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PREFACE

This letter report documents a comparison of three plant specific pressurized thermal shock risk analyses performed at ORNL. The information presented in this letter report is the opinion of the author, and although it has undergone the normal internal review, it has not been subjected to the rigorous technical and editing review performed for the actual specific-plant study reports.

OUTLINE

1.0 Introduction

Over the past four years, ORNL has been involved in the pressurized thermal shock (PTS) analysis of three nuclear power plants: Oconee Unit 1, Calvert Cliffs Unit 1, and H. B. Robinson Unit 2. The purpose of these analyses was to develop a PTS evaluation process, to determine the best estimate of the actual PTS risk, to identify the dominant overcooling sequences, and to evaluate potential risk reductions measures. The results of these analyses indicated that: 1) the best estimate of PTS risk was different for each plant, 2) each plant had different dominant sequences, and 3) potential risk reduction measures can have different effects on risk reduction for each plant since the dominant risk sequences were different. A review of the three analyses revealed that each plant had unique design features which tended to impact the potential for and the consequences of overcooling events. Also, as a result of a learning process, some changes were made in the analysis approach in going from one plant to another plant analysis. This was recognized as an additional impact on the results. This letter report has been written to identify the plant features and analysis characteristics which to a great extent explain the differences in the best estimate PTS risk factors obtained for the three plants.

In Chapter 2 the design features of the three plants are discussed and compared. Although general statements are made in this chapter concerning the impact of these features, the specific effects of the most important design features are actually discussed in Chapters 3 and 4.

In Chapter 3 the frequency of potential overcooling transients are discussed and compared. The impact of design features on event frequency is identified in this chapter. In addition, the impact of differences in the approach used to determine the event frequency is discussed.

Chapter 4 discusses the differences in the thermal hydraulic analyses performed for each plant and the impact of different design features on downcomer pressure and minimum downcomer temperature.

The fracture mechanics analysis performed for each plant is addressed in Chapter 5. Since the general approach was basically the same for all three plants, the discussion in this Chapter will focus on the different plant vessel characteristics which impact the through-wall-crack (TWC) probability.

In Chapter 6, the design and analysis differences identified in Chapters 3, 4, and 5 are combined to illustrate the differences in the TWC probability obtained for each of the three plants. In addition, the effect of potential risk reduction measures is discussed relative to the three different plants.

In Chapter 7, the sensitivity and uncertainty analysis is discussed and differences in analysis approach are identified.

2.0 Comparison of Plant Designs

The following sections of this chapter provide a comparison of the three plant designs including operating procedures. In section 2.1 generic differences are identified. In the remaining sections of this chapter these Generic differences are discussed with respect to their general impact.

2.1 General Design Comparison

Ten plant characteristics were identified which were considered substantially different in at least one of the three plants analyzed and in addition were considered important features with respect to potential PTS risk. These ten features are:

1. Number of plant loops
2. HPI shutoff head
3. Main Steam Isolation Valve operation
4. Vent valve operation
5. Isolation of AFW during steamline break events
6. Steam generator size
7. Charging system operation
8. AFW flow rate
9. Control system response
10. Steamline flow restrictors

These design features will be referred to repeatedly in Chapters 3 and 4 but are summarized in the remainder of this chapter.

2.2 Two Loop vs Three Loop Plant

One of the principle design features of the plant is the number of loops in the design. Both Oconee Unit 1 and Calvert Cliffs Unit 1 are two loop plants while H. B. Robinson Unit 2 is a three loop plant. The use of three loops has a significant impact on the potential PTS risk. First of all, the additional loop introduces an additional location for failure. For example, if there is a particular valve on each line, there are two valves available for failure on the two loop plant while there are three valves which can fail on the three loop plant. This introduces a 50% increase in the probability of having a single valve failure. Thus, as will be discussed in Chapter 3, the frequency of potential overcooling sequences is higher for the 3 loop plant when both the 2 loop and 3 loop plants have similar designs. However, it was found that the consequences of an event occurring on 1 of 3 loops was considerably less than the consequence of a similar event which occurs on 1 of 2 loops. Thus, in general it was concluded that the 3 loop design would have the potential for a higher frequency of overcooling events but a lower frequency of significant overcooling events.

A review of overcooling event frequencies based on LER's and Owners Group Reports revealed that the data supports this conclusion (Ref. 1). Table 2.1 is a summary of the data collected. From this table it is seen that with respect to total overcooling events, the 3 loop Westinghouse design did indeed have a higher event frequency, i. e. over twice the frequency of the 2 loop Combustion design. However with respect to actual significant events, (those events with cooldowns greater than 100 degrees/hour), the 3 loop Westinghouse design had the lowest frequency. The actual thermohydraulics effect of the 2 loop vs. 3 loop design will be discussed in Chapter 4.

Table 2.1. Frequencies of Overcooling Events and Precursors Among U.S. Vendors

Potential Consequences of Event	Babcock & Wilcox (Per RY)	Combustion Engineering (Per RY)	Westinghouse (Per RY)
Insignificant	.637	.407	1.0
Significant	.312	.083	.054
Total	.949	.490	1.054

2.3 HPI Shutoff Head

One of the important aspects of PTS stress is the repressurization process following the pressure drop which accompanies the initial cooldown of the primary system. The speed of this repressurization process is greatly controlled by the HPI system. In the case of the Oconee system, HPI can fully repressurize the system and in most sequences examined does so rather rapidly. (It should be noted that since the repressurization process was rapid, no credit was taken for operator intervention to control the repressurization process.) In the case of both Calvert Cliffs and H. B. Robinson, the HPI shutoff head, 1275 psia for Calvert Cliffs and 1500 psia for H. B. Robinson, is well below the normal full pressurize operating condition. This slows the repressurization process and reduces the pressure component of stress when the thermal stress is at its peak thus reducing the potential for the generation of a through-the-wall crack.

2.4 Main Steam Isolation Valve Operation

In the event of steam line break events the main steam isolation valves can serve two functions. First, if the break is down stream of the MSIVs, the closure of the valves will isolate the break and thus terminate the cooldown effects. Secondly, if the break is upstream of the MSIVs, closure of the valves will isolate the break to one steam generator and thus limit the effects of the secondary blowdown. Oconee does not have MSIVs. Instead, the Oconee design has turbine stop valves which are located on each steam line prior to the common header. However, since these turbine stop valves are located downstream of the turbine bypass valves, the closure of the turbine stop valves will not isolate the turbine bypass valves. Calvert Cliffs has MSIVs which close on low pressure in the steamlines. As a result, breaks downstream of the MSIVs (including turbine bypass valve failure) are of little consequence (except in the lower frequency case where the MSIVs fail to close). H. B. Robinson has MSIVs similar to Calvert Cliffs but the valves require both a low pressure and high steam flow signal to obtain automatic closure. This means that for medium and small steamline breaks the closure of the MSIVs is left to the operator. This is not necessarily bad since there is approximately 30 minutes to perform the action before the consequences become severe. However, it does introduce a potential common mode failure on all three MSIVs if the operator neglects to close them.

2.5 Vent Valve Operation

The Oconee Unit 1 plant is somewhat different from the other two plants in that it has the vent valve feature which under certain conditions allows significant flow to the downcomer region from inside the core barrel. These vent valves supply some hot water to the downcomer region and has the potential to greatly reduce the formation of cold plumes in the downcomer region when there is very low flow in the loops. Thus, loop stagnation in Oconee has less of a potential for a severe consequence than loop stagnation in either Calvert Cliffs or H. B. Robinson.

2.6 Isolation of AFW During Steamline Break Events

The cooldown potential associated with steamline breaks is to a great extent proportional to the extent of the blowdown. As a result, in all three plants effort is made to stop the flow of water into a steam generator which is blowing down. In the case of the Calvert Cliffs plant this is accomplished automatically. The same signal which closes the MSIVs terminates main feed flow by closure of the Main Feedwater Isolation Valves. In the case of a break upstream of the MSIVs, a delta pressure signal between the two steam generators will result in the stoppage of auxiliary feed flow to the low pressure steam generator thus terminating flow to the broken loop in a matter of seconds following the break. In the case of both Oconee and H. B. Robinson this particular action is left to the operator. Again, this is not necessarily unreasonable. However, it was our opinion in the analysis that there would be some delay before the operator would perform this action. This resulted in additional flow to the generator and increased the extent of the blowdown.

2.7 Steam Generator Inventory

The steam generator inventory also has an effect on the extent of blowdown which accompanies a steamline break event. Calvert Cliffs had the largest inventory of the three plants particularly at the low decay heat zero power condition when the generators contained approximately 95,000 kg of water (62,350 at full power). This compares with 17,700 kg and 42,000 kg at full power and 26,400 kg and 58,000 kg at hot zero power for Oconee and H. B. Robinson respectively. In the larger inventory cases there is a larger base of potential energy removal available and thus resulting in the potential for a more severe cooldown. There is however a somewhat compensating effect in the case of AFW flow. In the higher inventory plants there appears to be a longer delay before AFW is actuated. This means that the cooldown effects of the colder AFW water is delayed. In the case of the low inventory steam generators the cooldown effects of AFW are seen very early in the transient.

2.8 Charging System Operation

Since the HPI system in Oconee can fully repressurize the system, the charging system is not an important PTS concern for this plant. However for both Calvert Cliffs and H. B. Robinson, repressurization is accomplished primarily by the charging system once the HPI shutoff head is reached. For the Calvert Cliffs plant the charging system will fully repressurize thesystem unless the operator intervenes to stop or limit the repressurization process. Since in many instances the repressurization process via charging flow is relatively slow, some credit was taken for potential operator action to limit the repressurization. In the case of H. B. Robinson the charging system automatically slows as the pressurizer refills thus limiting the repressurization in many sequences.

2.9 AFW Flow Rate

Since the temperature of the AFW water is considerably colder than normal feedwater, the cooling effects of AFW must be examined. The temperature of this water was considered to be similar for all plants. Therefore, it is the AFW flow rate which is important when distinguishing the differences in potential cooling effects. AFW initiates with a flow rate of 1400, 320, and 600 gpm respectively for the Oconee, Calvert Cliffs and H. B. Robinson plants. Thus the Oconee plant has a substantially larger AFW flow. In instances where the AFW flow is maintained it would appear that the impact would be most severe in the Oconee system. In addition the AFW is sprayed into the Oconee steam generator from the top vs. flow from the bottom in the other two plants. In many instances this contributes to a more efficient and thus faster cooldown of the system.

2.10 Control System Response

Each plant has its own control system logic. There are, however, both similarities and differences in the control system logic which applies to the overcooling sequences of each of the three plants. Examples of similar control logic are feedwater runback and Turbine bypass control. All three plants have a runback system which rapidly reduces main feedwater flow following a turbine trip and also each plant has an operating mode which results in an automatic opening of the turbine bypass valves following a turbine trip. One example of a difference in control logic is the AFW actuation. In both Oconee and H. B. Robinson, AFW is automatically actuated very early for most of the events analyzed while there is some time delay before the Calvert Cliffs AFW system is actuated. An example of this is the large steam line break. AFW is actuated at 4.4 and .1 seconds for Oconee and H. B. Robinson for this transient, but the Calvert Cliffs AFW system is not actuated until 58 seconds when the steam generator low level signal is generated. Other control system differences will be discussed with respect to specific transients in Chapters 3 and 4 of this report.

2.11 Steam Line Flow Restrictors

Both Calvert Cliffs and H. B. Robinson have flow restrictors in the steam lines. These flow restrictors limit the speed at which a steam generator blowdown can occur. In the case of the blowdown of a single generator the effective size of the break is limited to the size of the flow restrictor. Thus, a full guillotine steam line pipe break at Calvert Cliffs will look no worse than a 2.5 sq. ft. break. The same event would appear to be a 1.4 sq. ft. break on H. B. Robinson (flow restrictor is smaller). With the failure of multiple MSIVs, larger effective breaks can be achieved since multiple steam generators would be involved. In most cases, however, flow restrictors will slow the cooldown associated with large steam line breaks. The Oconee plant does not have flow restrictors in the steam lines. As a result, large steam line breaks would be expected to have initial faster cooldown rates in Oconee than in either Calvert Cliffs or H. B. Robinson.

3.0 Comparison of Event Frequencies

In this chapter the event frequencies derived for each of the three plants is discussed. In section 3.1 the initiating event and individual branch frequencies are compared and discussed. Then, in section 3.2 the frequency is given for each of the dominant sequences defined in the three plant-studies. In each case the frequency of the equivalent sequence is given for the other two plants. The reasons for any differences in sequence frequency are then discussed.

3.1 Comparison of Frequencies Used in the Event Trees

In general the same approach was used to develop the initiating event frequencies for each of the three plants. The initiating event frequencies used in each of the studies are given in Table 3.1. The differences in these values are discussed below.

Reactor trip
The reactor trip numbers are based on actual data from the plant. Therefore the differences in the reactor trip number represent differences in actual plant operation experience.

Small steam line break at power
The steam line break frequency used for the full power condition was obtained by taking a base steam line break frequency and subtracting that fraction assumed to occur at a low decay heat condition as discussed below. The base small steam line break frequency value used in the Oconee study is the generic number reported in most PRA studies. The slightly higher base value used in the Calvert Cliffs study is based on the actual number of observed events in the industry. The even higher base number used in the H. B. Robinson study reflects the increased potential associated with the 3 loop plant vs. the 2 loop plant. It should be noted that the choice of a low decay heat factor as described in the next section had a small effect on the full power sequence frequency.

Small steam line break at 0% power

These values were obtained by multiplying the basic small steam line break event frequency by a low decay heat factor. In the Oconee analysis this value was derived based on the percent of time spent at the hot 0% power condition. It was determined after the Oconee analysis that the potential for a small steam line break might actually be higher when there is a constant transient condition of matching feed flow and steam flow at the low decay heat level. In addition one of the four observed small steam line breaks occurred at a low decay heat condition. Thus a much higher factor (25%) was used as the low decay heat multiplier for both Calvert Cliffs and H. B. Robinson.

Large steam line break at power

The frequency value used for the large steam line break at power was essentially the same for all three plants. The slightly smaller value used for the Calvert Cliffs analysis reflects the larger hot 0% power multiplier used in the case of the Calvert Cliffs analysis as discussed below.

Large steam line break at 0% power

As in the case of the small break, the time ratio was used as the 0% power factor in the Oconee analysis. In the Calvert Cliffs analysis the same argument used for the small steam line break was used to obtain a 25% factor for the large steam line break. After the Calvert Cliffs analysis, it was determined that the argument used for the small steam line break did not apply to the large steam line break and the decision was made to return to the use of the time ratio for the H. B. Robinson analysis.

Small break LOCA at power

The frequency value used for the Oconee analysis represents the generic screening value used in the NREP study. The value is somewhat higher in the Calvert Cliffs study since the decision was made to lump the tube rupture events with the LOCA events. In the H. B. Robinson analysis the tube rupture events were treated separately as in the Oconee analysis. The slightly smaller frequency number represents the relatively high 0% power multiplier used in the H. B. Robinson analysis.

Small break LOCA at 0% power

This event was not considered in the Oconee analysis. For the Calvert Cliffs analysis a hot 0% power multiplier was used based on the percent of time spent at the hot 0% power condition. After the Calvert Cliffs analysis, a review of historic small break LOCA data was performed. It was determined that approximately 10% of the observed small break LOCAs actually occurred at a low decay heat condition. As a result, a 10% factor was used in the H. B. Robinson analysis which led to the higher frequency for this event.

Medium break LOCA at power

The same value derived for the small steam line break was also applied to the medium size break in the Oconee analysis. After the Oconee analysis, it was determined that this frequency should be lower since in the case of the medium break we are no longer talking about valve failures but are now concerned only with actual pipe breaks. In lieu of no substantial data, zero occurrences in the total number of PWR reactor years was used to estimate the value used in the Calvert Cliffs analysis. The same value was then used in the H. B. Robinson analysis.

Medium break LOCA at 0% power

This event was not considered in the Oconee analysis. In the Calvert Cliffs analysis there did not appear to be sufficient information to identify a 0% power multiplier. As a result, the conservative assumption was made to use the same frequency value derived for the full power case. After the Calvert Cliffs analysis, it was determined that a time ratio was appropriate for defining a 0% power multiplier factor for this initiator. This factor was used in defining the H. B. Robinson value and lead to a much lower event frequency.

The general branch frequencies used in the three studies are given in Table 3.2. In addition to these branch frequencies there are numerous conditioning factors used in each of the studies. These factors are too numerous to mention in this report. However, it can be stated that these conditioning factors were derived based on failure experience or plant design and were used in a similar manner in each of the studies. As seen in Table 3.2 there are many instances where there are variations in the frequency numbers used in the three studies. Small variations represent slight differences in plant experience. Those instances where the numbers are considerably different are explained below:

Atmospheric dump valves

The higher frequency numbers used in the H. B. Robinson study reflect the three loop design of the Robinson plant. With the three loop design there are three valves available for failure vs. the two available valves in the Calvert Cliffs plant. It should be noted that Oconee does not have automatic atmospheric dump valves and thus no frequency is reported.

Turbine bypass valves

The higher frequency numbers used in the H. B. Robinson study for two, three, or more failures reflect the presence of five valves compared with the four valves in the other two plants. The lower value used in the Oconee study reflects the use of a lower coupling factor for the third and forth valve failures.

Feedwater fails to runback

The considerable difference reported for the three plants is based on the different experience at the three plants. With essentially the same number of demands, there are four reported instances of failure to runback at Oconee while there is only one reported instance at the Calvert Cliffs plant. For H. B. Robinson there was no evidence of a runback failure with a larger average number of demands.

MSIVs fail to close

As in the case of the atmospheric dump valves, the higher numbers used in the H. B. Robinson study reflect the presence of three valves in the three loop plant compared with the two valves in the two loop Calvert Cliffs plant. Again it should be noted that the Oconee plant does not have MSIVs and therefore no frequencies are reported.

MFIVs fail to close
The higher failure frequency for H. B. Robinson is based on three valves vs. two valves and the lesser number of demands which have occurred at the plant.

AFW fails to start
The lower numbers used in the Calvert Cliffs and H. B. Robinson plant studies are based on the newly designed AFW systems in these plants which have been designed to increase the availability of AFW.

AFW control valve fails to open
The variation for the three plants is based on the presence of four control valves at Calvert Cliffs, three control valves at H. B. Robinson, and two control valves at Oconee.

Pressurizer PORV fails to reseat
The same frequency value for actual valve failure was used in all three plants. However, after the Oconee study was completed it was determined that the PORV failing to reseat would have overcooling impact only if the valve were left open for at least 15 minutes. As a result, in the Calvert Cliffs and Robinson studies the potential for the operator to close the PORV block valve was considered as part of the frequency for pressurizer PORV failure rather than as a separate branch in the trees. This resulted in the lower branch failure frequency used in both the Calvert Cliffs and H. B. Robinson studies.

Failure of feedwater pumps to trip on high SG level
There is no steam generator high level trip of the feedwater pumps in the Calvert Cliffs design and thus no failure probability is reported. In the case of Oconee and H. B. Robinson plant the failure frequencies are very similar. The value used in the H. B. Robinson study is slightly smaller since this event is expected to result in SIAS which will also cause the feedwater pumps to trip.

3.2 Comparison of Sequence Frequencies for Dominant Sequences

In this section the frequencies of the dominant sequences are identified for each plant and compared with compatible sequences for the other two plants. An explanation is provided when considerable differences in sequence frequency are noted.

3.2.1 Oconee Dominant Sequences

Ninety-six percent of the through-wall-crack risk was composed of the residual group and five specific transient sequences. The frequencies for these transients are given in Table 3.3 along with the estimated frequency of an equivalent transient at both Calvert Cliffs and H. B. Robinson. In some cases in Table 3.3 there are additional values provided in parenthesis. These represent an alternative comparison that will be explained in the following section.

As seen in Table 3.3, the frequencies of Calvert Cliffs and H. B. Robinson sequences which are comparable to the Oconee dominant risk sequences are, in many instances, considerably lower than the frequencies applied to the Oconee sequences. This can be explained in the following manner:

O.1- Residual group -

For both the Calvert Cliffs and H. B. Robinson analysis the residual was divided into several residual groups based on the nature of the residual sequence. The estimated frequency of each individual residual sequence is given in Table 3.3. The total of all residual groups in the Calvert Cliffs analysis has a somewhat lower frequency than the total residual value obtained in the Oconee analysis. An attempt was made to reduce the residual group frequency in the Calvert Cliffs analysis. This was done by using a 1.0E-7 screening value in the Calvert Cliffs analysis vs. the 1.0E-6 value used in the Oconee analysis. However it was considered impractical to use a 1.0E-7 screening value for the reactor trip event tree. Thus, the reduction in residual group frequency was only a factor of about 2.5. In the H. B. Robinson analysis the 1.0E-7 screening value was used for all event trees. This led to twice as many sequences for specific analysis but resulted in a total residual which was nearly a factor of 100 lower than the frequency used in the Oconee analysis.

O.2- Large steam line break at full power with blowdown of one line and system response normal -

As seen in Table 3.3 the frequency for this transient is essentially the same for all three plants.

O.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that only one steam generator blowsdown -

There is no comparable case for either Calvert Cliffs or H. B. Robinson. In order to achieve this condition the TBVs or SSRVs must fail, one MSIV must fail open, and the equipment (Calvert Cliffs) or operator (H. B. Robinson) must fail to isolate AFW. In both the Calvert Cliffs and H. B. Robinson analysis it was determined that the more likely event was the failure of the TBVs followed by the failure of all MSIVs. In this case it is assumed with a probability of 1.0 that AFW flow is not isolated and with both steam generators blowing down this is a more severe condition.

O.4- All turbine stop valves fail to close. Both steam generators blowdown -

This state can only be achieved on Calvert Cliffs and H. B. Robinson if the MSIVs fail to close. This reduces the frequency of the transient by approximately a factor of 1000. In the H. B. Robinson analysis some additional credit was given for closure of the turbine control valves. This is the reason for the slightly smaller frequency used in the H. B. Robinson study. The frequency numbers given in parenthesis for both Calvert Cliffs and H. B. Robinson represent the sequence (all turbine stop valves fail to close) frequency with closure of the MSIVs. However, this results in only minor cooldown conditions.

O.5- One TBV or SSRV fails to reseat. One steam generator blowsdown -

The frequency of this transient in the Oconee analysis is very high because of the assumption made concerning safety valve lift. On Oconee at least some of the safeties lift on each reactor trip. This gives the potential for 16 valves that can fail open. On both Calvert Cliffs and H. B. Robinson the system is designed to preclude the lifting of safety valves following a reactor trip. Thus even though the failure rate per demand is essentially the same for all three plants, the number of demands is significantly higher in the Oconee analysis. In addition the frequency associated with the same transient is relatively low on the Calvert Cliffs plant since to achieve this transient the additional failure of one MSIV is required. In the case of H. B. Robinson, the MSIVs will not receive an automatic closure signal and due to the smallness of the break no credit was taken for operator closure of the MSIVs. This leads to a somewhat more severe blowdown since all three steam generators are assumed to blowdown.

O.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. Both steam generators blowdown -

Again, it is the MSIVs which make the difference in the frequency of the sequence. However, a coupled failure of the MSIVs and MFIVs is considered which results in a frequency reduction factor of about 100 for Calvert Cliffs instead of the previous factor of 1000. The H. B. Robinson sequence does not appear to have a potential couple factor and the additional control signal to the feedwater pumps reduces the frequency for this transient below the 1.0E-7 screening value.

3.2.2 Calvert Cliffs Dominant Sequences -

Six sequences were determined to contribute 98% of the PTS risk in the Calvert Cliffs analysis. These sequences are defined and their estimated frequencies are given and compared with the frequencies of comparable sequences in the Oconee and H. B. Robinson analysis in Table 3.4.

Again there are differences between the frequencies of comparable sequences. These differences are explained below;

CC.1- Small break LOCA at low decay heat -

Due to the assumed operation of the vent valves in Oconee the small break LOCA at low decay heat was not considered in the analysis of that plant. For the H. B. Robinson analysis the frequency of this transient is about a factor of 3 higher. This is due to the higher low decay heat factor used in that analysis.

CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (at ~1.5 hours) -

For reasons given above this transient was not considered in the Oconee analysis. In the H. B. Robinson analysis the frequency of this transient is about a factor of 6 higher. This is due to the higher low decay heat factor and a slightly higher frequency used for late isolation of the break.

CC.3- Medium break LOCA at low decay heat -

For reasons given in the discussion of sequence CC.1 above this transient was not considered in the Oconee analysis. The frequency of this transient in the H. B. Robinson analysis is nearly a factor of 50 smaller than that used in the Calvert Cliffs analysis. In the Calvert Cliffs analysis no low decay heat factor was applied in the process of determining the frequency of this sequence. At the time there was indecision since with no observed medium break LOCAs the failure mechanism was undefined and thus the potential for failure at any given state could not be evaluated. The conservative assumption was made to use the same frequency factor for the full power and low decay heat cases. After the Calvert Cliffs analysis and during the H. B. Robinson analysis, it was determined that there was no evidence to support a higher potential for the occurrence of a medium sized LOCA at low decay heat vs. the full power condition. Thus, in the H. B. Robinson analysis a low decay heat factor was used which reduced the frequency of the medium sized LOCA at low decay heat. It should be noted that in H. B. Robinson both the full power and low decay heat cases resulted in early stagnation of the loops. This resulted in similar thermal hydraulic behavior for each sequence. Thus the use of a low decay heat factor did not have a major impact on the H. B. Robinson results.

CC.4- Small steam line break upstream of the MSIVs with low decay heat condition -

Although small steam line breaks were considered in the Oconee analysis, a sequence comparable to this transient was not considered since it was not believed that credit could be given for controlling the repressurization process. In both Calvert Cliffs and H. B. Robinson the repressurization process is slowed by the shutoff head of the HPI system. This allows for operator intervention in the Calvert Cliffs plant and charging pump runback in the H. B. Robinson plant to limit repressurization. In Oconee the repressurization process is much more rapid and no credit is given for limiting pressure. Thus since this sequence involves limiting repressurization there is no comparable Oconee sequence. The frequency number used for the H. B. Robinson case is a factor of 2 smaller. This is due to the fact that in H. B. Robinson half of the break potential was assumed to be upstream of the MSIVs while the other half was assumed to be downstream of the MSIVs. In the Calvert Cliffs analysis the break was always assumed to be upstream of the MSIVs. The Calvert Cliffs assumption was made because the upstream break was always the worst location for the break. The H. B. Robinson assumption was made because the existence of check valves in the steam lines makes the downstream break the worst location in certain situations.

CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process -

In the Oconee analysis of the small breaks at low decay heat, the AFW flow was always assumed to be controlled by level indication. As a result, AFW flow is assumed to continue as in the case of CC.6. Therefore, there was no comparable case for CC.5 in the Oconee analysis. The H. B. Robinson frequency for this transient is a factor of 2 lower than the Calvert Cliffs sequence frequency for the same reason described in item 4 above.

CC.6- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process or throttle AFW -

The frequency for this sequence at Calvert Cliffs is the same as the sequence described for sequence CC.5 above. The reason for this is the high coupling factor assumed for the two operator actions identified. In the case of the Oconee analysis, however, no credit was taken for either of the operator actions described. Thus a much higher frequency of event would be expected. However, the smaller low decay heat factor used in the Oconee analysis (12.5 times lower than that used in the Calvert Cliffs analysis) compensates and the actual frequency used for this sequence in Oconee was only a factor of 4 higher. It would appear that the higher low decay heat factor should have been used in the Oconee analysis and thus the actual frequency of this sequence for Oconee should have been 2.5E-3. The impact of using this value rather than the value used in the analysis will be discussed in Chapter 7 of this report. In the H. B. Robinson analysis the repressurization process is controlled by an automatic charging system. Thus, the coupling factor which might be used if both AFW and charging system control were operator actions does not exist. Inclusion of the failure of this equipment along with operator backup drops the estimated frequency for this sequence from the value given for dominant sequence CC.5 by a factor of 100 for the H. B. Robinson sequence.

3.2.3 H. B. Robinson Dominant Sequences

The six most dominant PTS risk sequences for H. B. Robinson were determined to contribute 72% of the total PTS risk. These sequences are defined and their estimated frequencies are given and compared with the frequencies of comparable sequences in the Oconee and Calvert Cliffs analysis in Table 3.5. The differences in frequency for the sequences described in the table are explained below:

HBR.1- All steam side PORVs fail to close following a reactor trip -

Since Oconee does not have steam side PORVs this sequence is not applicable to Oconee and thus no frequency is given. The Calvert Cliffs frequency for this sequence is slightly smaller due to a reduced reactor trip frequency.

HBR.2- Two steam side PORVs fail to close following a reactor trip -

The identification of a similar transient in the two loop plants presents a problem since the failure of two steam side PORVs in a two loop plant is the same as the failure of all steam side PORVs. Since the two steam side PORVs represents a partial failure of the PORV system in H. B. Robinson the single PORV failure in the two loop system was chosen as the comparable system. The frequency given for Calvert Cliffs thus represents the failure of a single PORV and is higher than the failure given for the H. B. Robinson sequence which involves the failure of two PORVs. It should be noted that this sequence is not applicable to Oconee for the same reason presented for sequence HBR.1 above.

HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs -

Since Oconee does not have MSIVs this condition can be achieved with just the failure of three or more TBVs. Thus the frequency for this sequence is much higher in Oconee. The frequency is nearly a factor of 50 lower for Calvert Cliffs when a comparison of the H. B. Robinson and Calvert Cliffs values is made. This is primarily due to the fact that MSIV closure is automatic for the TBV failures and the sequence can only be achieved if both MSIVs mechanically fail to close.

HBR.4- Three or more TBVs fail to close and two MSIVs fail to close -

This sequence represents a partial failure of the MSIV system. As in sequence HBR.2 above this poses a problem when trying to identify a similar sequence in the 2 loop systems. The Calvert Cliffs sequence considered similar involves the failure of one MSIV. The frequency given for the Calvert Cliffs sequence is still lower than that used in the H. B. Robinson analysis. This is due to the higher reactor trip frequency and higher potential for three or more TBV failures developed from H. B. Robinson data. This sequence is not applicable to Oconee since without MSIVs the failure of three or more TBVs will automatically result in the blowdown of both lines and thus a partial blowdown cannot occur.

HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills -

The frequency given for the equivalent Calvert Cliffs sequence is higher primarily due to the fact that throttling of the charging system is operator controlled vs. automatically controlled with operator backup in the H. B. Robinson plant. As previously stated, Oconee does not have steam side PORVs and thus this sequence is not applicable to that plant.

HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW -

This sequence falls into the residual group in both the Oconee and Calvert Cliffs analysis. The reason for the higher frequency associated with H. B. Robinson is that the closure of the MSIVs and throttling of AFW are both operator actions. However, closure of the MSIVs is not a operator action at the Calvert Cliffs plant and the throttling of the AFW is not an operator action at the Oconee plant. Thus, these two plants do not have the common mode failure coupling factor used in the H. B. Robinson analysis for this sequence.

Table 3.1. Comparison of Initiating Event Frequencies

Initiating Event	Oconee Frequency (per RY)	Calvert Cliffs Frequency (per RY)	H. B. Robinson Frequency (per RY)
Reactor Trip	6	5.5	8.7
Steam Line Break			
Base Small Break	1.0E-2	1.6E-2	2.0E-2
Small at Power	1.0E-2	1.2E-2	1.5E-2
Small at 0% P	2.0E-4	4.0E-3	5.0E-3
Base Large Break	1.0E-3	1.2E-3	1.2E-3
Large at Power	1.0E-3	9.0E-4	1.2E-3
Large at 0% P	2.0E-5	3.0E-4	2.3E-5
LOCA			
Small at Power	1.0E-2	1.5E-2	8.0E-3
Small at 0% P		3.0E-4	8.0E-4
Medium at Power	1.0E-2	1.0E-3	1.0E-3
Medium at 0% P		1.0E-3	2.0E-5

Table 3.2. Comparison of Event Tree Branch Probabilities

Event Branch	Oconee Frequency (per demand)	Calvert Cliffs Frequency (per demand)	H. B. Robinson Frequency (per demand)
Turbine fails to trip	2E-4	2E-4	2E-4
ADVs fail to close			
One	NA	1.3E-2	1.8E-2
Two	NA	6.4E-4	1.7E-3
Three	NA	NA	5E-4
TBVs fail to close			
On	2E-3	2E-3	2E-3
Two	1E-4	1.5E-4	3E-4
Three or more	1E-5	3E-5	4E-4
FW fails to runback			
One line	3E-2	9E-3	3E-3
Two lines	3E-3	9E-4	3E-4
Three lines	NA	NA	8E-5
Failure to initiate SGIS	NA	3E-5	3E-5
MSIVs fail to close			
One	NA	3E-3	7E-3
Two	NA	9E-4	E-3
Three	NA	NA	5E-4
MFIVs fail to close			
One	NA	1E-3	1E-2
Two	NA	1E-4	3E-4
Three	NA	NA	6E-5
AFW fails to auto isolate to low pressure SG	NA	2E-4	NA
AFW fails to start	1.4E-3	3E-4	3E-4
AFW control valve fails open	1.7E-3	3E-2	7.5E-3
HPI fails to start	3E-3	2E-3	6E-4
Pressurizer PORV fails to reseat	3E-2	2E-3	2E-3
Failure of feedwater pumps to trip on high SG level	4E-3	NA	1E-3

Table 3.3. Frequencies of Oconee Dominant Risk Sequences

Sequence Definition	Oconee Frequency (per RY)	Calvert Cliffs Frequency (per RY)	H. B. Robinson Frequency (per RY)
0.1- Residual	5E-4 Group	1) 4E-8	1) 9E-7
		2) 5E-7	2) 2E-7
		3) 7E-7	3) 1E-7
		4) 6E-6	4) 7E-9
		5) 2E-6	5) 7E-7
		6) 3E-6	6) 4E-7
		7) 5E-5	7) 3E-7
		8) 9E-5	8) 2E-7
		9) 6E-5	9) 4E-8
		10) 1E-6	10) 2E-6
		11) 2E-7	11) 5E-8
			12) 4E-7
0.2- Large steam line break at full power with blowdown of one line and system response normal	1E-3	9-E4	1E-3
0.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that only one steam generator blowsdown.	2.2E-4	NA	NA
0.4- All Turbine stop valves fail to close. Both steam generators blowdown	1.0E-3	1.0E-6 (1.0E-3)	1.7E-7 (4.0E-4)
0.5- One TBV or SSRV fails to reseat. One SG blowsdown.	7.0E-1	3.7E-5	1.3E-2
0.6- One or two TBV or SSRV fail to reseat with feed-water overfeed. Both SG blowdown.	2.4E-5	7E-7	<1E-7

Table 3.4. Frequencies of Calvert Cliffs Dominant Risk Sequences

Sequence Definition	Calvert Cliffs Frequency (per RY)	Oconee Frequency (per RY)	H. B. Robinson Frequency (per RY)
CC.1- Small break LOCA at low decay heat	3E-4	NA	8E-4
CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours)	5E-6	NA	3E-5
CC.3- Medium break LOCA at low decay heat.	1.0E-3	NA	2.0E-5
CC.4- Small steam line break upstream of the MSIVs with low decay heat condition.	4E-3	NA	2E-3
CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process.	5.0E-5	2E-4	2.4E-5
CC.6- Small steam line break upstream of the MSIVs with low decay heat condition. In addition the operator fails to control the repressurization process and does not throttle AFW.	5.0E-5	2E-4	2.5E-7

Table 3.5. Frequencies of H. B. Robinson Dominant Risk Sequences

Sequence Definition	H. B. Robinson Frequency (per RY)	Oconee Frequency (per RY)	Calvert Cliffs Frequency (per RY)
HBR.1- All steam side PORVs fail to close following a reactor trip.	4.1E-3	NA	3.4E-3
HBR.2- Two steam side PORVs fail to close following a reactor trip.	1.4E-2	NA	6.8E-2
HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs.	7E-6	1.8E-4	1.3E-7
HBR.4- Three or more TBVs fail to close and two MSIVs fail to close.	7E-6	NA	5E-7
HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills.	4.2E-5	NA	9E-5
HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW.	3.5E-6	<1E-6	<1E-7

4.0 Comparison of Thermal Hydraulics

This chapter has been divided into two major sections. The first of these sections compares the thermal hydraulic methodologies used to obtain the temperature and pressure profiles. The second section compares the actual temperature and pressure profiles obtained for the dominant sequences of each of the plants. In this section reasons are given for different thermal hydraulic behavior at the different plants.

4.1 Comparison of Thermal Hydraulic Methodologies

For all three analyses a selected number of transients were modeled using a full scope plant model in either a TRAC (LANL) or RELAP5 (INEL) calculation. The data from these selected calculations along with simplified plant models were then used to estimate the pressure and temperature profiles for the bulk of sequences identified for analysis.

4.1.1 Full Scope Calculations

It was the opinion of the analyst at both LANL and INEL that the Oconee plant was the most difficult to model. It was their opinion that the integrated response control system and relatively fast response of the system made it very difficult to successfully model transient conditions. This modeling difficulty was verified by the fact that for at least one transient their was an initial difference between the TRAC and RELAP5 calculation of 140 F in the final transient temperature. In cases of this type, unless the differences could be resolved, ORNL always chose the the lower temperature conservative calculation for use in the PTS program. In addition large uncertainties were applied to the thermal hydraulics results in the analysis of the uncertainties for the Oconee study.

In general both LANL and INEL analysts felt that the Calvert Cliffs and H. B. Robinson plants were much easier to model and in general felt that the thermal hydraulics uncertainties should be lower for these plants. Although both TRAC and RELAP5 were not used to calculate the same transient in either Calvert Cliffs or H. B. Robinson, a comparison of similar transients calculated using the different codes revealed similar results.

4.1.2 Simple Model Analyses

This aspect of the thermal hydraulics analysis was improved with each plant analyzed. In the Oconee analysis a 2 node model was used to estimate the effect of sequence perturbations from the full scope calculations. Since this model was recognized as being potentially over simplified, very conservative assumptions were made in arriving at the actual temperatures and pressures. In many instances a straight line extrapolation was made on temperature rather than the decaying exponential shape expected for the type of sequences in question. As a result the speed at which physically bounding temperatures are reached is over estimated.

An attempt was made in the Calvert Cliffs analysis to improve the simplified model and thus remove some of the conservatism included in the Oconee analysis. For this reason even though the 2 node model was retained the input considered within each node was greatly enhanced. Several of the temperature profiles obtained from the 2 node analysis were later confirmed by a series of RETRAN calculations performed by Baltimore Gas & Electric.

However, there was still felt to be some conservatism in the repressurization model. Finally, for the H. B. Robinson analysis the decision was made to go to a simplified base 13 node RELAP5 model of the plant. This model was then adjusted as necessary for each type of transient. The simplified model used for each type of transient was then benchmarked against a full scope RELAP5 model. In those few instances where the simplified model was deemed inappropriate the full scope RELAP5 model was used to supply results.

4.2 Comparison of Thermal Hydraulics Results for Dominant Sequences

In this section the thermal hydraulics results for each of the dominant sequences will be compared with similar transients analyzed for the other two plants. This comparison will be made in a manner similar to that used in Chapter 3 to compare event sequence frequencies.

4.2.1 Thermal Hydraulics Results for Oconee Dominant Sequences

The minimum temperature and subsequent maximum pressure are given for each of the Oconee dominant sequences in Table 4.1. In addition the data is supplied in Table 4.1 for the Calvert Cliffs and H. B. Robinson sequence considered to be similar in description to the Oconee sequence. The thermal hydraulic differences are explained in the following sections:

O.1- Residual group -

As previously stated, the residual group was divided into several groups in both the Calvert Cliffs and H. B. Robinson analysis. Each of these groups was then assigned bounding thermal hydraulics conditions for the particular group. In Oconee only one residual group was used and the worst calculated transient was assigned to the residual. The worst sequence was a secondary side event that led to the blowdown of both steam generators with continued AFW flow to the break. This led to a minimum temperature of 163^{O}F at full pressure. The worst residual sequence identified in both Calvert Cliffs and H. B. Robinson also involved a secondary side event that resulted in the blowdown of all steam generators. However in both cases the temperature was significantly warmer than that obtained for the similar event in Oconee (minimum temperature of 212^{O}F at full pressure for Calvert Cliffs and minimum temperature of 200^{O}F at full pressure for H. B. Robinson). The colder temperature obtained for the Oconee analysis appears to be due to the much higher auxiliary feedwater flow rate and the fact that the water is introduced into the steam generator from the top rather than from the bottom as it is in both Calvert Cliffs and H. B. Robinson. In addition the extrapolation performed in the Oconee analysis appears to be somewhat conservative.

O.2- Large steam line break at full power with blowdown of one line and system response normal -

Again the Oconee temperatures used in the analysis were significantly lower than those obtained in the Calvert Cliffs and H. B. Robinson analysis. The Oconee temperature was obtained from an extrapolation of the LANL steam line break calculation. In the Oconee PTS report it is stated that,

> "In the absence of other means of estimation, the approach used in the evaluation of the main steam line break cases was to use a linear extension of the early cooldown trends. This assumption is clearly conservative."

Subsequent to this analysis an additional detailed calculation was performed by LANL using TRAC. This calculation resulted in a declining cooldown rate in the downcomer which suggested an asymptotic approach to a temperature higher than 212°F. Thus it would appear that the Oconee temperatures are colder due to very conservative assumptions used in the extrapolation process. The Calvert Cliffs temperature is relatively high for this transient. The principle reason for this appears to be stoppage of auxiliary feedwater flow to the broken line due to automatic isolation. In both Oconee and H. B. Robinson this action is left to the operator. Thus it was assumed that there would be some time delay before this action would take place. In Oconee, flow was assumed to be isolated at 20 minutes into the transient. In the H. B. Robinson analysis isolation was assumed to occur at 10 minutes. The 10 minute isolation may have been somewhat optimistic although the 20 minute isolation used in Oconee may be somewhat conservative. If the H. B. Robinson isolation were made at 20 minutes the minimum temperature would drop to 240°F. The impact of this difference in the isolation times will be discussed in Chapter 7.

O.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that both steam generators blowdown -

As previously discussed there is no comparable case in either the Calvert Cliffs or H. B. Robinson analysis. Thus no comparison of thermal-hydraulic conditions was made.

O.4- All turbine stop valves fail to close. Both steam generators blowdown -

This sequence led to thermal hydraulic conditions which were very similar at all three plants. The principle difference is in the final system pressure. Due to the high head HPI system in Oconee, the Oconee sequence led to rapid full repressurization of the system. In the case of both Calvert Cliffs and H. B. Robinson, the shutoff head of the HPI system and controlled operation of the charging system led to lower transient final pressures. The temperature and pressure values given in parenthesis represent sequences for Calvert Cliffs and H. B. Robinson given appropriate closure of the MSIVs.

O.5- One TBV or SSRV fails to reseat. One SG blowsdown -

This sequence results in relatively warm temperatures for the Oconee plant and should not in actuality be a dominant sequence. This sequence appears simply because the lowest fracture mechanics conditional failure calculated for Oconee was 1.0E-7. This value was then used for all warm transients. This coupled with the high frequency associated with this transient led to a dominant sequence. The comparable Calvert Cliffs sequence led to a somewhat higher temperature due to difference in operation of the AFW system. In the H. B. Robinson analysis no credit was given for the closure of the MSIVs in the event of a single TBV failure. Thus, the comparable case in the

H. B. Robinson analysis results in the blowdown of all three steam generators. This results in a slightly more severe transient which produces somewhat colder temperatures.

O.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. Both steam generators blowdown -

In the case of the Oconee plant the final temperature is dominated by the relatively large AFW cold water flow. In both Calvert Cliffs and H. B. Robinson the AFW flow is significantly less and the final temperature is dominated by the blowdown of the system. Thus the temperature for the Calvert Cliffs sequence is higher. The H. B. Robinson sequence fell into the residual group. As a result, it was treated by a large steam line break case which involved the blowdown of all steam generators and continued flow to the break. This led to temperatures which were similar to the Oconee temperatures. In actuality, it is our opinion that if the actual temperatures were calculated for this case they would be closer to the Calvert Cliffs values.

4.2.2 Thermal Hydraulics Results for Calvert Cliffs Dominant Sequences -

The minimum temperatures and maximum subsequent pressures are given in Table 4.2 for the Calvert Cliffs dominant sequences. The differences identified in Table 3.4 are discussed in the following paragraphs. It should be noted that sequences 1, 2, 3, and 4 in Table 4.2 were not considered in Oconee for reasons previously explained. Thus no Oconee thermal hydraulic data is given in Table 4.2 for these transients.

CC.1- Small break LOCA at low decay heat -

The TRAC calculation performed for this transient in the Calvert Cliffs analysis exhibited early loop flow stagnation in both loops. Although there was later some concern that loop flow would resume and thus preclude the very cold temperatures, the conservative assumption was made that loop flow stagnation continued for the duration of the 2-hour analysis period. Purdue's analysis of the complete stagnation case predicted two thermal regions: a cold plume region approximately two cold leg diameters wide and a well mixed region which included all regions not in the cold plume. Although the critical welds were outside of the two cold leg diameter distance, it was determined that the welds were too close to the cold plume to assume well mixed conditions. Therefore again the conservative approach was taken and the cold plume temperatures were used in the analysis. This led to the very cold temperature of 122^{o}F at the end of the two hour analysis period. In the H. B. Robinson analysis the same size LOCA was unable to cause complete stagnation of the loops. This appears to be a result of higher HPI flow and higher HPI injection pressure. Since the loops did not stagnate, the temperature remained considerably warmer than the Calvert Cliffs transient. It should be noted that as previously discussed this sequence was not addressed in the Oconee analysis.

CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours) -

In the Calvert Cliffs analysis this transient is identical to the transient described in item 1 with the exception that the break is isolated late in the transient. The cooldown is terminated when the pressure rises to the shutoff head of the HPI system. Thus the temperature is slightly warmer than the temperature shown for sequence CC.1. Due to the rapid repressurization process associated with this transient no credit was taken for the operator controlling the repressurization process. Thus, the pressure reaches 2400 Psi in a very short period of time. For the same reasons previously described in sequence CC.1, the comparable H. B. Robinson transient results in considerably warmer temperatures. In addition since the throttling of the charging system is an automatic function, the repressurization process is slowed and the pressure only reaches 1550 Psi within the two hour analysis period. It should be noted that the temperature profile used for this sequence in the H. B. Robinson analysis was taken from a conservatively bounding case. This accounts for the colder temperature in CC.2 when compared with CC.1. In actuality the minimum temperature of CC.2 should be about equal to that of CC.1 in the H. B. Robinson analysis.

CC.3- Medium break LOCA at low decay heat -
This sequence led to loop stagnation in all loops for both Calvert Cliffs and H. B. Robinson. In the Calvert Cliffs analysis the pressure was taken from the medium break LOCA case at full power. As a result, the pressure is an over estimation of actual pressure. The faster cooldown associated with the low decay heat case will also result in a faster drop in pressure. The temperature given for the H. B. Robinson sequence also appears to be overly conservative. Inadvertently, the temperature given and used in the analysis was taken from the RELAP analysis and assumes zero mixing. According to the Purdue analysis there is, in fact, some mixing which results in actual downcomer temperatures as much as 40°F warmer. The temperatures used in the Calvert Cliffs analysis were taken from the Purdue analysis.

CC.4- Small steam line break upstream of the MSIVs with low decay heat condition -
In the Calvert Cliffs analysis the thermal hydraulic data used to represent the small steam line break was obtained based on the one square foot steam line break. Thus, portions of the temperature contain steeper drops than the actual small break would produce. The principle difference, however, between the Calvert Cliffs and H. B. Robinson results appear to be the steam generator inventory and the three loop vs. two loop design.

CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process -
In actuality the Calvert Cliffs minimum temperature for this transient should be no lower than that given for sequence CC.4 above. The temperature given for this transient, however is 8 degrees colder than that reported for sequence CC.4. This is due to the fact that thermal-hydraulically this transient was represented by sequence CC.6 discussed below. This sequence involves an additional failure that results in slightly colder temperatures. The H. B. Robinson minimum temperature for this sequence is again higher for the same reasons noted for CC.4.

CC.6- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process or throttle AFW -

The minimum temperature of this transient in Calvert Cliffs is 8 degrees colder than that given for sequence CC.4. This slightly colder temperature is due to the failure to throttle AFW to the unaffected steam generator. The comparable Oconee transient produced the coldest temperatures for this case. This appears to be due to the AFW system design of the Oconee plant. Finally for the same reasons discussed in sequence C.4 above, the comparable H. B. Robinson sequence resulted in significantly higher temperatures.

4.2.3 Thermal Hydraulics Results for H. B. Robinson Dominant Sequences -

The minimum temperatures and maximum subsequent pressures are given in Table 4.3 for the H. B. Robinson dominant sequences. The differences identified in Table 3.4 are discussed in the following paragraphs.

HBR.1- All steam side PORVs fail to close following a reactor trip -

The failure of all PORVs results in significantly colder temperatures for the H. B. Robinson plant than it does for the Calvert Cliffs plant. This is due to the relative size and number of PORVs involved. The H. B. Robinson system contains three PORVs each of which has a steaming capacity of 3.3% of total steam flow. With all three failed open the total steam flow would be ~10% of total steam flow. The Calvert Cliffs PORVs are somewhat smaller (steaming capacity of 2.5% each) and there are only two of them. With both failed the steaming capacity is 5% of total steam flow. Thus since the total steam flow for the two plants is reasonably close, the H. B. Robinson event represents a steam line break which is nearly twice the size of the one generated by the PORV failures on Calvert Cliffs. As a result, the cooldown associated with the H. B. Robinson event is more severe. It should be noted as explained earlier that the Oconee plant does not contain steam PORVs which automatically open following a reactor turbine trip, and thus no data is reported.

HBR.2- Two steam side PORVs fail to close following a reactor trip -

This sequence results in colder temperatures for the H. B. Robinson analysis for the reasons given in the discussion of HBR.1. The HBR.2 sequence is comparable to a break in the steamline which has a steaming capacity of 6.6% of total steam flow. The comparable transient for Calvert Cliffs was a single PORV failure with a steaming capacity of only 2.5% of the total steam flow. Thus the H. B. Robinson break is nearly three times larger and thus the cooldown is much more severe.

HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs -

A thermal-hydraulics calculation was not performed for this sequence in the Oconee analysis. Instead this sequence was assigned the thermal hydraulics characteristics of the large main steam line break. Thus, the minimum temperature used for this sequence in Oconee was 212°F. In retrospect it would appear that this may be a non-conservative assignment. Even though the steamline breach is smaller in size than that in the large steam line break, the failure of three or more TBVs results in the blowdown of both steam generators. In addition with the higher AFW flow rate this transient would be expected to reach temperatures somewhat colder than it would for the H. B. Robinson plant. This sequence would of course be bounded by the default Oconee case which is identical to this sequence with the additional failure to control AFW. The minimum temperature and maximum subsequent pressure associated with the default case are shown in parenthesis in Table 4.3. The Calvert Cliffs minimum temperature for this transient is somewhat warmer than that used for the H. B. Robinson analysis. The warmer temperature appears to be due to two factors. The first factor involves the AFW flow. In H. B. Robinson the AFW flow rate is 200 gpm for each generator for a total of 600 gpm. The AFW flow rate at Calvert Cliffs is only 160 gpm for a total of 320 gpm. Thus the higher AFW flow will result in some lower temperature for the H. B. Robinson plant. The second factor involves the sequence definition. The sequence chosen to be a comparable sequence for Calvert Cliffs, only involved the failure of three TBVs since the failure of all TBVs (all four which is equivalent in capacity to all five H. B. Robinson TBVs) was assigned to the residual and thus was not treated specifically. (It should be noted that even though there was a very high coupling factor between three TBV and four TBV failures, the 4 TBV failure case dropped below the 1.0E-07 screening value and thus was assigned to a residual group.) The bounding sequence for this transient would be the large steam line break with the failure of both MSIVs. The minimum temperature and maximum subsequent pressure for this bounding condition are given in parenthesis in Table 4.3.

HBR.4- Three or more TBVs fail to close and two MSIVs fail to close -
In the H. B. Robinson analysis a thermal-hydraulic analysis was not performed for this transient. As a result, a sequence which produced thermal-hydraulic results which bounded the potential thermal-hydraulic conditions of HBR.4 was used. Thus, the case chosen to represent HBR.4 was sequence HBR.3 described above. It was INEL's opinion that this assignment as made by ORNL was a very conservative treatment of the sequence and it was their opinion that the use of an actual calculation for this sequence would remove it from the dominant risk category. The minimum temperature reported for the Calvert Cliffs sequence is considerably warmer partly because of the conservatism built into the H. B. Robinson sequence assignment but also due to the definition of the transient. The H. B. Robinson sequence involves the failure of 2 of 3 loops while the Calvert Cliffs sequence involves the failure of 1 of 2 loops. In addition due to the automatic isolation of AFW for the asymmetric steam line break condition, the AFW flow to the break is terminated very early in the transient for the Calvert Cliffs case. It should be noted that since the failure of three or more TBVs in Oconee will always result in the blowdown of both steam generators the asymmetric blowdown which characterizes this sequence can not exist at the Oconee plant.

HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills -
The failure of the charging system to runback had very little effect on the minimum temperature of the sequence. As a result, the temperatures given for this sequence are very similar to those reported for sequence HBR.1.

The same arguments presented for the temperature differences in the discussion of HBR.1 also apply for HBR.5. The principle difference between this transient and transient HBR.1 is the rate at which repressurization occurs.

HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW -

This sequence is basically the Oconee default sequence. As stated earlier even though there appears to be some conservatism built into the thermal-hydraulics analysis, the major reason for the very low temperature reported for this sequence in the Oconee analysis appears to be the very high AFW flow rate and the fact that the AFW is introduced into the top of the steam generator. In the case of Calvert Cliffs and H. B. Robinson the lower AFW flow is only beginning to have an effect on the temperature at the end of the two hour analysis period. Continued operation of AFW over an extended period of time would result in continued cooldown of the systems in both the H. B. Robinson and Calvert Cliffs analysis.

4.2.4 Summary of Thermal-Hydraulics Comparisons

Although there are obviously some differences in sequence thermal-hydraulics characteristics which can be attributed to the method of calculation, it appears that (with the exception of a few Oconee transients) at least the majority of the differences observed between thermal-hydraulic conditions for similar transients at the different plants can be attributed to either differences in plant design or the assumptions made in describing or bounding the sequence. This was particularly true for the comparison of the Calvert Cliffs and H. B. Robinson plants where even the shapes of the temperature and pressure profiles were in most instances very similar. In general it would appear that there is more conservatism factored into the Oconee thermal-hydraulic analysis then there is on either of the other two plant studies.

Table 4.1. Comparison of Oconee Dominant Sequence Thermal Hydraulics with Calvert Cliffs and H. B. Robinson Sequences

Sequence Definition	Oconee		Calvert Cliffs		H. B. Robinson	
	Temp F	Press psi	Temp F	Press psi	Temp F	Press psi
O.1- Residual Group	163	2450	1) 230	2400	1) 205	1550
			3) 220	2400	3) 257	2371
			4) 257	2400	4) 100	144
			5) 300	1000	5) 234	1610
			6) 300	1400	6) 196	2371
			7) 340	2400	7) 241	2371
			8) 240	1285	8) 201	2995
			9) 257	2400	9) 205	1550
			10) 253	2400	10) 205	1550
			11) 131	600	11) 229	1772
					12) 303	2371
O.2- Large steam line break at full P with blowdown of one line and system response normal.	212	2450	370	2400	299	2371
O.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that both steam generators blowdown.	198	2430	NA		NA	
O.4- All Turbine stop valves fail to close. Both steam generators blowdown	212	2430	226 (370	1285 2400)	201 (300	1575 2371)
O.5- One TBV or SSRV fails to reseat. One SG blowsdown.	328	2430	379	2400	302	2371
O.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. All SG blowdown.	198	2430	225	1285	201	1575

Table 4.2. Thermal-Hydraulic Data for Calvert Cliffs Dominant Risk Sequences

Sequence Definition	Calvert Cliffs Temp F	Calvert Cliffs Press psi	Oconee Temp F	Oconee Press psi	H. B. Robinson Temp F	H. B. Robinson Press psi
CC.1- Small break LOCA at low decay heat.	122	900	NA		279	679
CC.2-Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours).	135	2400	NA		248	1518
CC.3- Medium break LOCA at low decay heat.	122	525	NA		100	144
CC.4- Small steam line break upstream of the MSIVs with low decay heat condition.	250	2210	NA		412	2371
CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process.	242	2400	234	2430	409	2371
CC.6- Small steam line break upstream of the MSIVs with low decay heat condition. In addition the operator fails to control the repressurization process and does not throttle AFW.	242	2400	234	2430	369	2371

Table 4.3. Comparison of Thermal-Hydraulics for H. B. Robinson Dominant Risk Sequences

Sequence Definition	H. B. Robinson Temp F	H. B. Robinson Press psi	Oconee Temp F	Oconee Press psi	Calvert Cliffs Temp F	Calvert Cliffs Press psi
Steam side PORVs fail to close following a reactor trip.	268	1615	NA		347	2400
HBR.2- Two steam side PORVs fail to close following a reactor trip.	295	1833	NA		419	1285
HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs.	203	1594	212 (163	2450 2450)	259 (230	1285 1285)
HBR.4- Three or more more TBVs fail to close and two MSIVs fail to close.	203	1594	NA		360	1285
HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills.	262	2371	NA		297	2400
HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW.	201	1575	163	2450	221	2400

5.0 Comparison of Conditional Failure Probabilities Obtained From Fracture Mechanics Calculations

This chapter has been divided into two major sections. In the first section the methodologies used to obtain the conditional failure probabilities will be discussed for each of the three plants. In the second section the conditional failure probabilities will be given for each of the dominant sequences of each plant. These values will then be compared with the conditional failure probability obtained for a similar transient on the other two plants. It should be noted that the actual comparison will be made for the plants at a common value of RTNDT (RTNDT + 2σ = 270°F).

5.1 Fracture Mechanics Calculations

In the Oconee analysis two methods were used to obtain conditional through-wall-crack probability values: 1) an OCA-P calculation was performed for the specific sequence in question or 2) the value obtained for a "similar" sequence which was calculated was assigned to the specific sequence in question. In the latter case the intention was to assign a conditional failure probability from a sequence which most resembled the sequence in question but which bounded the consequence of that sequence. Eighteen OCA-P calculations were performed and the results were then assigned to 245 system state categories.

After the Oconee analysis it was determined that an additional method for determining or bounding the conditional failure probability was necessary to treat relatively warm transients which had relatively high frequencies of occurrence. As a result a series of bounding calculations were made which involved step changes in temperature at constant full pressure. This led to very small failure probabilities which could then be applied to the warm transients. This methodology was used in the Calvert Cliffs analysis and further refined in the H. B. Robinson analysis.

In addition to the slightly different approach used in the analysis as described above, a change was made in the OCA-P code in going from the Oconee analysis to the Calvert Cliffs analysis. This change involved the crack depth modeling. The crack depth is modeled in OCA-P as a series of crack depth groups. In the Oconee analysis only a small number of groups were used. After the Oconee analysis a more refined geometric grouping was made which was felt to better representative of the available data. A parametric study was performed to determine the impact of using the updated crack depth grouping on the Oconee analysis. It was determined that using the updated data the Oconee conditional failure probabilities would have been between 6 and 20% lower.

It should be noted that in all three analyses the conditional failure probabilities are through-the-wall crack probabilities and not crack initiation probabilities. This is important to remember since the crack initiation probability for many transients, particularly low temperature low pressure sequences, may be considerably higher than the through-wall-crack probability. An example of this is sequence 2.1, a medium break LOCA event, in the H. B. Robinson analysis where the conditional TWC probability and the conditional crack initiation probability were estimated to be 7E-10 and 4E-6 respectively. Thus, crack initiation probability wasnearly four orders of magnitude higher than the TWC probability. Integrated over all sequences it would appear that the total crack initiation probability for each of the three plants may be between a factor of five and one order of magnitude higher than the total TWC probability.

5.2 Comparison of Conditional Failure Probabilities

In this section the conditional failure probabilities for each of the dominant sequences of the three plants are compared with sequences of similar description in the other two plants. A comparison of conditional failure probabilities at 32 EFPY was determined to be confusing due to the different RTNDT conditions of the plants (Oconee RTNDT ~270°F, Calvert Cliffs RTNDT ~256°F, and H. B. Robinson RTNDT ~130°F for the dominant weld). Thus for comparison purposes the conditional failure probabilities are compared for an RTNDT value of 270°F.

5.2.1 Comparison of Conditional Failure Probabilities for Oconee Dominant Sequences

The conditional failure probabilities are given for the Oconee dominant sequences and the comparable sequences for the other two plants in Table 5.1. The differences are discussed in the following paragraphs:

O.1- Residual group

The highest conditional failure probability identified for the residual groups involved a large steam line break with the blowdown of all loops and continued AFW flow to the break for all three plants examined. However, the worse case identified for Calvert Cliffs and H. B. Robinson produced failure probabilities which were factors of 20 and 10 respectively less than the worse case for Oconee. As stated in Chapter 4, the higher conservatism and much higher AFW flow capacity present in the Oconee analysis led to temperatures which were about 40 to 60 degrees colder than those for the H. B. Robinson and Calvert Cliffs residual. The colder temperatures in conjunction with the faster repressurization process inherent in the Oconee design lead to the higher conditional failure probability.

O.2- Large steam line break with full repressurization, blowdown of one line and system response normal

There is over five orders of magnitude difference between the conditional failure probability for this event on Oconee and the same event on either Calvert Cliffs or H. B. Robinson. This difference can be accounted for by the lower pressure and at least 90 degree warmer temperature associated with the Calvert Cliffs and H. B. Robinson sequences. The lower pressure is, as previously described, due to the lower head HPI systems. The higher temperatures are due to conservative extrapolations performed for the Oconee analysis and the time at which AFW is isolated to the break. In Oconee this isolation was assumed to be performed by the operator at 20 minutes. The isolation of AFW to the broken steamline is performed by automatic equipment in Calvert Cliffs and thus when the equipment operates as designed, AFW is isolated within the first 5 minutes of the transient. In the H. B. Robinson analysis AFW isolation is, as in Oconee, performed by the operator. When credit is given for this operator action, it is assumed that the isolation occurs at 10 minutes. It is our opinion that the 20 minute time frame may be somewhat over conservative while the 10 minute time frame may be somewhat optimistic. A better time for evaluation of isolation may have been 15 minutes for both Oconee and H. B. Robinson. In such a case the Oconee conditional failure probability would have been at least an order of magnitude lower and the H. B. Robinson value would have been as much as two orders of magnitude higher. (It should be noted that even with an increase of two orders of magnitude for the conditional failure probability of this transient, it would still not appear as a dominant sequence in the H. B. Robinson analysis.)

0.3 One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that both steam generators blowdown -

No Comparison can be made for this sequence.

0.4 All turbine stop valves fail to close. Both steam generators -

Again the conditional failure probabilities calculated for this transient are lower for both Calvert Cliffs and H. B. Robinson. In this case, however, the difference is almost exclusively due to the difference in the repressurization process. In the Oconee analysis it was determined that if the repressurization process were limited to 1000 Psi (similar to actual Calvert Cliffs transient) the conditional failure probability would be reduced to below 1E-7. Thus the lower pressures associated with the Calvert Cliffs and H. B. Robinson transients led to significantly lower conditional failure probabilities. It should be noted that in the case of the H. B. Robinson analysis this case was not specifically analyzed but was reprsented by a full guillotine pipe break. This led to somewhat colder temperatures and thus not nearly as much a difference from the Oconee calculated value. It should be noted that the conditional failure probabilities shown in parenthesis for both Calvert Cliffs and H. B. Robinson represent the conditional TWC probability when the MSIVs close as designed. This indicates the importance of the MSIVs.

0.5- One TBV or SSRV fails to reseat. One steam generator blowsdown -

The conditional failure probability used for this case in the Oconee analysis is significantly higher than that used for similar thermal--hydraulic conditions on the other two plants. The reason for this is that in the Oconee analysis the lowest conditional failure considered was 1E-7. Thus, this value was assigned to this transient even though only a minor cooldown of the system is involved. After the Oconee analysis, the need to obtain conditional failure probabilities for relatively warm transients was identified and Monte Carlo acceleration techniques were used to calculate the appropriately low conditional failure probabilities. Based on this analysis it appears that a more appropriate conditional failure probability for this transient in the Oconee analysis would be about 1E-10. This of course eliminates this transient from the the Oconee list of dominate sequences.

O.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. All steam generators blowdown.

The temperature differences between the Oconee and H. B. Robinson values are small and it is the pressure effect that results in the higher failure potential for Oconee. Limiting the Oconee pressure to 1000 Psi was again found to result in nearly two orders of magnitude reduction in conditional failure probability. This would make the case consistent with the H. B. Robinson results. In the case of the Calvert Cliffs analysis the somewhat higher temperature in conjunction with the lower pressure led to a considerably lower conditional failure probability.

5.2.2 Comparison of Conditional Failure Probabilities for Calvert Cliffs Dominant Sequences.

The conditional failure probabilities are given for the Calvert Cliffs dominant sequences and the comparable sequences for the other two plants in Table 5 2. The differences are discussed in the following paragraphs:

CC.1- Small break LOCA at low decay heat -

This sequence led to loop flow stagnation and the resulting 150 degree colder temperature. This temperature difference is exclusively responsible for the six order of magnitude difference in conditional failure probability.

CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours).

Again the H. B. Robinson sequence did not involve loop flow stagnation and thus resulted in higher temperatures. The three order of magnitude difference in the conditional failure probability can be completely accounted for by these higher temperatures.

CC.3- Medium break LOCA at low decay heat -

As stated in Chapter 4, even though the temperatures are very similar for this case, the pressure profile for the H. B. Robinson case was considerably lower throughout the analysis period. This pressure difference is responsible for the three order of magnitude lower Calvert Cliffs conditional failure probability.

CC.4- Small steam line break upstream of the MSIVs with low decay heat condition -

The 150°F warmer temperature associated with the H. B. Robinson sequence resulted in a very low conditional failure probability for this sequence. As previously stated, this temperature difference was a result of conservative Calvert Cliffs assumptions coupled with the lower steam generator inventory and three loop design of the H. B. Robinson system.

CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization Process -

The faster repressurization process associated with this transient led to a two order of magnitude increase in the Calvert Cliffs conditional failure probability when compared with sequence CC.4. The faster repressurization process did not have a measurable effect in the case of the H. B. Robinson analysis since the temperatures were relatively high. This led to a five order of magnitude difference between the Calvert Cliffs and H. B. Robinson potential failure values for the same transient. This difference is consistent with the parametric study performed for H. B. Robinson where it was determined that a similar temperature difference resulted in an eight order of magnitude difference in conditional failure probability assuming full pressure at all times.

CC.6- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization Process and does not throttle AFW

For the comparison of the Calvert Cliffs and H. B. Robinson values the argument used in the discussion of CC.5 also applies. with respect to the Calvert Cliffs and Oconee comparison, the Oconee conditional failure probability is about a factor of five higher. This increase is due partially to the somewhat lower temperature of the Oconee sequence but the primary reason for the increase is the faster repressurization process inherent in the Oconee design.

5.2.3 Comparison of Conditional Failure Probabilities for H. B. Robinson Dominant Sequences

In Table 5.3 the conditional failure probabilities for the H. B. Robinson dominant sequence are compared with conditional failure probabilities for similar sequences occurring at the Oconee and Calvert Cliffs plants. The difference identified in Table 4.3 are discussed in the following paragraphs.

HBR.1- All steam side PORVs fail to close following a reactor trip -

There is at least three orders of magnitude difference in the conditional failure probability reported for this event at H. B. Robinson vs. Calvert Cliffs. This difference appears to be almost entirely due to the different temperatures obtained for the transient. The parametric study which was performed as part of the H. B. Robinson analysis implies that a temperature difference similar to that observed could result in as much as four orders of magnitude difference in the conditional failure probability.

HBR.2- Two steam side PORVs fail to close following a reactor trip -

The large difference noted in conditional failure probability is due to the fact that we are essentially comparing apples and oranges. The Calvert Cliffs sequence, although the most similar in type to the H. B. Robinson sequence, is a much less sever of a cooldown event. As discussed in Chapter 4 this led to a 120°F higher temperature. This temperature difference accounts for the conditional failure probability differences. Although the H. B. Robinson parametric study did not address temperatures as high as 400°F, extrapolation shows that increasing the temperature by 120°F would lead to conditional failure probabilities on the order of the value reported for the Calvert Cliffs sequence.

HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs -

Some very interesting comparisons can be made with the data obtained from the three plants for this transient. The H. B. Robinson, Oconee, and alternate Calvert Cliffs sequence (shown in Parenthesis) all have similar minimum temperatures and the temperature profiles for both H. B. Robinson and Calvert Cliffs have very similar shapes. However, the conditional failure probabilities range from 7E-6 for Calvert Cliffs to 6E-4 for Oconee. This difference is a clear example of the impact of pressure and the repressurization process. This two order of magnitude factor is verified by the parametric study performed for Oconee which showed that after the system begins to repressurize a limitation of pressure to 1000 Psi would lead to a factor of 50 reduction in conditional failure probability. This would be comparable to the potential limitation of pressure which results from the slowed repressurization process in Calvert Cliffs once the HPI shutoff head of 1250 Psi is reached. In the case of the comparison of the H. B. Robinson sequence and the Calvert Cliffs alternate both the small temperature difference and the small pressure difference appear to be very important. The ~25 degree temperature difference is estimated to result in a factor of 4 in the conditional failure probability. This implies that the 400 Psi difference in final pressure may be worth as much as a factor of 3 in conditional failure probability. This agrees with the sensitivity analysis which, when extrapolated, estimated an increase factor of between 2.5 and 3 for a 400 psi increase in pressure.

HBR.4- Three or more TBVs fail to close and two MSIVs fail to close -

As previously stated in Chapter 4, this sequence was conservatively assigned the failure probability associated with sequence HBR.3. As a result, the conditional failure probability is considerably lower than that used in the Calvert Cliffs study. It is our opinion based on discussions with INEL that the actual temperatures for this sequence would result in nearly a two order of magnitude decrease in the conditional failure probability. This of course would eliminate this sequence from the H. B. Robinson dominant sequence list. However, since no plans have been made to actually calculate the thermal-hydraulic conditions for this sequence, we have chosen to continue to use the conditional failure probability associated with HBR.3.

HBR.5- All steam side porvs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills -

This sequence is comparable to HBR.1 with the addition of full repressurization. When compared with sequence HBR.1 it appears that the additional pressure stress results in slightly over an order of magnitude increase in the conditional failure probability for the H. B. Robinson plant. Even though there are "<" signs associated with the Calvert Cliffs numbers it appears that the higher pressure had a similar effect in the Calvert Cliffs analysis.

HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW -

This is similar to the HBR.3 case which has been discussed previously. It is interesting to note, however, that in the case of the Calvert Cliffs sequence the failure of the operator to throttle AFW is coupled with the failure of the operator to control the repressurization process. It is this pressure difference and not the effect of AFW which results in the conditional failure probability increase of an order of magnitude from the Calvert Cliffs case which is comparable to HBR.3.

Table 5.1. Comparison of Conditional Failure Probabilities for Oconee Dominant Sequences

Sequence Definition	Oconee P(F/E)	Calvert Cliffs P(F/E)	H. B. Robinson P(F/E)
0.1- Residual Group	5.4E-3	1)2.5E-4 2) 1.8E-4 3) 6.7E-5 4) 6.0E-6 5) <1E-9 6) <1E-8 7) <1E-9 8) 8.0E-7 9) 6.0E-6 10) 1.7E-5 11) <1E-7	1)5.6E-5 2) 1.0E-8 3) 2.8E-5 4) <1E-9 5) 1.1E-5 6) 5.5E-4 7) 3.6E-5 8) 6.6E-4 9) 5.6E-5 10) 5.6E-5 11) 1.0E-4 12) 3.9E-6
0.2- Large steam line break at full P with blowdown of one line and system response normal	6.2E-4	<1E-9	1E-9
0.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that both steam generators blowdown.	2.0E-3	NA	NA
0.4- All Turbine stop valves fail to close. Both steam generators blowdown	6.2E-4	7.2E-6 (<1E-9)	1E-4 (1E-9)
0.5- One TBV or SSRV fails to reseat. One SG blowsdown.	1E-7	<1E-11	<2E-9
0.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. All SG blowdown.	2E-3	6E-6	1E-4

Table 5.2. Comparison of Conditional Failure Probabilities for Calvert Cliffs Dominant Sequences

Sequence Definition	Calvert Cliffs P(F/E)	Oconee P(F/E)	H. B. Robinson P(F/E)
CC.1- Small break LOCA at low decay heat.	1.7E-4	NA	<1E-10
CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours).	3.5E-3	NA	1.1E-6
CC.3- Medium break LOCA at low decay heat.	2.3E-6	NA	<1E-9
CC.4- Small steam line break upstream of the MSIVs with low decay heat condition.	2.0E-7	NA	<1E-10
CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process.	1.7E-5	NA	<1E-10
CC.6- Small steam line break upstream of the MSIVs with low decay heat condition. In addition the operator fails to control the repressurization process and does not throttle AFW.	1.7E-5	1E-4	<1E-10

Table 5.3. Comparison of Conditional Failure Probabilities for H. B. Robinson Dominant Sequences

Sequence Definition	H. B. Robinson P(F/E)	Oconee P(F/E)	Calvert Cliffs P(F/E)
HBR.1- All steam side PORVs fail to close following a reactor trip.	9E-7	NA	<1E-9
HBR.2- Two steam side PORVs fail to close following a reactor trip.	2E-7	NA	<1E-11
HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs.	9.5E-5	6.2E-4 (5.4E-3)	<1E-7 (7.2E-6)
HBR.4- Three or more TBVs fail close and two MSIVs fail to close.	9.5E-5	NA	<1E-9
HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills.	1.2E-5	NA	<1E-7
HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW.	1E-4	5.4E-3	6.7E-5

6.0 Comparison of Final Results

Two topics will be covered in this chapter. In section 6.1 the final through-wall-crack risk numbers for each dominant sequence will be given and compared with values for similar sequences on the other plants. In addition, for each plant analyzed through-wall-crack (TWC) numbers will be identified by initiator type and compared. In section 6.2 a comparison of the impact of potential risk reduction measures is examined with respect to each of the three plants.

6.1 Comparison of Through-Wall-Crack Probabilities

The TWC probabilities were determined in each plant study by multiplying the conditional through-wall-crack value by the expected event frequency. Thus, it is the differences in event frequency and/or conditional failure probability which results in differences in the TWC probability for a given transient. As a result, the discussions which have been presented in Chapters 3, 4, and 5 will be referred to but not repeated in this section. In Tables 6.1, 6.2, and 6.3 the final through-wall-crack probabilities are given for the plant in question along with the values for a similar sequence on the other two plants. In the columns labeled "reason for difference" a series of letters are used to designate the principle reason for difference. The designation of each letter is defined below:

F - This represents the frequency factor used in the analysis for the event in question. If the frequency factor was at least an order of magnitude different, it is listed in Table 6.1, 6.2 or 6.3 as a contributor to the different risk values obtained for the different plants. An explanation as to why the different frequency numbers were used is supplied in Chapter 3.

T - The "T" represents the temperature factor. If the temperature difference for the same sequence on two different plants was greater than 30^{o}F. It was listed as a contributor to the different risk values obtained for the different plants. The different temperatures obtained for a given sequence at different plants are explained in Chapter 4.

P - This is the pressure contribution to the final risk value. In general, if the highest pressure subsequent to minimum temperature was at least 500 psi different for comparable sequences on different plants, it was determined to be a contributor to the difference in risk values. There were, however, exceptions to this rule. In several instances even though the final pressures were essentially the same, the repressurization process was much more rapid in one plant when compared to the others and when coupled with a temperature profile which reached a minimum with subsequent warming, led to higher pressure stresses when the vessel temperature was still low. In this case pressure was determined to be an important factor even though the final pressures were similar. Another exception was when the pressure was very low. In those instances where the temperature was very low (on the order of 100^{o}F) and the pressure was low (less than 1000 psi) it was determined that a small difference in pressure had a large impact on the conditional failure probability. As a result, under these conditions pressure was listed as a contributing factor when the pressure difference was greater than 100 psi. Explanations for the different pressures obtained for the sequences are explained in Chapter 4.

M - This implies that a different fracture mechanics approach was used to determine the conditional failure probability. As a result in comparing the conditional failure probability for a given sequence at two plants, the conditional TWC frequency values may be very different even though the thermal-hydraulic profiles are very similar. In general the difference can be traced to the use of a bounding approach on determining the TWC frequency for one plant while a specific calculation was performed to determine the conditional TWC frequency on the other plant. The differences in conditional TWC frequency are explained in Chapter 5.

In addition to the comparison of dominant sequence risk values as discussed above, it is important to examine the differences in risk by initiator type. This provides the data for a more generic discussion of plant differences. The final TWC probabilities by initiator type are given in Table 6.4 for each of the three plants. It should be noted that the sequences which result from an initial reactor trip as an initiator have been grouped into the initiator type which is most representative of the actual characteristics of the sequence. For example, the sequence which involves a reactor trip followed by the failure to close of a TBV is grouped with the small steam line breaks at full power. This provides a better basis for the comparison of event types. The differences observed in Table 6.4 are discussed in the remainder of this section.

Steam line breaks

Large steam line break at full power

The large steam line break sequences examined produced similar results in both the Calvert Cliffs and H. B. Robinson plants. The most important steam line break sequences for these two plants involved breaks which included the blowdown of more than one steam generator. This was accomplished via the failure of two or more MSIVs. In addition, sequences involving the blowdown of one steam generator and the failure of the operator to isolate AFW to the broken steam line was also a contributing factor in the H. B. Robinson analysis. The TWC risk reported for the large steam line break at full power in the Oconee analysis is nearly four orders of magnitude higher than it is for either Calvert Cliffs or H. B. Robinson. This difference can be attributed to three factors. 1) About one third of the risk associated with the large steam line break is due to the initiator turbine failing to trip which is treated as a large steam line break. In both the Calvert Cliffs and H. B. Robinson plants the presence of the MSIVs makes this event a minor transient. The failure of the MSIVs to close would of course lead to a similar event but the frequency for this condition is substantially lower. 2) The AFW flow rate is substantially higher than that in either Calvert Cliffs or H. B. Robinson and the AFW enters the steam generator from the top. As a result the temperatures for this event are expected to be lower for the Oconee plant thus causing a higher conditional failure probability. 3) A review of the thermal-hydraulics calculations for the steam line break in the Oconee analysis reveals that the Oconee calculations may be overly conservative. It is our opinion that the temperatures for this event at Oconee should be lower than those obtained for the calculations of steam line breaks of either Calvert Cliffs or H. B. Robinson; but it is our belief that the rate of temperature drop should be less rapid than that used in the Oconee analysis and the minimum temperatures should be higher than those actually used in the analysis.

Large steam line break at low decay heat

In general the relationship of different TWC values obtained for this class of event for the three plants is consistent with the expected order. The higher inventory of the Calvert Cliffs steam generators at low decay heat would be expected to produce colder temperatures and thus higher conditional failure probabilities than H. B. Robinson. On the other hand, the high AFW flow rate for Oconee is still expected to dominate rather than the initial steam generator inventory. Thus, when the AFW in Oconee is not assumed to be isolated by the operator until 20 minutes, the steam line break would produce colder temperatures than those for Calvert Cliffs where the AFW is automatically isolated very early in the transient.

Small steam line break at full power

For both Oconee and H. B. Robinson this event is dominated by multiple TBV failures. In both Oconee and H. B. Robinson TBVs are not automatically isolated following failure to close as they are for Calvert Cliffs (automatic MSIV closure for this event will isolate TBVs). At the Oconee plant the TBVs can be isolated manually at the location of the valve. There is no question that given enough time these valves will most likely be isolated given failure. However for the PTS analysis which covers only the first two hours of the event no credit was taken for the isolation of these valves given failure. At H. B. Robinson there are MSIVs which can be used to isolate TBV failures. However, the MSIVs will not close automatically for the small breaks, as they do at the Calvert Cliffs plant, and closure is left to the operator. Thus, there is a common mode failure for the closure of all MSIVs that produces a higher failure probability than would be obtained for simply the mechanical failure of all MSIVs. In summary the small steam line break at full power is more important at H. B. Robinson than at Calvert Cliffs due to the increased probability of occurrence of those small steam line break cases considered to be severe. This probability of occurrence is further increased at Oconee due to the absence of MSIVs making the TWC probability due to a small steam line break the highest of the three plants. It should be noted that at H. B. Robinson multiple failures of the ADVs also contribute to the small steam line break class. The failure of ADVs was not found to be important on either of the other two plants since: 1) Oconee does not have ADVs which automatically open on turbine trip and 2) even though Calvert Cliffs does have ADVs which open on most turbine trips, the size of these valves is substantially smaller than those on the H. B. Robinson plant making the consequence of such failures significantly less.

Small steam line break at low decay heat

One would suspect that the relationship of TWC frequency for the small steam line break at low decay heat for the three plants would be similar to the relationship obtained for the large steam line break at low decay heat. The value for the small steam line break at low decay heat which appears to be significantly out of line is the one given for Calvert Cliffs. However, as stated in Chapter 4 it appears that a conservative approach was taken in obtaining the temperature profiles for this type of event, i.e. the temperature profiles obtained from the simple model were based on the large break calculations since no full scale calculation was performed for the small steam line break at low decay heat. This would imply that the TWC value given in Table 6.4 for the small steam line break at low decay heat is somewhat high.

LOCAs

Small break LOCA at full power

The TWC frequency for this event is very similar for both Calvert Cliffs and H. B. Robinson but about two orders of magnitude higher for Oconee. A review of the Oconee small break LOCA events reveals that the higher TWC frequency is not due to the LOCA event per se but due to secondary side events that occur following the LOCA. The small break LOCA event at Oconee yielded a value <8E-10 when secondary side events were not considered. This is very consistent with the total values for this type of initiator as given for the Calvert Cliffs and H. B. Robinson plants. The two events which cause the Oconee value to be two orders of magnitude higher involve: 1) continuous AFW overfeed and 2) MFW overfeed on both lines. In the later case since no thermal-hydraulic data was available the default fracture mechanics value was used. This appears to be an over-estimation of the risk involved with that particular event. In the former case AFW overfeed is assumed to occur over the entire two hour period. This includes the complete filling of the steamlines and the cycling of AFW through the TBVs back to the steam generator. In both the Calvert Cliffs and H. B. Robinson plants the AFW flow rate is significantly lower. As a result within a two hour period the level of cooldown associated with this event is not nearly as high for the Calvert Cliffs and H. B. Robinson plants.

Small break LOCA at low decay heat

The probability of TWC for this type of event is significantly higher for the Calvert Cliffs plant than it is for the H. B. Robinson plant. The principle difference in the two plant analyses evolves around the question of loop flow stagnation. In the Calvert Cliffs analysis performed by LANL, very low loop flow is predicted for this sequence within about 10 minutes of the initiation of the event. This led to localized cooldowns to very low mixed mean temperatures in the downcomer region and the formation of even colder plumes in the downcomer within two diameters of the cold leg pipes. In the H. B. Robinson analysis performed by INEL, very low loop flow was predicted for this event for a very short period of time. After this time, loop flow was restored and the cooldown continued at a slow rate based on the blowdown of the primary system. As a result of the H. B. Robinson analysis, the stagnation issue with respect to the small break LOCA was further examined. It was determined that there were physical differences in plant design which led to a higher potential for loop flow stagnation on Calvert Cliffs than on H. B. Robinson. However, it was INEL's opinion that if the LANL calculation had been continued after stagnation occurred, loop flow would have been recovered within a period of time that would have precluded the very cold temperatures predicted for the Calvert Cliffs sequence. At present the issue has not been resolved and work by Purdue University is proceeding to address these issues. If prolonged loop flow stagnation for this event does not take place for Calvert Cliffs, the TWC probability for this type of event would be similar to that reported for H. B. Robinson. On the other hand if H. B. Robinson is shown to exhibit prolonged loop flow stagnation, the TWC probability for that plant would be raised significantly but not to as high a value as that reported for Calvert Cliffs since the HPI water at H. B. Robinson is heated.

Medium break LOCAs at full power

Even though the Oconee TWC probability for this class is small, it is still at least two orders of magnitude higher than it is for either Calvert Cliffs or H. B. Robinson. A review of the Oconee fracture mechanics analysis of this transient reveals that the conditional failure probability assigned to each of the sequences examined in this class was the minimum calculated value of 1.0E-7. It is our opinion that with the low pressures associated with this event a more extensive fracture mechanics calculation, such as those performed as part of the Calvert Cliffs and H. B. Robinson analyses, would produce conditional failure probabilities which were lower than the 1.0E-7 used in the analysis. This would most likely make the results consistent with the Calvert Cliffs and H. B. Robinson results.

Medium break LOCA at low decay heat

For reasons similar to those given for the small break LOCA at low decay heat, the Calvert Cliffs sequences in this category produced higher TWC probabilities than those for H. B. Robinson. As a result, the arguments presented there will not be repeated in this section.

Steam generator overfeed

It is important that the steam generator overfeed class be qualified before it is discussed. The steam generator overfeed cases involved main feedwater overfeed (single, double, and in the case of H. B. Robinson triple loop overfeeds) and auxiliary feedwater overfeed. After the overfeed analysis was performed, the potential for an overfeed causing steam line breaks and/or tube ruptures was identified. These cases are presently being analyzed and their impact will be reported at a later date. The comparison and discussion in this section, therefore, will center only on the work which has been done in the area of overfeeds.

The Calvert Cliffs and H. B. Robinson TWC values associated with overfeeds are very small reflecting the minor cooldowns associated with the overfeed events. As in previous cases, the TWC frequencies associated with the overfeed events in the Oconee analysis are somewhat artificially high due to the use of a minimum conditional failure probability of 1.0E-7. The Oconee sequences are, however, not expected to produce TWC frequencies as low as either Calvert Cliffs or H. B. Robinson since the AFW system of the Oconee plant provides substantially larger cooling capacity.

Tube rupture events

Single tube rupture events were not expected to be any more severe than the small break LOCA events. This has been confirmed from the analysis of tube rupture events in both the Oconee and H. B. Robinson analyser. It should however be noted that multiple tube rupture events which could lead to relatively cold temperatures at pressures as high as 1100 psi have not been examined due to the perceived frequency of such events. It has subsequently been brought to our attention that such events may be tied to other events, particularly overfeeds and steamline breaks, in such a manner that the frequency may be higher than originally perceived. As a result, multiple tube ruptures will be examined as part of the overfeed review.

Residual

The residual group was a dominant sequence in the Oconee analysis and thus a comparison of the residual class in the three plant studies has already been made (see Table 6.1).

6.2 Comparison of the Impact of Potential Mitigation Measures

In all three studies potential mitigation measures were examined to provide means by which TWC risk could be reduced. It should be noted that none of the proposed mitigation measures have been evaluated with respect to total plant safety, operation, and cost effectiveness. The mitigation measures examined and their impact on the TWC frequency of each plant are given in Table 6.5 and discussed in the remainder of this chapter.

Reduction in fluence

Fluence reductions have a clear positive impact on the reduction of TWC risk. However, the degree of impact varies with the different plants. The actual impact of a fluence reduction is determined by the type of sequences which dominate the TWC risk for the plant in question. A curve of conditional TWC vs. fluence can be constructed for each sequence. Each of these curves will have the shape of a decaying exponential with the TWC probability approaching the probability that a flaw in the material exists. Thus the curve can be described as having a steep slope when the TWC probability is substantially less than the maximum value and a relatively flat slope as the TWC probability approaches the maximum value. The impact of a fluence reduction at any point in time (a set fluence level) will then be determined by the slope of the TWC probability curves vs. fluence for the sequences which dominate the risk. If a fluence reduction does not move you out of the flatter portions of the curve, the impact of the fluence reduction will be minimal. Examples of this are fluence reductions of a factor of 2, from the value at RTNDT equals 270^{o}F, for the Oconee O.1, Calvert Cliffs CC.2, and H. B. Robinson HBR.3 sequences. In these cases the factor of 2 reduction does not move you out of the flatter portions of the curve and the TWC probability reduction is only a factor of ~0.6, 0.4, and 0.3 respectively for the three sequences. On the other hand, if a fluence reduction moves you substantially into the steep portion of the curve, the fluence reduction will have a major effect in the reduction of TWC probability. Fluence reductions of a factor of 2 for sequences CC.5, HBR.1, and HBR.2 are examples of this effect. A factor of 2 reduction in fluence for these cases moves you well into the steep portion of the curve and produces large reduction factors in TWC frequency, .05, .08, and .04 respectively for the three sequences.

With this understanding of the impact of fluence reductions, the differences in the impact of a fluence reduction for the three plants, as shown in Table 6.5, can be explained. In the case of Oconee, the TWC probability is dominated by sequence O.1. As stated above this is one of the severe sequences where for a RTNDT value of 270°F, a factor of 2 reduction in fluence will not move you from the flat portion of the TWC probability curve. On the other hand a factor of two reduction in fluence for the Calvert Cliffs and H. B. Robinson plants does move you into the steeper portion of the curve for the dominant sequences. As a result, the fluence reduction has a much larger effect on the reduction of the TWC probability than it does for the Oconee plant. This pattern continues for fluence reductions of factors of 4 and 8. However in the H. B. Robinson analysis, changes in fluence of factors of 4 and 8 results in a change in the dominant sequences. The new dominant sequences have TWC curves which are much flatter in the fluence ranges being considered. This results in a decrease of the impact of additional fluence reductions. Thus, even though a factor of 2 reduction in the fluence yields the same impact for both H. B. Robinson and Calvert Cliffs, a factor of 8 decrease in fluence has a substantially larger impact for Calvert Cliffs than it does for H. B. Robinson.

Limit on repressurization
In the Oconee analysis the repressurization process was found to be very important. Therefore the impact of limiting pressure in some manner to 1000 psi was examined. It was found that this action would decrease the TWC probability for Oconee by a multiplicative factor of .02. Subsequent to the Oconee analysis it was decided not to pursue this mitigation measure since such a requirement was extreme and could have impact on other safety issues. This does point out, however, the importance of the repressurization process for the Oconee plant. If a repressurization limit had been evaluated for Calvert Cliffs and H. B. Robinson, the effect would not have been nearly as large since the HPI shutoff heads of these plants already limit the repressurization process to some extent.

Annealing of the vessel
Test results from small specimens indicate that essentially full recovery of the initial fracture toughness might be achieved by annealing in the temperature range of 750-850°F for ~200 hours. Thus, in this analysis by definition annealing returns the vessel to its initial toughness. In order to perform a comparison of the effects of annealing, it was assumed that each vessel was annealed at nine years. This led to the TWC probability reductions as shown in Table 6.5. (It should clearly be noted that annealing at later times would yield larger effects, and the nine-year point was chosen simply for example purposes.)

High steam generator level feedwater pump trip
Both Oconee and H. B. Robinson already have automatic feedwater pump trip on high steam generator level indication and thus this mitigation measure is not applicable to those two plants. In the Calvert Cliffs analysis it was

determined that the overfeed cases contributed less than one percent of the TWC probability. Therefore the introduction of a high level trip would not impact the total TWC probability. However, as stated earlier in this chapter, the potential for overfeeds leading to steam line breaks is being examined. If important sequences are identified from this additional study, the impact of a high steam generator level feedwater pump trip would have to be re-examined for Calvert Cliffs.

Heating HPI water to 100°F

Since the H. B. Robinson HPI water is already heated to 100°F, this mitigation measure was not applicable to that plant. In the Oconee analysis the heating of HPI water would have very little impact since the dominant sequences involve cooldowns which are primarily secondary side effects and the HPI flow contributed little to the actual downcomer temperature. In the case of Calvert Cliffs, however, the dominant sequences involve stagnate primary loops where the principle cooldown mechanism is the HPI water. In this case the heating of the HPI water would result in warmer downcomer temperatures and, as shown in Table 6.5, about a factor of three reduction in the TWC probability. In should be noted that it appears that the H. B. Robinson plant will soon be changed in such a manner that the HPI water will no longer be heated. Since the H. B. Robinson TWC probability would still be expected to be dominated by secondary side cooldown events, it would appear that the impact of heating the HPI water is more like what we see for Oconee than what we see for Calvert Cliffs. Thus, it would appear that a reduction in HPI water temperature will have only a small effect on the analysis results for that plant.

Automatic isolation of AFW

The Calvert Cliffs plant has a system whereby AFW is automatically isolated in the case of a steam line break and therefore, this mitigation action is not applicable to that plant. This action was also not evaluated explicitly for the other two plants. However, based on discussion which has previously been presented in this report, it appears that this potential mitigation action could have an impact on the results of both the Oconee and H. B. Robinson results.

Table 6.1. Comparison of Oconee Dominant Sequence Final TWC Probabilities with Values for Similar Sequences on Calvert Cliffs and H. B. Robinson

	Oconee	Calvert Cliffs		H. B. Robinson	
Sequence Definition	TWC Value	TWC Value	Reason for Diff	TWC Value	Reason for Diff
0.1- Residual Group	2.6E-6	1) 1E-11	F	1) 5E-11	F,T,P
		2) 9E-11	F	2) 2E-15	F,P
		3) 5E-11	T,F	3) 3E-12	F,T
		4) 4E-11	T,F	4) <7E-18	P,F
		5) <2E-15	T,F,P	5) 8E-12	F,T,P
		6) <3E-14	T,F	6) 2E-10	F
		7) <5E-14	T	7) 1E-11	F,T
		8) 7E-11	T,P	8) 2E-10	F
		9) 4E-10	T	9) 2E-12	F,T,P
		10) 2E-11	T,F	10) 2E-10	F,T,P
		11) <2E-14	P,F	11) 5E-12	F,T,P
				12) 2E-12	F,T
Total	2.6E-6	7E-10		7E-10	
0.2- Large steam line break at full P with blowdown of one line and system response normal	6.2E-7	<9E-13	T	1E-12	T
0.3- One or two TBV or SSRV fail to reseat with continued flow to the break. Failures occur in such a manner that both steam generators blowdown.	4.4E-7	NA		NA	
0.4- All Turbine stop valves fail to close. Both SG blowdown.	3.1E-7	7.2E-12 (<1E-12)	F,P T	2E-11 (4E-13)	F,P T
0.5- One TBV or SSRV fails to reseat. One SG blowsdown.	7.0E-8	<4E-16	M,F	<3E-11	M
0.6- One or two TBV or SSRV fail to reseat with feedwater overfeed. All SG blowdown.	4.8E-8	4.2E-12	P,F	1E-11	F,P

Table 6.2. Comparison of Calvert Cliffs Dominant Sequence Final TWC Probabilities with Values for Similar Sequences on Oconee and H. B. Robinson

	Calvert Cliffs	Oconee		H. B. Robinson	
Sequence Definition	TWC Value	TWC Value	Reason For Diff	TWC Value	Reason For Diff
CC.1- Small break LOCA at low decay heat.	5E-8	NA		8E-14	T
CC.2- Small break LOCA at low decay heat which is isolated late in the transient time (~1.5 hours).	2E-8	NA		3E-11	T,P
CC.3- Medium break LOCA at low decay heat.	8E-10	NA		<2E-14	P,F
CC.4- Small steam line break upstream of the MSIVs with low decay heat condition.	8E-10	NA		2E-13	T
CC.5- Small steam line break upstream of the MSIVs with low decay heat condition and failure of the operator to control the repressurization process.	9E-10	NA		2E-15	T
CC.6- Small steam line break upstream of the MSIVs with low decay heat condition. In addition the operator fails to control the repressurization process and does not throttle AFW.	9E-10	2E-8	P	3E-17	T,P

Table 6.3. Comparison of Calvert Cliffs dominant sequence final TWC probabilities with values for similar sequences on Oconee and H. B. Robinson

	H. B. Robinson	Oconee		Calvert Cliffs	
Sequence Definition	TWC Value	TWC Value	Reason For Diff	TWC Value	Reason For Diff
HBR.1- All steam side PORVs fail to close following a reactor trip.	3.7E-9	NA		<3E-12	T
HBR.2- Two steam side PORVs fail to close following a reactor trip.	2.8E-9	NA		7E-13	T,P
HBR.3- Three or more TBVs fail to close and the operator neglects to close the MSIVs.	7E-10	1E-7 (1E-6)	F,P F,P,T	1E-14 (1E-12)	T,F F,T
HBR.4- Three or more TBVs fail to close and two MSIVs fail to close.	7E-10	NA		5E-16	T,F
HBR.5- All steam side PORVs fail to close following a reactor trip and the charging system fails to runback as the pressurizer refills.	5E-10	NA		<1E-11	T
HBR.6- Three or more TBVs fail to close. The operator neglects to close the MSIVs and throttle AFW.	4E-10	<5E-9		<7E-12	F

Table 6.4. Comparison of Final Through-Wall-Crack Probabilities by Initiator Type

Initiator Type	Oconee Final TWC Probability	Calvert Cliffs Final TWC Probability	H. B. Robinson Final TWC Probability
1) Steam line break			
a) Large at full power	9E-7	2E-10	3E-10
b) Large at low decay heat	3E-9	2E-10	2E-11
c) Small at full power	6E-7	4E-10	1E-8
d) Small at low decay heat	2E-8	1E-8	1E-11
2) LOCAs			
a) Small at full power	3E-8	2E-10	4E-10
b) Small at low decay heat	NA	1E-7	4E-11
c) Medium at full power	1E-10	<3E-12	1E-12
d) Medium at low decay heat	NA	3E-8	2E-14
3) Steam generator Overfeed	3E-8	<4E-11	3E-13
4) Tube rupture	4E-9	NA	3E-11
5) Residual	3E-6	7E-10	7E-10
Total	4.5E-6	1.5E-7	1.3E-8

Table 6.5. Comparison of the Impact of Potential Mitigation Measures

Potential Mitigation Measure	Oconee TWC Reduction Factor	Calvert Cliffs TWC Reduction Factor	H. B. Robinson TWC Reduction Factor
1. Reduction in fluence			
a) factor 2	.48	.14	.15
b) factor 4	.16	.02	.05
c) factor 8	.07	.007	.03
2. Limit on Repressurization	.02	NE	NE
3. Annealing at nine years	.54	.54	.1
4. High steam generator trip	NA	1.0	NA
5. Heating HPI water to 100°F	.9 - 1.0	.31	NA
6. Automatic isolation of AFW	NE	NA	NE

7.0 Sensitivity, Uncertainty, and Bias

A sensitivity and uncertainty analysis was performed for each of the three plant analyses. These efforts will be discussed in sections 7.1 and 7.2 respectively. In addition there are nonrandom assumptions which introduce potential bias in the results. These identified biases are presented and discussed in section 7.3.

7.1 Sensitivity Analysis

A sensitivity analysis was performed as a part of each plant study by perturbing individual variables with all other variables held constant and examining the impact on the through-wall-crack (TWC) probability. The results of the sensitivity analyses are summarized in Table 7.1. It should be noted that the amount of change in the variable is not necessarily related to the uncertainty in the variable. In many instances the amount of change is simply a value chosen for a common evaluation in all three plant analyses.

With only one exception it appears that the impact of a change in the identified variables is reasonably consistent for all three plants. The one exception is the change in RTNDT for the H. B. Robinson plant. The larger impact in the H. B. Robinson case is due to the fact that the top two dominant sequences involve considerably less cooldowns than the top dominant sequences in either Oconee or Calvert Cliffs. This is exemplified by the fact that the minimum temperature for the most important sequence is 163 ^{O}F for Oconee and 122 ^{O}F for Calvert Cliffs while it is considerably warmer at 268 ^{O}F for H. B. Robinson. Since the minimum temperatures for the Oconee and Calvert Cliffs cases are already well below the RTNDT value, an increase in the RTNDT value will have less of an effect than it does for the H. B. Robinson case. It is interesting to note that with respect to the other two plants a similar effect might be seen for a 30% increase in fluence for the H. B. Robinson vessel. The 30% fluence increase was not evaluated for H. B. Robinson; but since a fluence increase can be presented as an increase in RTNDT, it would appear that the impact of the fluence increase would be much larger in the H. B. Robinson analysis.

7.2 Uncertainty Analysis

A somewhat different approach was used for performing the uncertainty analysis in each of the three plant studies. It is our opinion that the uncertainty analysis was improved with each plant analysis. However, even though the uncertainty analysis performed for the H. B. Robinson analysis is considered the most technically sound, it still has some deficiencies associated with it that will be discussed later. In section 7.2.1 the approach used in each of the analysis is presented. In section 7.2.2 the results of each of the three uncertainty analyses are presented and discussed.

7.2.1 Approaches Used in the Uncertainty Analyses

For the Oconee PTS study, a Taylor series expansion approach was chosen. In this approach, the mean of the distribution was assumed to be equal to the value computed from the point estimates; and the variance was approximated by the terms of a Taylor series including second order terms and no covariance between the variables. In many situations, the above technique works extremely well. However, one must recognize that this is an approximation and can be significantly in error in some cases. In particular, for nonlinear problems and cases where a few variables dominate the results, one must be extremely cautious. These conditions are both true in the PTS uncertainty analysis. The estimation of the mean of the system by substituting the means of the underlying variables into the system equation is exact only when all second and higher order partial derivatives are zero; for example when the system is a linear combination of the underlying variables. In the instance of TWC probabilities, the OCA-P code is known to be nonlinear. The magnitude of the second and higher derivatives is not to be expected to be zero. Consequently, the estimate of the mean of the resulting distribution will be biased.

A measure of the uncertainty in the estimated TWC frequency at RTNDT = 270^{o}F was determined in the Calvert Cliffs analysis using a Monte Carlo analysis. Distributions were developed for each analysis variable. For each Monte Carlo trial a value for each variable was determined by a random selection from the variable distribution curve. The principle problem for this approach was that it was impractical to perform a fracture mechanics calculation for each trial. Thus, it was necessary to develop some means of estimating the conditional TWC probability associated with the conditions of each trial. In the case of the steam-line break cases at hot 0% power, sufficient fracture mechanics calculations existed at alternate variable values to permit the expected TWC probability to be modeled using a multidimensional surface fit. For the remaining sequences each fracture mechanics parameter was separately modeled by a log-linear relationship with the variable. This, of course, assumes no interactions with respect to changes in other variables, i.e. temperature is determined to have a set impact on the base TWC probability independent of changes in the pressure associated with the sequence. However, since these interactions are known to exist, this approach introduces a random bias in the uncertainty analysis.

A Monte Carlo approach was also used for the uncertainty analysis in the H. B. Robinson study. However, a series of fracture mechanics calculations were made to provide the 75 data points necessary to comprise a central composite design of three response surface models. The most appropriate response surface model was then used to determine the conditional TWC probability for the conditions existing for each Monte Carlo trial. It is our opinion that short of performing a fracture mechanics calculation for each of the 6000 or so trials, this is the most appropriate means of determining the impact of uncertainties in the fracture mechanics variables.

7.2.2 Results of the Uncertainty Analysis

The 95th percentile error factors used in the uncertainty analysis for each of the three plants are given in Table 7.2. Two items should be noted about the data presented in this table:

1. The error factors used in all three analyses were essentially the same. However, in the Oconee analysis the error factor was assumed to cover 99+% of the distribution while the same error factor in the Calvert Cliffs and H. B. Robinson analysis was used to represent 95% of the distribution. As a result as shown in Table 7.2, the 95th percentile inferred by the Oconee analysis is much smaller than that used in either of the other two analyses. It is our feeling that the error factors provided are indeed 95th percentile numbers and thus the Calvert Cliffs and H. B. Robinson values are more appropriate. This means that the uncertainty values as provided in the Oconee analysis are probably underestimates of the uncertainty as we understand it.

2. The 1 sigma values listed are smaller in the Calvert Cliffs and H. B. Robinson analysis for many of the fracture mechanics parameters. The values as given for the Oconee analysis are the recommended 1 sigma values presented in chapter 5 of each of the three plant studies. However, after the Oconee analysis it was recognized that the distributions of these variables about a fixed mean are simulated in the OCA-P fracture mechanics calculations. Thus, the use of the actual 1 sigma value in an uncertainties analysis would constitute a double counting of uncertainty. In both the Calvert Cliffs and H. B. Robinson analysis the one-third value was chosen to represent the uncertainty in the mean values of the parameters, and the variability around a fixed mean is included in the OCA-P simulation.

The actual error factors obtained as a function of distribution percentile are given in Table 7.3. As seen from this table, the error factors for the three analyses are substantially different. It is our opinion that the actual error factors for each plant should be much closer and should be between those listed for Oconee and those listed for H. B. Robinson. The Oconee values are clearly low due to the use of the supplied error factors as a 99+% value rather the actual 95% value. However, following the Calvert Cliffs and H. B. Robinson analyses, it was determined that in our use of the flaw density as a direct multiplier of the total TWC probability, we have introduced a over-counting effect for high flaw density values. This has a major effect on the tails of the distribution and will result in a reduction in the error factors as shown for Calvert Cliffs and H. B. Robinson in Table 7.3. This over-counting effect is explained in Appendix A. At present the major components of the uncertainty are the flaw density and the downcomer temperature. In the Oconee analysis the downcomer temperature is the dominant uncertainty contributing to nearly 60% of the total uncertainty while the flaw density can be attributed to 29% of the uncertainty. Thus the downcomer temperature and the flaw density together account for 99% of the total uncertainty. In both the Calvert Cliffs and H. B. Robinson studies the uncertainty is almost totally dominated by the flaw density. However, with the analysis errors in the three uncertainty analyses as explained above, it is impossible to determine the dominant uncertainties at this time. The elimination of the over-counting effect associated with the flaw density will reduce its impact on the uncertainty and the use of more appropriate uncertainties in the downcomer temperature for the Oconee analysis, i. e. recognize physical minimum temperatures, will reduce the magnitude of the temperature uncertainty for Oconee. It is very possible that uncertainties in the initiating event and branch point frequencies will become an important component of the uncertainty once the deficiencies in the previous analyses are eliminated.

7.3 Comparison of Analysis Bias

In the previous section uncertainties due to the simple randomness of certain variables was examined. In addition to these uncertainties there are biases introduced in the analysis every time an assumption is made. In this section the known major biases which have been introduced into the study will be identified and quantified whenever possible. These biases will be divided into five groups: 1) sequence identification, 2) sequence quantification, 3) thermal hydraulics, 4) fracture mechanics, and 5) uncertainty analysis. The use of the terms negligible (N), small (S), moderate (M), and large (L) in the tables and text of this section refer to factors of change in the final TWC probability of less than 10%, less than a factor of two, less than a factor of 10, and greater than a factor of 10 respectively. Thus even though an assumption is deemed to be extremely conservative, it would be listed as a negligible conservatism if the assumption has no impact on the final TWC value. In addition, one should be very careful in trying to combine biases to determine the impact of a set of biases since the impact of each bias is based on all other factors remaining as they are. It is very important to note that the impact of the different biases as given in the remainder of this chapter are estimates based on extrapolations of available data and not elaborate calculations.

7.3.1 Biases Associated with Sequence Identification

The identification of sequences will always result in the elimination of certain sequences and therefore an optimistic bias is automatically introduced. However, by the use of the system state trees to actually examine the states in which each plant system might exist and by the use of a probability screening criteria, it is our opinion that this effect has been minimized. The one area which the system state trees may not cover, however, is those sequences which are either initiated or enhanced by the operator or external events. As stated in the ground rules of each study, these types of events were not examined. It would appear that these types of events would produce a measurable optimistic bias in the results. It should be noted, however, that most of these sequences would also appear as an end state of the system state trees and thus, in most instances the impact of the operator or external event initiation or enhancement would be to increase the frequency of an end state and not to introduce a new sequence. The biases which we have examined in the identification of the sequences are given in Table 7.4.

7.3.2 Bias Associated with Sequence Quantification

The random uncertainties associated with the probabilities of equipment failures and operator actions have already been discussed in section 7.2. However, there are biases which have been introduced by the sequence quantification process itself. The biases associated with the sequence quantification which have been identified are shown in Table 7.5.

7.3.3 Bias Associated with Thermal-Hydraulic Analysis

In the Oconee analysis there appears to be substantial conservatism involved in the extrapolation process used to obtain the temperature profiles for many of the dominant sequences. It would appear that this may be the dominant bias in the Oconee analysis. The dominant biases for Calvert Cliffs and H. B. Robinson analyses may also involve the thermal-hydraulic analysis. The LANL calculation of the small break LOCA at low decay heat predicted loop flow stagnation very early in the sequence. It was LANL's opinion that stagnation would continue for the remainder of the two hour analysis period and thus the calculation was terminated. In the INEL's analysis of this type of transient for the H. B. Robinson study, stagnation was predicted early in the sequence but flow was predicted to be recovered in a relatively short period of time, thus precluding the cold temperature and relatively high pressure conditions obtained for the Calvert Cliffs analysis. There does appear to be design differences which could lead to prolonged stagnation for the Calvert Cliffs system and early flow recovery for the H. B. Robinson system. However, the potential for prolonged stagnation in both or neither one is still being considered. If in the final analysis, neither system is found to lead to prolonged loop flow stagnation in all loops, the Calvert Cliffs analysis as it now stands would include a large bias by assuming complete stagnation for the two hour period. If on the other hand both systems are found to lead to prolonged loop flow stagnation in all loops, there would be a large optimistic bias in the present H. B. Robinson analysis. These biases as well as other identified thermal-hydraulic biases are included in Table 7.6.

7.3.4 Bias Associated with Fracture Mechanics Analysis

The most highly discussed bias associated with the fracture mechanics analysis is the assumption of no credit for warm prestressing (WPS). This was perceived by many to be a very large conservatism since warm prestressing is an observed phenomenon and has the potential to greatly reduce the probability of a TWC. However, it was our finding that in all three plants examined at least one of the top six sequences was only slightly effected by WPS, thus limiting the overall impact WPS could have on the overall TWC probability. Credit for WPS was not taken for any sequences in the analysis since the KI vs. time curves are very flat for the shallow flaws and unforeseen variations in pressure and coolant temperature might exist and defeat WPS. If the transients actually behaved as the thermal hydraulic codes have predicted, a moderate conservative bias has been introduced into the study. It should be noted that we now feel credit should be given for WPS for those sequences which involve those small break LOCA events which cannot be isolated and for which HPI cannot keep up with the flow out the break. Thus by definition pressure cannot be recovered to the levels that would defeat warm prestressing in these three plants. Thus credit for WPS would have a measurable impact only on the Calvert Cliffs analysis. This bias along with other fracture mechanics biases are summarized in Table 7.7.

7.3.5 Bias Associated with the Uncertainty Analysis

In order to have a point of reference, the biases associated with the uncertainty analysis will be discussed with respect to the 95 percentile value. The largest bias introduced into the uncertainty analysis appears to be the manner in which large flaw densities were treated. In the uncertainty analysis it was assumed that the TWC frequency was always proportional to the flaw density. As stated earlier, it has come to our attention that as the probability of having a critical depth flaw approaches one, the impact of increasing the flaw density approaches zero. Thus when we sampled in the high range of the flaw density curve in the uncertainty analysis for Calvert Cliffs and H. B. Robinson, we overestimated the impact of that point. The uncertainties are presently being reevaluated in light of this understanding. At this point it is perceived that this will have a moderate to high reduction effect on the 95 percentile value. If this is determined to be true, the uncertainty values as now presented in the Calvert Cliffs and H. B. Robinson studies contain a moderate to high bias. This bias along with other biases associated with the uncertainty analysis are summarized in Table 7.8.

7.3.6 Summary of Biases

It would appear that the balance of the biases are conservative for both Oconee and Calvert Cliffs with the balance of the biases for H. B. Robinson being optimistic or conservative depending on the resolution of the stagnation issue. However, as pointed out earlier, one should be very careful when trying to combine biases. The impact of each of the bias effects which have been discussed in this section are based on the sequence TWC probabilities as they presently exist. If credit is taken for one of the biases, the impact of other biases may change significantly.

Table 7.1. Results of Sensitivity Analysis

Variable Changed	Amount	Oconee TWC Change Factor	Calvert Cliffs TWC Change Factor	H. B. Robinson TWC Change Factor
Flaw density	x100	100	100	99.8
Temp.	-50°F	8.3	8.2	10.4
RTNDT	+28°F	2.9	3.5	12.4
Cu	+.025%	1.8	3.3	NE
Fluence	+30%	1.7	2.3	NE
KIc	-15%	2.5	2.7	3.3
KIa	-10%	1.0	1.1	1.1
Pressure	+50 Psi	1.1	1.1	1.2
h	+25%	1.1	1.1	1.3

Table 7.2. The 95th Percentile of Median Error Factors Used in the Uncertainty Analysis

Variable	Oconee 95% Error Factor	Calvert Cliffs 95% Error Factor	H. B. Robinson 95% Error Factor
Initiating events			
Large SLB	2.4	15	15
Small SLB	3.5	10	10
LSLB 0% P factor	NE	3	15
SSLB 0% P factor	NE	3	3.8
Reactor trip		10	10
Medium LOCA	NE	10	10
Small LOCA	3.5	10	10
LOCA 0% P factor	NE	15	10
Loss of feedwater	3.5	10	15
Loss of service water	NE	NE	10
SG tube rupture	3.5	NA	10
Inadvertent SI	3.5	NA	NA
Branch points			
Turbine trips	3.5	15	15
ADVs close			
One fails	NA	10	10
Two fail	NA	15	15
Three fail	NA	15	15
TBVs close			
One fails	3.5	10	10
Two fail	3.5	15	15
Three fail	3.5	15	15
More than three	3.5	15	15
SI signal generated	NE	NE	15
MFW runback			
One line fails	3.5	10	10
Two lines fail	3.5	15	15
Three lines fail	NA	NA	15

Table 7.2 - (Cont.)

Variable	Oconee 95% Error Factor	Calvert Cliffs 95% Error Factor	H. B. Robinson 95% Error Factor
Branch points (cont.)			
MFW Isolates			
One line fails	NA	10	10
Two lines fail	NA	NE	15
Three lines fail	NA	NE	15
HPI fails	3.5	15	10
AFW actuation fails	3.5	NE	10
AFW flow control fails	3.5	15	15
P break not isolated	3.5	10	10
Charging fails to RB	NA	NA	10
OA: fails to RB char.	NA	10	NA
OA: fail to isola. AFW	NE	NA	10
OA: fail to throt. AFW	NE	10	10
MSIVs close			
One fails	NA	10	10
Two fail	NA	15	15
Three fail	NA	15	15
PORV fails to reseat	3.5	15	15
SSRV fails to reseat	3.5	NA	NA
Thermal-hydraulics			
Temperature	a	b	b
Pressure	a	b	b
Heat transfer	a	NE	NE
Fracture mechanics			
Flaw density	22.6	200	200
Fluence	30%(1)	10%(1)	10%(1)
Cu%	.025%(1)	.008%(1)	.008%(1)
Ni%	NE	NE	NE

Table 7.2 - (Cont.)

Variable	Oconee 95% Error Factor	Calvert Cliffs 95% Error Factor	H. B. Robinson 95% Error Factor
Fracture mechanics (cont.)			
RTNDTo	17°F	6°F	6°F
RTNDT	24°F	8°F	8°F
KIc	15%	5%	5%
KIa	10%	3%	3%

a. A set of constant one sigma values were used to represent the uncertainty in the temperature, pressure, and heat transfer coefficients in the Oconee analysis. The one sigma values used were 50°F, 50 psi, and 100 Btu/hr-ft2-°F) respectively.

b. Uncertainties in the terperature, pressure, and heat transfer coefficients were sequence dependent and determined by the thermalhydraulics analysts. In many instances thse uncertainties were bounded on the low side by physical constraints.

Table 7.3. The TWC Error Factors Obtained from the Uncertainty Analysis

Percentile	Oconee Error Factors	Calvert Cliffs Error Factors	H. B. Robinson Error Factors
.01	.01	1.9E-3	8.3E-5
.05	.04	1.2E-2	8.3E-4
.10	.08	.03	4.8E-3
.20	.19	.10	.03
.25	.28	.16	.06
.30	.36	.24	.12
.40	.61	.51	.35
.50	1.0	1.0	1.0
.60	1.6	1.9	2.7
.70	2.8	4.1	8.7
.75	3.6	6.3	16.5
.80	5.2	9.8	31.7
.90	12.3	29.4	165.
.95	25.0	68.5	652.
.99	96.7	308.	5.7E+3

Table 7.4. Bias Associated with Sequence Identification

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
1) Noninclusion of operator initiated or enhanced events	M optimism	M optimism	M optimism
2) Noninclusion of events other than events covered in item one, i.e. external events	M to S optimism	S optimism	M to S optimism
3) No credit for operator control of pressure prior to HPI shutoff head	M conservatism	S conservatism	S conservatism
4) No credit for operator actions other than AFW isolation and those covered in item 3	S conservatism	NA	NA
5) When valves fail to close they are assumed to fail in a full open position and no credit is given for recovery unless it could enhance the event	M conservatism	M conservatism	M conservatism
6) Letdown is assumed to isolate for all reactor trips	N optimism	N optimism	S optimism
7) Time at which credit is first taken for the isolation of AFW to a broken steam line	M conservatism	NA	M optimism

Table 7.4 - (Cont.)

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
8) Multiple tube ruptures not considered as initiating event	N optimism	S optimism	M optimism
9) Cascading events not considered	M to S optimism	S optimism	S optimism

Table 7.5. Bias Associated with Sequence Quantification

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
1) Use of a time history vs. operational data for 0% power factor	S optimism	NA	NA
3) Use of SSLB data to provide 0% power factor for LSLB	NA	N conservatism	NA
4) All secondary system safety valves lift following a reactor trip	N conservatism	NA	NA
5) Inappropriate use of a low decay heat factor for the 0% power LOCA events	NA	M optimism	NA
6) Steam line break always assumed to be upstream of the MSIVs	NA	N conservatism	NA
7) Use of a high coupling factor for the failure of operator actions	NA	N conservatism	N conservatism
8) Failure to use a high coupling for failure of multiple secondary safety valves	M optimism	NA	NA

Table 7.6. Bias Associated with Thermal-Hydraulic Analysis

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
1) Temperature Extrapolation	L conservatism	S conservatism	NE
2) Stagnation of all loops due to a small break LOCA at low decay heat	NA	L (?) conservatism (see 7.3.3)	L (?) optimism (see 7.3.3)
3) Use of infinite time decay heat curve in determining the decay heat level	NE	N optimism	NE
4) Limit on the minimum value of the heat transfer coefficient	S conservatism	S conservatism	S conservatism
5) Use of cold plume tempertures in stagnation cases even though the welds were determined to be outside the plume region	NA	M conservatism	NA
6) Failure to account for choked flow in the estimation of small steam line break temperatures	NA	N conservatism	NA

Table 7.7. Bias Associated with the Fracture Mechanics Analysis

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
1) No credit taken for warm prestressing	M(?) conservatism (see 7.3.4)	M conservatism	M(?) conservatism (see 7.3.4)
2) Use of bounding calculations to represent sequences	M conservatism	N conservatism	N conservatism
3) Use of coarse crack depth group modeling	S to N conservatism	NA	NA
4) Choice of ,k values for clad material	S conservatism	S conservatism	S conservatism
5) Fracture toughness used for base material	S conservatism	S conservatism	S conservatism
6) Flaw Orientation	S conservatism	S conservatism	S conservatism

Table 7.8. Bias Associated with 95 Percentile Value as Determined in the Uncertainty Analysis

Bias	Impact on Oconee TWC Probability	Impact on Calvert Cliffs TWC Probability	Impact on H. B. Robinson TWC Probability
1) Flaw density double counting effects at high flaw density values ignored	NA	M to L(?) conservatism (see 7.3.5)	M to L(?) conservatism (see 7.3.5)
2) Use of error factors as 99+ percentile values rather than as 95 percentile values	M optimism	NA	NA
3) Exclusion of pressure, KIa, and downcomer heat transfer coefficient from the uncertainty analysis	NA	NA	S optimism

8.0 Summary of the Comparison Study

The results of the individual comparisons as presented in each of the chapters of this report are too numerous to mention in this section. However, there are certain points that should be made from an overview of the comparison study:

1. In general the differences between the three plant studies can be explained by either plant design differences or the analysis methods used.

2. There are distinct but sometimes small differences in plant design which tend to lead to significantly different TWC probabilities for a given type of event. This should be carefully considered when applying these results on a generic basis. The important plant differences identified for the three plant studies and their effect are summarized in Table 8.1.

3. Differences in analysis approach are apparent between the Oconee analysis and either Calvert Cliffs or H. B. Robinson analysis. The Oconee analysis was the first study performed and the analysis process was refined as a result of the initial study. The differences in approach and their impact are presented in Table 8.2. The process was further refined in going from the Calvert Cliffs to the H. B. Robinson analysis, but the effect of these changes appear to be negligible.

4. The largest conservatism in the studies, particularly in the Oconee analysis, appears to be associated with the thermal hydraulics behavior. The largest optimism in the three studies appear to be associated with the question of completeness of events or sequences covered by the analysis.

5. The question of prolonged loop flow stagnation for small break LOCAs is extremely important. There is nearly a five order of magnitude difference in TWC probability for this event when comparing stagnation vs. no stagnation. This is the difference between being the dominant class of PTS event for any plant vs. being an event that may not even violate the tech. spec. cooldown rate.

6. Three plant studies have now been completed at ORNL and a great deal of information has been accumulated with respect to transient behavior, mixing, fracture mechanics, etc. These analyses imply that there are three general types of sequences which are of most concern from a PTS risk perspective:

    a. LOCAs which involve prolonged very low flow in all loops and pressures in the range of 900 to 1000 psi or greater,
    b. Steam line breaks with continued flow to the break over a prolonged period of time, and
    c. Steam line breaks which involve the blowdown of multiple steam generators over a prolonged period of time.

With this in mind it may be wise to consider these transients from the stand point of a deterministic analysis to determine if or when TWCs may actually be generated.

7. In all three plants there were sequences which led to a significant number of crack initiations which arrested and did not lead to a TWC condition. It should be recognized that the probability of damaging the vessel to the point where costly repairs would be necessary before returning to operation may be significantly higher than the probability of the generation of a TWC. It is our opinion that from an economic perspective there should be considerable incentive on the part of the utilities to adopt risk reduction measures such as fluence reduction, changes in operational procedure, etc. as necessary to go beyond the NRC proposed rule limits since the NRC proposed rule has been based on the safety implications of a TWC and does not consider the economic implications of generated cracks which do not completely penetrate the vessel.

Table 8.1. Identified Important Design Features and Their Impact

Plant Feature	Feature Applicable to: Oconee	Calvert Cliffs	H. B. Robinson	Feature Impact
1. Vent valves	Yes	No	No	Decreases downcomer stagnation potential
2. Over-designed AFW System	Yes	No	No	Very important cooldown feature for Oconee. Makes the operator action to control AFW flow on steamline breaks more crucial at Oconee plant
3. HPI system which does not fully repressurize the system	No	Yes	Yes	Slows the repressurization process and thus significantly decreases the TWC potential
4. Automatic AFW isolation to broken line	No	Yes	No	Decreases the potential for isolation failure. Also isolation occurs much sooner thus limiting the cooldown potential
5. Three loop design	No	No	Yes	Increases the design potential for secondary side cooldown events but decreases the cooldown magnitude of most secondary side events
6. Automatic runback of charging system	No	No	Yes	Limits the repressurization process and thus reduces the TWC potential
7. Lack of MSIVs	Yes	No	No	Increases the potential for prolonged steamline break
8. Steamline flow restrictors	No	Yes	Yes	Greatly reduce the cooldown rate associated with large steamline breaks

Table 8.2. Analysis Features Which Were Identified as Being Different for at Least One of the Plant Analyses

Analysis Feature	Feature Applicable to: Oconee	Calvert Cliffs	H. B. Robinson	Feature Impact
1. Extensive extrapolations used in the evaluation of thermal hydraulic conditions	Yes	No	No	Led to what are considered to be very conservative temperature profiles
2. Increased no. of flaw groups in fracture mechanics calculations	No	Yes	Yes	Led to more accurate representation of flaw size which in general reduced the conditional TWC probability by ~10-30%
3. Use of Monte Carlo model to evaluate analysis uncertainty	No	Yes	Yes	Led to a better representation of the uncertainties
4. More extensive use of initiator specific event trees	No	Yes	Yes	Led to a more sequence specific analysis that reduced the conservatism inherent when multiple sequences are treated as a group
5. An elaborate evaluation of reliability values for operator actions	No	Yes	Yes	Led to more definitive values which were conditional on the sequence of events
6. An elaborate evaluation of potential support system failures and their impact	No	Yes	Yes	Led to the identification of potential support system failures which could contribute to PTS risk
7. Use of importance sampling techniques to calculate TWC probabilities for the relatively warm sequences	No	Yes	Yes	This allowed for the actual estimation of the very low TWC probabilities associated with these sequences rather than the use of a minumum consequence

Appendix A. Explanation of Double Counting Effects for High Flaw Density Values

In the fracture mechanics analysis the probability of a TWC is dependent upon the probability of having at least one crack of critical size in the weld in question for a given trial. The expression used for the probability of a particular crack size is taken from the Marshall report and is not a probability but an expected (average) number of flaws in a volume V. This can be used as an approximation to the probability as long as the average number of flaws in the region is <1. However as the average number of flaws in the region becomes greater than one the potential for multiple flaws in a region increases. With multiple flaws one must now be concerned about the dependency of failure associated with different flaws. One approach would be to assume that the failure probability associated with each flaw is independent of that associated with any other flaw. Under this assumption the probability of failure for N flaws is:

$$P_N = 1 - (1-P_1)^N \quad ,$$

where

P_N = the conditional failure probability for N flaws per cubic meter of material

P_1 = the conditional failure probability for assuming one flaw per cubic meter of material.

This was the approach used in both the Calvert Cliffs and H. B. Robinson evaluation of the uncertainty in TWC associated with flaw density. For $P_1 < 1.0E-3$, this expression reduces to $P_N = NP_1$ for flaw densities as high as 500 flaws per cubic meter (the point of truncation of the flaw density distribution in this study). The problem with this approach is that there actually are some dependencies between the failure of one flaw and the failure of another flaw. The alternative approach is to assure complete dependency of flaw failures, i.e. given failure of a particular size flaw, any other size flaw would also fail. In this case we are only interested in the probability of the existence of at least one flaw. This probability can be expressed as:

$$P_N = 1 - \exp(-NV) \quad ,$$

where

P_N is the probability of at least one flaw being present in volume under consideration,

N is the Flaw Density and,

V is the volume of the region under consideration.

Using this approach, flaw density increases beyond ~75 flaws per cubic meter would not result in increases in conditional failure probability since at that point the probability of having at least one flaw in the weld is very close to one. More importantly the conditional failure probability loses its proportionality relationship with the flaw density at flaw density levels as low as 25 to 50 flaws per cubic meter. Table A.1 compares the conditional failure probability obtained using each methodology for sequence 8.2 of the Calvert Cliffs analysis as a function of flaw density. It is interesting to note that the differences between the two approaches are insignificant for flaw density values less than ten flaws per cubic meter. However for the tails of the flaw density distributions where we may be sampling flaw density values as high as 500 flaws per cubic meter, the difference in TWC probability as predicted by the different approaches is significant. It is our opinion that these two approaches bound (at both ends) the uncertainty in the analysis which is associated with flaw density. A more precise estimation of this uncertainty, although very important due to its major impact on the overall uncertainty and the mean TWC value, cannot be supplied at this time.

Table A.1. Comparison of the P(F|E) Values Obtained for Calvert Cliffs Sequence 8.2 Using Two Different Approaches for Determining the Effect of Flaw Density Increases

Flaw Density (Per M3)	P(F|E) using Poisson approximation	P(F|E) using ANF* in the region	Ratio of Values obtained using two methods
0.1	3.5E-5	3.5E-5	1.00
0.5	1.8E-4	1.8E-4	1.01
1.0	3.5E-4	3.4E-4	1.02
5.0	1.6E-3	1.8E-3	1.08
10.0	3.0E-3	3.5E-3	1.16
25.0	6.2E-3	8.8E-3	1.42
50.0	9.1E-3	1.8E-2	1.93
75.0	1.0E-2	2.6E-2	2.51
100.0	1.1E-2	3.5E-2	3.16
250.0	1.2E-2	8.8E-2	7.51
500.0	1.2E-2	1.8E-1	15.0
750.0	1.2E-2	2.6E-1	22.5

* ANF - Average number of flaws in region

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