The Management of ATWS

by

Boron Injection

and

Water Level Control

Prepared by

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for the

BOILING WATER REACTOR OWNERS' GROUP
GENERAL ELECTRIC COMPANY

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Section 1

INTRODUCTION

The Boiling Water Reactor Owners' Group (BWROG) has developed a set of generic Emergency Procedure Guidelines (EPGs) to provide a technical basis for Emergency Operating Procedures (EOPs) in their plants. These EPGs evolved over a period of eight years to the most recent version, BWR Emergency Procedure Guidelines Revision 4[1, 2], which was issued in 1987 and approved for implementation by the Nuclear Regulatory Commission (NRC) in 1988[3]. At present, the EOPs in use at all US Boiling Water Reactor (BWR) plants are derived from these EPGs.

Operator actions appropriate to mitigate the consequences of scram failure events, which include Anticipated Transients Without Scram (ATWS), were first incorporated in the Revision 2 EPGs issued in 1982. These actions were developed based upon system configurations, operating regimes, and the state of knowledge regarding boron mixing which existed at that time. All of these have changed in the intervening years. The capability to rapidly insert negative reactivity by the injection of soluble boron has been increased, the allowable power/flow operating envelope has been extended, and a recent study by Dr. T. Theofanous and others[4] has indicated that the earlier assumptions regarding the mixing of soluble boron in the lower plenum of the BWR Reactor Pressure Vessel (RPV) may have been overly conservative. Further, the BWROG is presently proposing to modify the EPGs to provide more explicit direction for the prevention and mitigation of the consequences of potential reactor instabilities[5].

The BWROG qualitatively evaluated the effect of each of these changes as it was identified. Specifically, for each change, the reactor and containment response were re-examined to determine whether the EPGs continued to specify the correct operator actions for scram failure events. Based on these qualitative evaluations, the BWROG concluded that the current Revision 4 EPGs provide appropriate and adequate guidance for response to these events, and that the EPGs as the BWROG proposes to modify them will improve this generic guidance.

Recently, the General Electric Company performed extensive quantitative analyses of the response of the reactor to a scram failure event in which the reactor is not isolated from the main condenser[6]. This event was chosen because the purpose of the analyses was to determine the effect of proposed operator actions on potential reactor instabilities, and a scram failure without isolation is more limiting with respect to instabilities. These analyses provide quantitative support for the earlier BWROG conclusion that, with respect to the response of the reactor, the operator actions in the EPGs as the BWROG proposes to modify them are appropriate for scram failure events.

The purpose of this report is to document the results of analyses which quantitatively address the response of the containment to a scram failure event and the operator actions in the EPGs, both as the BWROG proposes to modify them[5] and as others have suggested that they might be modified[4]. The event analyzed is a scram failure in which the reactor is isolated from the main condenser, as this event is the most limiting with respect to the response of the containment. The event is described in Section 2.

The analysis was performed using the model and assumptions described in Section 3. Current data from BWR plants representative of the spectrum of plant designs which are presently operating in the US was collected and input to the model. These data are described in Section 4 and listed in Appendix A.

The results of the analyses are presented in Section 5. Section 6 discusses the uncertainty in the important assumptions and illustrates the sensitivity of the results of the analysis to variations of these assumptions. The model has been benchmarked against several analyses reported in the public domain, and these comparisons are described in Section 7. Section 8 provides a summary and conclusion of the results of this work.

Section 2

SCRAM FAILURE WITH ISOLATION TRANSIENT

The scram failure with isolation transient is generally considered the event which most quickly challenges the integrity of the containment because this event results in the transfer of a large quantity of energy to the containment in a short period of time.

The transient is initiated with the reactor at rated conditions and all plant systems functioning normally. The Main Steam Isolation Valves (MSIVs) are assumed to close, but the reactor scram function associated with MSIV closure fails. RPV pressure rapidly increases, the recirculation pumps trip and Safety Relief Valves (SRVs) open to relieve steam from the RPV into the suppression pool. In this transient the high RPV pressure and high neutron flux scrams are also assumed inoperative. RPV pressure continues to increase until SRV steam flow equilibrates with steam generation in the reactor core.

At this point in the transient, plant response will diverge depending upon whether the plant is equipped with motor-driven feedpumps or turbine-driven feedpumps. With the MSIVs closed, turbine-driven feedpumps will coast down and feed flow will be lost. RPV water level will drop until Emergency Core Cooling Systems (ECCS) are actuated, but these will be inadequate to supply sufficient makeup to match the steam generation rate in the core, and water level will continue to fall. As RPV water level decreases, core power and flow also decrease. This results in a reduced core steaming rate and, consequently, a lower RPV pressure. The operator is directed by the EPGs to prevent automatic initiation of the Automatic Depressurization System (ADS). Without further operator action, RPV water level will continue to decrease until SRV steam flow and ECCS injection equilibrate, at which point reactor power and RPV water level will stabilize.

Motor-driven feedpumps will continue to operate and control RPV water level within or near the normal operating range until the condenser hotwell is depleted. At this point the pumps will trip, RPV water level will begin to drop, and the transient will proceed as in the plant equipped with turbine-driven feedpumps.

With SRVs open and steam flowing into the suppression pool, pool temperature rapidly rises. The operator is directed by the EPGs to initiate the Standby Liquid Control System (SLCS) and inject soluble boron into the RPV before pool temperature reaches the Boron Injection Initiation Temperature (BIIT), which is typically 110 °F for the high reactor power associated with this transient. The operator is not required to wait until pool temperature reaches the BIIT and, based on training and simulator observations, it is expected that he will initiate boron injection shortly after he has exhausted the several methods for tripping the Reactor Protection System (RPS) specified in the EPGs.

The EPG modifications proposed by the BWROG[5] direct the operator to immediately lower RPV water level to below the feedwater sparger, and the current EPGs require him to lower it further when suppression pool temperature reaches the BIIT. Lowering water level will generally require defeating automatic ECCS initiation logic. Under the EPGs, the operator is permitted to lower water level to as low as the Minimum Steam Cooling RPV Water Level (MSCRWL), which is approximately thirty inches below the Top of the Active Fuel (TAF). He is also directed to place all available suppression pool cooling in service when pool temperature reaches the most limiting Limiting Condition for Operation (LCO) for the plant, typically between 90 and 95 °F.

As the soluble boron is injected into the RPV, it mixes with the reactor coolant. Once again plant response will diverge, this time depending upon the location of the point of injection of soluble boron within the RPV. If injection is into the lower plenum of the RPV, boron will mix with the reactor coolant and be drawn up into the core region only so long as there is sufficient recirculation flow to entrain and transport the boron into the core. When flow decreases below this point, whether as a result of deliberate water level reduction or a decrease in void fraction due to boron injection, the injected boron will not effectively mix with the reactor coolant and will stagnate in the lower plenum. After boron sufficient to shut down the reactor at high pressure (hot shutdown conditions) has been injected, the operator is directed to raise RPV water level thereby increasing core flow, drawing the unmixed boron up into the core, and shutting down the reactor.

If the soluble boron is injected through the core spray sparger above the core, it will mix with the reactor coolant and enter the core region irrespective of the recirculation flow, quickly shutting down the reactor. Under these conditions, the operator is not directed to raise RPV water level to increase core flow because this action may sweep the borated water from the core and replace it with unborated water, causing the reactor to return to power.

The transient is generally considered to have terminated when the reactor is shutdown. However, suppression pool temperature and primary containment pressure will continue to rise until pool temperature reaches the point at which the suppression pool cooling system is capable of removing all the heat rejected to the containment by the reactor or until shutdown cooling can be placed in service.

If boron cannot be injected into the RPV and control rods cannot be inserted, the reactor cannot be shutdown and suppression pool temperature will increase until the Heat Capacity Temperature Limit (HCTL) is reached. When this occurs, RPV depressurization is required and pool temperature will be further increased. Pool temperature and primary containment pressure will continue to rise following the RPV depressurization until the Primary Containment Pressure Limit (PCPL) is reached. When this occurs, the primary containment must be vented to assure its continued integrity.

Section 3
ANALYSIS MODEL

3.1 Analytical Bases

The analysis model is a time-incremented deterministic model consisting of closed solution derivations of the important neutronic and thermal-hydraulic parameters. Ten nodes or regions are employed to model the RPV, as illustrated in Figure 3.1-1. This permits an accurate representation of the distribution of soluble boron within the RPV as well as both downcomer and in-shroud RPV water levels as a function of time.

Core inlet flow and RPV steam flow as a function of RPV water level in an unrodded and unborated core operating in natural circulation are provided by an input table of RPV water level, core inlet flow, and RPV steam flow. Table 3.1-1 specifies this generic data for the nominal (100% rod pattern) condition, and Table 3.1-2 specifies the data for the maximum extended operating domain (MEOD) initial condition. The MEOD data was obtained from the ATWS instability mitigation analyses reported in NEDO-32164[6]. An initial core average void fraction is also input. The natural circulation driving head for each RPV water level listed in the table is computed, and an average flow coefficient is calculated for each water level. The slip, or difference in the steam

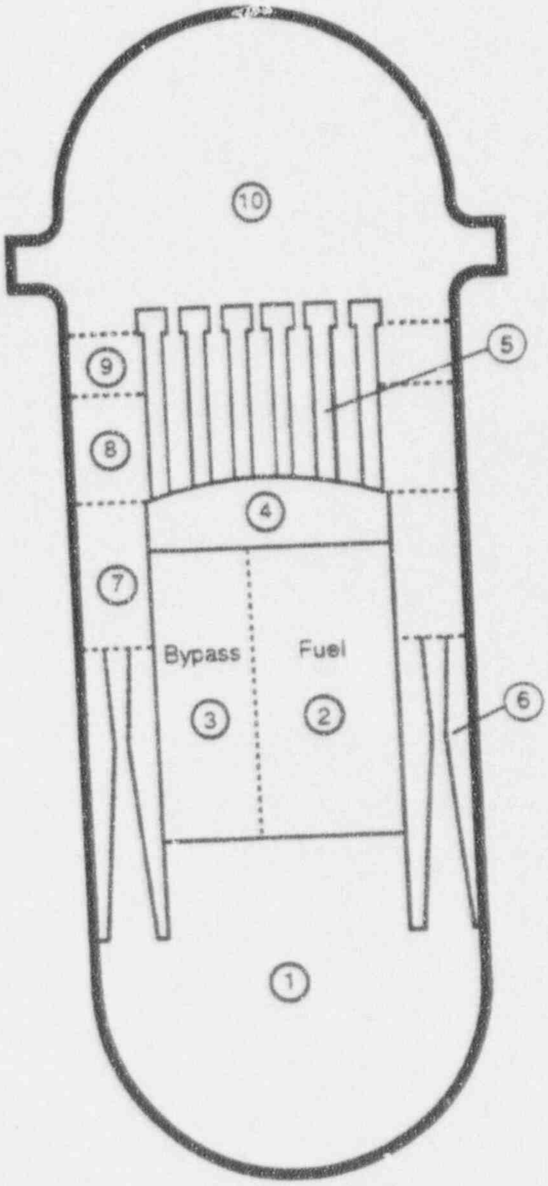

Figure 3.1-1 RPV regions.

RPV Water Level	Core Inlet Flow (% rated)	RPV Steam Flow (% rated)
Bottom of Active Fuel (BAF)	0	0
Top of Active Fuel (TAF)	9	15
TAF + 60 inches	18	25
Normal Water Level (NWL)	30	45

Table 3.1-1 Nominal (100% rod pattern) initial conditions.

RPV Water Level	Core Inlet Flow (% rated)	RPV Steam Flow (% rated)
BAF	0	0
Minimum Steam Cooling RPV Water Level (MSCRWL)	8	19
TAF + 0.19 meters	13	24
TAF + 1.24 meters	18	33
NWL	30	63

Table 3.1-2 MEOD initial conditions.

and liquid velocities in the core, is also computed for each water level in the table.

The boron mixing efficiency is obtained from another input table of core inlet flow and mixing efficiency. Boron mixing efficiency is equal to the fraction of the soluble boron injected into the RPV lower plenum which effectively mixes with the reactor coolant and is drawn up into the core region. Generally, mixing efficiency improves as core inlet flow increases. If boron is injected above the core through the core spray sparger, boron mixing efficiency is independent of core inlet flow and equal to 100%.

Injected boron which is not drawn up into the core region stagnates in the RPV lower plenum, where it remains until core flow increases to a value sufficient to entrain the stagnant boron and carry it into the core region. The boron remixing time constant (BRTC) is defined to be the length of time required for half of the stagnant boron to be entrained in the recirculating reactor coolant and transported to the core. The BRTC is a function of core inlet flow and has been determined experimentally in the 3D Boron Mixing Test Facility at the General Electric Valecetos Nuclear Center[7]. It is input to the model from a table of core inlet flow and BRTC. Table 3.1-3 specifies the BRTC data input to the model.

Three boron inventories are maintained by the model: boron recirculating through the core with the reactor coolant, boron stagnated in the lower plenum, and boron trapped in the core region. Boron injected above the core through the core spray sparger is trapped in the core region whenever the in-shroud two-phase water level is below the top of the separators and no liquid is flowing out the separators. The concentration of soluble boron in the core region is obtained by dividing the total quantity of boron in the core region by the mass of water in the region.

Core Inlet Flow (% rated)	**Boron Remixing Time Constant (sec^{-1})**
<5	∞
5	100
8.5	25
13.5	20
100	10

Table 3.1-3 Boron remixing time constant.

Core average void fraction is obtained from a reactivity balance of the core. While the reactor is critical, the core average void fraction is determined by requiring the core reactivity to remain at zero. Thus as rods are inserted or soluble boron is injected, the core average void fraction decreases to maintain the reactor critical. Core void fraction cannot decrease below the void fraction which results from the transfer of decay heat to the reactor coolant. A minimum core void fraction which results from decay heat at flow stagnation (no liquid flow out the separators) is input, and the slip associated with this void fraction is calculated. From these data, minimum core void fractions for non-stagnant conditions are computed, and the core average void fraction is not permitted to decrease below these minima. The minimum decay heat core void fraction at flow stagnation utilized in these analyses is 30%, obtained from the 1992 work by Dr. T. Theofanous[4].

From the core average void fraction and the downcomer water level, the natural circulation driving head is computed. The core flow coefficients and slip velocities obtained from the input correlations of flow and water level are then employed to derive core inlet flow and core steam flow.

Both automatic and manual operation of the feedwater and emergency core cooling systems are modeled. The time at which the operator is presumed to take manual control of RPV injection in order to control RPV water level is one of the assumptions input into the model. Prior to this time, the operation of these systems is automatic; afterwards, the systems are controlled manually to effect the RPV water level control strategy being analyzed. Only injection systems the use of which is authorized in the EPGs are employed to effect RPV water level control strategies.

A mass balance between the water injected into the RPV and the steam flowing out the SRVs is employed to determine the total mass of water in the RPV. Condensation of steam by water injected into the RPV steam space is also modeled. The mass of liquid in the RPV and in-shroud void fractions are utilized to determine the single-phase downcomer water level and the two-phase in-shroud water level.

Containment response is determined by mass and energy balances between the RPV and the containment. Steam flow through the SRVs into the suppression pool is integrated to obtain the mass and energy of the pool, from which suppression pool temperature is calculated. Heat transfer to the suppression pool liner and submerged steel components is modeled. Primary containment pressure is computed from the pressure of the water vapor in the suppression chamber and ideal gas representations of the initial drywell and suppression chamber gas inventories.

3.2 Assumptions

Constant equilibrium conditions are assumed for the duration of each time step. Specifically, core inlet flow, core steam flow, RPV injection flow, SRV steam flow, downcomer and in-shroud water levels, boron injection rate, boron mixing efficiency, and the boron remixing time constant are assumed to remain constant throughout a time step. The length of the time step is a function of the BWR design, the containment type, and the transient analyzed. Time step length is constant throughout an analysis and is selected so that the variation of plant parameters from the beginning of one time step to the beginning of the next is relatively small.

Initial conditions representative of the average (year round) values of plant parameters are assumed. These are as follows:

Suppression pool temperature	80 °F
Service water temperature	65 °F
Condensate storage tank (CST) temperature	90 °F
Soluble boron storage tank temperature	70 °F

Nominal values for the timing of operator actions are utilized in the analysis. The following event timing, referenced to the commencement of the event (scram failure) is assumed:

Soluble boron reaches the RPV	1.5 min.
RPV injection is terminated for RPV water level control	2.5 min.
Suppression pool cooling is initiated	5.0 min.

Nominal system performance is also employed in the analysis. This is obtained by increasing certain design or technical specification system parameters by margins based on observed system tests. These margins are as follows:

Suppression pool cooling system performance	10 %
Standby Liquid Control System (SLCS) pump capacity	5 %
SLCS tank sodium pentaborate solution concentration	15 %

The following core average parameters are utilized in the model:

Void reactivity coefficient	-0.0014 dK/%
Soluble boron reactivity coefficient	-0.000167 dK/ppm

In addition, the following assumptions and model simplifications have been made to expedite the analysis:

1. The following short-term transient effects are not modeled:
    - RPV pressure rise before SRV actuation
    - Recirculation pump trip and coastdown

- Feedpump coastdown
- Transfer of the initial stored energy in the fuel to the reactor coolant

2. The isolation condenser (BWR/2 and 3) is not modeled.
3. The operator controls SRVs to maintain RPV pressure constant at the lowest SRV lifting setpoint until RPV depressurization is required.
4. The reactivity due to soluble boron in the reactor coolant varies linearly with the concentration of boron in the coolant.
5. All soluble boron which is injected into the RPV and mixed with the recirculating reactor coolant remains in solution for the duration of the event.
6. The water in the suppression pool and the gas and water vapor in the suppression chamber airspace are in thermal equilibrium.
7. The temperature of the gas in the drywell remains constant throughout the event.
8. If the RPV is manually depressurized, the energy stored in the fuel, clad, channels, RPV, internals, recirculation piping, and reactor coolant is converted into steam and transported to the suppression pool at a rate which decays exponentially with a time constant of two minutes.
9. Core inlet flow and core steam flow are obtained in the same manner both before and after depressurization of the RPV.

3.3 Limitations

The model employed for this analysis and described in Section 3.1 is a simple model which utilizes results obtained from much more sophisticated analytical tools in order to predict the integrated response of various plant types to transients which extend beyond those analyzed with the more sophisticated tools. The validity this methodology is limited to the validity of the results of the more sophisticated tools, the validity of extrapolating these results beyond the bounds of the analysis from which they were derived, and the validity of applying these results to different plant designs.

The core inlet flow and core steam flow correlations utilized by the model to analyze transients initiated from the MEOD were obtained from three analyses of a single hypothetical plant. The RPV geometry and core power density of the analyzed plant were specifically chosen to maximize the potential for reactor instability in the three analyses. It may be expected that differences between the characteristics of the hypothetical plant and those of an existing plant may limit the validity of applying these correlations to the existing plant. For example, the differences between the geometry of the RPV internals of the hypothetical plant, a BWR/5 with jet pumps, and the geometry of a BWR/2, which has no jet pumps, would be expected to result in differences between the natural circulation characteristics of the two plants.

The model employs average core flow coefficients and slip velocities to calculate core inlet flow and core steam flow. This simplification has been made to reduce the computer resources required to perform an analysis. Further, a simple linear interpolation algorithm is employed to obtain slip velocity as the core void fraction decreases. Several more sophisticated and potentially more accurate interpolation algorithms were evaluated, but the simple algorithm was selected because the validity of the more sophisticated algorithms could not be confirmed and because the simple algorithm will result in overpredicting rather than underpredicting the core steam flow and, consequently, containment heatup. This is confirmed by one of the benchmark cases described in Section 7. In summary, it may be expected that a more sophisticated representation of slip velocity would result in lower core steam flow, containment temperature, and containment pressure.

Similarly, as identified in Section 3.2, the model obtains core inlet flow and core steam flow in the same manner both before and after depressurization of the RPV. It may also be expected that a more sophisticated calculation would result in lower core steam flow, containment heatup, and containment pressurization after the depressurization.

Section 4

PLANT DATA

Current data from BWR plants representative of the spectrum of plant designs which are presently operating in the US was collected for input to the model. This data encompasses rated plant conditions, containment geometry, RPV geometry, systems capacities and control logic, and operating limits.

The plants from which this data was obtained, together with the BWR design and containment type of each, is identified in Table 4-1. The data from each plant is tabulated in Appendix A.

Plant	BWR design	Containment
Nine Mile Point Unit 1	BWR/2	Mark I
Monticello	BWR/3	Mark I
Browns Ferry	BWR/4	Mark I
WNP-2	BWR/5	Mark II
Grand Gulf	BWR/6	Mark III

Table 4-1 Representative BWR plants.

Section 5
RESULTS

The results of the containment response analyses are presented in this section. These results are expressed in terms of either the suppression pool temperature at which the reactor is ultimately shut down or the margin between that temperature and the Heat Capacity Temperature Limit (HCTL). The HCTL is a function of RPV pressure and is the suppression pool temperature at which manual RPV depressurization is required by the EPGs.

5.1 Containment Response With Boron Injection

Soluble boron injected into the RPV early in the event significantly reduces reactor power during the first few minutes of the transient because the boron effectively mixes with the reactor coolant and quickly reduces the core average void fraction. For plants which inject soluble boron into the RPV lower plenum, effective mixing continues until RPV water level decreases to the point at which the associated core flow can no longer support it. Effective mixing continues indefinitely for plants which inject soluble boron above the core through the core spray sparger. Boron concentration in the reactor coolant will also increase as RPV water level is lowered, since lowering RPV water level reduces the total mass of water in the RPV. This early power reduction contributes to the substantial margin to HCTL for all BWR designs.

5.1.1 RPV Water Level Control Under the EPGs

The containment response with the operator actions specified in the Revision 4 EPGs[1,2] modified as proposed by the BWROG[5] has been calculated for each representative plant. Operation at the 100% rod line and perfect (100%) boron mixing above 5% rated recirculation flow have been assumed.

The transient is illustrated by the response of the representative BWR/4 plant. The principal RPV and primary containment parameters from this plant are plotted in this section.

Following the isolation and recirculation pump trip, feedwater flow is lost and downcomer water level decreases until the high pressure ECCS actuate. This reduces the rate of water level decrease. ECCS continue to inject into the RPV until the operator takes manual control of these systems and terminates injection into the RPV in order to lower downcomer water level and reduce reactor power. Downcomer water level decreases until it drops below the top of the active fuel (TAF), at which time the operator restores RPV injection to maintain RPV water level between TAF and the Minimum Steam Cooling RPV Water Level (MSCRWL). The two-phase in-shroud water level remains at least ten feet above TAF during this evolution. The plots of downcomer water level, in-shroud water level, and RPV injection illustrate this portion of the transient.

The operator also initiates the injection of soluble boron into the RPV, and reactor power is further reduced as this boron reaches the core region. However, the downcomer water level reduction reduces core inlet flow, and when core flow drops below the assumed threshold for effective boron mixing, the injected boron is no longer entrained in the reactor coolant and drawn up into the core. Boron injected under these conditions stagnates in the lower plenum of the RPV, where it remains until core inlet flow is increased. The Hot Shutdown Boron Weight (HSBW) is defined to be the amount of boron required to shut down the reactor at high pressure with RPV water level at the high level trip setpoint if the boron is uniformly distributed throughout the RPV. After the operator has injected the HSBW into the RPV, injection of water into the RPV is increased to raise downcomer water level and increase core inlet flow. As core flow increases, the stagnant boron is swept from the lower plenum into the core region, where it rapidly shuts down the reactor. The plots of RPV water level, core inlet flow, boron mixing efficiency, and in-core boron concentration illustrate this effect.

As downcomer water level is reduced and in-core boron concentration increases, core steam flow, which is directly related to reactor power, decreases. When injection into the RPV is restored to maintain downcomer water level between TAF and the MSCRWL, core steam flow stabilizes. When injection into the RPV is increased to raise downcomer water level and increase core inlet flow, core steam flow increases until the boron swept into the core from the lower plenum shuts down the reactor, at which time core steam flow drops to a steady-state value equal to the rate of steam production due to decay heat. The plots of RPV water level, in-core boron concentration, and core steam flow illustrate this response.

Early in the transient, RPV steam flow and core steam flow are equal. However, when the ECCS actuate, a large fraction of the steam flowing out the separators is condensed by the relatively cold ECCS flow, which is injected through the feedwater sparger into the steam space above the downcomer water level. This results in a significant reduction in RPV steam flow, which continues until the operator terminates injection into the RPV in order to lower downcomer water level and reduce reactor power. When this occurs, the ECCS no longer condense steam flowing from the separators, and RPV and core steam flow are once again equal. When the operator restores injection to control downcomer water level between TAF and the MSCRWL, RPV steam flow is reduced, and it remains below core steam flow until downcomer water level increases to above the feedwater sparger near the end of the transient. If ECCS injection is sufficient to condense all steam generated in the core, there can be no steam flow through the SRVs if RPV pressure is to remain constant. Under these conditions, RPV steam flow is set equal to zero. The effect of ECCS injection on RPV steam flow is illustrated by the plots of RPV injection, core steam flow, and RPV steam flow.

Since the RPV is isolated from the main condenser, all steam flow from the RPV is directed through the SRVs to the suppression pool, and suppression pool temperature increases rapidly during the first few minutes of the transient. The rate of temperature increase is reduced after the operator terminates injection into the RPV in order to lower downcomer water level and reduce reactor power.

The rate of suppression pool temperature increase is also reduced when the operator places suppression pool cooling in service. Pool temperature continues to increase until the reactor is shutdown.

The principal RPV and primary containment parameters for this transient in the representative BWR/4 plant are plotted in the following figures:

Figure 5.1.1-1	RPV water level
Figure 5.1.1-2	RPV injection
Figure 5.1.1-3	Core inlet flow and boron mixing efficiency
Figure 5.1.1-4	Boron mixing efficiency and in-core boron concentration
Figure 5.1.1-5	In-core boron concentration and core steam flow
Figure 5.1.1-6	Core steam flow and RPV steam flow
Figure 5.1.1-7	RPV steam flow and suppression pool temperature

The behavior of these parameters under this transient in the representative BWR/2 and BWR/3 plants is similar to that illustrated for the representative BWR/4. However, the response of the representative BWR/5 and BWR/6 plants is significantly different.

In each of the representative BWR/5 and BWR/6 plants, soluble boron is injected through the core spray sparger above the core. Once the two-phase in-shroud water level drops below the steam separator liquid exit, liquid flow out the separators ceases and all boron subsequently injected through the spray sparger is retained within the core shroud. Because the mass of water within the core shroud is significantly less than the total mass of water in the RPV, the concentration of soluble boron in the core region rapidly increases, independent of core inlet flow, and the reactor is shutdown within a few minutes.

To illustrate this effect, the principal RPV and primary containment parameters for this transient in the representative BWR/6 plant are plotted in the following figures:

Figure 5.1.1-8	RPV water level
Figure 5.1.1-9	RPV injection
Figure 5.1.1-10	Core inlet flow
Figure 5.1.1-11	In-core boron concentration and core steam flow
Figure 5.1.1-12	Core steam flow and RPV steam flow
Figure 5.1.1-13	RPV steam flow and suppression pool temperature

The value of the HCTL with RPV pressure at the lowest SRV lifting setpoint, the suppression pool temperature at which the reactor is ultimately shutdown, and the margin to the HCTL for each representative plant are listed in Table 5.1.1-1. All the representative plants are shutdown before suppression pool temperature reaches the HCTL.

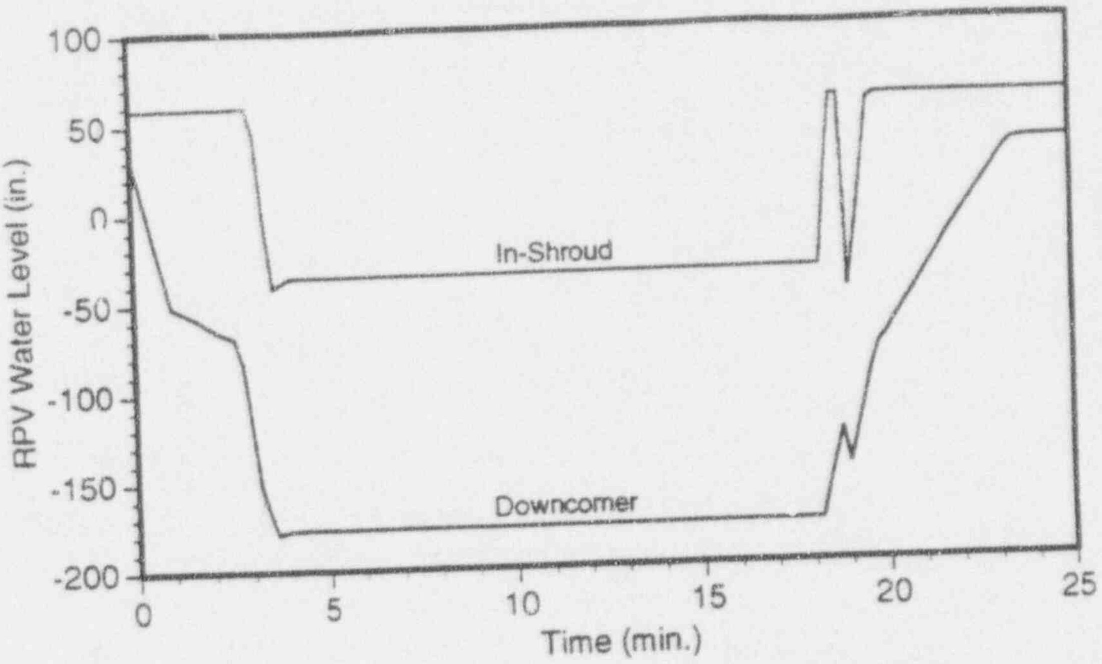

Figure 5.1.1-1 RPV water level, BWR/4, EPG water level control

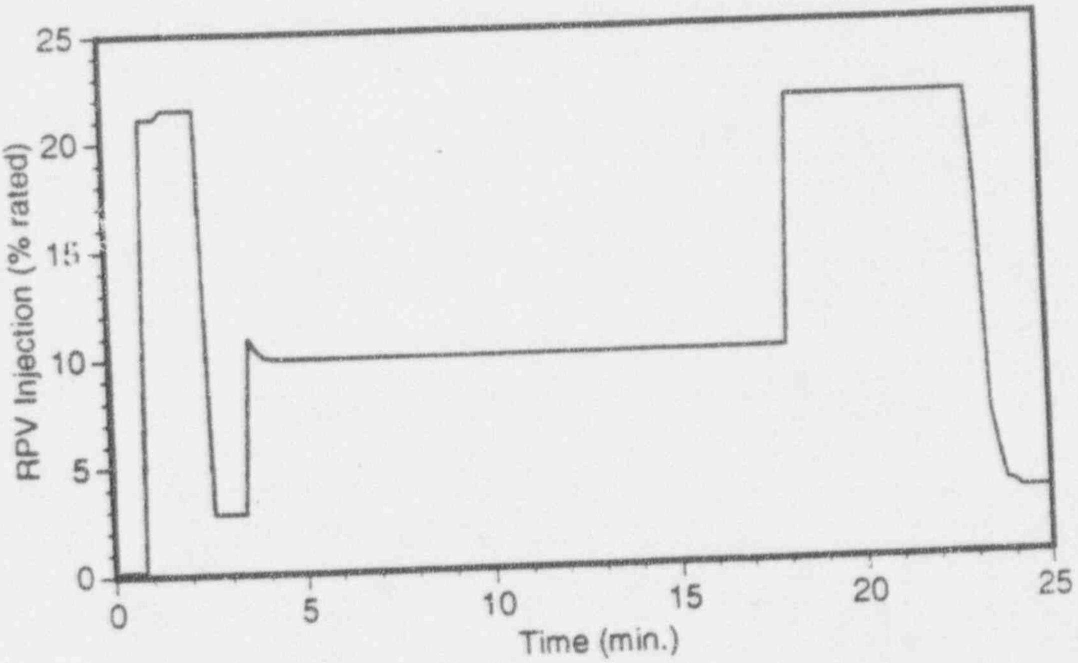

Figure 5.1.1-2 RPV injection, BWR/4, EPG water level control

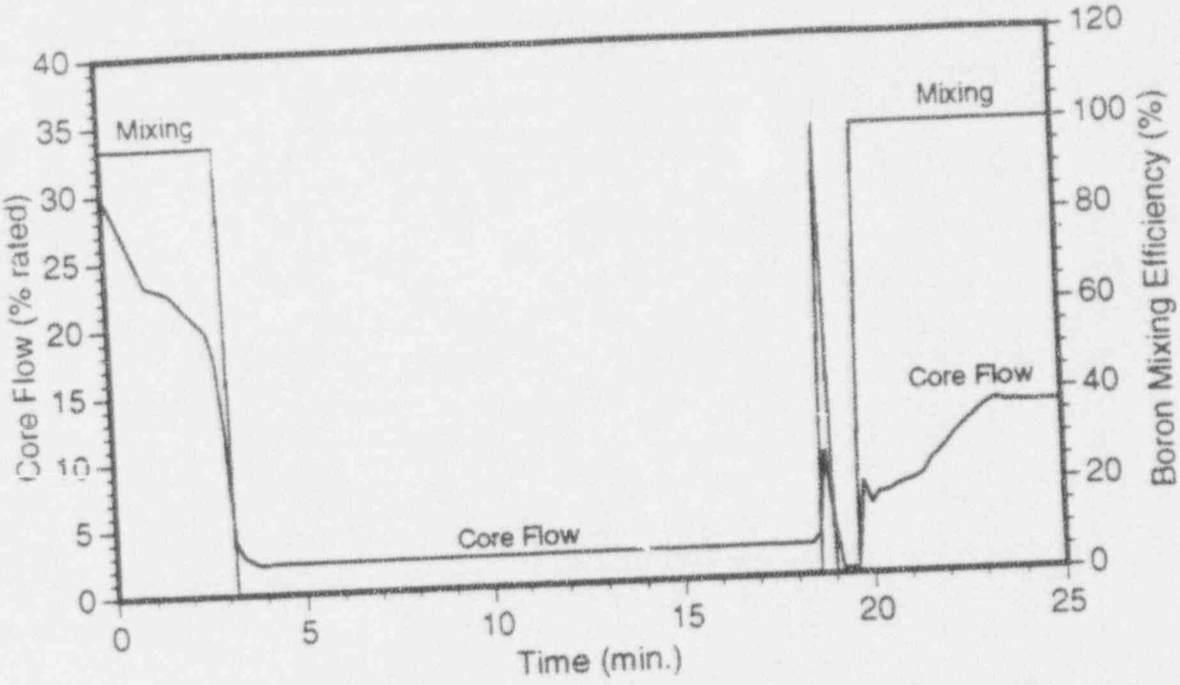

Figure 5.1.1-3 Core inlet flow and boron mixing efficiency, BWR/4, EPG water level control

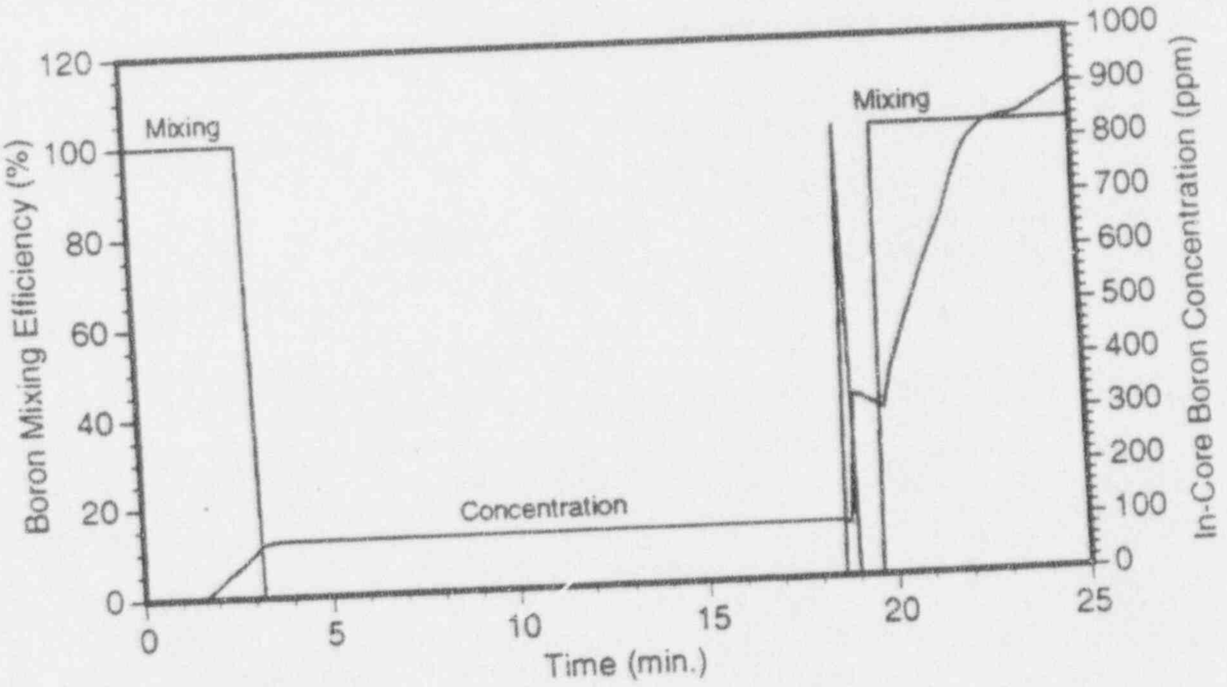

Figure 5.1.1-4 Boron mixing efficiency and in-core boron concentration, BWR/4, EPG water level control

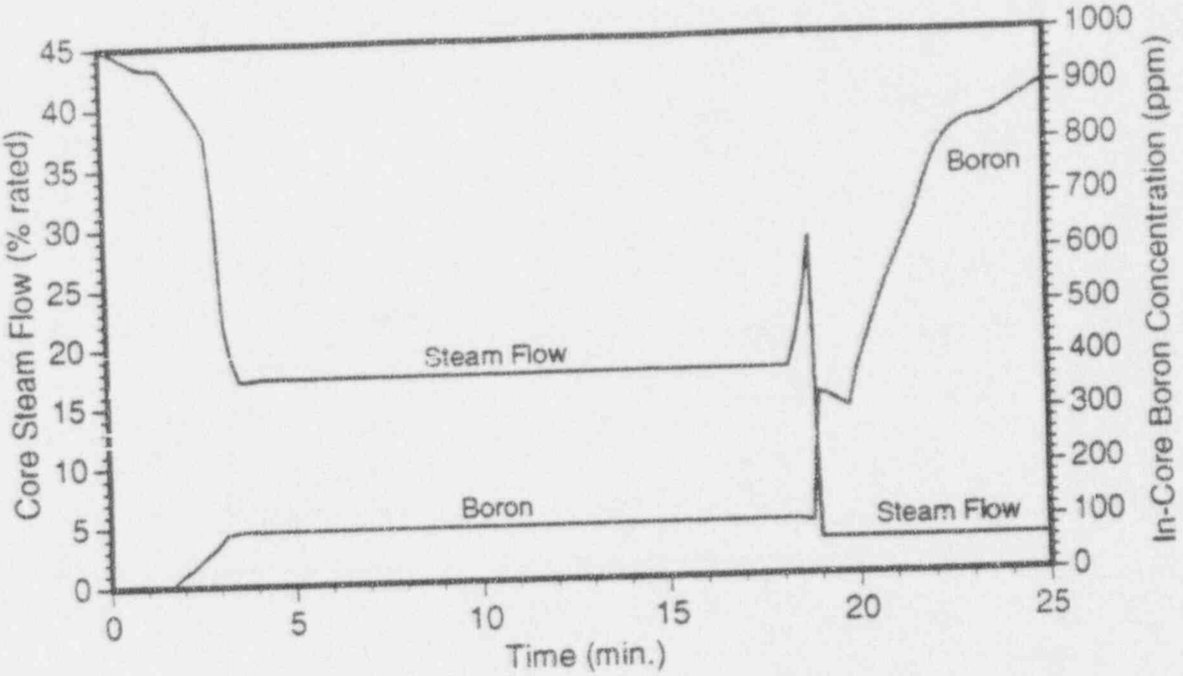

Figure 5.1.1-5 In-core boron concentration and core steam flow, BWR/4, EPG water level control

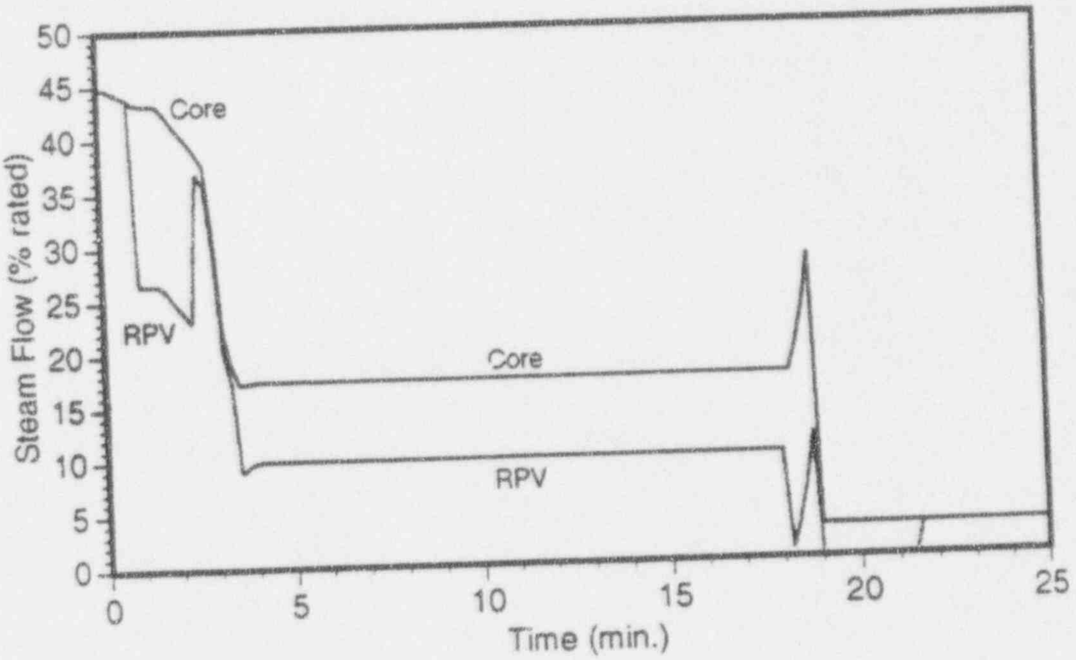

Figure 5.1.1-6 Core steam flow and RPV steam flow, BWR/4, EPG water level control

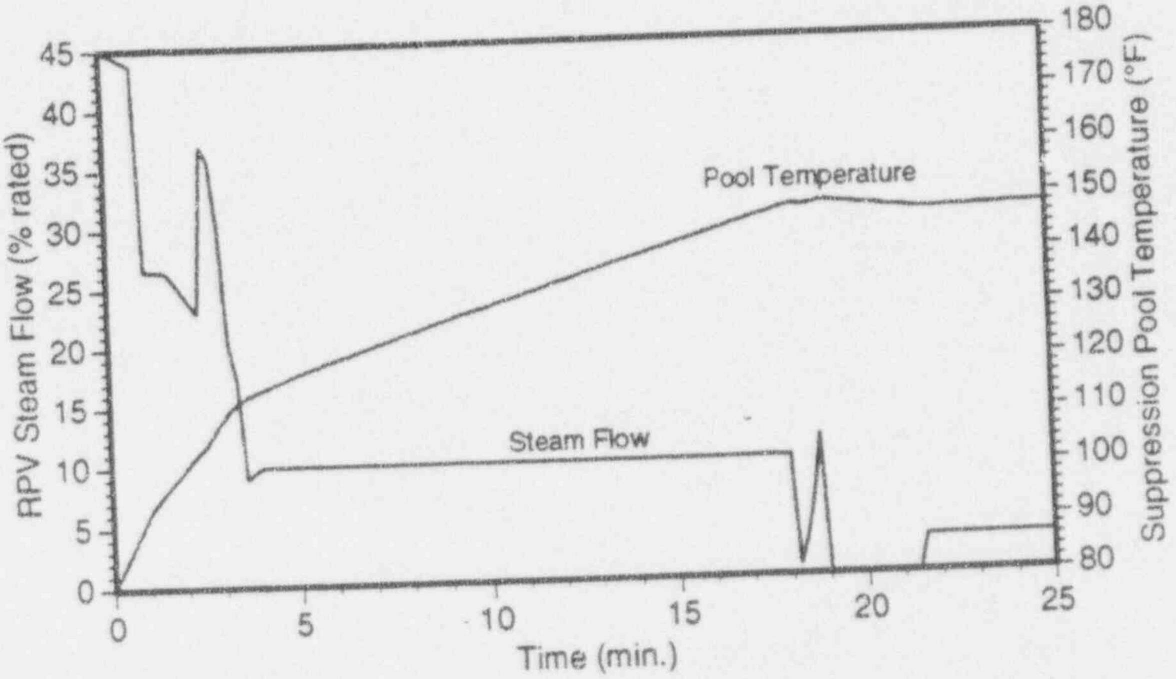

Figure 5.1.1-7 RPV steam flow and suppression pool temperature, BWR/4, EPG water level control

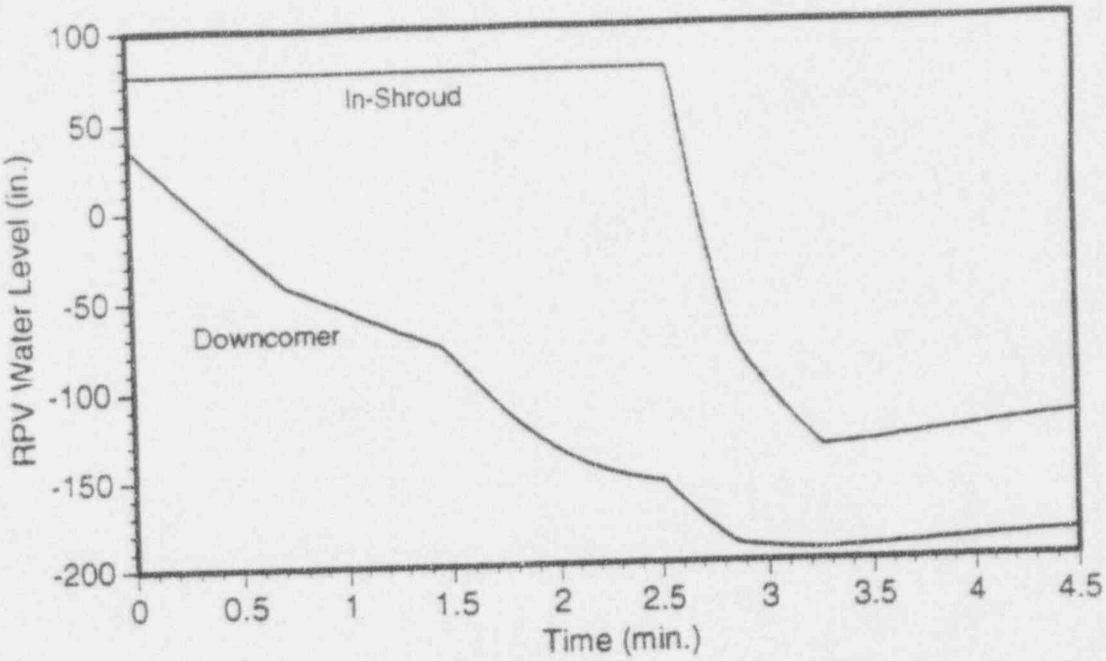

Figure 5.1.1-8 RPV water level, BWR/6, EPG water level control

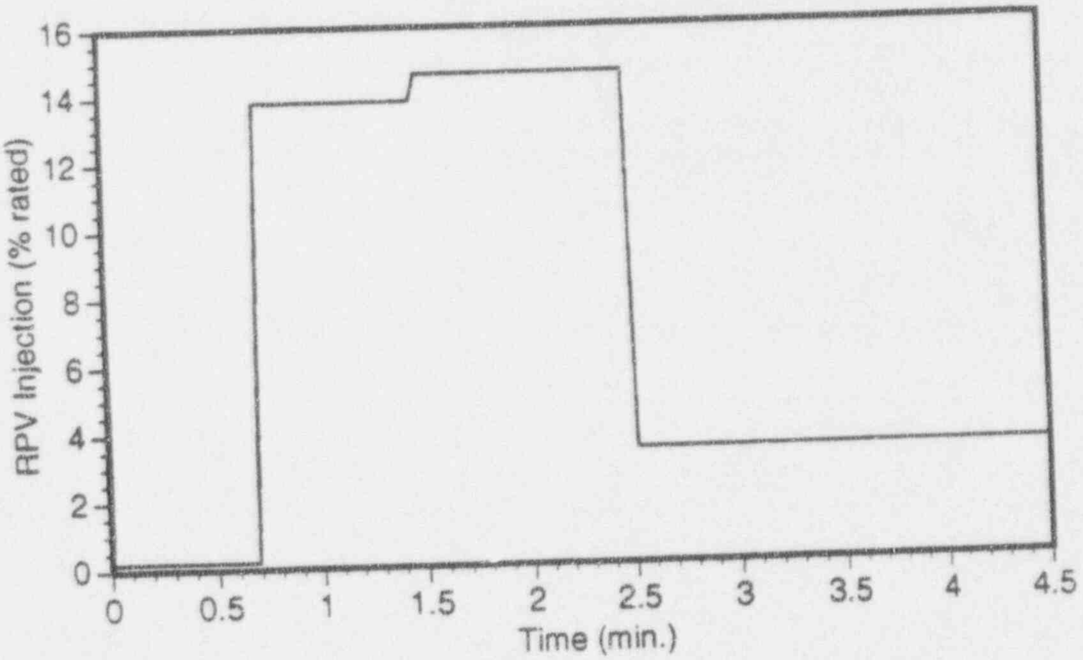

Figure 5.1.1-9 RPV injection, BWR/6, EPG water level control

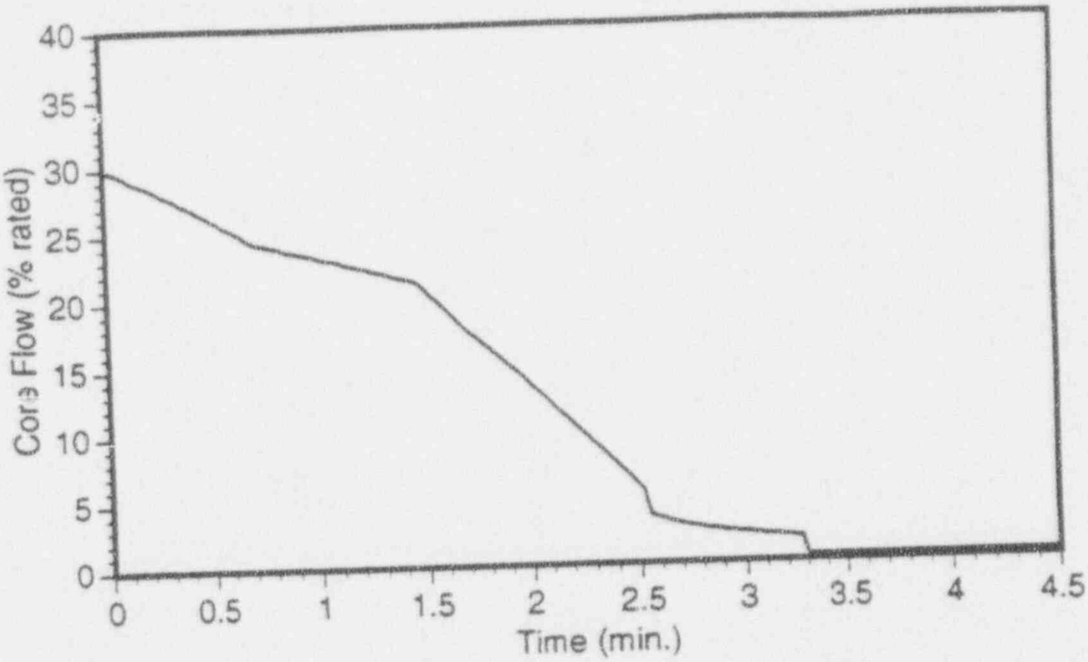

Figure 5.1.1-10 Core inlet flow, BWR/6, EPG water level control

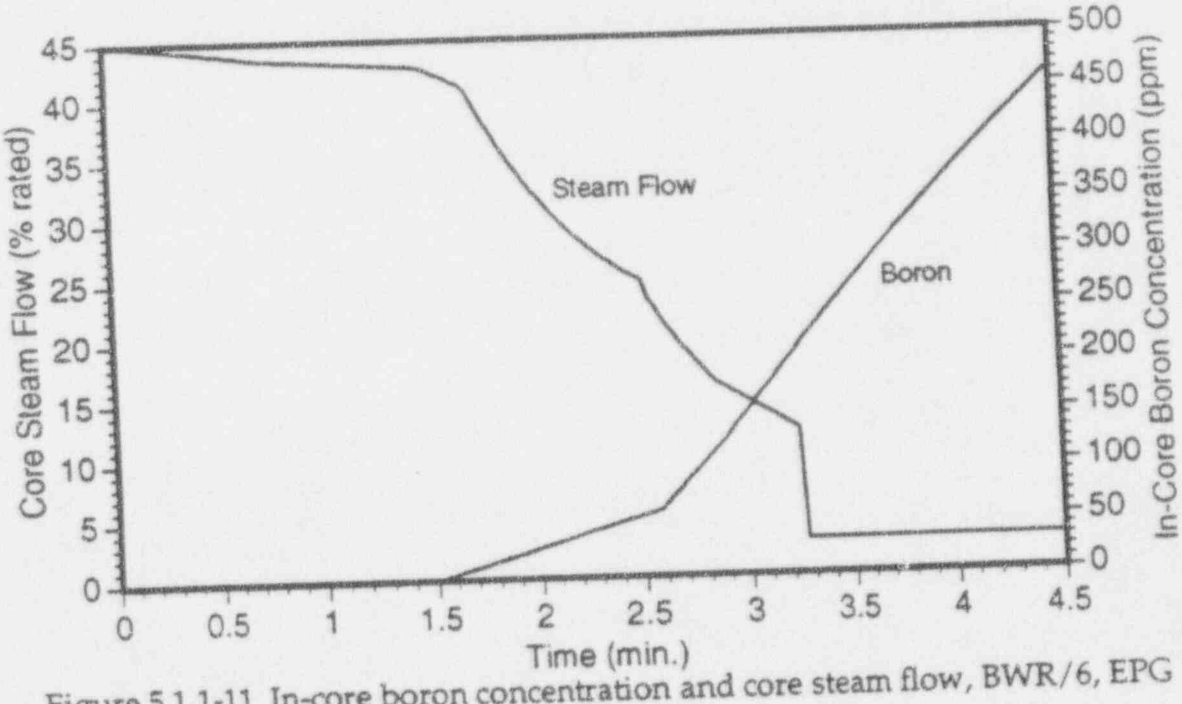

Figure 5.1.1-11 In-core boron concentration and core steam flow, BWR/6, EPG water level control

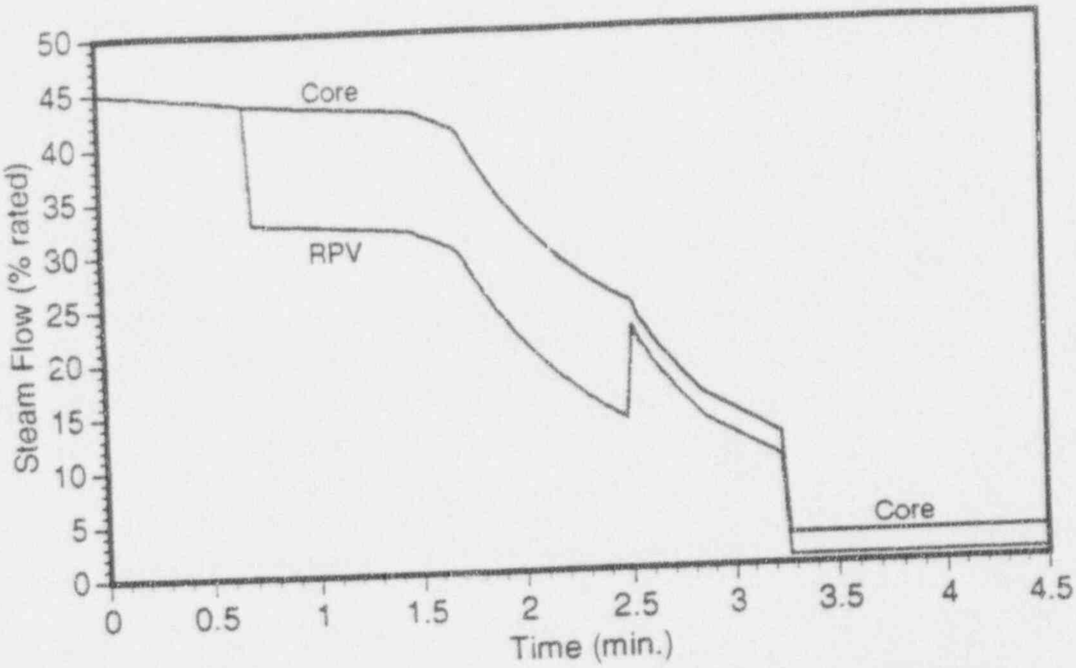

Figure 5.1.1-12 Core steam flow and RPV steam flow, BWR/6, EPG water level control

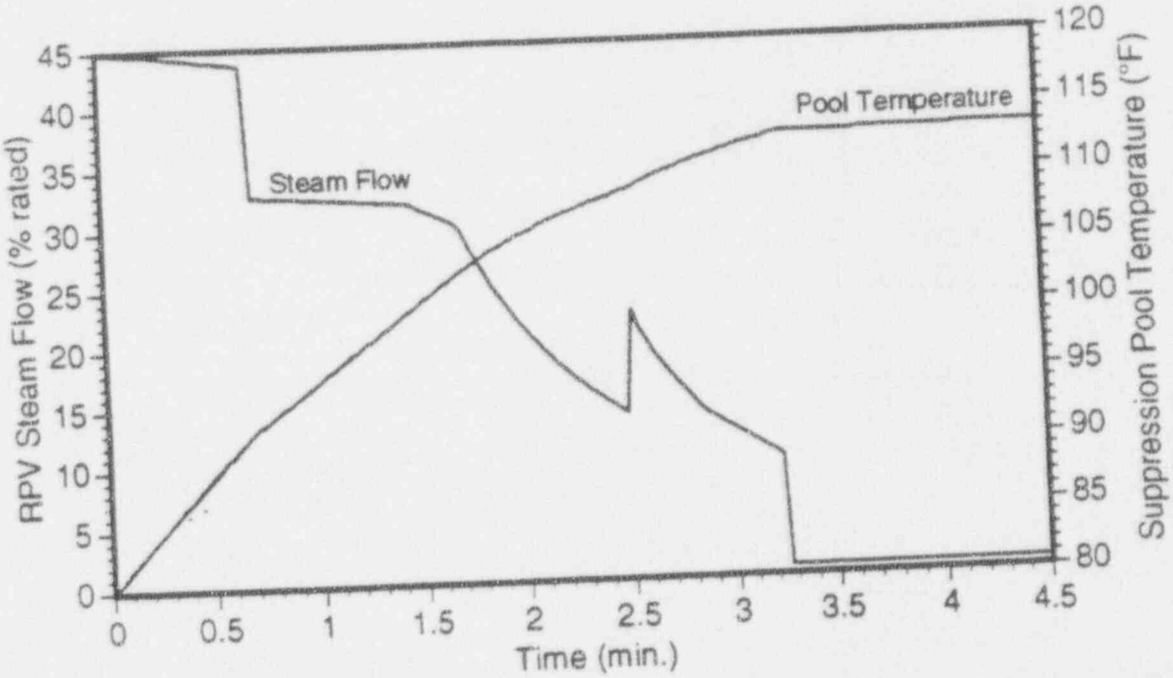

Figure 5.1.1-13 RPV steam flow and suppression pool temperature, BWR/6, EPG water level control

Plant	Containment Type	Heat Capacity Temperature Limit (°F)	Pool Temperature at Reactor Shutdown (°F)	Margin (°F)
BWR/2	Mark I	196	155	41
BWR/3	Mark I	180	157	23
BWR/4	Mark I	180	149	31
BWR/5	Mark II	162	109	53
BWR/6	Mark III	120	113	7

Table 5.1.1-1 Containment response, EPG water level control

5.1.2 Alternate RPV Water Level Control

Since the Revision 4 EPGs[1,2] were submitted in 1986, various alternatives to the ATWS mitigation actions specified in the EPGs have been suggested. Specifically, it has been proposed[4] that RPV water level should not be lowered to below TAF under ATWS conditions but rather should be controlled approximately five feet above TAF in order to promote better boron mixing and therefore, presumably, shut down the reactor sooner.

This alternate method of RPV water level control has been evaluated using the analysis model described in Section 3, and the results of this evaluation are presented in this section. For purposes of comparison, the alternate method of water level control is referred to as Strategy A, and the BWROG EPG method of water level control is denoted Strategy B. The reactor and containment response under Strategy B have been described in the preceding section.

The plant response to Strategy A is illustrated by the response of the representative BWR/4 plant. The principal RPV and primary containment parameters from this plant are plotted in this section.

The transient proceeds as described in the preceding section, except that downcomer water level is controlled five feet above TAF instead of between the MSCRWL and TAF. The higher water level initially results in increased core inlet flow, reactor power, and core steam flow, but these decrease as soluble boron is transported to the core region. The increase in in-core boron concentration reduces reactor power and core steam flow by decreasing the core average void fraction. This in turn decreases the natural circulation driving head and, as a result, core inlet flow. At some point, as with Strategy B, the core inlet flow drops below the minimum required for effective boron mixing, and in-core boron concentration, reactor power, and core steam flow stabilize. After the operator has injected the HSBW, injection into the RPV is increased to raise downcomer water level and increase core inlet flow. As core flow increases, the previously unmixed boron is swept from the lower plenum into the core region, and the reactor shutdown is completed.

The principal RPV and primary containment parameters for this transient in the representative BWR/4 plant are plotted in the following figures:

Figure 5.1.2-1	RPV water level
Figure 5.1.2-2	RPV injection
Figure 5.1.2-3	Core inlet flow and boron mixing efficiency
Figure 5.1.2-4	Boron mixing efficiency and in-core boron concentration
Figure 5.1.2-5	In-core boron concentration and core steam flow
Figure 5.1.2-6	Core steam flow and RPV steam flow
Figure 5.1.2-7	RPV steam flow and suppression pool temperature

The containment response of each of the representative plants following each strategy is presented in Table 5.1.2-1. It should be noted that it is not possible to implement Strategy A in the representative BWR/5 and BWR/6 plants because the high-pressure outside-shroud injection capacity in these plants is insufficient to preclude RPV water level from dropping below TAF. It is not possible to implement Strategy A in the representative BWR/2 plant because the feedwater sparger is only 67 inches above TAF in this plant, and downcomer water level must be maintained at least 24 inches below the feedwater sparger in order to minimize the potential for reactor instabilities. The representative plants which are capable of implementing Strategy A reach hot shutdown before suppression pool temperature reaches the HCTL. For these cases, the margin to HCTL at reactor shutdown is approximately twice as great following Strategy B as opposed to Strategy A.

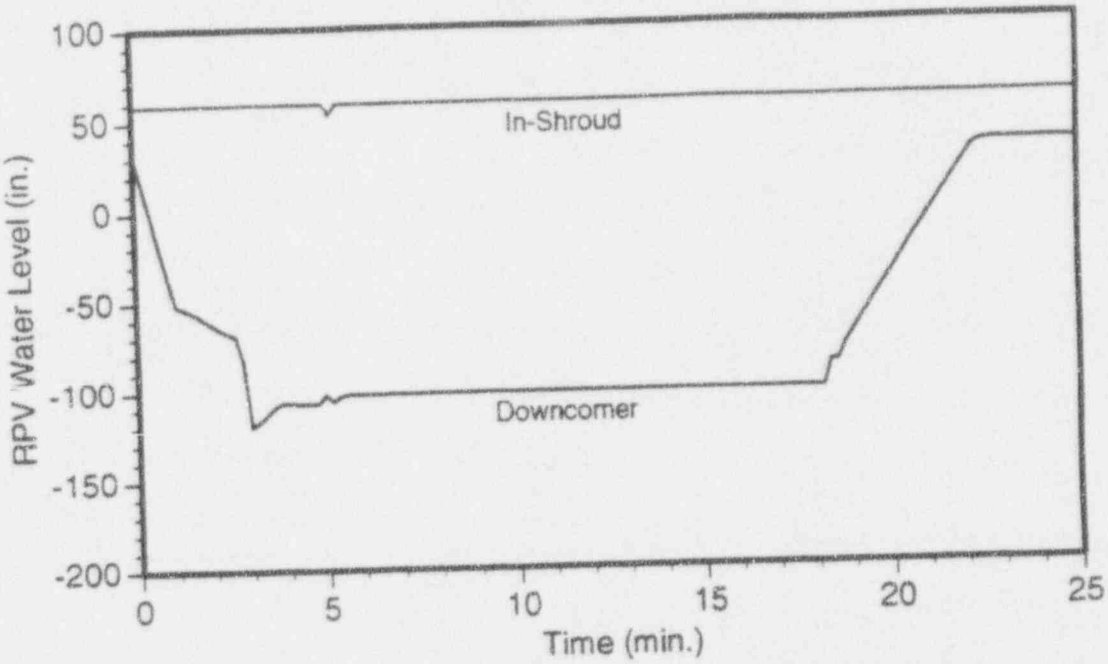

Figure 5.1.2-1 RPV water level, BWR/4, alternate water level control

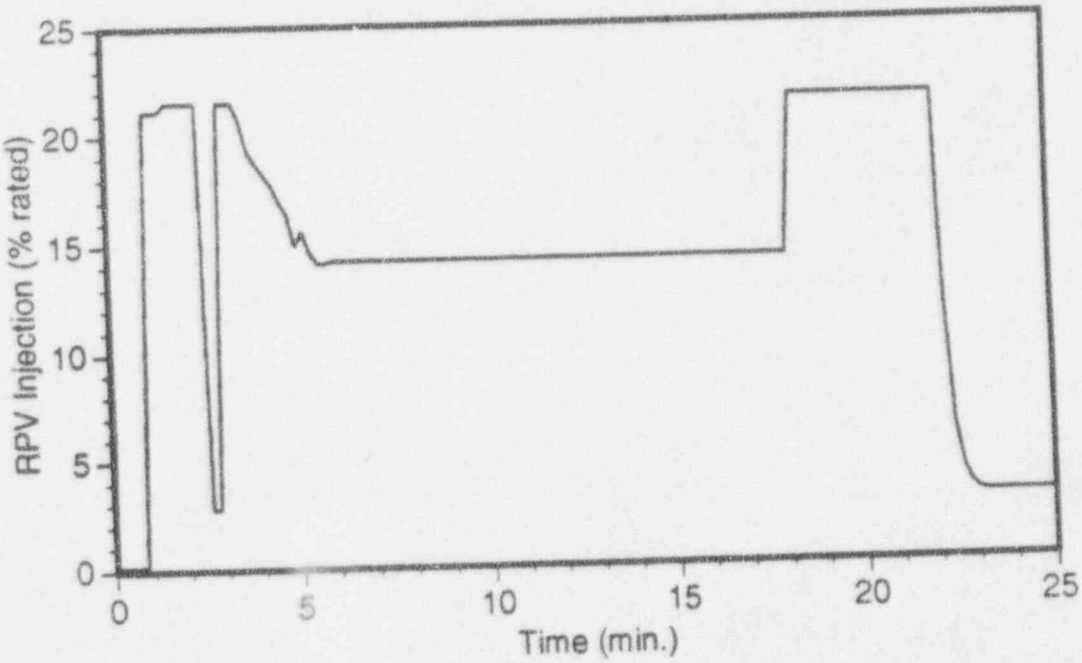

Figure 5.1.2-2 RPV injection, BWR/4, alternate watcr level control

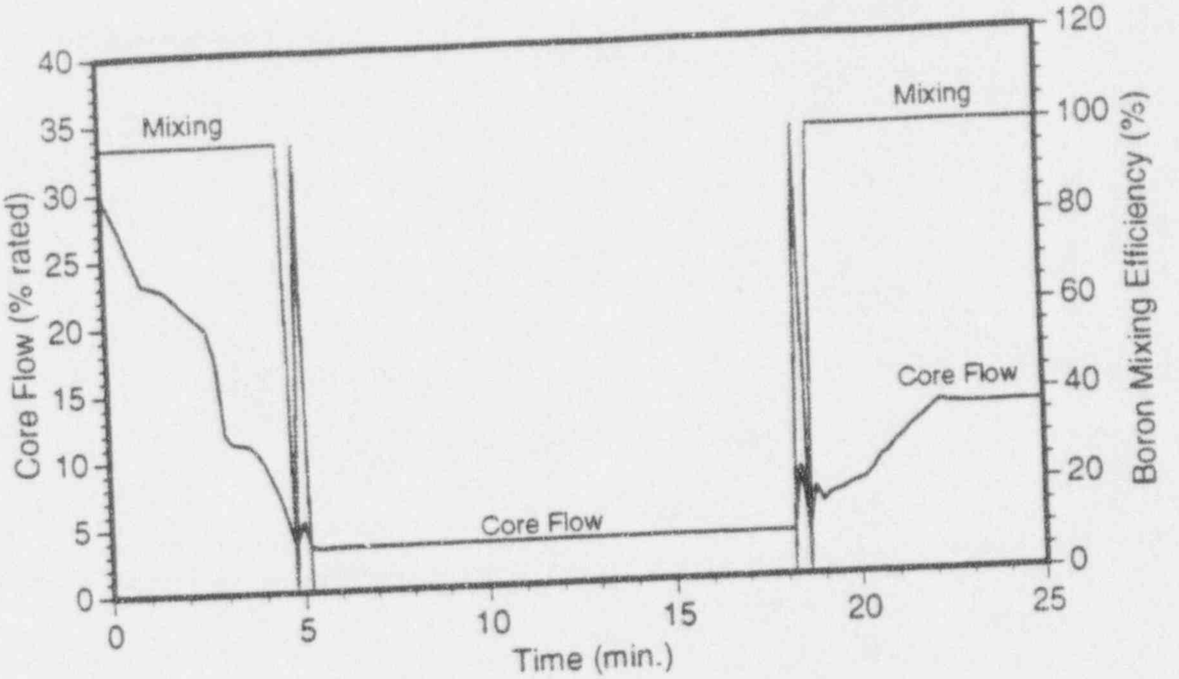

Figure 5.1.2-3 Core inlet flow and boron mixing efficiency, BWR/4, alternate water level control

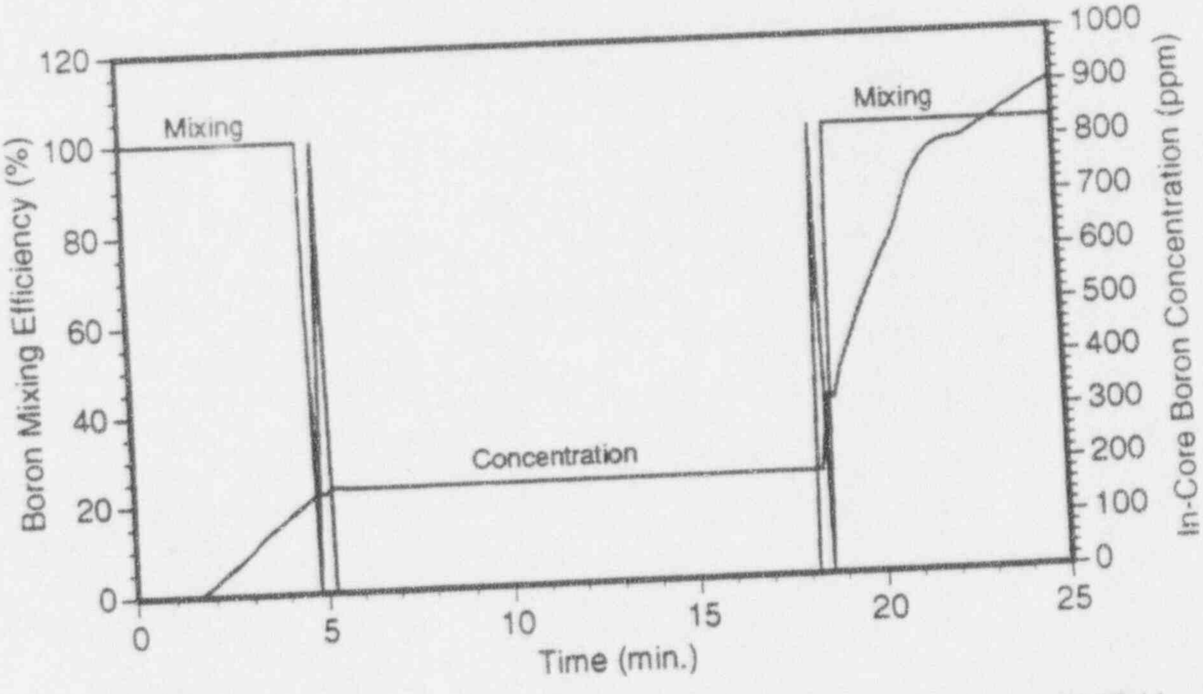

Figure 5.1.2-4 Boron mixing efficiency and in-core boron concentration, BWR/4, alternate water level control

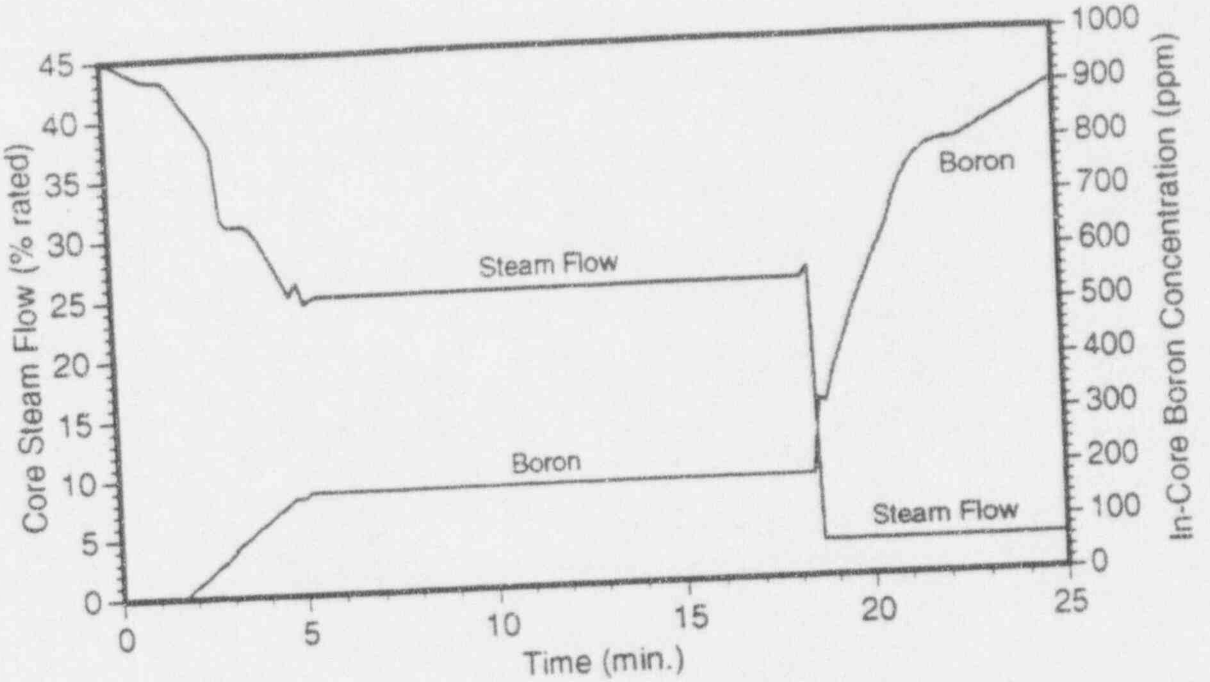

Figure 5.1.2-5 In-core boron concentration and core steam flow, BWR/4, alternate water level control

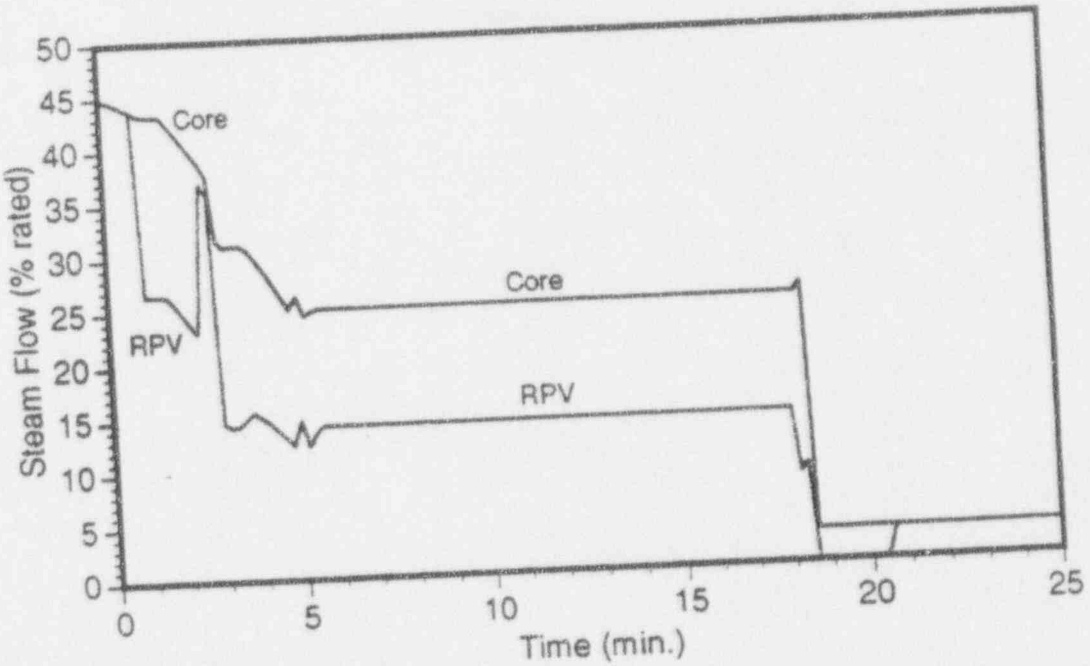

Figure 5.1.2-6 Core steam flow and RPV steam flow, BWR/4, alternate water level control

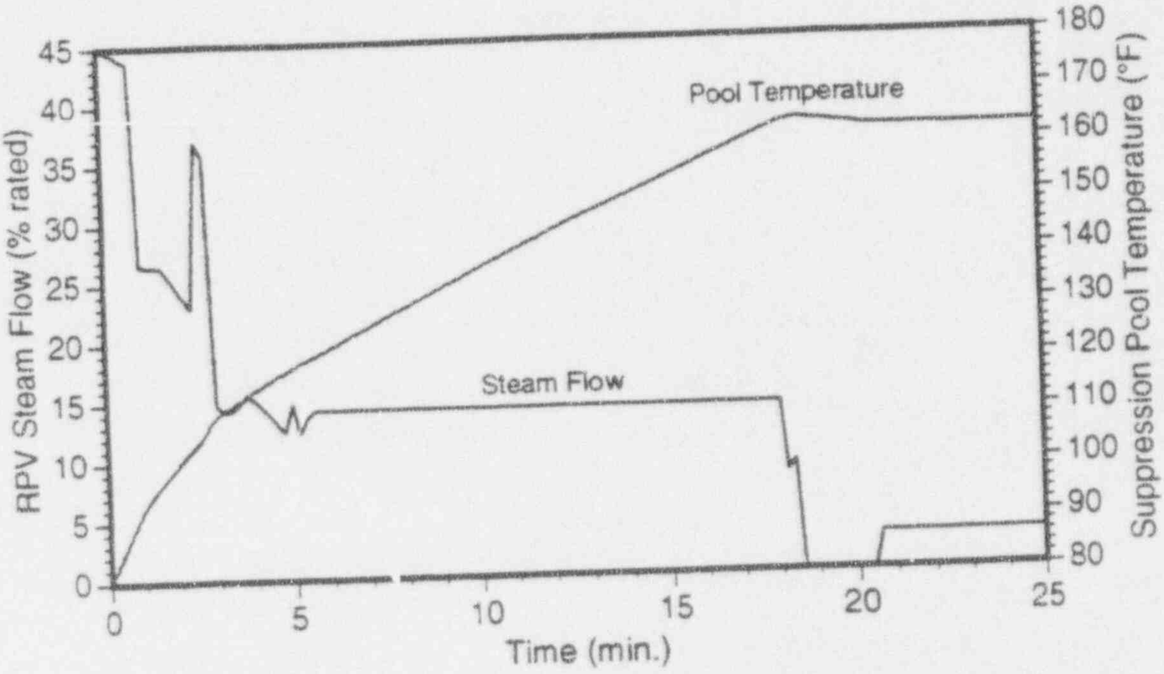

Figure 5.1.2-7 RPV steam flow and suppression pool temperature, BWR/4, alternate water level control

Plant	Margin to HCTL (°F)	
	Strategy A	Strategy B
BWR/2	Note (1)	41
BWR/3	12	23
BWR/4	16	31
BWR/5	Note (2)	53
BWR/6	Note (2)	7

Table 5.1.2-1: Containment response, two RPV water level control strategies

Note (1) Strategy A cannot be implemented consistent with the EPG changes proposed by the BWROG to mitigate potential reactor instabilities.

Note (2) Strategy A cannot be implemented because the high-pressure outside-shroud injection capacity is insufficient to preclude RPV water level from dropping below TAF.

5.2 Containment Response Without Boron Injection

If boron cannot be injected into the RPV and control rods cannot be inserted, the reactor cannot be shutdown and suppression pool temperature will increase until the HCTL is reached. When this occurs RPV depressurization is required, which will further increase pool temperature. Pool temperature and primary containment pressure will continue to increase following the RPV depressurization until the Primary Containment Pressure Limit (PCPL) is reached. When this occurs, the primary containment must be vented to assure its continued integrity.

The transient is illustrated by the response of the representative BWR/4 plant. The important reactor and primary containment parameters following each of the two potential RPV water level control strategies are plotted as a function of time in the following figures:

Figure 5.2-1	Collapsed downcomer water level
Figure 5.2-2	Suppression pool temperature
Figure 5.2-3	Primary containment pressure

The containment response under each of the two potential RPV water level control strategies is similar except for the rate at which suppression pool temperature and primary containment pressure increase. Under Strategy A, suppression pool temperature reaches the HCTL and the RPV must be depressurized 16.5 minutes after the MSIVs close. Under Strategy B nearly twice as much time, 29 minutes, elapses before the RPV must be depressurized.

The difference in containment response is even more pronounced with respect to primary containment pressure. Under Strategy A, the PCPL is reached and the containment must be vented 47 minutes after the MSIVs close. Under Strategy B, the operating crew has nearly two hours (108 minutes) to prepare to vent the containment. This is particularly significant since, for most plants, the Technical Support Center (TSC) is expected to be operational between one and two hours after the initiation of an event. Thus under Strategy A, the operating crew can expect no assistance in assessing the radionuclide inventory in the containment or determining which areas, if any, should be evacuated prior to venting the containment. On the other hand, Strategy B permits the emergency response organization to become operational, support the operating crew, and interface with Federal and state authorities regarding the potential for evacuation and other matters of public health and safety.

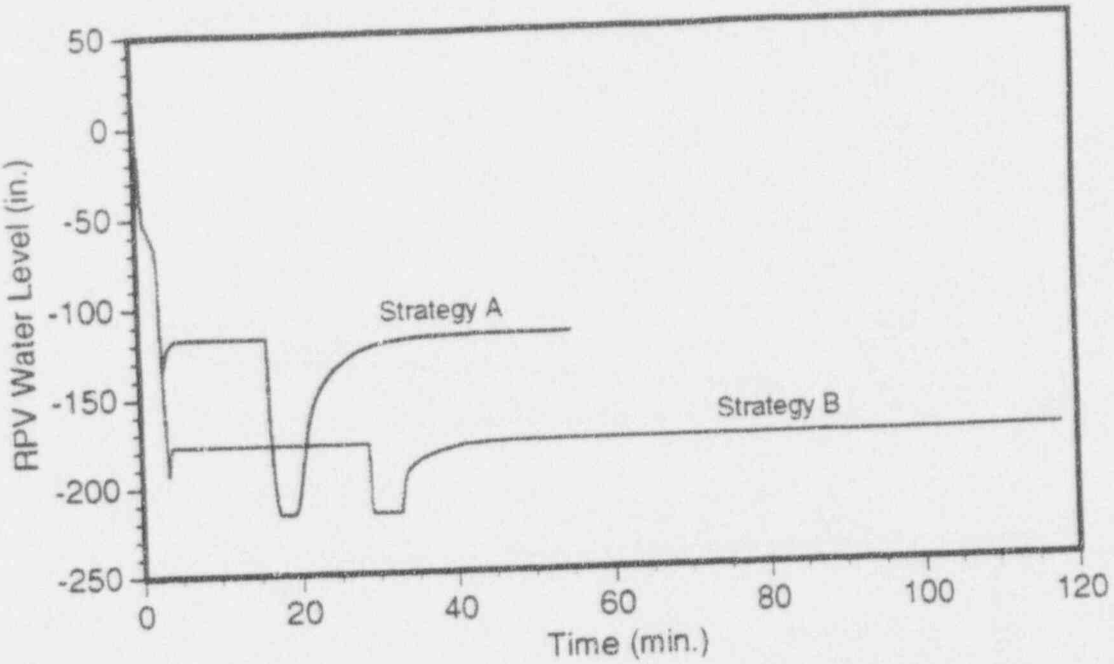

Figure 5.2-1 Collapsed downcomer water level, no boron injection, BWR/4, two RPV water level control strategies

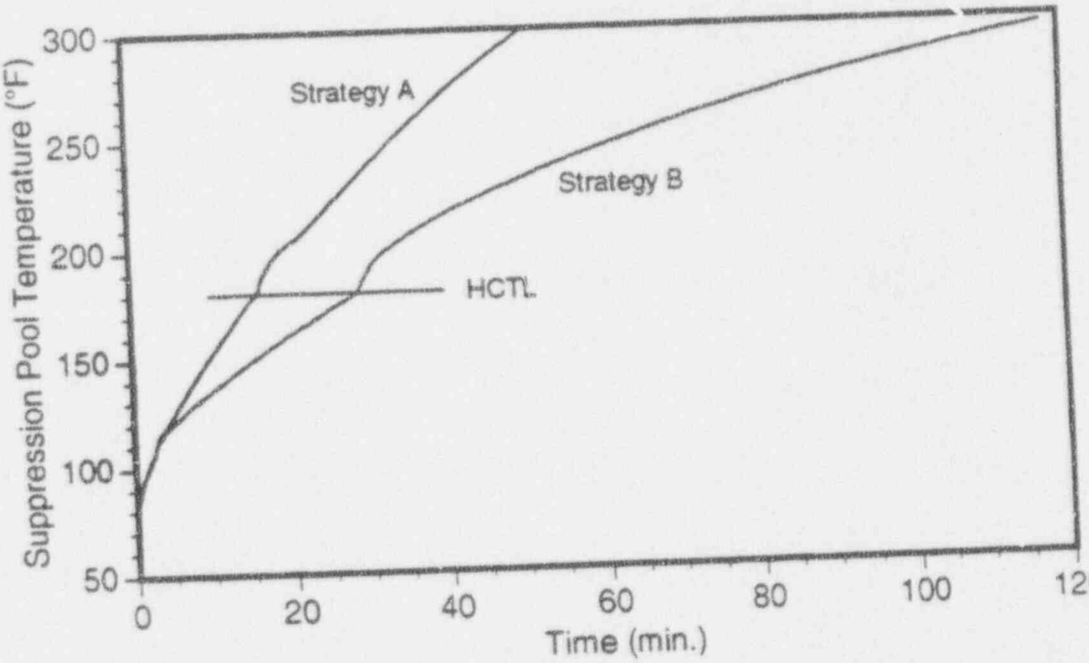

Figure 5.2-2 Suppression pool temperature, no boron injection, BWR/4, two RPV water level control strategies

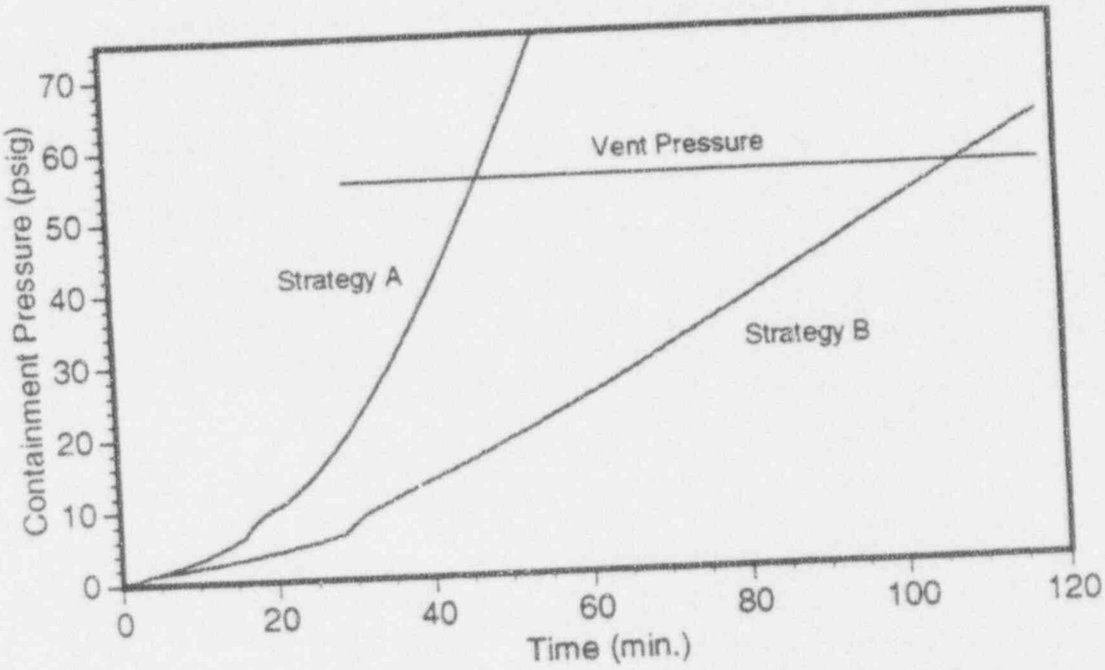

Figure 5.2-3 Primary containment pressure, no boron injection, BWR/4, two RPV water level control strategies

Section 6

UNCERTAINTY AND SENSITIVITY

Uncertainty in the important assumptions and the sensitivity of the analysis results to variations in these assumptions are discussed in this section. The representative BWR/4 plant is employed to assess the sensitivity of the analysis results to variations in these assumptions. In general, sensitivity is illustrated by varying the parameter of interest above and below the value assumed in the base analyses reported in Section 5, calculating the suppression pool temperature at which the reactor is ultimately shut down under these conditions, and fairing a second-order polynomial curve through the results. Unless otherwise stated, the sensitivities are calculated for initial operation on the 100% rod line, perfect mixing above five percent rated core inlet flow, and operator actions in accordance with the EPGs[1,2] as the BWROG proposes to modify them[5].

6.1 Boron Mixing Efficiency

The results discussed in Section 5 were obtained assuming perfect (100%) boron mixing above five percent rated core inlet flow and no boron mixing below this threshold. This assumption is supported by the recent studies by Dr. T. Theofanous and others[4] utilizing a full-scale test facility. However, there remains considerable uncertainty in the boron mixing phenomenon under actual reactor operating conditions.

Figure 6.1-1 illustrates the effect of varying the boron mixing threshold between four and ten percent rated core inlet flow. As expected, an increase in the threshold is accompanied by an increase in the suppression pool temperature when the reactor is ultimately shutdown. The effect is small due the rapidity with which core inlet flow decreases when soluble boron reaches the core. Strategy B results in the lower suppression pool temperature for all boron mixing thresholds.

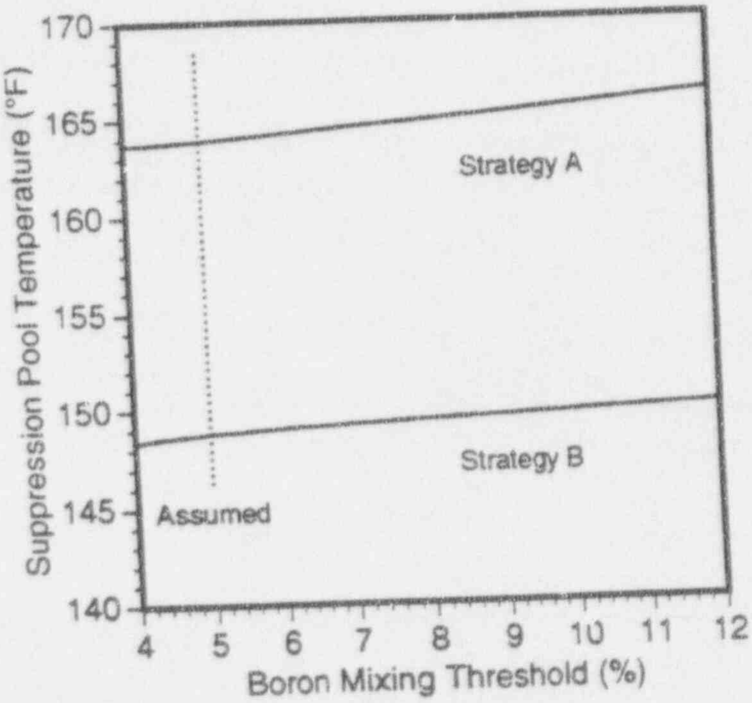

Figure 6.1-1 Suppression pool temperature, BWR/4, various boron mixing thresholds

6.2 Initial Temperatures

The results discussed in Section 5 were obtained assuming nominal year-round average temperatures for service water and the water in the suppression pool, the Condensate Storage Tank (CST), and the Standby Liquid Control System (SLCS) storage tank. Variation in these temperatures is expected.

Figure 6.2-1 illustrates the effect of variations in the initial suppression pool temperature. As expected, a higher initial suppression pool temperature results in a higher suppression pool temperature when the reactor is ultimately shutdown. The effect is essentially the same for both RPV water level control strategies. Strategy B results in the lower final suppression pool temperature for all initial suppression pool temperatures.

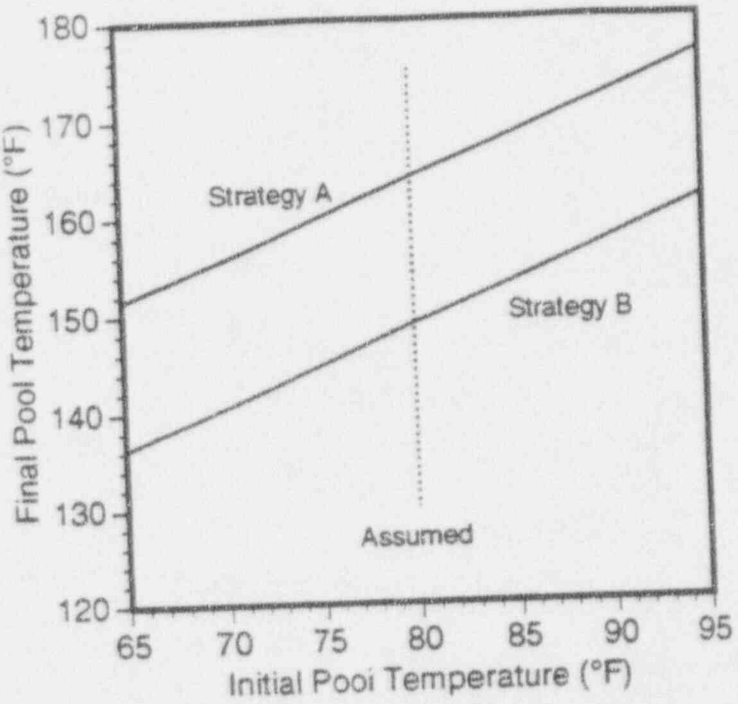

Figure 6.2-1 Suppression pool temperature, BWR/4, various initial pool temperatures

Figure 6.2-2 illustrates the effect of variations in the temperature of the service water. Higher service water temperature reduces the Residual Heat Removal (RHR) system efficiency and decreases suppression pool cooling during the transient, causing a higher suppression pool temperature when the reactor is ultimately shutdown. The effect is small and essentially the same for both RPV water level control strategies. Strategy B results in the lower suppression pool temperature for all initial service water temperatures.

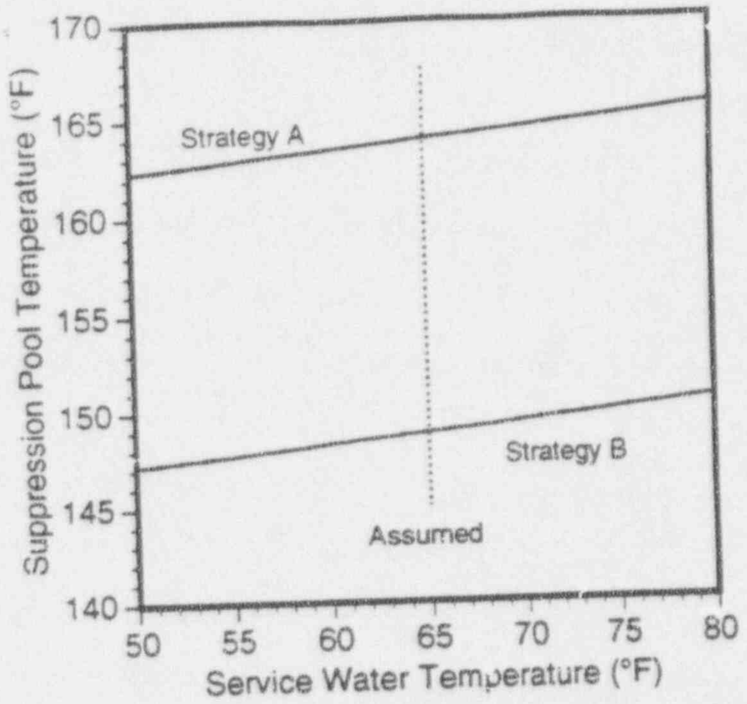

Figure 6.2-2 Suppression pool temperature, BWR/4, various service water temperatures

Variation in the CST or SLCS storage tank temperature has little effect on the suppression pool temperature. Raising or lowering each temperature twenty degrees above or below its assumed value results in less than one degree change in the pool temperature when the reactor is ultimately shutdown.

6.3 Operator Action Timing

In order to perform the analyses, it is necessary to make certain assumptions with respect to the timing of operator actions during the course of the transient. These are identified and discussed in Section 3.2. The sensitivity of the results of the analyses to these assumptions is evaluated in this section.

6.3.1 Boron Injection Initiation

The operator is directed by the EPGs to initiate the Standby Liquid Control System (SLCS) and inject soluble boron into the RPV before suppression pool temperature reaches the Boron Injection Initiation Temperature (BIIT), which is typically 110 °F for the high reactor power associated with this transient.

After the operator initiates the SLCS, between fifteen and sixty seconds is required for soluble boron to begin reaching the RPV. Figure 6.3.1-1 illustrates the effect of variations in the time required for soluble boron to reach the RPV. As expected, an increase in the length of time required for soluble boron to reach the RPV is accompanied by an increase in the suppression pool temperature when the reactor is ultimately shutdown. Strategy B results in the lower suppression pool temperature for all time intervals evaluated.

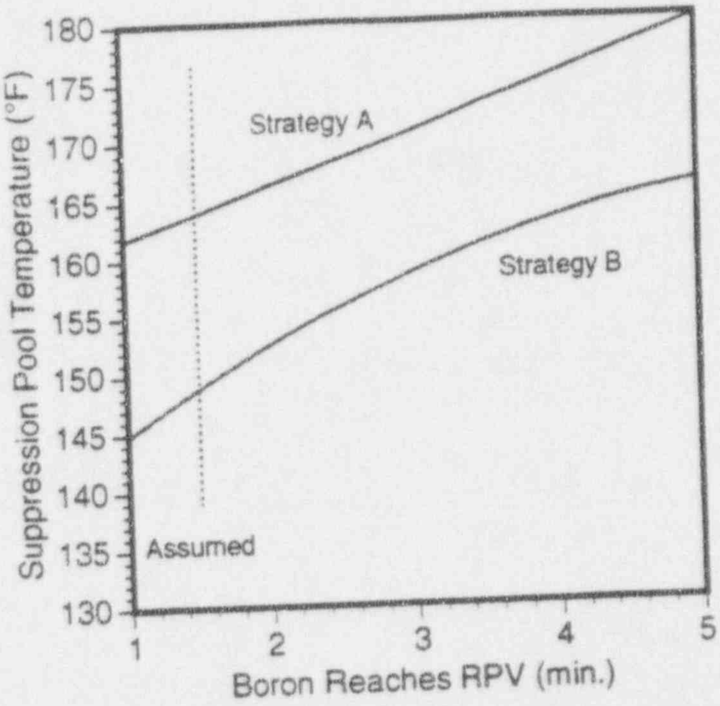

Figure 6.3.1-1 Suppression pool temperature, BWR/4, various times for soluble boron to reach the RPV

6.3.2 RPV Injection Termination

The operator is directed by the EPGs to terminate injection into the RPV and to lower RPV water level to below the feedwater sparger as soon as the scram failure condition is identified.

Figure 6.3.2-1 illustrates the effect of variations in the time at which injection into the RPV is terminated in order to lower RPV water level. The effect is small, and Strategy B results in the lower suppression pool temperature for all RPV injection termination times evaluated.

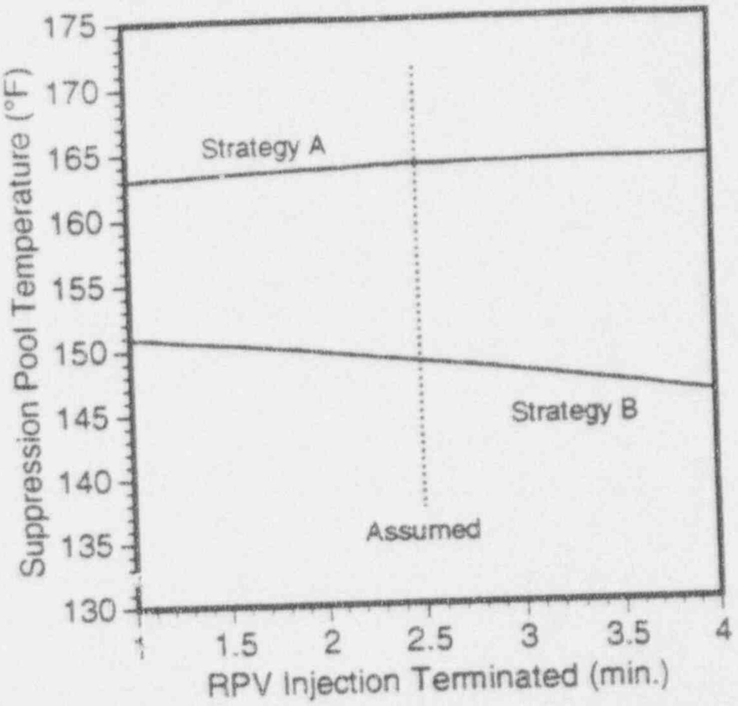

Figure 6.3.2-1 Suppression pool temperature, BWR/4, various RPV injection termination times

6.3.3 Suppression Pool Cooling Initiation

The operator is directed by the EPGs to place all available suppression pool cooling in service when pool temperature reaches the most limiting Limiting Condition for Operation (LCO) for the plant, typically between 90 and 95 °F.

Figure 6.3.3-1 illustrates the effect of variations in the time at which suppression pool cooling is initiated. As expected, an increase in the suppression pool cooling initiation time is accompanied by an increase in the suppression pool temperature when the reactor is ultimately shutdown. The effect is essentially the same for both RPV water level control strategies. Strategy B results in the lower suppression pool temperature for all suppression pool cooling initiation times evaluated.

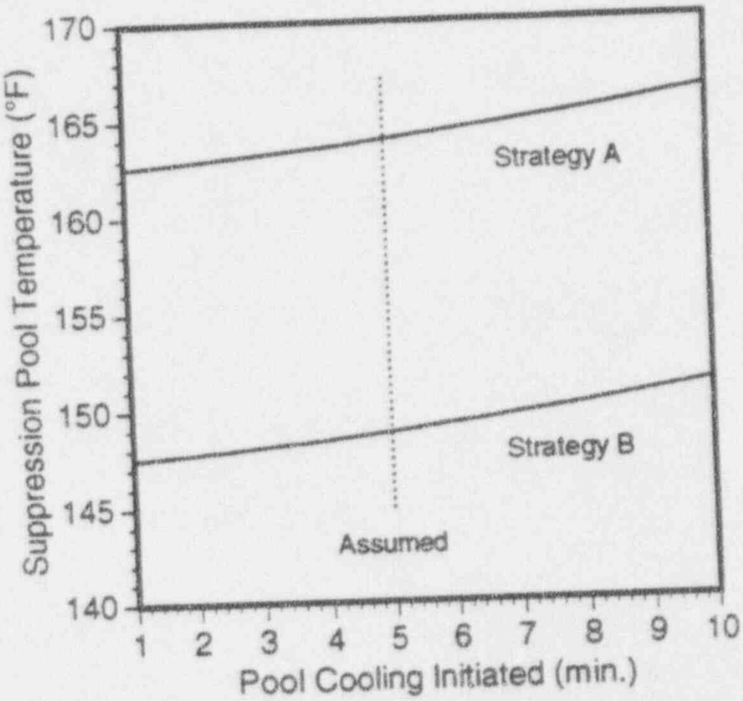

Figure 6.3.3-1 Suppression pool temperature, BWR/4, various suppression pool cooling initiation times

6.4 System Performance

In order to properly reflect actual system performance, the minimum or design specifications for certain equipment were adjusted by assumed performance margins in the model to account for the equipment performance typically observed during periodic surveillance testing. These assumed margins are identified and discussed in Section 3.2. The sensitivity of the results of the analyses to variations in these margins is evaluated in this section.

6.4.1 Standby Liquid Control System

The principal components of the SLCS are a storage tank containing an aqueous solution of sodium pentaborate, pumps which may be aligned to take suction on the tank, and the valves and piping necessary to transport the sodium pentaborate solution from the storage tank to the RPV.

Plant technical specifications require a minimum concentration of sodium pentaborate in the SLCS storage tank. Plant administrative procedures generally require a somewhat greater concentration to assure that the technical specification requirement will always be met. Thus it can be expected that the actual SLCS storage tank sodium pentaborate solution concentration will exceed the technical specification requirement by some margin.

A typical SLCS tank sodium pentaborate solution margin is assumed in the analysis. Figure 6.4.1-1 illustrates the effect of variations in this margin on the results of the analysis. Generally, an increase in the SLCS tank solution margin is accompanied by an decrease in the suppression pool temperature when the reactor is ultimately shutdown. Strategy B results in the lower suppression pool temperature for all SLCS tank solution concentration margins evaluated.

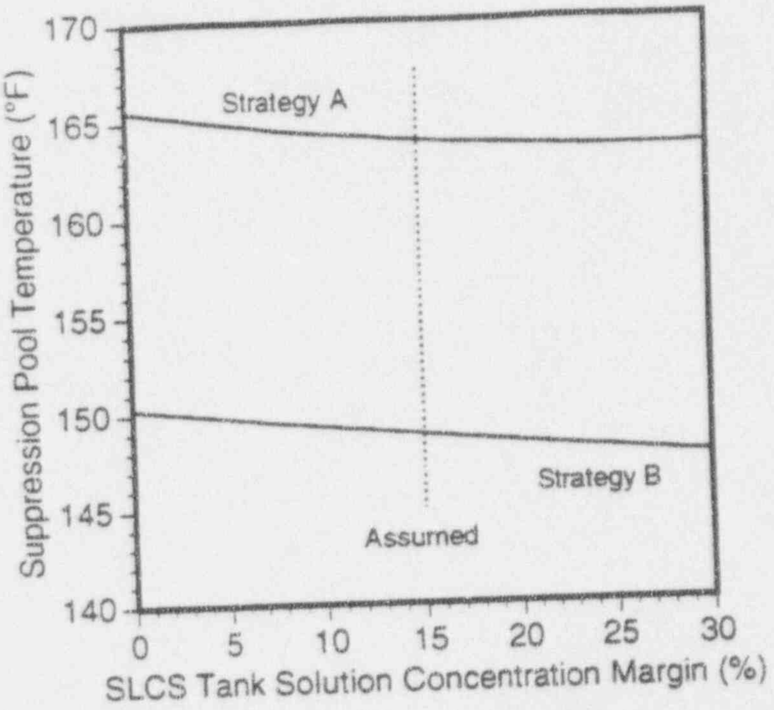

Figure 6.4.1-1 Suppression pool temperature, BWR/4, various SLCS storage tank sodium pentaborate solution concentration margins

Plant technical specifications also require a minimum capacity for the SLCS pumps. Each pump is periodically tested to assure that the minimum required capacity can be achieved. The results of these tests indicate that a significant margin exists between the required pump capacity and the actual measured capacity.

A typical SLCS pump performance margin is assumed in the analysis. Figure 6.4.1-2 illustrates the effect of variations in this margin on the results of the analysis. As expected, an increase in the pump performance margin is accompanied by an decrease in the suppression pool temperature when the reactor is ultimately shutdown. The effect is essentially the same for both RPV water level control strategies. Strategy B results in the lower suppression pool temperature for all SLCS pump performance margins evaluated.

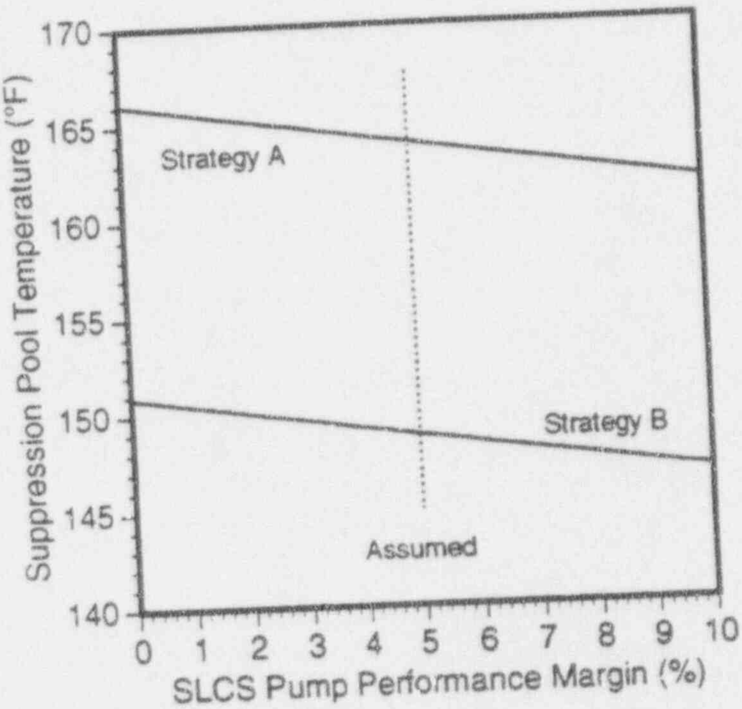

Figure 6.4.1-2 Suppression pool temperature, BWR/4, various SLCS pump performance margins

6.4.2 Suppression Pool Cooling System

The suppression pool cooling system was designed to accommodate pump and heat exchanger degradation over the life of the plant. System testing indicates that a significant difference between design and actual system performance exists even after many years of plant operation.

A typical suppression pool cooling system performance margin is assumed in the analysis. Figure 6.4.2-1 illustrates the effect of variations in this margin on the results of the analysis. As expected, improved suppression pool cooling results in lower ultimate suppression pool temperatures, but the effect is small for both RPV water level control strategies. Strategy B results in the lower suppression pool temperature for all suppression pool cooling system performance margins evaluated.

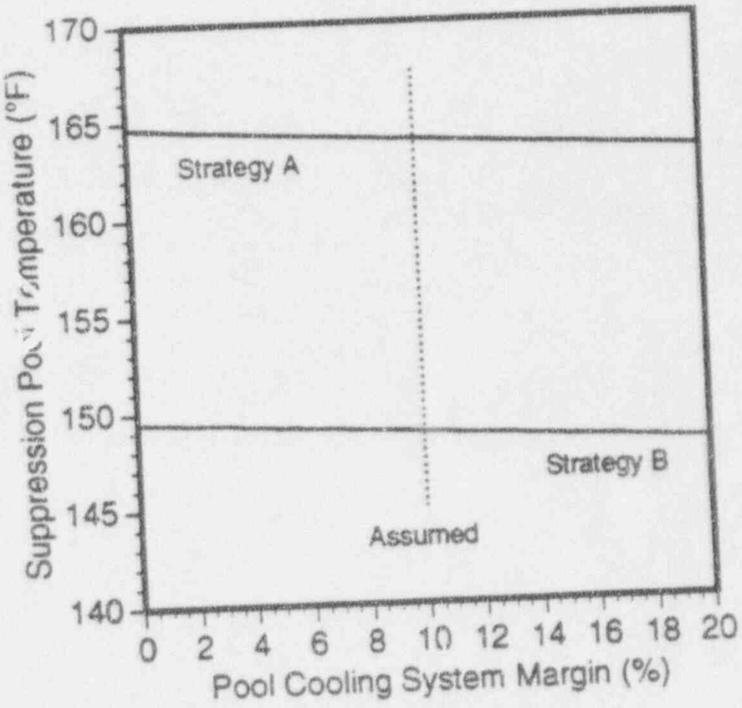

Figure 6.4.2-1 Suppression pool temperature, BWR/4, various suppression pool cooling system performance margins

6.5 Rod Insertion

The results discussed in Section 5 were obtained assuming a condition which should trip the RPS occurs but no rods move. However, the nature of the RPS failure may be such that some rod motion occurs, although not enough to shut down the reactor. Further, the EPGs direct the operator to insert rods manually under scram failure conditions, irrespective of whether soluble boron can be injected into the RPV.

Figure 6.5-1 illustrates the effect of partial rod insertion on the results of the analysis. In this figure, rod insertion is expressed as a percentage of the total rod worth required to bring the reactor to hot shutdown conditions with no core voiding. As expected, partial rod insertion results in lower ultimate suppression pool temperatures, but the effect is significantly more pronounced for Strategy B. Strategy B results in the lower suppression pool temperature for all rod insertions evaluated.

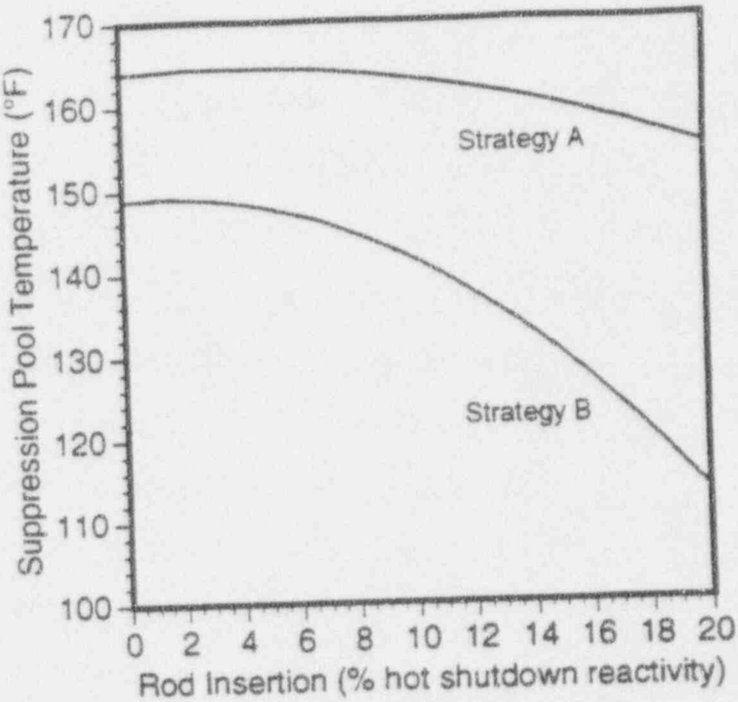

Figure 6.5-1 Suppression pool temperature, BWR/4, various rod insertions

6.6 Initial Rod Line

The results discussed in Section 5 were obtained assuming the transient was initiated with the reactor operating on the 100% rod line in the allowable power/flow operating regime. Many plants now operate consistently above this line and, for brief periods, may operate well above it. The maximum rod line currently permitted is the upper bound of the Maximum Extended Operating Domain (MEOD).

In general, operation in the MEOD results in a higher power-to-flow ratio when the MSIVs close. This causes a higher power to be associated with a given core flow and RPV water level, which results in a higher suppression pool temperature when the reactor is ultimately shutdown. The limiting MEOD core inlet flow and RPV steam flow correlation specified in Table 3.1.2 was employed to quantify the effect of MEOD operation on suppression pool temperature at shutdown. Following Strategy B, this temperature is only marginally below the Heat Capacity Temperature Limit, or the suppression pool temperature at which manual depressurization of the RPV is required. The representative BWR/4 plant is not equipped with sufficient high-pressure RPV injection capacity to adhere to Strategy A when the transient is initiated from these limiting MEOD conditions. Even with full flow from all high-pressure injection, downcomer water level drops to within a few inches of TAF and cannot be recovered to the Strategy A water level until the in-core boron concentration exceeds half that required for hot shutdown.

Section 7

MODEL BENCHMARKS

The analysis model described in Section 3 and used to calculate the results presented in Section 5 has been benchmarked against other codes and methods by comparing the reactor and containment response calculated by the model to the response reported for the other methods.

7.1 TRACG Benchmarks

NEDO-32164[6] documents the results of the ATWS instability mitigation analyses performed to determine the response of a hypothetical BWR/5 plant to several different postulated combinations of operator actions. The TRACG code was used for this work.

The reactor response calculated by the model and that reported in the NEDO have been compared for four of the analyzed events. Containment response was not calculated in the ATWS instability mitigation analyses. Plant data, initial conditions, and assumptions regarding the timing of operator actions in the model calculations were modified to match those identified in the NEDO.

7.1.1 RPV Water Level Control Below the Feedwater Sparger

This event is initiated with a turbine trip and scram failure. The RPV is not isolated, and therefore the feedwater system remains operational throughout the transient. After approximately two minutes, the operator secures injection from the feedwater system and the RPV downcomer water level begins to decrease. When the water level drops to approximately 1.5 meters below the feedwater sparger, the operator resumes injection into the RPV from the feedwater system to control RPV water level at this lower elevation.

RPV water level, RPV steam flow, and core inlet flow for this event as calculated by the model are plotted in the figures which follow. Triangles indicate the average of the oscillatory response reported in the NEDO. The minor differences observed in the portion of the transient during which downcomer water level is being reduced are probably due to differences in the manner in which manual feedwater control is modeled in the two codes.

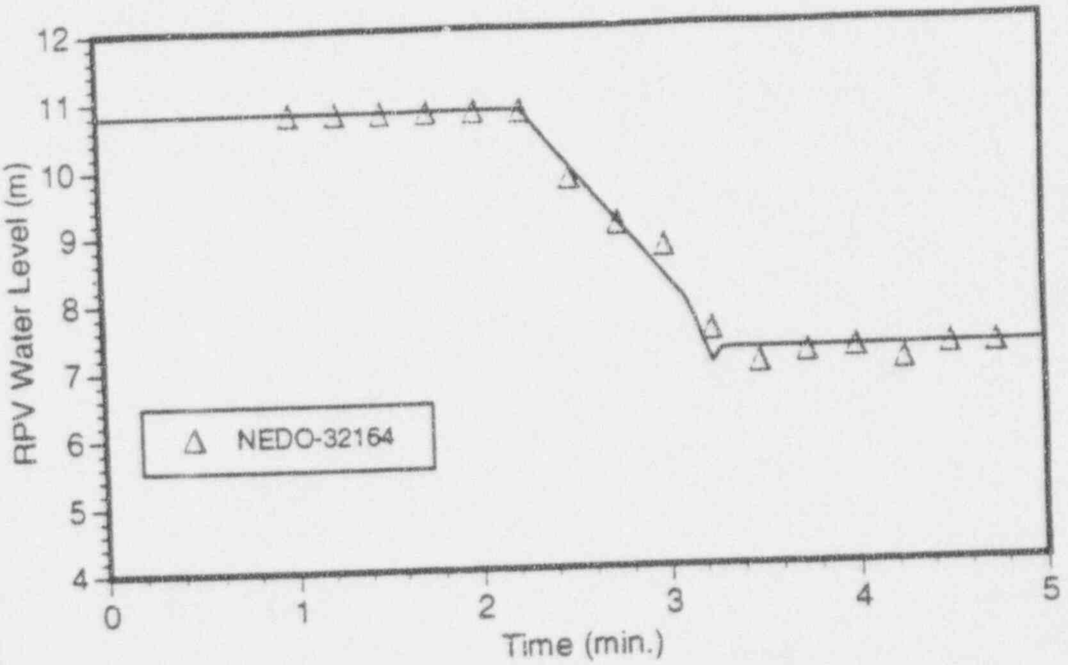

Figure 7.1.1-1 RPV water level, level control below feedwater sparger, TRACG benchmark

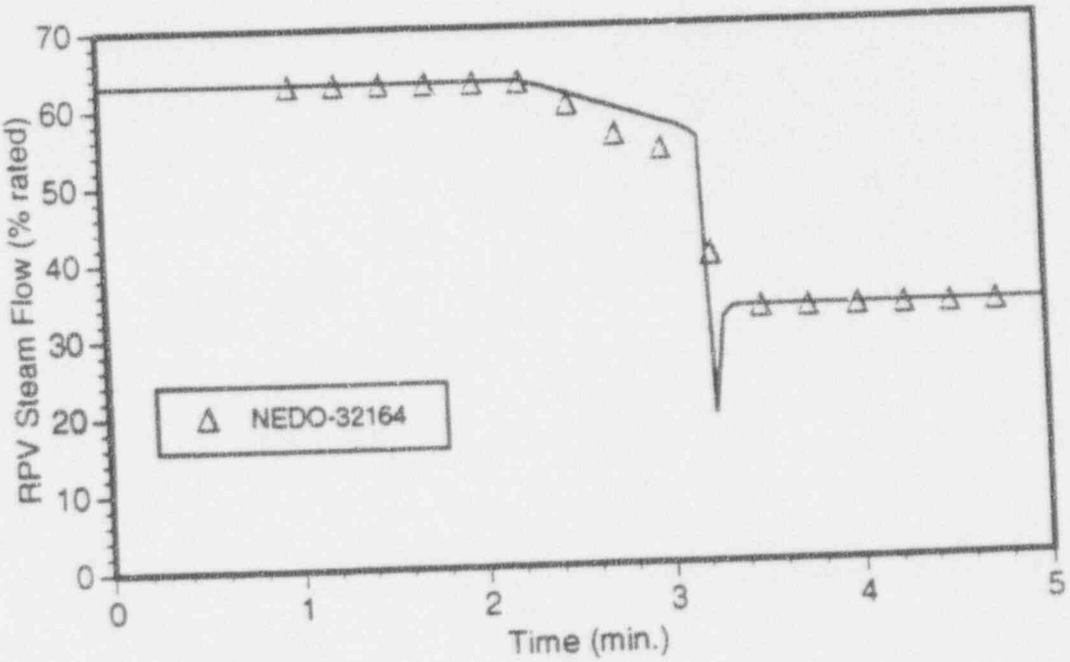

Figure 7.1.1-2 RPV steam flow, level control below feedwater sparger, TRACG benchmark

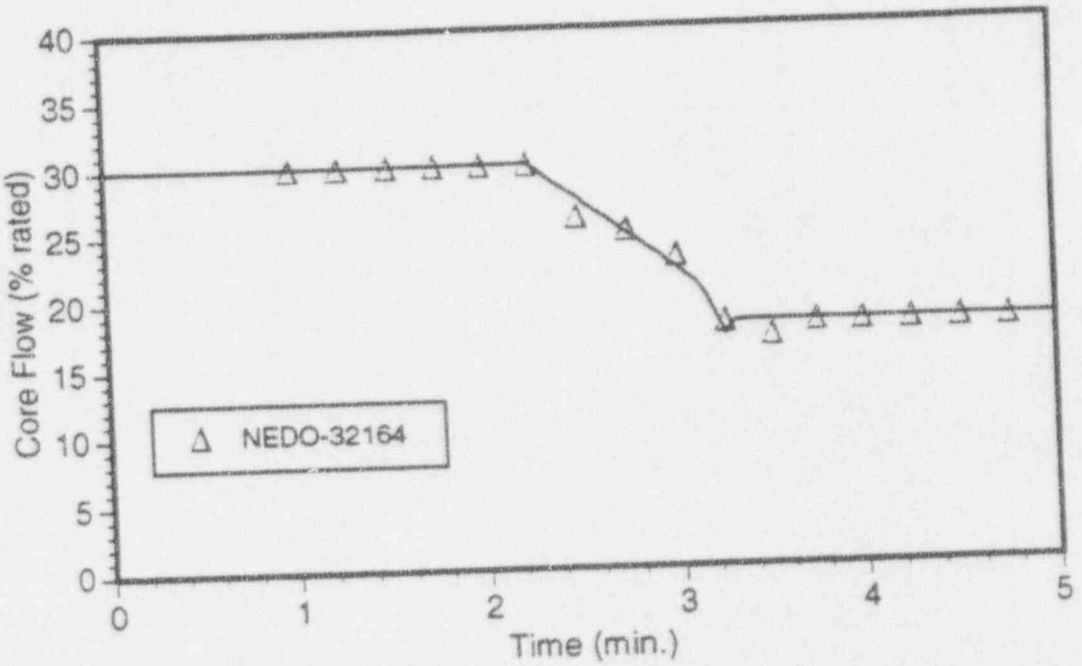

Figure 7.1.1-3 Core inlet flow, level control below feedwater sparger, TRACG benchmark

7.1.2 RPV Water Level Control Near TAF

This event is identical to the preceding event except that RPV water level is lowered to and controlled near the top of the active fuel (TAF).

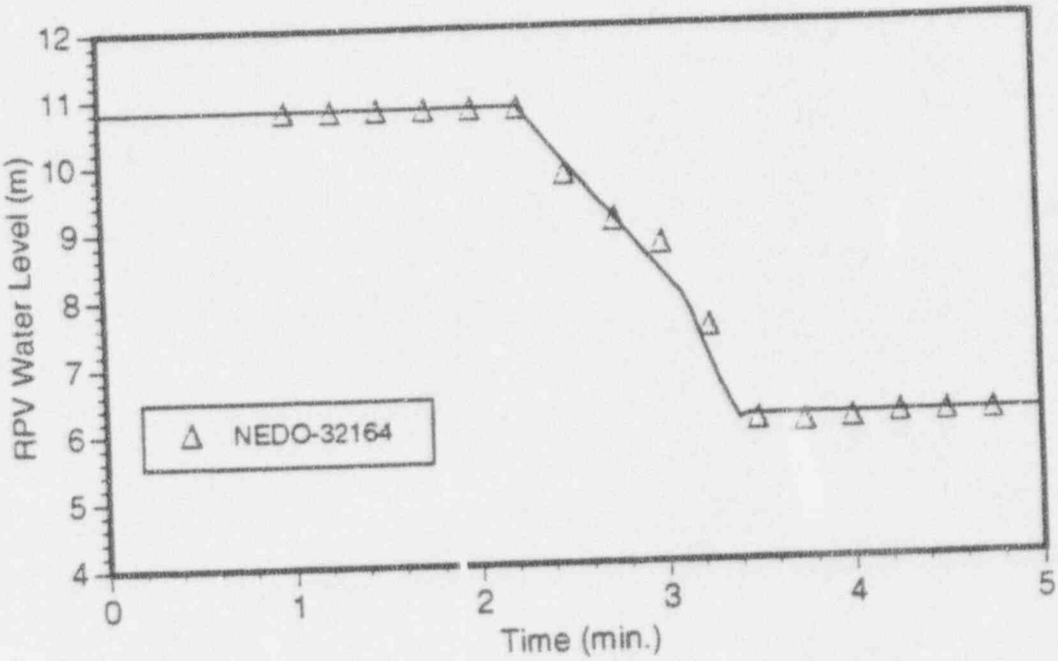

Figure 7.1.2-1 RPV water level, 'evel control near TAF, TRACG benchmark

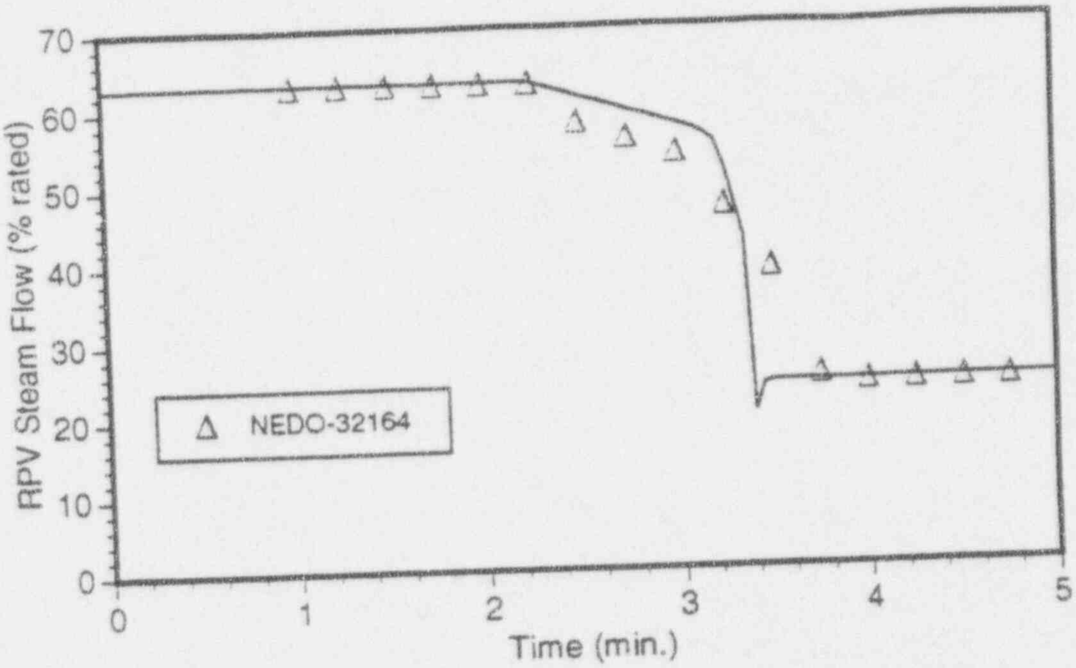

Figure 7.1.2-2 RPV steam flow, level control near TAF, TRACG benchmark

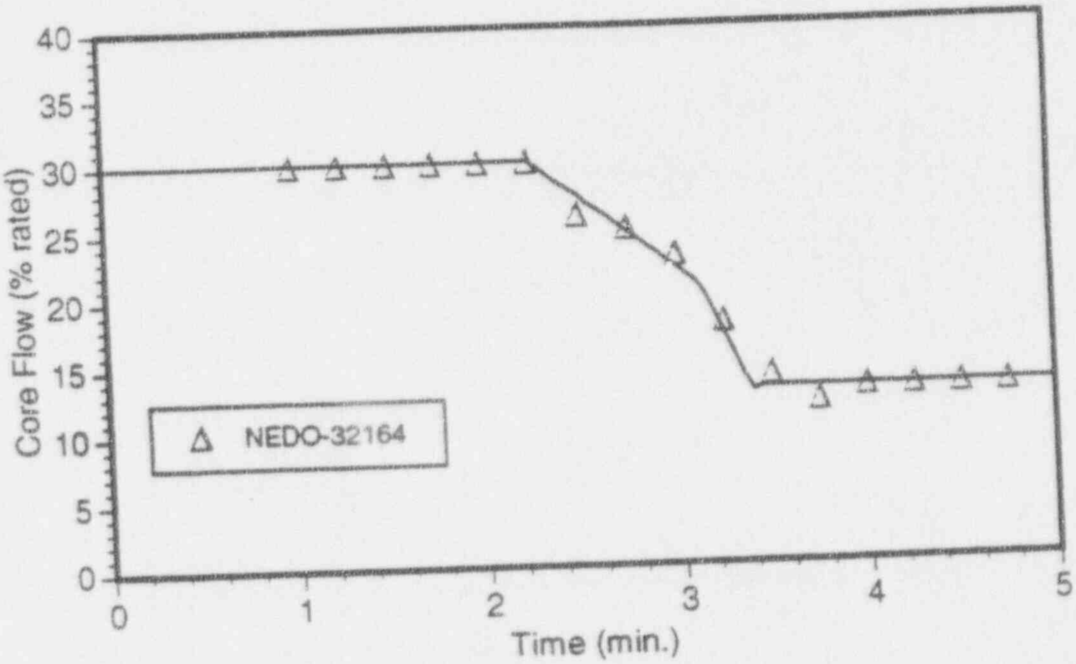

Figure 7.1.2-3 Core inlet flow, level control near TAF, TRACG benchmark

7.1.3 RPV Water Level Control at the MSCRWL

This event is identical to the two preceding events except that RPV water level is lowered to and controlled at the Minimum Steam Cooling RPV Water Level (MSCRWL), which is approximately thirty inches below TAF.

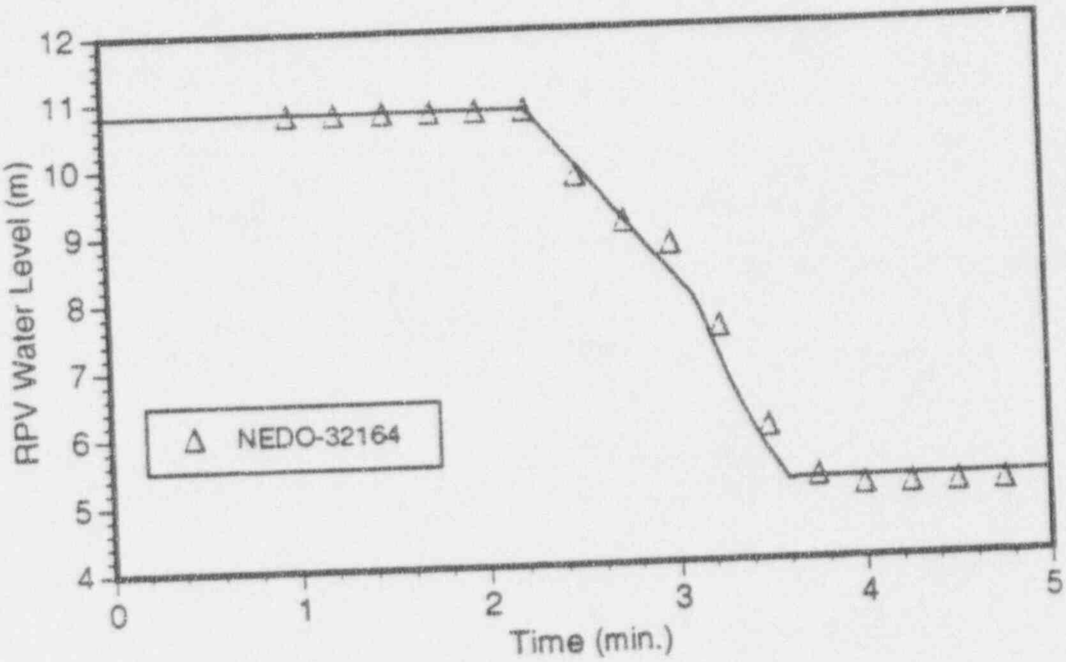

Figure 7.1.3-1 RPV water level, level control at MSCRWL, TRACG benchmark

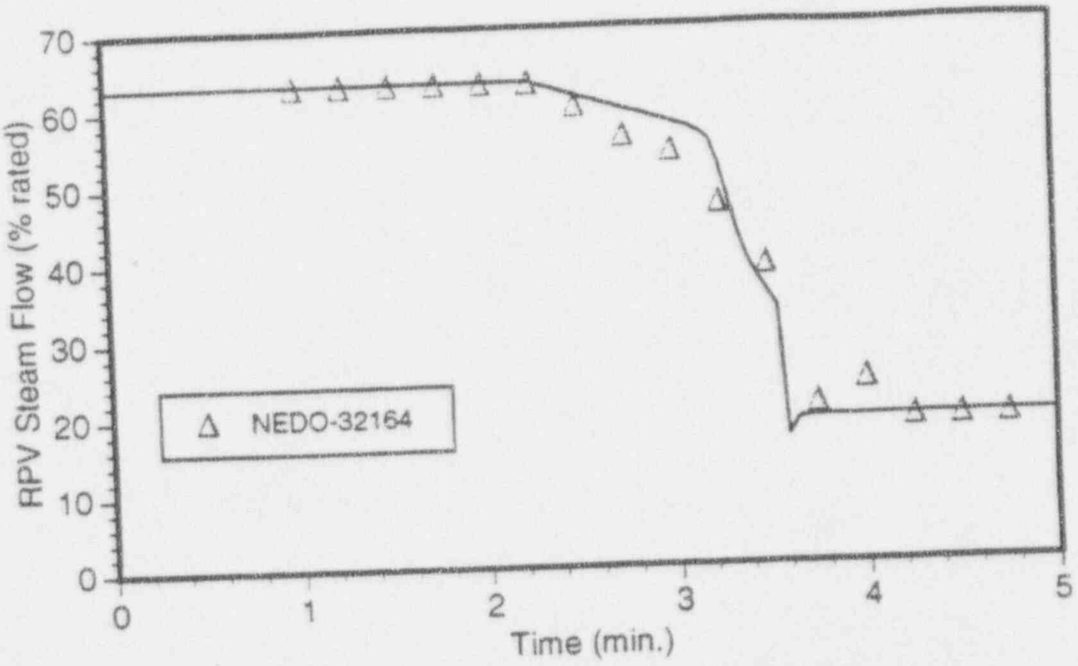

Figure 7.1.3-2 RPV steam flow, level control at MSCRWL, TRACG benchmark

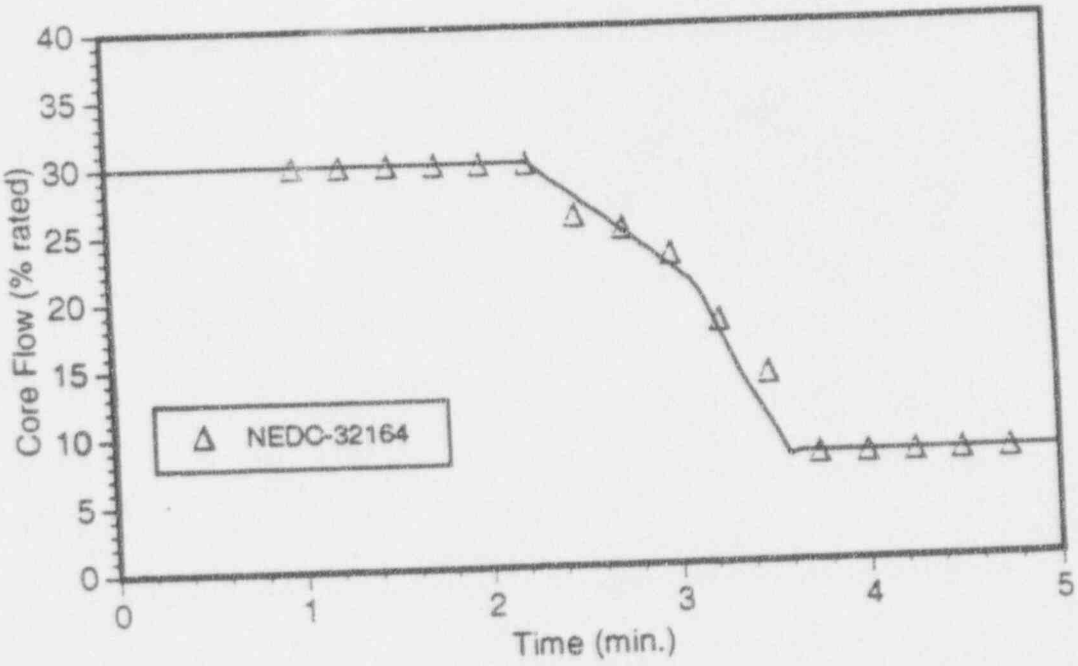

Figure 7.1.3-3 Core inlet flow, level control at MSCRWL, TRACG benchmark

7.1.4 Boron Injection

This event is initiated with a turbine trip and scram failure as in the preceding three events. However, in this case, the operator continues to inject into the RPV from the feedwater system to maintain RPV downcomer water level at the normal operating level throughout the transient. The operator also initiates the Standby Liquid Control System (SLCS), which injects soluble boron through the core spray sparger above the core in this hypothetical BWR/5. Boron begins reaching the core region in approximately two minutes.

RPV water level and RPV steam flow for this event as calculated by the model are plotted in the figures which follow. Triangles indicate the average of the oscillatory response reported in the NEDO. The plot of RPV steam flow demonstrates that the model employed for the analyses reported in this document overpredicts RPV steam flow, as discussed in Section 3.3.

Although not documented in the NEDO, the author was able to obtain some limited in-core boron concentration data from this TRACG analysis. This data together with the in-core boron concentration calculated by the model is plotted in Figure 7.1.4-3.

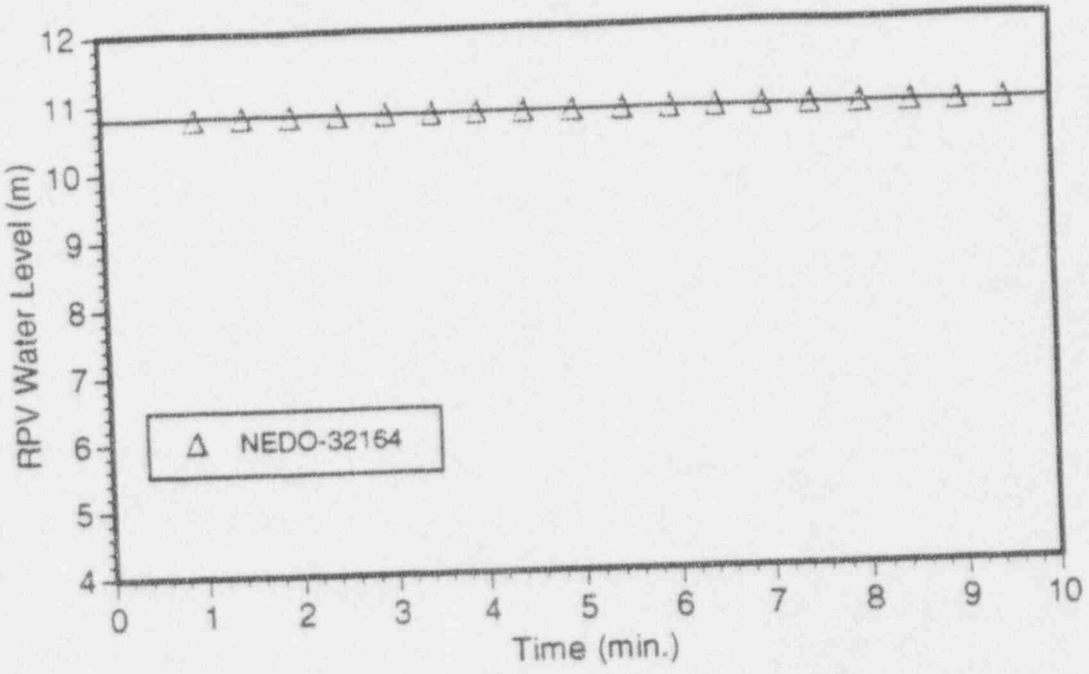

Figure 7.1.4-1 RPV water level, boron injection, TRACG benchmark

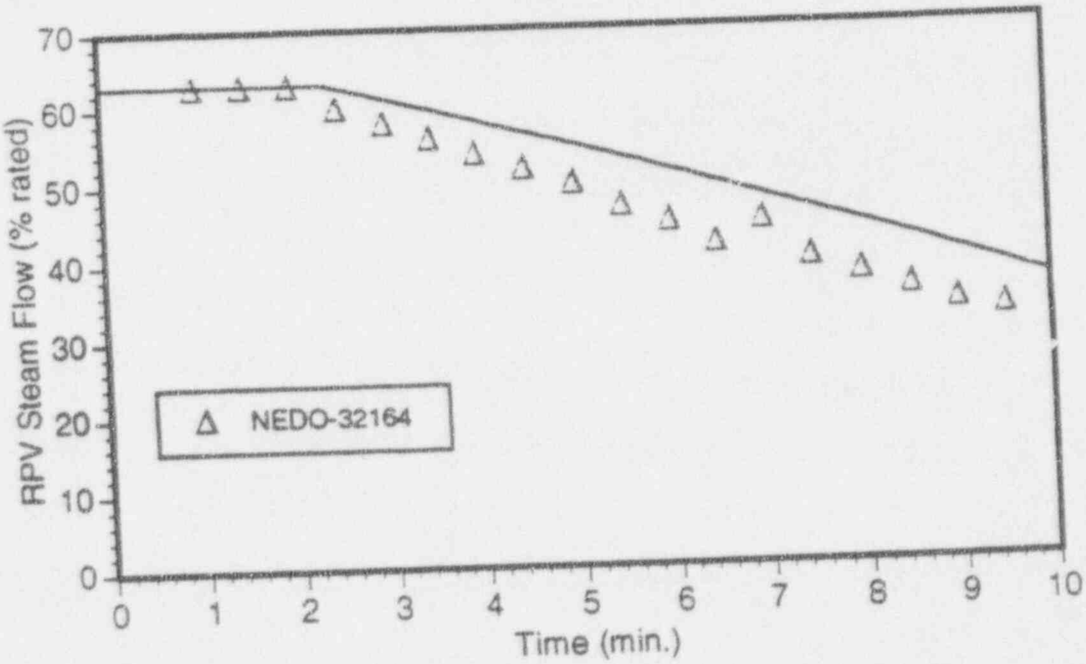

Figure 7.1.4-2 RPV Steam flow, boron injection, TRACG benchmark

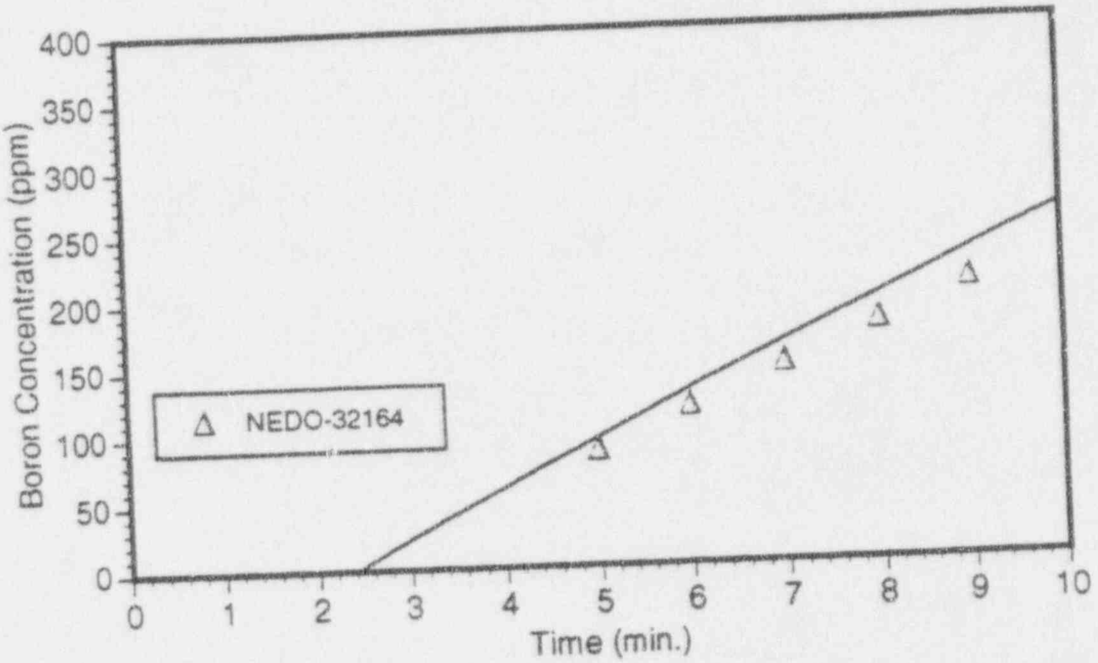

Figure 7.1.4-3 In-core boron concentration, boron injection, TRACG benchmark

7.2 BWR-LACP Benchmark

NUREG/CR-3470[8] documents a 1984 study of the response of the Browns Ferry BWR/4 plant to several scram failure events. The BWR-LACP code modified as discussed in the NUREG was used for this work. The containment response calculated by the model and that reported in the NUREG have been compared for one of the analyzed events. Plant data, initial conditions, and assumptions regarding the timing of operator actions in the model calculations were modified to match those identified in the NUREG.

The event for which results were compared is a scram failure without operator action. In this event, it is assumed that the operator takes no action to inject soluble boron, lower RPV water level, or initiate suppression pool cooling. The NUREG analysis proceeds on the assumption that the High Pressure Coolant Injection (HPCI) system will fail when the suppression pool temperature reaches 190 °F, which is calculated to occur 14.8 minutes after the closure of the MSIVs. This results in RPV water level reduction to below the initiation setpoint for the Automatic Depressurization System (ADS), RPV depressurization, and large power spikes associated with the automatic operation of the low pressure Emergency Core Cooling Systems (ECCS). The assumptions and model simplifications described in Section 3 do not permit the model to accurately track the reactor through these evolutions, so that a comparison of results between the model and the BWR-LACP code for this transient is valid for only the first fifteen minutes of the transient.

The suppression pool temperature for this event as calculated by the model is plotted in Figure 7.2-1. Triangles indicate the response reported in the NUREG. Close agreement between the model calculations and the NUREG results is apparent.

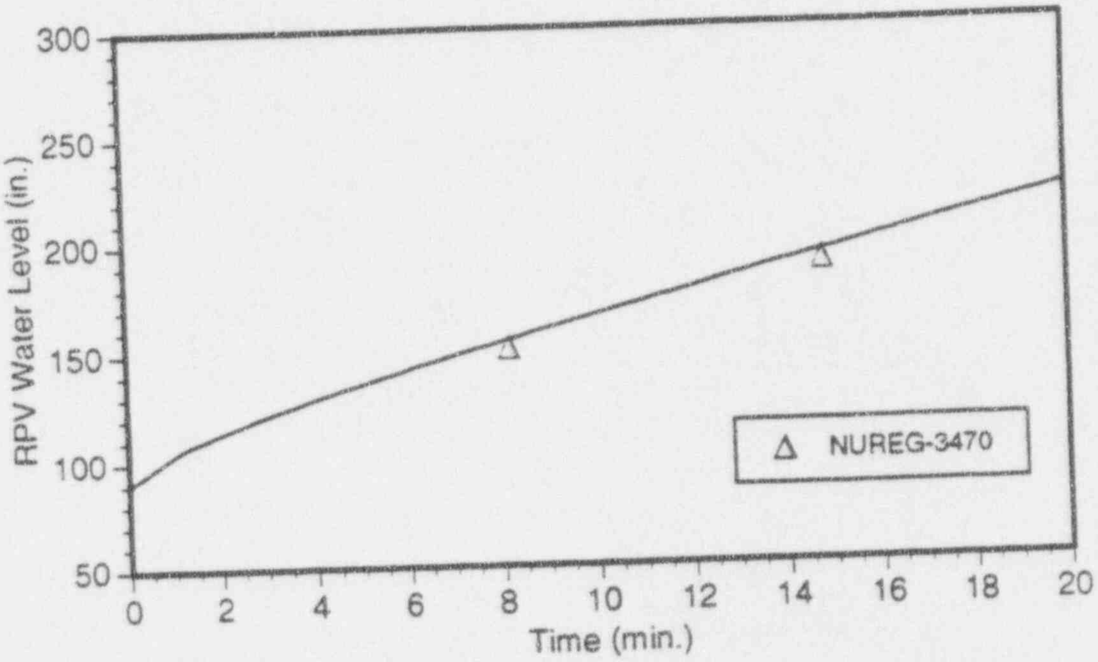

Figure 7.2-1 Suppression pool temperature, BWR-LACP benchmark

Section 8
CONCLUSION

This report documents the results of analyses which quantitatively address the response of the containment to a scram failure event (ATWS) and the operator actions in the Emergency Procedure Guidelines, both as the BWR Owners' Group proposes to modify them[5] and as others have suggested that they might be modified[4]. The event analyzed is a scram failure in which the reactor is isolated from the main condenser.

The model employed for these analysis is a time-incremented deterministic model driven by input tables of RPV water level, core inlet flow, and RPV steam flow for different initial operating conditions. The model has been benchmarked against several analyses reported in the public domain. Current data from BWR plants representative of the spectrum of plant designs which are presently operating in the US was used in the analyses.

Two strategies for the control of RPV water level during the scram failure event were evaluated. The strategy currently implemented in the BWROG EPGs, denoted Strategy B, requires the operator to intentionally lower downcomer water level to below the top of the active fuel (TAF) and to control it below TAF but above the Minimum Steam Cooling RPV Water Level (MSCRWL) while soluble boron is being injected into the RPV. The MSCRWL is approximately thirty inches below TAF for all plants. Generally, soluble boron injected through a standpipe in the lower plenum of the RPV does not mix effectively with the reactor coolant under these conditions; it stagnates in the lower plenum and so has little effect on reactor power while downcomer water level is below TAF. After a quantity of soluble boron sufficient to shut down the reactor at high pressure, the Hot Shutdown Boron Weight (HSBW), has been injected into the RPV, the operator is directed to raise downcomer water level to increase natural circulation and sweep the stagnant boron from the lower plenum into the core region, shutting down the reactor.

An alternate RPV water level control strategy, Strategy A, has been proposed. Following this strategy, downcomer water level is maintained approximately five feet above TAF while the soluble boron is being injected into the RPV. This provides greater natural circulation and, therefore, better mixing of the injected soluble boron with the reactor coolant. However, as the injected boron reduces reactor power, the core average void fraction is also reduced, and natural circulation decreases until the injected boron no longer effectively mixes with the reactor coolant. As with Strategy B, after the HSBW has been injected, the operator is directed to raise downcomer water level to increase natural circulation and sweep the stagnant boron from the lower plenum into the core region, shutting down the reactor.

Soluble boron is injected into the RPV at the same point in time in the transient under both Strategy B and Strategy A.

The analyses demonstrate quantitatively that the containment is less challenged when Strategy B is implemented as compared to Strategy A. The difference in containment response is particularly significant if the operator is unable to insert control rods or inject soluble boron into the RPV. The initial conditions and model assumptions were varied over wide ranges, and the calculated containment response was always less severe under Strategy B. The analyses also show that the in-shroud two-phase water level remains well above TAF, providing adequate core cooling throughout the transient irrespective of the water level control strategy implemented.

It is therefore concluded that Strategy B, currently implemented in the BWROG EPGs, remains the better approach to the management of ATWS in BWRs.

Section 9

REFERENCES

1. *BWR Owners' Group Emergency Procedure Guidelines, Revision 4*, Operations Engineering, Inc., Document 8390-4 (January, 1987) [General Electric Co. NEDO-31331 (March, 1987)]

2. *BWR Owners' Group Emergency Procedure Guidelines, Revision 4, Appendix A*, Operations Engineering, Inc., Document 8390-4A (January, 1987) [General Electric Co. NEDO-31331 Supplement A (March, 1987)]

3. Letter from Mr. Ashok C Thadani, Assistant Director for Systems, Division of Engineering and Systems Technology, Office of Nuclear Reactor Regulation, US Nuclear Regulatory Commission, to Mr. Donald Grace, Chairman, BWR Owners' Group (September 12, 1988)

4. Dias, M. P., Yan, H., and Theofanous, T. G., "The Management of ATWS by Boron Injection," *Proceedings, NURETH5, September 21-24, 1992, Salt Lake City, Utah*

5. Operations Engineering, Inc., Letter 93-002 from Mr. S. Taggart Rogers, Executive Consultant, Operations Engineering, Inc., to Mr. John E. Dale, Senior Program Manager, BWR Owners' Group Programs, General Electric Company (January 20, 1993)

6. *Mitigation of BWR Core Thermal-Hydraulic Instabilities in ATWS*, General Electric Co. NEDO-32164 (December, 1992)

7. L. Chu, *Power Suppression and Boron Remixing Mechanism for General Electric Boiling Water Reactor Emergency Procedure Guidelines*, General Electric Co. NEDC-22166 (August, 1983)

8. Harrington, R. M., and Hodge, S. A., *ATWS at Browns Ferry Unit One - Accident Sequence Analysis*, NUREG/CR-3470 (July, 1984)

OEI Document 9402-3

Appendix A

Plant Specific Data

PRELIMINARY UNVERIFIED

March, 1994

ATWS Analysis Plant-Specific Data

Plant-Specific Parameters:	Nine Mile 1
Plant name	1850
Rated thermal power (MWt)	7.29
Rated steam flow (million lbm/hr))	67.5
Rated core flow (million lbm/hr))	11.0
Suppression pool water level (normal) (ft above bottom)	84,955
Suppression pool volume (normal water level) (ft3)	Not Required
Suppression chamber volume (total air and water) (ft3)	Not Required
Drywell and vent system volume (ft3)	0.03866
Suppression pool steel thickness (ft)	61.665
Torus major radius (ft)	13.5
Torus minor radius (ft)	
Suppression pool submerged steel mass (normal) (lbm)	100
RPV water level at top of separators (in.)	95
RPV water level at high level trip setpoint (in.)	72
RPV water level (normal) (in.)	-17
RPV water level at feedwater sparger (in.)	53
RPV water level at which HPCI/RCIC/HPCS initiate (in.)	-14.5
RPV water level at top of separator steam dome (in.)	N/A
RPV water level at which CRD trips (in.)	-84
RPV water level at TAF (in.)	-133
RPV water level at top of jet pumps (in.)	-12
RPV water level at bottom of wide range indication (in.)	110
RPV water level at top of fuel zone indication (in.)	-240
RPV water level at bottom of fuel zone indication (in.)	2809.97
Free-flooding volume of RPV lower plenum (rods out) (ft3)	675.13
Free-flooding volume in fuel region (ft3)	761.68
Free-flooding volume in core bypass region (ft3)	912.44
Free-flooding volume inside steam dome (ft3)	186.90
Free-flooding volume inside separators (ft3)	195.25
Free-flooding downcomer volume between WLrpv-sep and WLrpv-nor (ft3)	1666.52
Free-flooding downcomer volume between WLrpv-nor and WLrpv-dome (ft3)	1769.95
Free-flooding downcomer volume below WLrpv-dome (ft3)	213
Inside diameter of RPV at core midplane (in.)	179
Outside diameter of core shroud at core midplane (in.)	1879.7
Recirculation system volume (ft3)	807
RWCU system volume (ft3)	Not Required
Mass of RPV, internals, recirculation loops, and main steam lines (lbm)	Not Required
Mass of clad and channels (lbm)	Not Required
Mass of fuel (lbm)	Yes
Motor-driven feedpumps (Yes/No)	256.11
RHR heat exchanger duty (BTU/sec-°F)	1
Number of RHR heat exchangers	3420
HPCI flowrate (gpm)	N/A
HPCS flowrate at lowest SRV lifting pressure (gpm)	N/A
RCIC flowrate (gpm)	65
CRD flowrate (normal cooling) (gpm)	125
CRD flowrate (maximum) (gpm)	1090
Lowest SRV lifting pressure (psig)	Not Required
Primary Containment Pressure Limit (normal water level) (psig)	196.25
Heat Capacity Temperature Limit high-pressure endpoint (°F)	30
SLCS flowrate (minimum) (gpm)	51,826
Equivalent natural boron concentration in SLCS tank (minimum) (ppm)	

ATWS Analysis Plant-Specific Data

Plant-Specific Parameters:	
Plant name	Monticello
Rated thermal power (MWt)	1670
Rated steam flow (million lbm/hr))	6.4
Rated core flow (million lbm/hr))	57.6
Suppression pool water level (normal) (ft above bottom)	11.208
Suppression pool volume (normal water level) (ft3)	70,831
Suppression chamber volume (total air and water) (ft3)	176,250
Drywell and vent system volume (ft3)	134,200
Suppression pool steel thickness (ft)	0.0487
Torus major radius (ft)	49.00
Torus minor radius (ft)	13.833
Suppression pool submerged steel mass (normal) (lbm)	
RPV water level at top of separators (in.)	56
RPV water level at high level trip setpoint (in.)	48
RPV water level (normal) (in.)	32.5
RPV water level at feedwater sparger (in.)	-12
RPV water level at which HPCI/RCIC/HPCS initiate (in.)	-47
RPV water level at top of separator steam dome (in.)	-55.5
RPV water level at which CRD trips (in.)	N/A
RPV water level at TAF (in.)	-126
RPV water level at top of jet pumps (in.)	-174
RPV water level at bottom of wide range indication (in.)	-50
RPV water level at top of fuel zone indication (in.)	65
RPV water level at bottom of fuel zone indication (in.)	-335
Free-flooding volume of RPV lower plenum (rods out) (ft3)	2372.79
Free-flooding volume in fuel region (ft3)	613.78
Free-flooding volume in core bypass region (ft3)	640.07
Free-flooding volume inside steam dome (ft3)	784.71
Free-flooding volume inside separators (ft3)	147.33
Free-flooding downcomer volume between WLrpv-sep and WLrpv-nor (ft3)	195.81
Free-flooding downcomer volume between WLrpv-nor and WLrpv-dome (ft3)	1506.99
Free-flooding downcomer volume below WLrpv-dome (ft3)	1894.78
Inside diameter of RPV at core midplane (in.)	205
Outside diameter of core shroud at core midplane (in.)	169
Recirculation system volume (ft3)	965.4
RWCU system volume (ft3)	168.4
Mass of RPV, internals, recirculation loops, and main steam lines (lbm)	1,708,849
Mass of clad and channels (lbm)	58,996
Mass of fuel (lbm)	187,360
Motor-driven feedpumps (Yes/No)	Yes
RHR heat exchanger duty (BTU/sec-°F)	197.5
Number of RHR heat exchangers	2
HPCI flowrate (gpm)	3339
HPCS flowrate at lowest SRV lifting pressure (gpm)	N/A
RCIC flowrate (gpm)	471
CRD flowrate (normal cooling) (gpm)	48
CRD flowrate (maximum) (gpm)	150
Lowest SRV lifting pressure (psig)	1120
Primary Containment Pressure Limit (normal water level) (psig)	56
Heat Capacity Temperature Limit high-pressure endpoint (°F)	180.4
SLCS flowrate (minimum) (gpm)	24
Equivalent natural boron concentration in SLCS tank (minimum) (ppm)	52,960

PRELIMINARY UNVERIFIED

ATWS Analysis Plant-Specific Data

Plant-Specific Parameters:	
Plant name	Browns Ferry
Rated thermal power (MWt)	3293
Rated steam flow (million lbm/hr))	13.37
Rated core flow (million lbm/hr))	102.5
Suppression pool water level (normal) (ft above bottom)	14.87
Suppression pool volume (normal water level) (ft3)	126,309
Suppression chamber volume (total air and water) (ft3)	254,585.3
Drywell and vent system volume (ft3)	171,758
Suppression pool steel thickness (ft)	0.0625
Torus major radius (ft)	55.5
Torus minor radius (ft)	15.5
Suppression pool submerged steel mass (normal) (lbm)	334,932
RPV water level at top of separators (in.)	59
RPV water level at high level trip setpoint (in.)	51
RPV water level (normal) (in.)	33
RPV water level at feedwater sparger (in.)	-24.5
RPV water level at which HPCI/RCIC/HPCS initiate (in.)	-46
RPV water level at top of separator steam dome (in.)	-85
RPV water level at which CRD trips (in.)	N/A
RPV water level at TAF (in.)	-162
RPV water level at top of jet pumps (in.)	-216
RPV water level at bottom of wide range indication (in.)	-155
RPV water level at top of fuel zone indication (in.)	32
RPV water level at bottom of fuel zone indication (in.)	-268
Free-flooding volume of RPV lower plenum (rods out) (ft3)	3774.94
Free-flooding volume in fuel region (ft3)	968.87
Free-flooding volume in core bypass region (ft3)	882.37
Free-flooding volume inside steam dome (ft3)	1366.99
Free-flooding volume inside separators (ft3)	369.14
Free-flooding downcomer volume between WLrpv-sep and WLrpv-nor (ft3)	275.98
Free-flooding downcomer volume between WLrpv-nor and WLrpv-dome (ft3)	3031.7
Free-flooding downcomer volume below WLrpv-dome (ft3)	2785.36
Inside diameter of RPV at core midplane (in.)	251
Outside diameter of core shroud at core midplane (in.)	207.125
Recirculation system volume (ft3)	1227
RWCU system volume (ft3)	Not Used
Mass of RPV, internals, recirculation loops, and main steam lines (lbm)	2,435,133
Mass of clad and channels (lbm)	161,328
Mass of fuel (lbm)	346,480
Motor-driven feedpumps (Yes/No)	No
RHR heat exchanger duty (BTU/sec-°F)	276.9
Number of RHR heat exchangers	4
HPCI flowrate (gpm)	5000
HPCS flowrate at lowest SRV lifting pressure (gpm)	N/A
RCIC flowrate (gpm)	600
CRD flowrate (normal cooling) (gpm)	65
CRD flowrate (maximum) (gpm)	105
Lowest SRV lifting pressure (psig)	1105
Primary Containment Pressure Limit (normal water level) (psig)	55
Heat Capacity Temperature Limit high-pressure endpoint (°F)	180.3
SLCS flowrate (minimum) (gpm)	49.1
Equivalent natural boron concentration in SLCS tank (minimum) (ppm)	45,190

ATWS Analysis Plant-Specific Data

Plant-Specific Parameters:	
Plant name	WNP-2
Rated thermal power (MWt)	3323
Rated steam flow (million lbm/hr))	14.30
Rated core flow (million lbm/hr))	108.5
Suppression pool water level (normal) (ft above bottom)	31.146
Suppression pool volume (normal water level) (ft3)	127,500
Suppression chamber volume (total air and water) (ft3)	Not Required
Drywell and vent system volume (ft3)	Not Required
Suppression pool steel thickness (ft)	N/A
Torus major radius (ft)	N/A
Torus minor radius (ft)	N/A
Suppression pool submerged steel mass (normal) (lbm)	641,030
RPV water level at top of separators (in.)	80
RPV water level at high level trip setpoint (in.)	54.5
RPV water level (normal) (in.)	35.6
RPV water level at feedwater sparger (in.)	-34.5
RPV water level at which HPCI/RCIC/HPCS initiate (in.)	-50
RPV water level at top of separator steam dome (in.)	-87.5
RPV water level at which CRD trips (in.)	N/A
RPV water level at TAF (in.)	-161
RPV water level at top of jet pumps (in.)	-209.0
RPV water level at bottom of wide range indication (in.)	-161.5
RPV water level at top of fuel zone indication (in.)	71.5
RPV water level at bottom of fuel zone indication (in.)	-375.5
Free-flooding volume of RPV lower plenum (rods out) (ft3)	3815
Free-flooding volume in fuel region (ft3)	1000
Free-flooding volume in core bypass region (ft3)	776
Free-flooding volume inside steam dome (ft3)	1159
Free-flooding volume inside separators (ft3)	400
Free-flooding downcomer volume between WLrpv-sep and WLrpv-nor (ft3)	870
Free-flooding downcomer volume between WLrpv-nor and WLrpv-dome (ft3)	3036
Free-flooding downcomer volume below WLrpv-dome (ft3)	2951
Inside diameter of RPV at core midplane (in.)	253
Outside diameter of core shroud at core midplane (in.)	207.125
Recirculation system volume (ft3)	1004
RWCU system volume (ft3)	______
Mass of RPV, internals, recirculation loops, and main steam lines (lbm)	Not Required
Mass of clad and channels (lbm)	Not Required
Mass of fuel (lbm)	Not Required
Motor-driven feedpumps (Yes/No)	No
RHR heat exchanger duty (BTU/sec-°F)	413
Number of RHR heat exchangers	2
HPCI flowrate (gpm)	N/A
HPCS flowrate at lowest SRV lifting pressure (gpm)	1650
RCIC flowrate (gpm)	650
CRD flowrate (normal cooling) (gpm)	65
CRD flowrate (maximum) (gpm)	125
Lowest SRV lifting pressure (psig)	1076
Primary Containment Pressure Limit (normal water level) (psig)	Not Required
Heat Capacity Temperature Limit high-pressure endpoint (°F)	162
SLCS flowrate (minimum) (gpm)	86
Equivalent natural boron concentration in SLCS tank (minimum) (ppm)	24,930

ATWS Analysis Plant-Specific Data

Plant-Specific Parameters:	Grand Gulf
Plant name	3833
Rated thermal power (MWt)	16.49
Rated steam flow (million lbm/hr))	112.5
Rated core flow (million lbm/hr))	18.6
Suppression pool water level (normal) (ft above bottom)	135.291
Suppression pool volume (normal water level) (ft3)	Not Required
Suppression chamber volume (total air and water) (ft3)	Not Required
Drywell and vent system volume (ft3)	N/A
Suppression pool steel thickness (ft)	N/A
Torus major radius (ft)	N/A
Torus minor radius (ft)	
Suppression pool submerged steel mass (normal) (lbm)	76
RPV water level at top of separators (in.)	53.5
RPV water level at high level trip setpoint (in.)	36
RPV water level (normal) (in.)	-41
RPV water level at feedwater sparger (in.)	-41.6
RPV water level at which HPCI/RCIC/HPCS initiate (in.)	-76.53
RPV water level at top of separator steam dome (in.)	-150.3
RPV water level at which CRD trips (in.)	-166.7
RPV water level at TAF (in.)	-217
RPV water level at top of jet pumps (in.)	-160
RPV water level at bottom of wide range indication (in.)	-117
RPV water level at top of fuel zone indication (in.)	-317
RPV water level at bottom of fuel zone indication (in.)	4223
Free-flooding volume of RPV lower plenum (rods out) (ft3)	1103
Free-flooding volume in fuel region (ft3)	1005
Free-flooding volume in core bypass region (ft3)	1468
Free-flooding volume inside steam dome (ft3)	514
Free-flooding volume inside separators (ft3)	624
Free-flooding downcomer volume between WLrpv-sep and WLrpv-nor (ft3)	2755
Free-flooding downcomer volume between WLrpv-nor and WLrpv-dome (ft3)	2323
Free-flooding downcomer volume below WLrpv-dome (ft3)	253
Inside diameter of RPV at core midplane (in.)	211
Outside diameter of core shroud at core midplane (in.)	1000
Recirculation system volume (ft3)	100
RWCU system volume (ft3)	Not Required
Mass of RPV, internals, recirculation loops, and main steam lines (lbm)	Not Required
Mass of clad and channels (lbm)	Not Required
Mass of fuel (lbm)	No
Motor-driven feedpumps (Yes/No)	540
RHR heat exchanger duty (BTU/sec-°F)	2
Number of RHR heat exchangers	N/A
HPCI flowrate (gpm)	3700
HPCS flowrate at lowest SRV lifting pressure (gpm)	800
RCIC flowrate (gpm)	62
CRD flowrate (normal cooling) (gpm)	238
CRD flowrate (maximum) (gpm)	1103
Lowest SRV lifting pressure (psig)	Not Required
Primary Containment Pressure Limit (normal water level) (psig)	120.3
Heat Capacity Temperature Limit high-pressure endpoint (°F)	82.4
SLCS flowrate (minimum) (gpm)	24,744
Equivalent natural boron concentration in SLCS tank (minimum) (ppm)	