section applied to account for boron when present. More information on this development is provided in Reference 3.

OPERATOR ACTIONS

When the suppression pool temperature reaches 95°F, operators were required to initiate RHR suppression pool cooling mode. When the suppression pool temperature reaches 110°F as a result of ATWS, the following actions should be considered based on EPGs:

- lower water level, and
- initiate SLCS

Since these actions are all manually initiated and all involve critical decisions on the part of operators, some delay would be associated with each of the three actions. Table 1 presents two operator action models considered in this analysis. Operator Action 1 was based on preliminary information. Operator Action 2 was based on a survey of the shift supervisors at RBS which provided best estimate response times for the operator actions.

THERMAL-HYDRAULIC MODELING

The nodalization of the RPV and related injection systems is essentially the same as that used for Reference 3. The only modifications made included the following:

- Subcooled Injection Model

  The original subcooled injection model used in Reference 3 was developed to circumvent expected oscillation problems when subcooled water is injected into a region filled with a two-phase mixture. This model was used for cases 1, 2 and 3 of the ATWS analysis but was later replaced by artificially lowering the feedwater (FW) injection point to lower elevations.

- Constant Pressure Safety Valve Model

  Previous experience with RETRAN indicated that at low vessel water levels, unrealistic power spikes and other unstable numerical behavior resulted when the SRVs were allowed to cycle open and closed. To alleviate this problem, "constant-pressure" SRVs were modeled. The constant-pressure SRV model consists of holding the steam dome pressure constant by modulating the SRV with the highest pressure setpoint while holding open the other SRV banks with lower pressure setpoints. As the system power decreased, the pressure continuously decreased below the highest pressure setpoint even with the corresponding SRV bank completely closed. When the steam dome pressure fell to the next pressure setpoint, the pressure was maintained at this point by modulating the SRV bank while holding open the remaining SRV banks with lower pressure setpoints. This process was repeated until the lowest pressure setpoint was reached and the pressure was maintained at this point by modulating the last SRV bank. Sensitivity studies were performed to provide evidence that this simplification produced valid results.

- Nodalization

  The plant model consists of a nodalization almost identical to that used in Reference 3. The only difference is the division of the lower plenum into two volumes to more realistically model the thermal-hydraulic phenomena (e.g., split fraction between bypass flow and active core flow). Figure 2 shows the RETRAN nodalization diagram for the River Bend ATWS model.

BORON TRACKING MODELS

In this section four boron tracking models used for the River Bend ATWS analyses are discussed These methods are presented in ascending order of complexity. The four boron tracking models are 1) Empirical Correlation based on mixing coefficient, 2) Mechanistic Model using time dependent DELAY and LAG control ,blocks, 3) Ad-Hoc Fix to Model 2, and 4) Mechanistic Model based on local mass balance. A summary of these models is presented in Table 2.

Empirical Correlation Based on Mixing Coefficient

An empirical correlation obtained from mixing tests performed on a 1/6-scale BWR model was used to calculate the boron concentration in the core. The mixing test results provided a mixing coefficient n, defined as the ratio between solution concentration in the core and that over the entire vessel assuming perfect mixing.

The mixing test correlation is applicable for values of f (where f is fraction of rated core flow) from 0.05 to 0.20. For f between 0.20 and 0.35 the value of n obtained for f equal to 0.20 was used as suggested in Reference 5. For values of f less than 05, Reference 6 showed that inadequate mixing in the lower plenum would not allow boron into the core.

Since actual core flow rates vary during SLCS injection, the correlation was reformulated. This was done by using the control system blocks to perform the integration of n for each time step.

The total core boron mass was obtained by multiplying the core liquid inventory and the core boron concentration. The boron mass in each of the 12 active core regions is obtained by evenly distributing the total core boron mass.

Mechanistic Model Using Time-Dependent DELAY and LAG Control Blocks

The methodology is based to a large extent on that proposed by Metloch ,et. al., [5]. This methodology utilizes control blocks to calculate the boron concentration in fluid volumes. The boron reactivity worth is calculated from the core boron concentration and is used with the RETRAN 1-D kinetics to provide shutdown reactivity. The following represent major deviations of the River Bend ATWS analysis from that reported in Reference 5:

- a full reactor system simulation of the ATWS scenario was analyzed
- 1-D kinetics was used
- 12 core regions were used
- transport of boron mass between core volumes was modeled using time dependent DELAY control blocks

Figure 3 shows a simplified boron concentration model adapted from Reference 5 for the ATWS analysis of the River Bend Station.

Ad-hoc Fix to the Mechanistic Model

The model described in the previous subsection introduced significant oscillations of boron concentration and power. To correct the inadequacy caused by the numerical oscillations, an ad-hoc fix to the model was implemented in the revised model. The ad-hoc fix consists of specifying a non-negative values as a minimum (10E-6) in the control blocks that calculate the boron mass increment at each time step. In addition, the water injection was modified to provide a less drastic change in water addition to the vessel.

A Mechanistic Model Based on Local Mass Balance

The ad-hoc fix as described in previous subsection yielded slightly biased results because of the artificial minimum values imposed on control blocks calculating the boron mass increment. The artificial imposition of minimum boron mass increment at each time step biased the oscillation in such a way that overall boron mass undergoes a step increase during power oscillations. Therefore, a boron model based on local mass balance is developed to accurately track the boron transport. The following assumptions provide the basis for the new mechanistic model.

- Instantaneous mixing of boron takes place in a volume. The boron influx from the upstream volume is mixed uniformly within a time step. This may be slightly conservative because it actually takes some time for boron to achieve uniform mixing. Boron concentration would be higher closer to the source, i.e., core volumes would see higher concentration than that assumed for uniform mixing.

- Boron flow is equal to the product of concentration and junction liquid flow. The flow of boron is treated as a slug flow, being carried with the liquid.

Based on the above considerations, the following expressions are derived for boron transport modeling:

B(i,t-delta t) - Boron Mass in Volume i, at time t-delta t
B(i,t) - Boron Mass in Volume i, at time t
B(i-1,t) - Boron Mass in Volume i-1, i.e., upstream volume, at time t
J(i+1,t) - Junction Liquid Flow for Junction i+1, at time t
J(i,t) - Junction Liquid Flow for Junction i, at time t

M(i,t) - Liquid Mass for Volume i, at time t
M(i-1,t) - Liquid Mass for Volume i-1, at time t
delta t - Incremental Time, i.e., time step

Junction i is inlet to Volume i, Junction i+1 is outlet to Volume i+1,

$$B(i,t) - B(i,t\text{-}to) + t \; x \; (B(i\text{-}1,t)/M(i\text{-}1,t)) \; x \; J(i,t) - (B(i,t)/M(i,t)) \; x \; J(i+1,t)$$

or to solve implicitly,

$$B(i,t) = B(i,t\text{-}to) + \; t \; x(\; B(i\text{-}1,t)/M(i\text{-}1,t)) \; x \; J(i,t) \; / \; 1 + (J(i+1,t)/M(i,t)) \; x \; \; t$$

For flow reversal situations, other expressions are used.

In addition to the revised boron transport model, control blocks were added to calculate the total boron injected, the total boron in the vessel, and the difference between the two. This provided a boron mass error calculation.

The major features of the revised boron model are:

- Better tracking of boron transport
- More reasonable results.

Section 4

ANALYSES PERFORMED AND RESULTS

A total of 12 cases was studied in the River Bend ATWS analysis work. Each case consists of a different combination of water level being maintained, boron enrichment, operator actions, and various boron tracking models. The calculated maximum suppression pool temperatures for various cases studied are presented in Table 3. Table 4 presents a typical timing of major events for the various cases analyzed. It is noted that the sequence of events (mainly, the timing) is identical for all the 12 cases analyzed until the suppression pool temperature reaches 110°F. From then on, the following assumptions would impact the transient response significantly.

o Operator actions

Operator actions to initiate the SLCS, to reduce vessel water level, and to initiate RHR suppression pool cooling could have significant impact on the maximum suppression pool temperature.

o Water Level Being Maintained

The water level was maintained at TAF, TAF+5ft, and TAF+10ft for various cases studied. Higher water level tended to provide a better mixing but a slightly higher power due to less void. However, water level at TAF did not provide sufficient core flow (i. e., less than 5% of the rated flow) to carry the boron into the core.

o Enrichment of B-10 and Concentration of Sodium Pentaborate Solution

Various combinations of B-10 enrichment and solution concentration change the number of B-10 atoms per unit volume. The higher the enrichment of B-10 is, the lower the maximum suppression pool temperature.

A typical analyzed worst case ATWS scenario begins with the closure of the MSIVs and the failure of the control rods to scram. The MSIVs close in approximately four seconds, during which steam flow decreases and pressure begins to rise.

Shortly after the MSIVs shut, pressure will increase enough to lift the SRVs. The steam discharge from the SRVs is directed to the suppression pool (SP) and heats up the pool Thirty (30) seconds (Operator Action Model 1) or 90 seconds (Operator Action Model 2) after the SP temperature reaches 110°F, feedwater (FW) flow is, temporarily terminated to cause the downcomer water level to drop. When the water level falls to the desired level (TAF, TAF+5ft, or TAF+10ft, depending on the case analyzed), FW flow is reinstated as necessary to maintain the level. Two minutes (for Operator Action Model 1) or 72 seconds (for Operator Action Model 2) after the SP temperature reaches 110°F, the SLCS is activated, injecting boron into the lower plenum. The transport of boron through the vessel varies as a different boron tracking model is used for different cases. The RHR system is activated ten minutes (for Operator Action Model 1) or 90 seconds (for Operator Action Model 2) after the SP temperature reaches 95 F. The RHR system provides cooling at approximately 5% of the rated reactor power.

For the cases in which the calculated SP temperature exceeds the heat capacity temperature limit (HCTL) as specified in the GSU EOPs, automatic depressurization system (ADS) operation will be initiated. However, this work did not model the subsequent transient response following an ADS for such cases.

For the cases in which the calculated maximum SP temperatures comply with the HCTL, the analysis was terminated shortly after the SP temperatures started to decrease or when the reactor power dropped to below 5%. All cases are summarized in Table 3.

Cases 1, 11 and 12 provides useful results for comparison. Case 1 represent lowering the water level to TAF, Case 11 represented lowering the water level to TAF + 5 feet, and Case 12 represented lowering the water level to TAF + 10 feet.

Figure 4 presents the comparison of these three cases for core flow percentage versus water level. As shown in Figure 4, the core flow is basically a reflection of power level, i.e., the higher the water level, the higher the power level which corresponds to a high core flow rate. The important point presented in Figure 4 is for the TAF case at approximately 470 seconds into the transients, the core flow drops below 5 percent. Based on Boron mixing test results provided in Reference 6, the core flow below 5 percent does not provide enough lower plenum mixing to allow the sodium pentaborate (being injected through the standpipe into the lower plenum) to be swept into the core. Therefore, with the core flow below 5 percent for standpipe injection plants, the effectiveness of the SLCS is negated due to the lower plenum stratification.

Figure 5 presents the power level with respect to water level and Figure 6 presents the suppression pool temperature with respect to water level. As one can see, the TAF suppression pool temperature will eventually exceed the heat capacity temperature line (HCTL) for the suppression pool due to the stratification of the boron in the lower plenum. It is noted that significant power oscillations were experienced in the cases analyzed when water injection and SRV cycling occurs. These oscillations were not indicated in Figures 4 and 5 for simplifying the presentation.

Section 5

CONCLUSIONS

This work was performed to achieve the following:

- demonstrate the effectiveness of the SLCS design for RBS
- perform a sensitivity study of boron tracking models,
- evaluate the effects of B-10 enrichment,
- determine the merits of reducing water level to higher than TAF, and

Based on the results of 12 cases presented in Table 3 with various combinations of B-10 enrichments, water level, boron tracking models and operator action models, the following conclusions can be reached

I. Technical Findings

- The higher the B-10 enrichment is, other things being equal, the more effective the SLCS is in reducing the power, hence the lower the SP temperature.

- Reducing water level to TAF+5ft and TAF+l0ft yields a best-estimate maximum suppression pool temperature of 150 F and 155 F, respectively, for the proposed SLCS design at RBS (i.e., 65% B-10 enrichment, at 9% nominal solution concentration). The case in which water level is maintained at TAF does not have sufficient boron mixing and hence the calculated suppression pool temperature is higher than the case where water level is maintained at TAF+5ft or TAF+l0ft.

- Of the four boron tracking models studied, Model 4 provides a best-estimate simulation of the boron transport in the vessel. Model 1, which is based on the mixing coefficient with a 118-second transport delay, and model 2, which uses time-dependent control system blocks DELAY and LAG, both give very conservative estimates of the SP temperature.

- The current SLCS design at the RBS, with water level being controlled at TAF+5ft or TAF+10ft, is adequate in limiting the suppression pool temperature within the heat capacity temperature limit specified in EOPs.

- The RBS ATWS analysis results provide supplementary information to the EPGs Revision 4 for scenarios in which SLCS is successfully injected. It is demonstrated with the current SLCS design either maintaining water level at TAF+5ft or TAF+10ft would provide a sufficient power reduction mechanism to mitigate the SP heatup.

- By lowering the water level to TAF may for lower plenum SLCS injection plants, negate the effectiveness of injecting the sodium pentaborate into the lower plenum for reducing the power level.

II. Practical Benefits to GSU

1. The RBS ATWS analysis provided significant cost savings in the implementation of ATWS modifications. Instead of using 90% B-10 enrichment, 65% enrichment has been demonstrated to be adequate for satisfying the requirements of the ATWS modifications.

2. The RBS ATWS analysis allowed elimination of heat tracing requirements for the SLCS because of the lower B-10 enrichment.

3. The RBS ATWS analysis demonstrated that for the scenarios in which SLCS injection is initiated in accordance with EPGs, maintaining water level at TAF+5ft or higher would provide sufficient shutdown capability. This finding eliminates the need to lower water level to TAF as proposed by EPG in which case uncertainties in the level reading may potentially introduce adverse impact on the core cooling. In addition, the RBS ATWS analysis shows that no ADS would be required because the core can be adequately shutdown by the SLCS. In the very unlikely case of SLCS failure, ADS would be required no matter where the water level is maintained.

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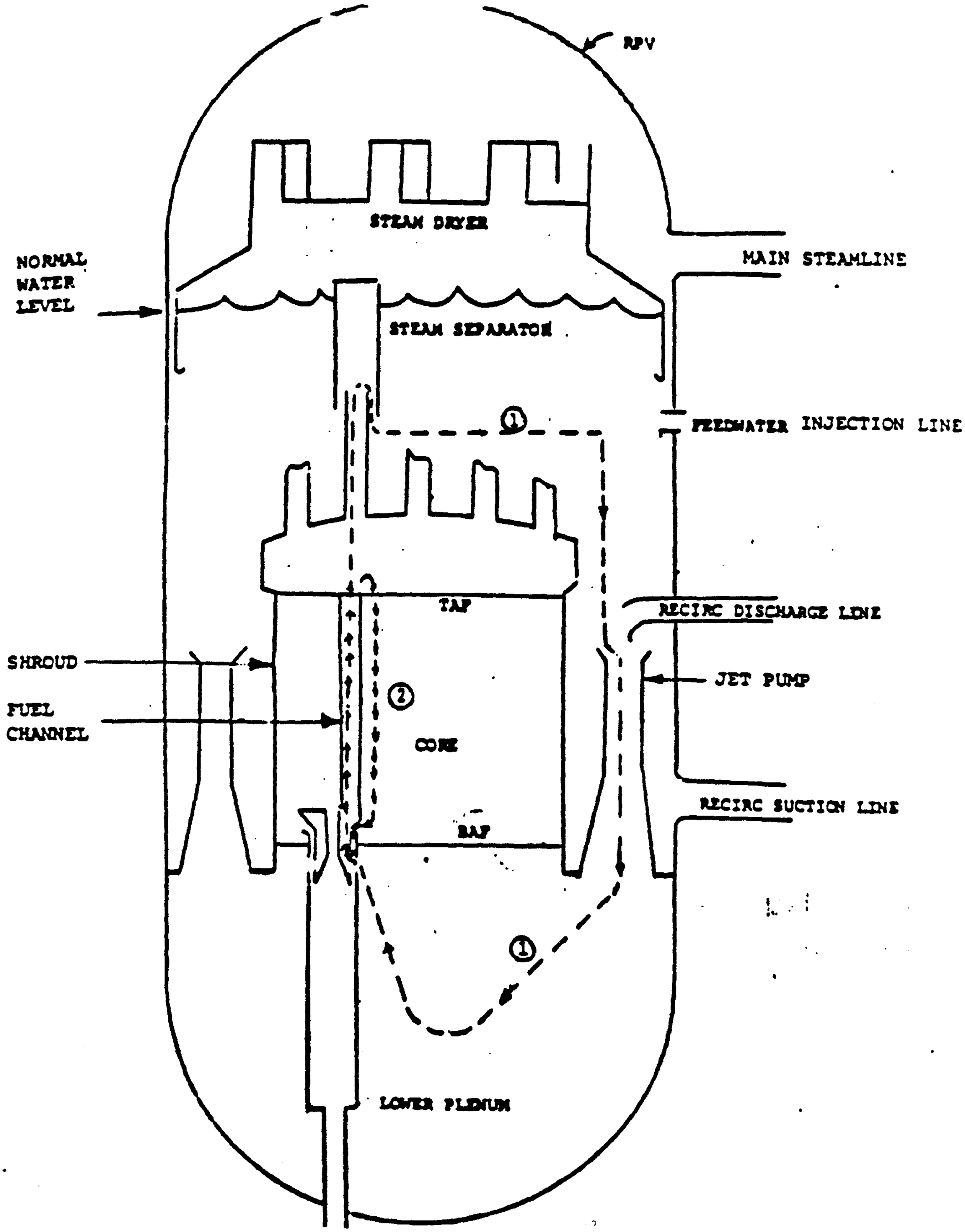

Figure 1. Internal and External Circulation Flow Paths at Low Power Conditions

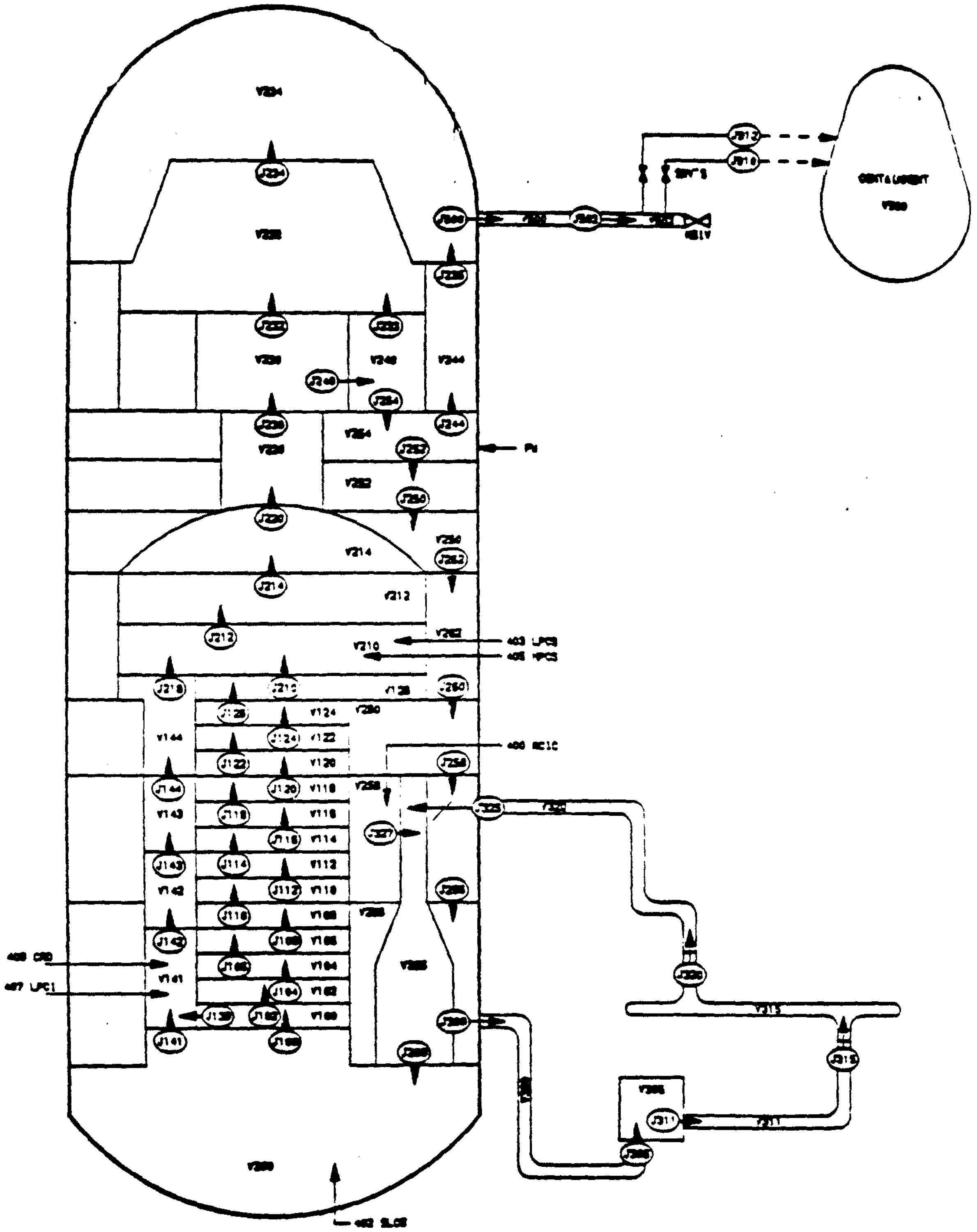

Figure 2 RETRAN Nodalization Diagram for the River Bend ATWS Model

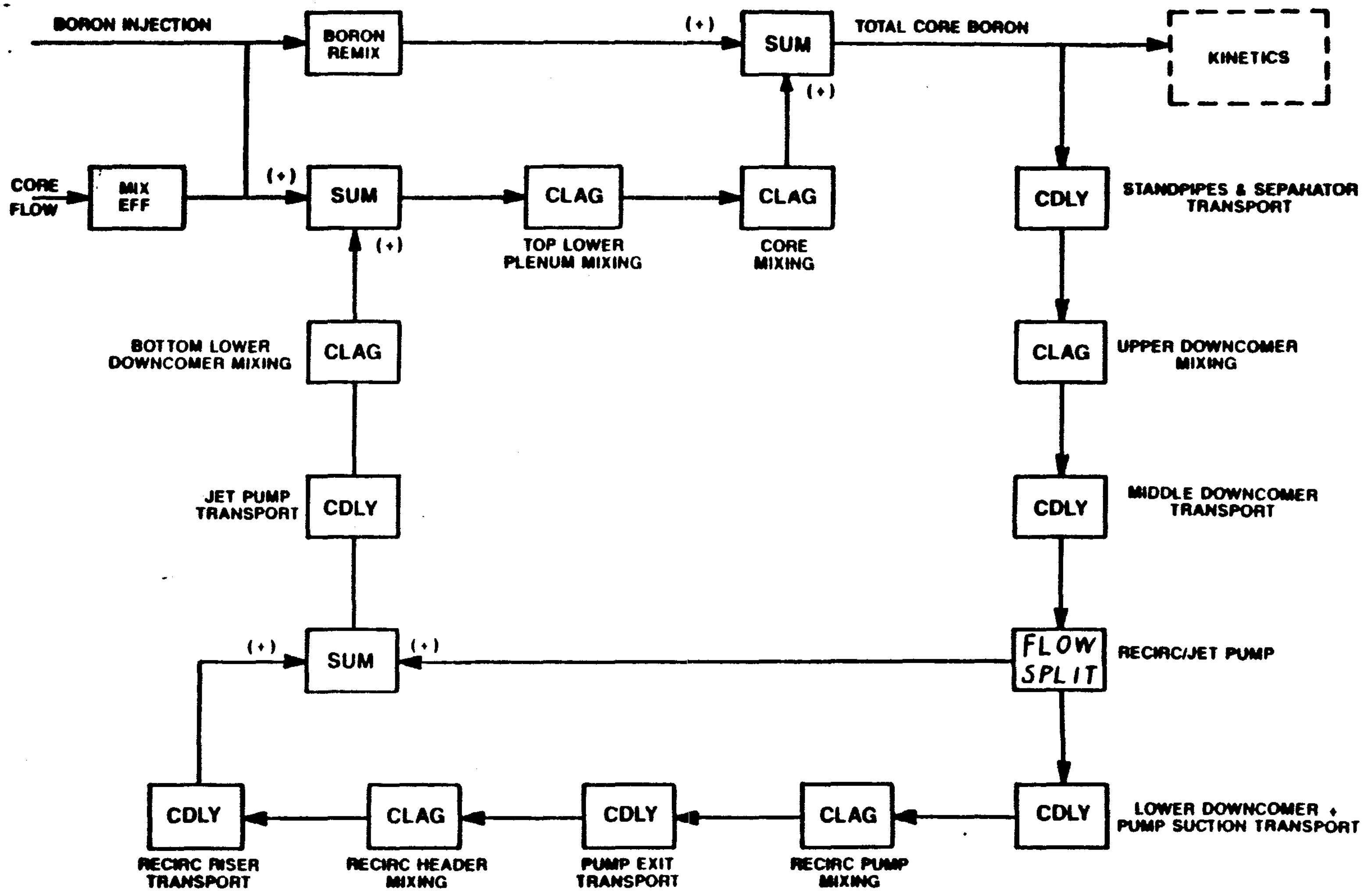

Figure 3. Simplified Boron Concentration Model Schematic

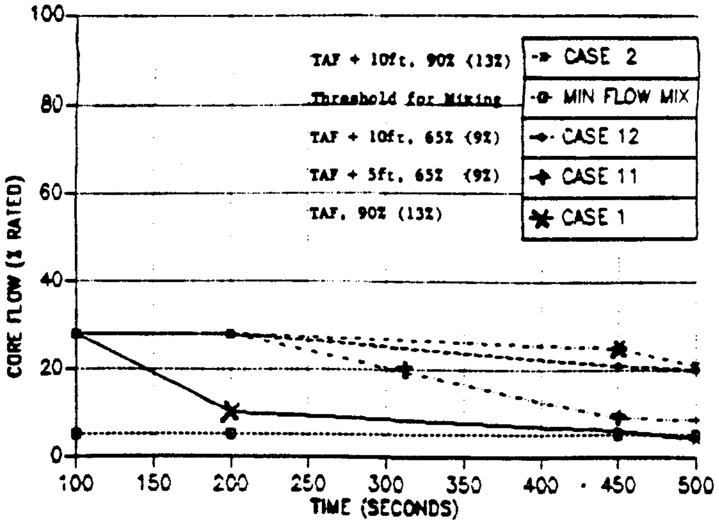

Figure 4. Core Flow Percentage With Respect To Different Water Levels

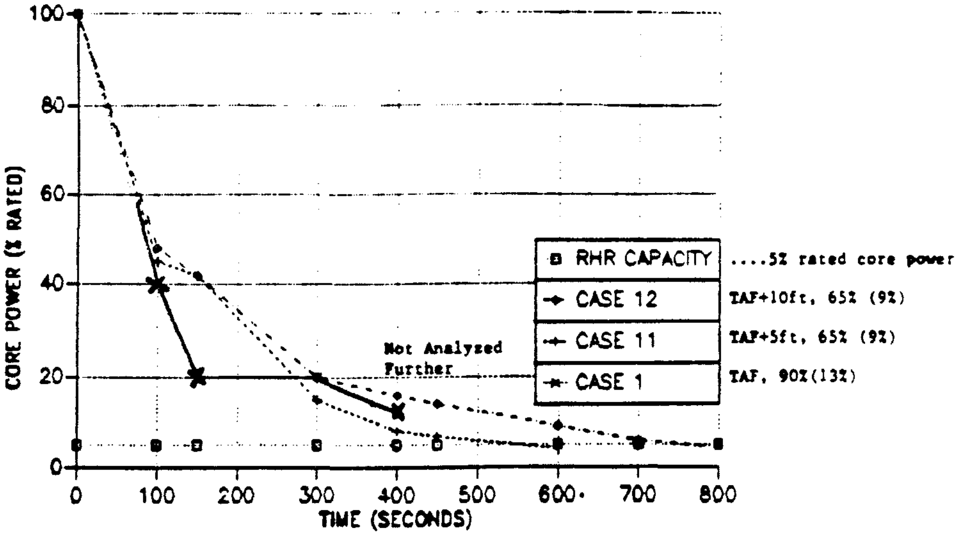

Figure 5. Core Power Percentage With Respect to Different Water Levels

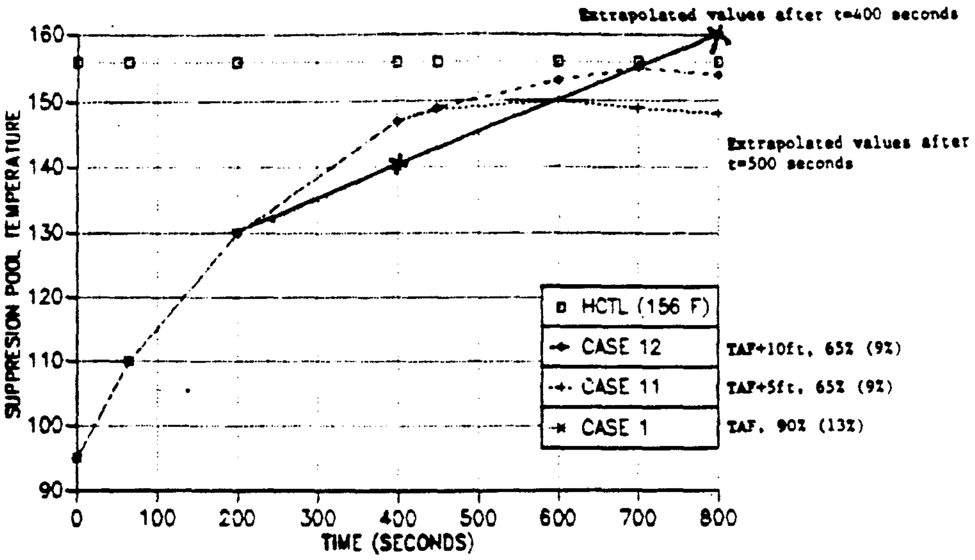

Figure 6. Suppression Pool Temperature With Respect to Different Water Levels

Table 1. A Comparison of Operator Actions Considered in the ATWS Analysis.

	SLCS Delay	Level Reduction Delay	RHR Initiation Delay
Action 1	120 sec	30 sec	600 sec
Action 2	72 sec	90 sec	90 sec

Table 2. A Summary of Boron Tracking Models Used in the ATWS Analysis.

Model 1

- Use an empirical correlation based on 1/6-scale BWR mixing tests
- Correlate mixing coefficient with fraction of core flow and time

Model 2

- Use time dependent LAG and time dependent DELAY
- Model boron flow through a volume as a LAG or DELAY

Model 3

- Ad Hoc Fix of the Model 2
- Boron mass change is restricted to a non-negative value

Model 4

- Use time dependent LAG for all volumes with implicit numerical scheme
- Consider potential flow reversal

Table 3. A Summary of Results and Major Assumptions for Cases 1 through 12.

Case	Water Level	Sodium Pentaborate Concentration	B-10 Enrichment	Operator Actions	Subcooled Injection Model	Boron Tracking Model	Max. SP Temp.
1	TAF	13%	90%	Action 1	Yes	Model 1	160°F
2	TAF+10ft	13%	90%	Action 1	Yes	Model 1	151°F
3	TAF+10ft	13%	40.6%	Action 1	Yes	Model 1	159°F
4	TAF+10ft	13%	40.6%	Action 2	No	Model 1	179°F
5	TAF+10ft	13%	40.6%	Action 2	No	Model 2	167°F
6	TAF+10ft	13%	90%	Action 2	No	Model 2	145°F
7	TAF+5ft	13%	40.6%	Action 2	No	Model 2	160°F*
8	TAF+10ft	13%	65%	Action 2	No	Model 2	152°F*
9	TAF+5ft	13%	65%	Action 2	No	Model 2	155°F*
10	TAF+5ft	9%	65%	Action 2	No	Model 3	142°F
11	TAF+5ft	9%	65%	Action 2	No	Model 4	150°F
12	TAF+10ft	9%	65%	Action 2	No	Model 4	155°F

* Analysis experienced severe numerical oscillations. Maximum suppression pool temperature was obtained based on extrapolation.

Table 4. A Typical Sequence of Events for a MSIV ATWS.

EVENT	TIME (SECONDS)
MSIV Closure	0.01
Vessel Water Level Setpoint Setdown	0.8
Low Level - 4	2.4
Recirc. Pump Trip (High RPV Pressure)*	3.2
SRV Opens	3.1 - 3.9
SP Temp. 95°F	3.5
High Level - 8	4.3
SP Temp. 110°F	62
RHR Initiated	93.5
SLCS Initiated	134 (Power 40%)**
Level Reduction Initiated	152***
First Pass of Boron into the Core	167
Level Reached TAF+5FT	247

* 1145 psia was used in the analysis, actual plant setpoint is 1142 psia.

** Assumes 72-second delay of operator action.

*** Assumes 90-second delay of operator action.