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Title: The Impact of Recovery From Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency

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Ideas That Change the World

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The Impact of Recovery From Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency

Date Published: February 2003

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EXECUTIVE SUMMARY

This letter provides an extension of the findings given in NUREG/CR-6771, GSI-191: *The Impact of Debris-Induced Loss of Emergency Core Cooling System (ECCS) Recirculation on Pressurized Water Reactor (PWR) Core Damage Frequency*. Namely, given here is an analysis of the recovery from the events discussed in NUREG/CR-6771 and the impact of recovery on core damage frequency.

Recovery options were described in NUREG/CR-6771 but not analyzed. The recovery options from debris-induced loss of net positive suction head (NPSH) are (1) continued cooling with ECCS recirculation and (2) alignment of an alternative source of borated cooling water. Continued ECCS recirculation could be achieved by the pumps if they provide sufficient flow despite loss of NPSH or by operator actions to restore NPSH. Cooling with alternative sources of borated water involves realigning the pumps to injection mode and refilling the refueling water storage tank (RWST).

NUREG/CR-6771 showed that debris effects resulted in a core damage frequency (CDF) for LOCA events that was almost 140 times the CDF without considering debris when traditional initiating event frequencies are used. (Note: corrections to the NUREG/CR-6771 results are reflected here.) Allowing for leak before break, the CDF with debris was 45 times the CDF without debris. The analysis discussed here shows that, considering the effects of debris and allowing for recovery, the CDF resulting from LOCA events for pressurized water reactors is on average 19 times higher than the CDF when debris effects are not considered. Allowing for leak before break initiating frequencies, the CDF with debris and recovery is twice the CDF without considering debris.

These results indicate that the potential for increased CDF due to LOCA events because of sump blockage is significant enough to warrant detailed plant-specific analysis of recovery options, leading to actions to mitigate the increase in CDF.

ABBREVIATIONS

ASEP	Accident Sequence Evaluation Program
BAM	Boric Acid Makeup
CD	Core Damage
CDF	Core Damage Frequency
CVCS	Chemical, Volume and Control System
ECCS	Emergency Core Cooling System
EF	Error Factor
GSI	Generic Safety Issue
HEP	Human Error Probability
HPI	High Pressure Injection
HPSI	High-Pressure Safety Injection
HRA	Human Reliability Analysis
IPE	Individual Plant Examinations
LBB	Leak Before Break
LLOCA	Large Loss-of-Coolant Accident
LOCA	Loss-of-Coolant Accident
LOFW	Loss of Feed Water
LPI	Low Pressure Injection
LPSI	Low-Pressure Safety Injection
MLOCA	Medium Loss-of-Coolant Accident
MOV	Motor Operated Valve
NPSH	Net Positive Suction Head
PORV	Power-Operated Relief Valve
PRV	Pressure Relief Valve
PWR	Pressurized Water Reactor
PWST	Primary Water Storage Tank
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RWST	Refueling Water Storage Tank
SDC	Shutdown Cooling
SFP	Spent Fuel Pool
SGTR	Steam Generator Tube Rupture
SLOCA	Small Loss-of-Coolant Accident
TRAN-LOFW	Transient with Loss of All Feed Water, Main and Auxiliary
TRAN-PORV	Transient with Stuck-Open Power-Operated Relief Valve

1.0. INTRODUCTION

Generic Safety Issue (GSI) 191, *Assessment of Debris Accumulation on PWR Sump Performance*, identified the potential for failure of the emergency core cooling system (ECCS) in pressurized water reactors (PWR) in recirculation mode. The conditions under which this failure could occur stem from the destruction and suspension of pipe insulation materials, containment surface coatings (paint), and particulate matter (dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. Under certain conditions, this debris can be transported to the floor of the containment and accumulate on the recirculation sump screen in sufficient quantity to severely impede recirculation flow.

The likelihood of sump blockage, accounting for plant-specific features, has been evaluated, as has the risk associated with the blockage leading to an increase in CDF. Results of these analyses are given in NUREG/CR-6771, GSI-191: *The Impact of Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency*. These studies postulated scenarios in which recovery from sump blockage could occur; however, likelihood of recovery and the impact of recovery on CDF were not quantified.

Below is the quantification of recovery from loss of NPSH. The event trees in NUREG/CR-6771 were extended to include the possibility of recovery given the sequence of events that lead to sump blockage. Fault trees and human reliability analysis (HRA) models were developed to quantify the likelihood of each recovery event. Finally, the overall CDF results given in NUREG/CR-6771 were revised, allowing for recovery actions.

The accidents addressed here are the same as those in NUREG/CR-6771, and are assigned to the following generic groupings:

- Small Loss-of-Coolant Accident (SLOCA)
- Medium Loss-of-Coolant Accident (MLOCA)
- Large Loss-of-Coolant Accident (LLOCA)
- Transient with Stuck-Open Power-Operated Relief Valve (TRAN-PORV)
- Transient with Loss of All Feedwater, Main and Auxiliary (TRAN-LOFW)

2.0. RECOVERY/MITIGATION

Recovery from sump blockage during an accident is treated as two possible modes: continuing cooling with ECCS recirculation, and reestablishing cooling with an alternate source of water through injection. Continued cooling with ECCS recirculation could be achieved if pump operations can continue despite loss of NPSH, or if the operator is able to take actions to restore NPSH. Reestablishing injection cooling requires aligning an alternate source of borated water.

A pump-specific analysis is required to estimate the possibility that the ECCS pumps could continue to operate with loss of NPSH margin. While there is reportedly some evidence of successful pump operation under these conditions, particular results were not available during this study.

To restore the ability to recirculate from the sump, it may be possible to restore NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled, if possible. For sub-atmospheric plants in which sprays provide heat removal, turning off all spray trains would not be acceptable. It may be possible to use high-head ECCS pumps that have a lower flow for recirculation instead of low-head pumps if the pump design allows extended operation at low pressure without runout; also, heat removal using a spray train or possibly fan coolers must be provided as there is typically no heat removal in the ECCS systems without the low-head ECCS pumps. (At some plants, the fan coolers (if the plant is equipped with them) are tripped on initiation of ECCS. At some plants the spray system has no heat removal capability, as it does not incorporate heat exchangers.)

For subatmospheric plants, operators might receive an early indication of debris-induced pump flow problems because the inside and outside spray recirculation pumps are designed to start drawing coolant from the sump within 2 and 5 min, respectively, after ECCS actuation, whereas the other ECCS pumps [low-pressure safety injection (LPSI), high-pressure safety injection (HPSI), and containment spray injection] initially draw suction from the RWST. Abnormal operation of the recirculation pumps before spray recirculation switchover of the remaining ECCS pumps might provide the operators with an opportunity to minimize sump flow by securing redundant ECCS pump trains, thereby increasing the likelihood that core cooling will be maintained.

It is also possible at some plants to clear the sump screen using a backflush system. This would remove debris from the screen by reversing the flow of water. This procedure presumably would have to be performed periodically. No details of the backflush system were available during this study.

To reestablish injection, a source of borated water must be found and lined up for use, and concerns with overfilling the containment with water must be addressed. Also, the complexity of switching the ECCS from recirculation back to injection is of concern.

Modern PWRs have "unrodded cores," in that they use chemical shim (borated water) to control reactivity and use rods only for fine level control and for scram. The use of chemical shim instead of insertion of rods for reactivity control prevents perturbations in flux and power that would result from the insertion of rods.

Below hot zero power (saturation temperature at the pressure of the steam generator secondaries, about 540°F), PWRs cannot always maintain shutdown margin (1% subcritical) on rods alone assuming the most reactive gang of rods fails to insert, and boration must be increased to maintain shutdown margin as the primary is cooled down. The actual shutdown margin available from the rods is dependent on the time of core life (the amount of fuel burnup).

It is assumed that the injection mode alignment will draw water from the RWST. After drawing water for some period, the RWST will need to be refilled. Sources for refilling include the spent fuel pool, fresh water that must be mixed with boric acid before use, and at some multi-unit sites, water can be drawn from an alternate RWST.

The likelihood of success and failure of each cooling option has been quantified, and is discussed in the attachment to this letter. It should be noted that the likelihood of success is particularly dependent on operator actions, which carry a large probability of failure. The human reliability factors are particularly pessimistic when actions must be performed in a short time span and stress is high, as is typically the case for these actions during an accident.

3.0. EVENT TREES

Event trees for each accident type are given in NUREG/CR-6771 for the base case, accidents without sump blockage, and for accidents in which sump blockage occurs. In the latter event trees, two recovery events were included on each tree, but the branches for success and failure were not expanded. Figures 1 through 6 show the event trees with the recovery branches expanded. The sequences identified in NUREG/CR-6771 for accidents with sump blockage that are further divided accounting for recovery are identified with an additional letter. For example, sequence 2 becomes sequences 2a, 2b, and 2c.

Figure 1 shows the event tree for a Large LOCA event. Without recovery, the event tree defines 9 sequences, 6 of which result in core damage (CD). With recovery options, 3 of these sequences are further divided to make a total of 15 sequences. The recovery options are to continue ECCS recirculation and to reestablish injection mode. In the event trees, continued ECCS recirculation, both continued operation of the pumps with reduced NPSH and restoring NPSH margin, are captured in the heading RECIRC_NPSHM_L. Establishing an alternate source of cooling in the injection mode is captured under the heading REC_DEBRIS_L.

The recovery paths further split the sequences that lead to core damage. Sequence 2 in the Large LOCA with debris effects event tree features containment spray working and recirculation working, but core damage occurring because NPSH is lost due to debris. Allowing for recovery, sequence 2 is further divided into 3 sequences. In sequence 2a, ECCS recirculation continues and no CD occurs. In sequence 2b, ECCS recirculation fails, but the plant is returned to injection mode with an alternate source of cooling water, and no CD occurs. In sequence 2c, ECCS recirculation fails, the operators are unable to restore injection cooling, and CD occurs. Similar branches occur in end states 4 and 7.

The event trees for the remaining accidents follow the same pattern, with three branches occurring for each sequence that is recoverable. Quantification of the recovery events is given in the analysis presented in the attachment to this letter.

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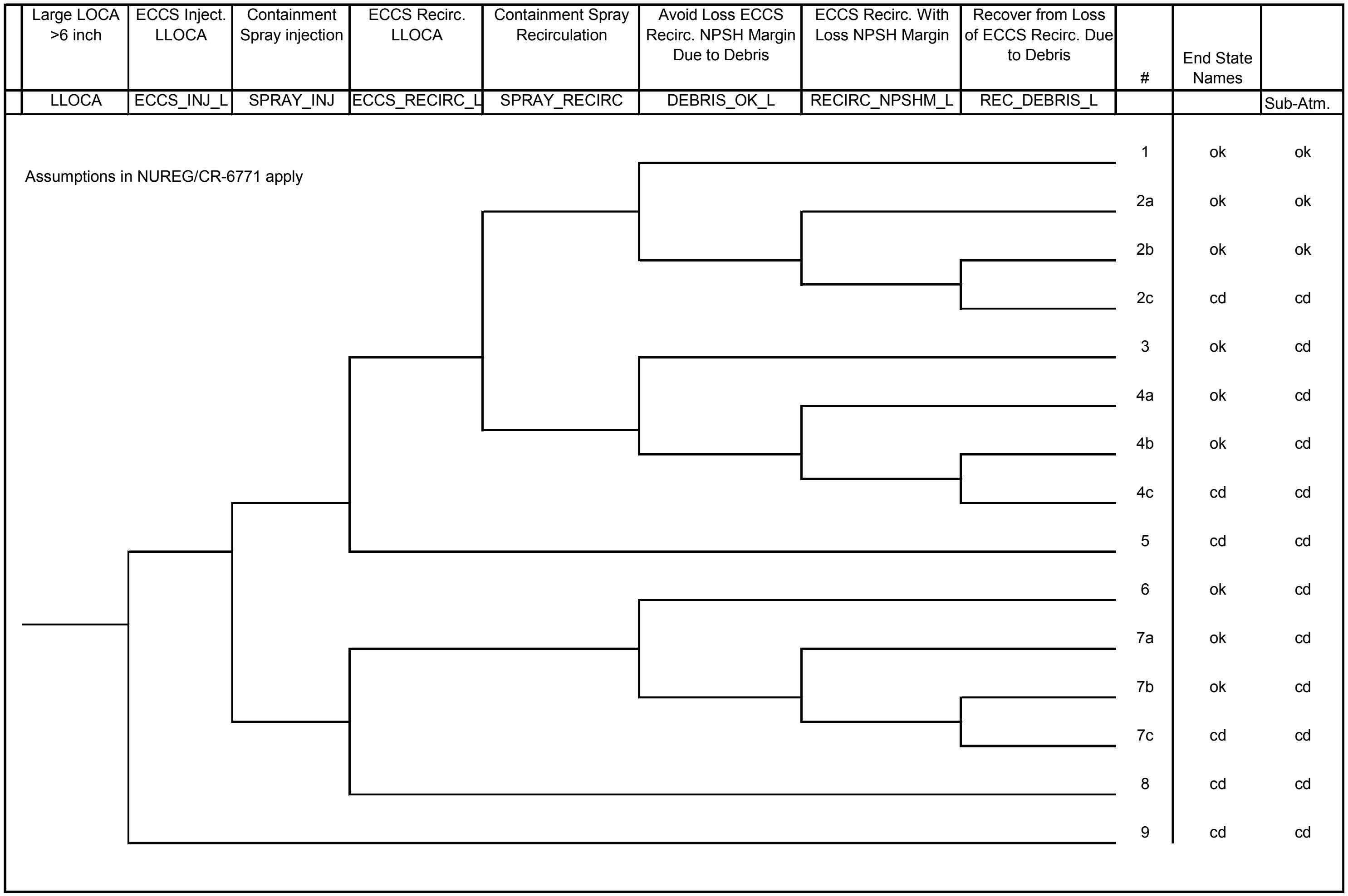

Figure 1. Event Tree for Large LOCA with Recovery.

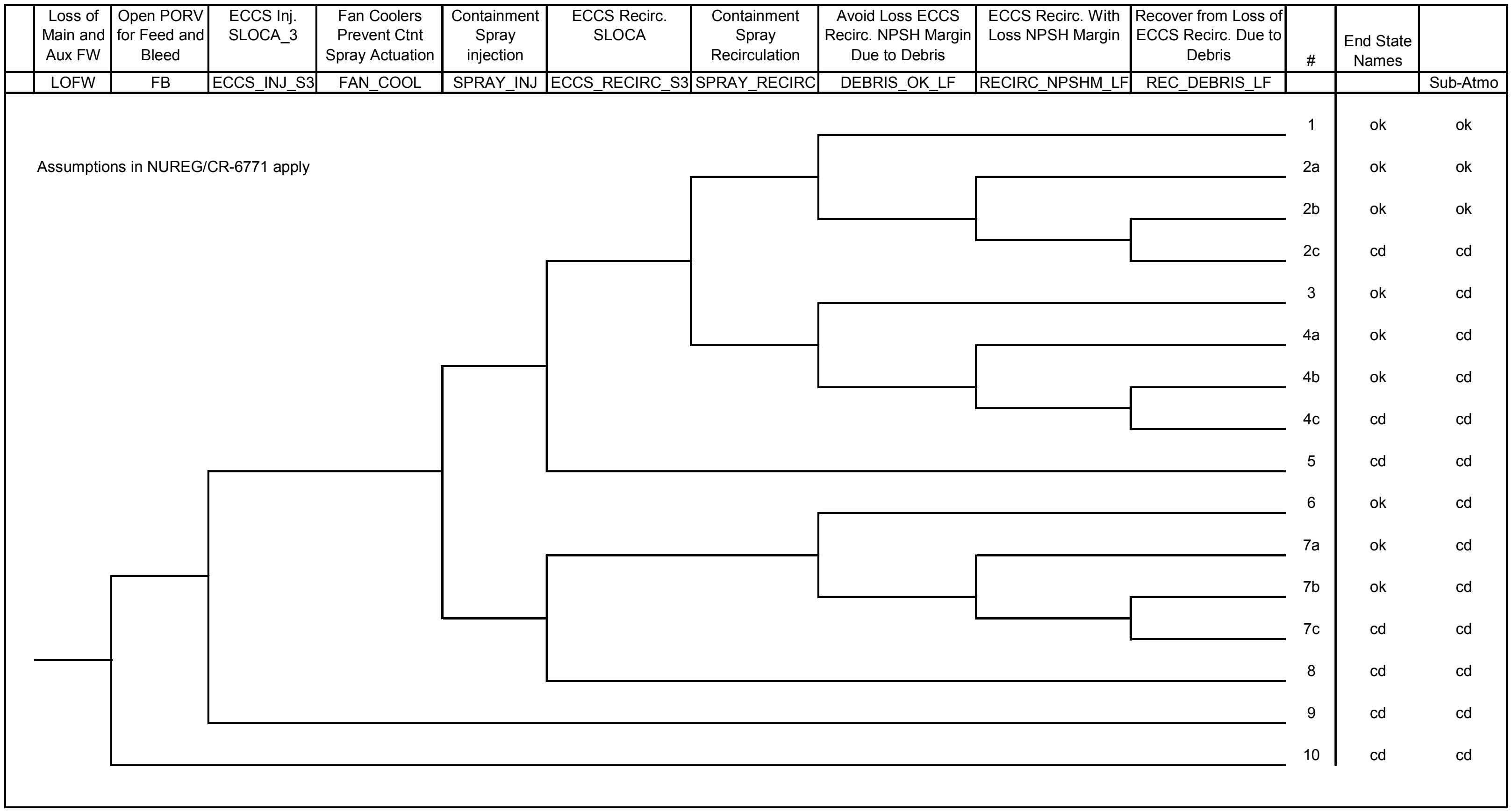

Figure 2. Event Tree for Loss of Feed Water (LOFW) with Recovery.

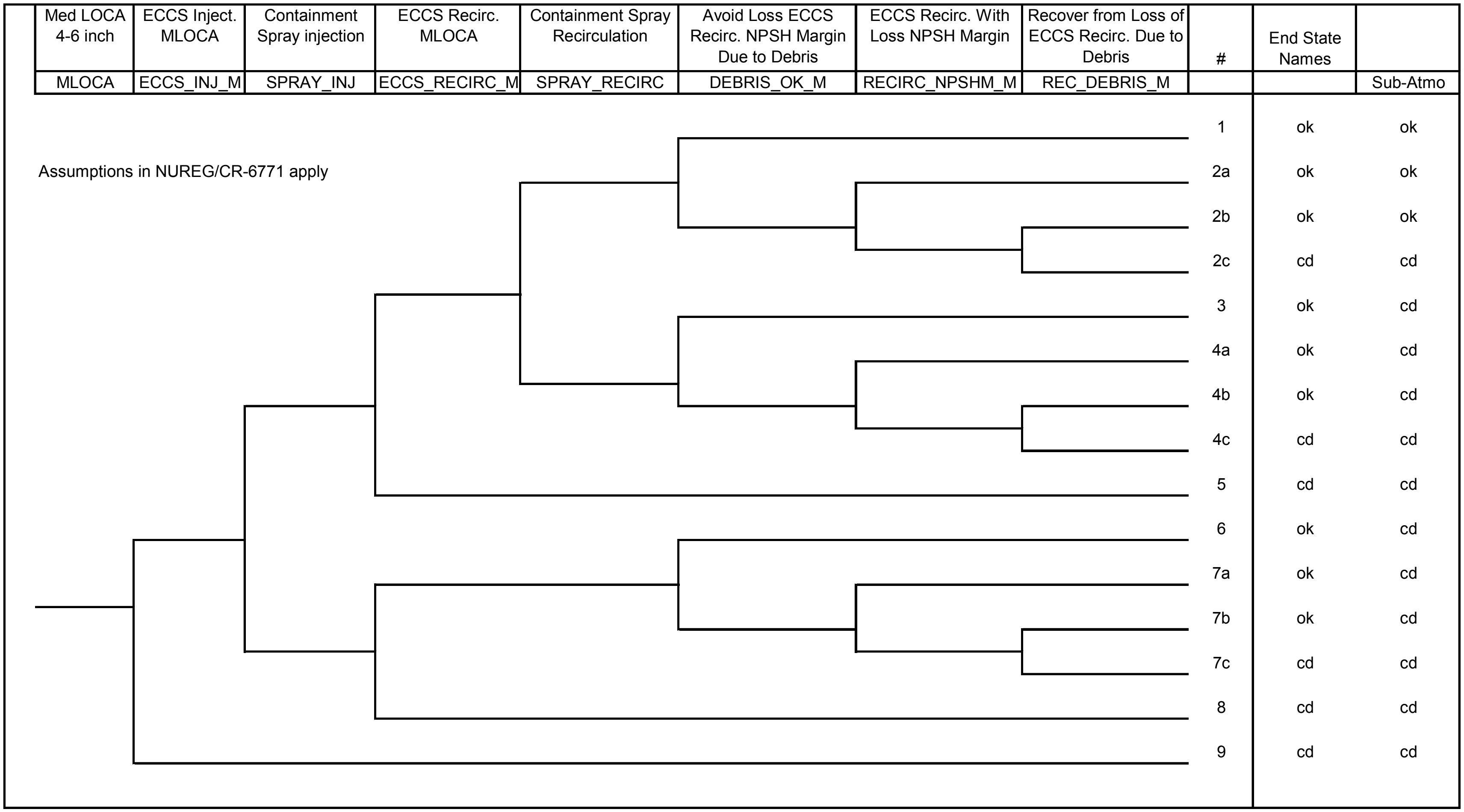

Figure 3. Event Tree for Medium LOCA with Recovery.

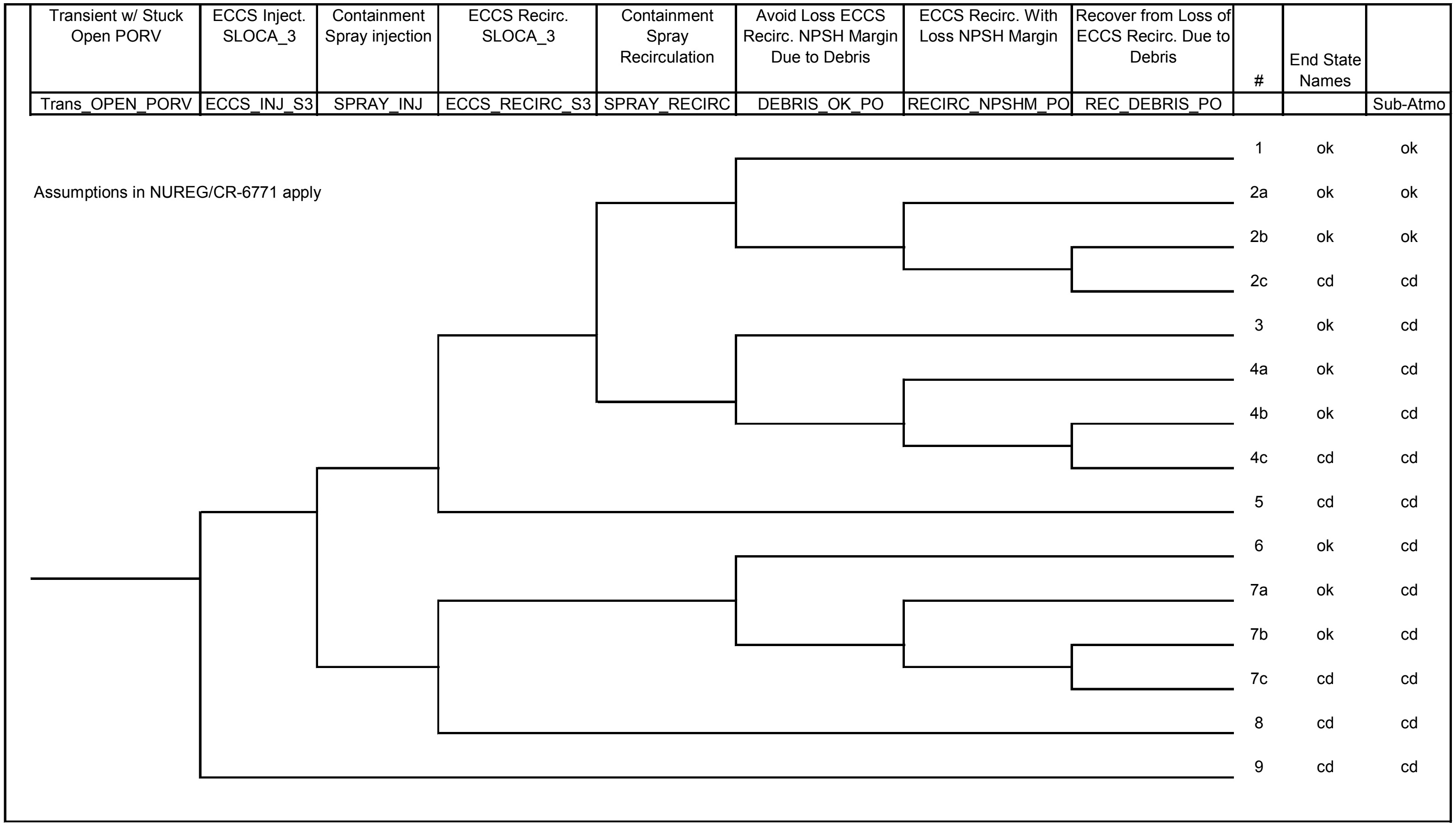

Figure 4 Event Tree for Transient with Open PORV with Recovery

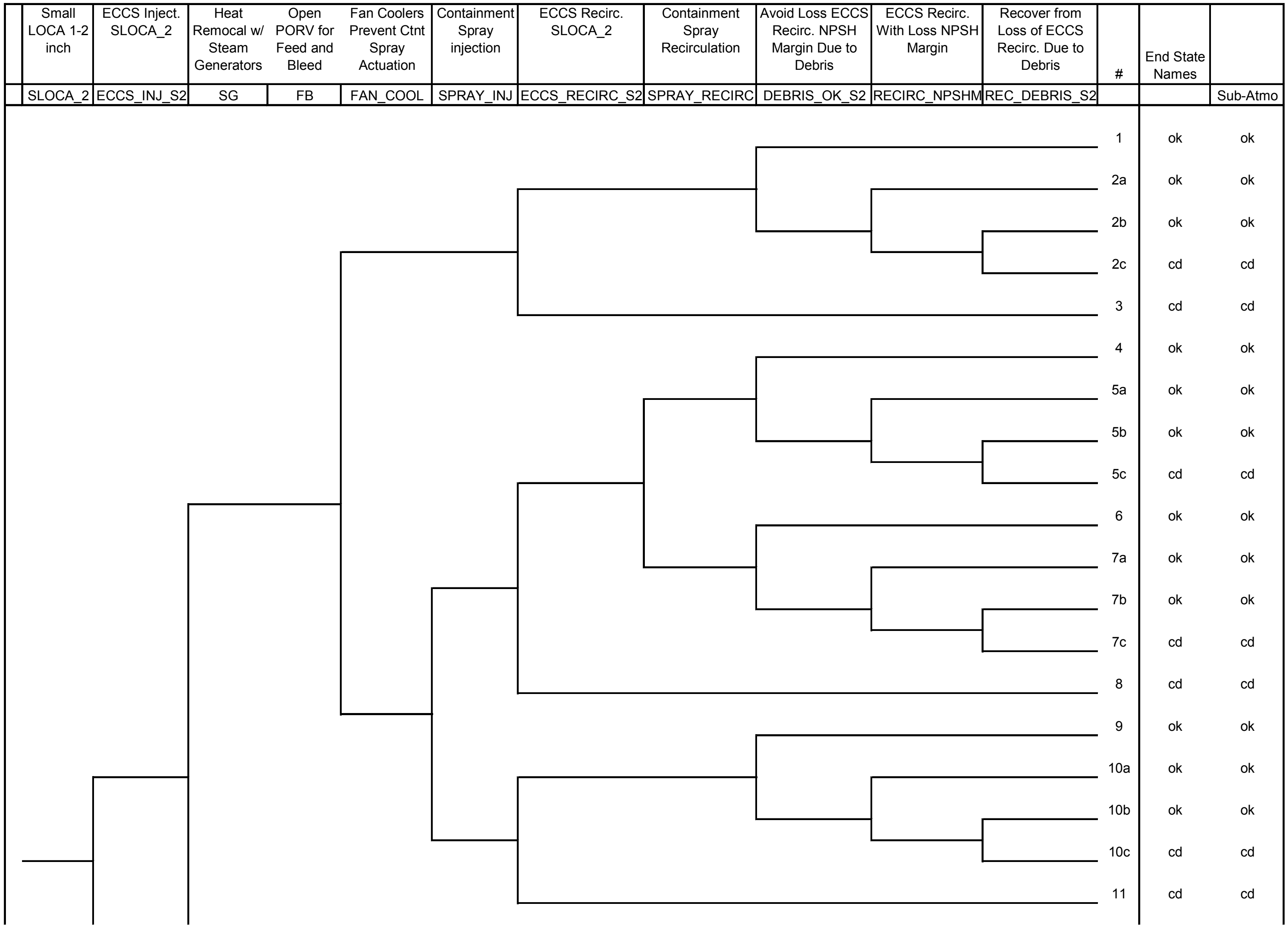

Figure 5. Event Tree for Small (S2) LOCA with Recovery (Part 1 of 2).

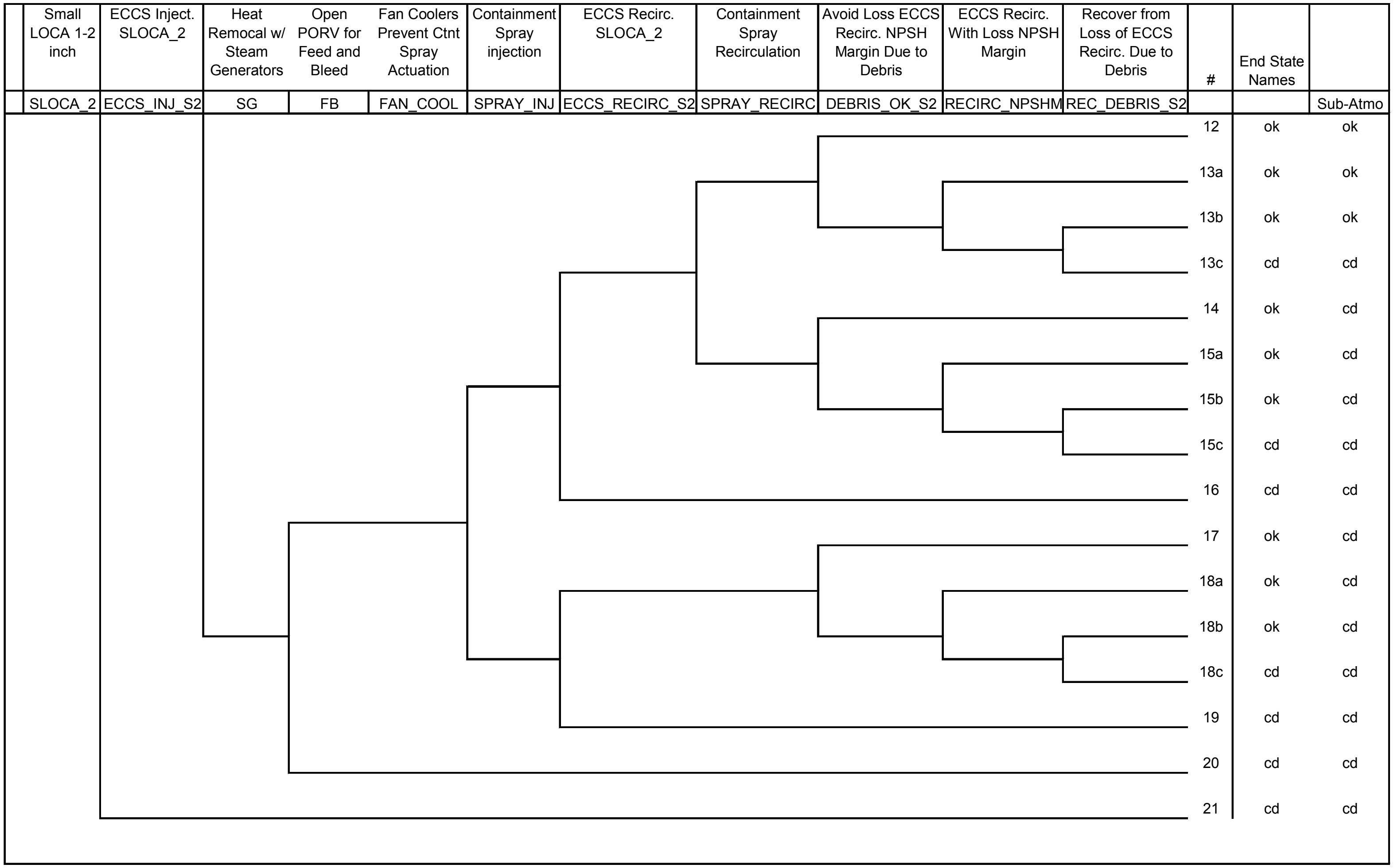

Figure 5 (Cont.) Event Tree for Small (S2) LOCA with Recovery (Part 2 of 2)

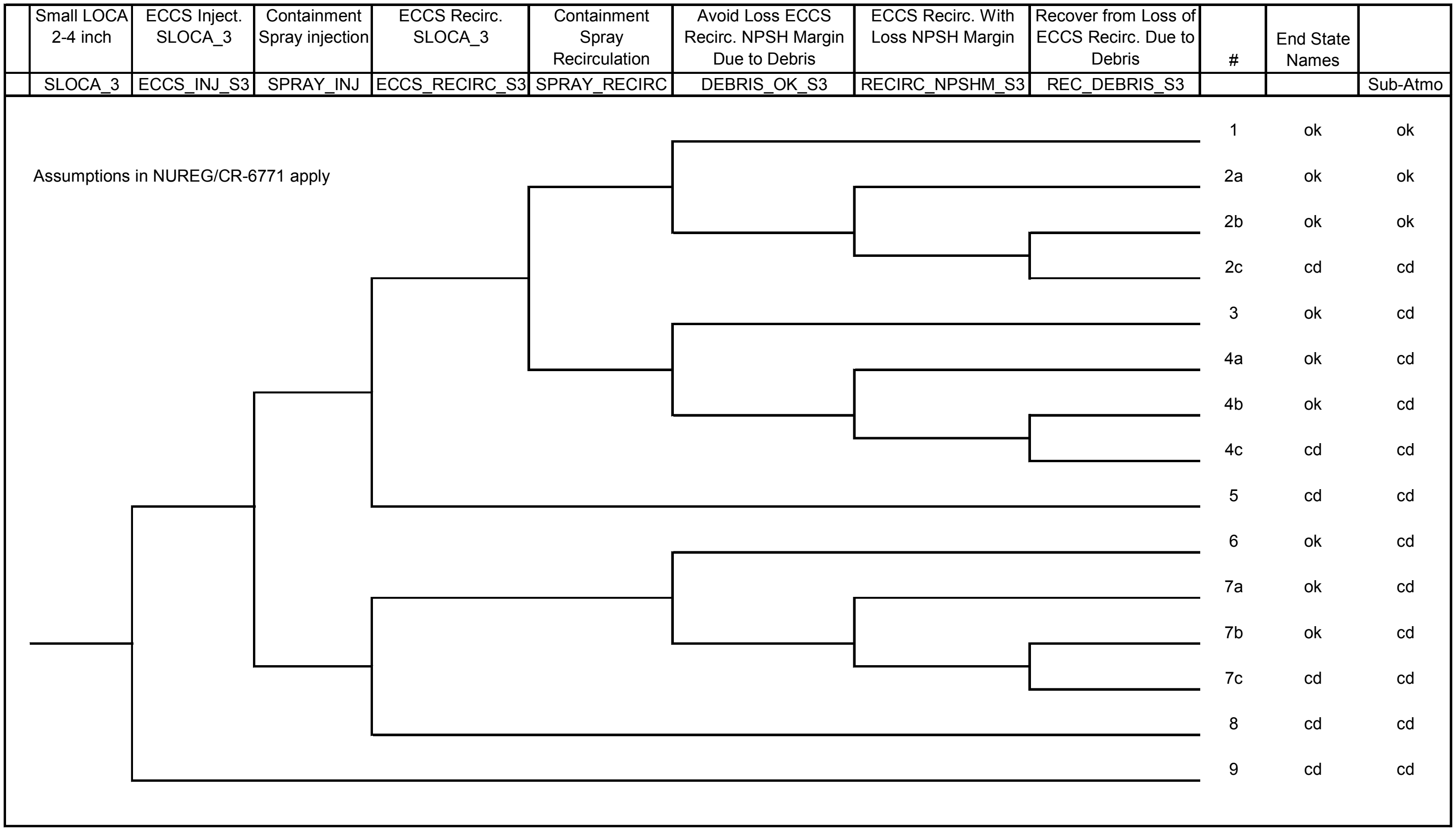

Figure 6. Event Tree for Small (S3) LOCA with Recovery.

4.0. RESULTS

The probability of success and failure for each recovery action was incorporated in quantifying the event trees. The probabilities for the sequences leading to CD for each accident type were summed to give the CDF for that accident, and the results from all accidents were combined to give an overall estimate of the CDF for each plant.

Figure 7 shows the CDF based on traditional LOCA initiating event frequencies for all 69 plants, ordered as in NUREG/CR-6771. For each plant, two bars are shown – the first is the CDF not considering debris effects, and the second for accidents with debris effects and recovery. By comparison to Fig. 5.1 of NUREG/CR-6771, it is evident that recovery actions reduce substantially the CDF with debris effects for all plants. In particular, the CDF for eight of the plants allowing for recovery is only slightly higher than the CDF without considering debris effects. Figure 8 shows a similar graph of CDF for the same plants but calculated using Leak Before Break (LBB) frequency for the initiating event.

An alternate presentation of the results is to express them as histograms of the plant CDF ratio. In Fig. 9 the ratio of the CDF for LOCA events with debris effects to the CDF with no debris effects is shown in the upper graphs. The bars indicate the number of parametric cases that have a CDF ratio that falls in the associated range. The lower graphs in Fig. 9 shows the ratio of the CDF allowing for recovery to the CDF with no debris effects. As is evident from the upper graph, 13 cases have CDF ratios in the lowest two categories, up to a ratio of 50, while two cases have ratios as high as 251. Allowing for recovery, as shown in the lower graph, all cases have CDF ratios below 30. The average CDF ratio for debris effects is approximately 140, while allowing for recovery it is 19.

Similar results can be seen in Fig. 10 using LBB initiating event frequencies. Allowing for LBB, the highest CDF ratio with debris effects is 92, with eight cases having ratios greater than 90. With recovery, all CDF ratios are less than 3. The average CDF ratio for debris effects is 45, while the average CDF ratio allowing for recovery is 2.

The contribution of each accident sequence to the change in CDF is shown in Table 1. It is evident that the LLOCA and MLOCA events contribute much of the change in CDF, a result of the higher likelihood of failure to recover from these events.

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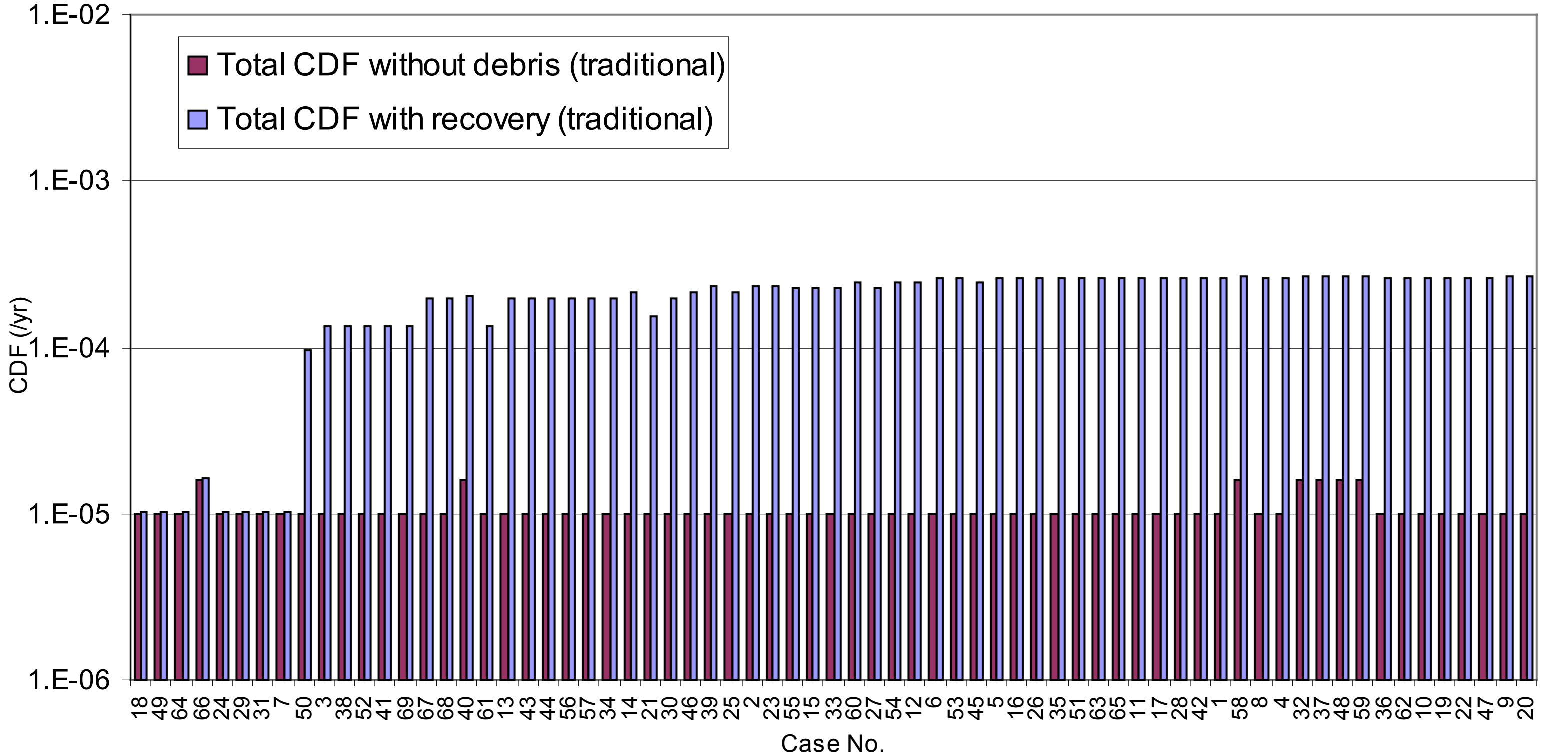


Figure 7. **Change in CDF From Debris-Induced Loss of Recirculation Sump Flow. Based on Traditional LOCA Initiating Event Frequencies.**

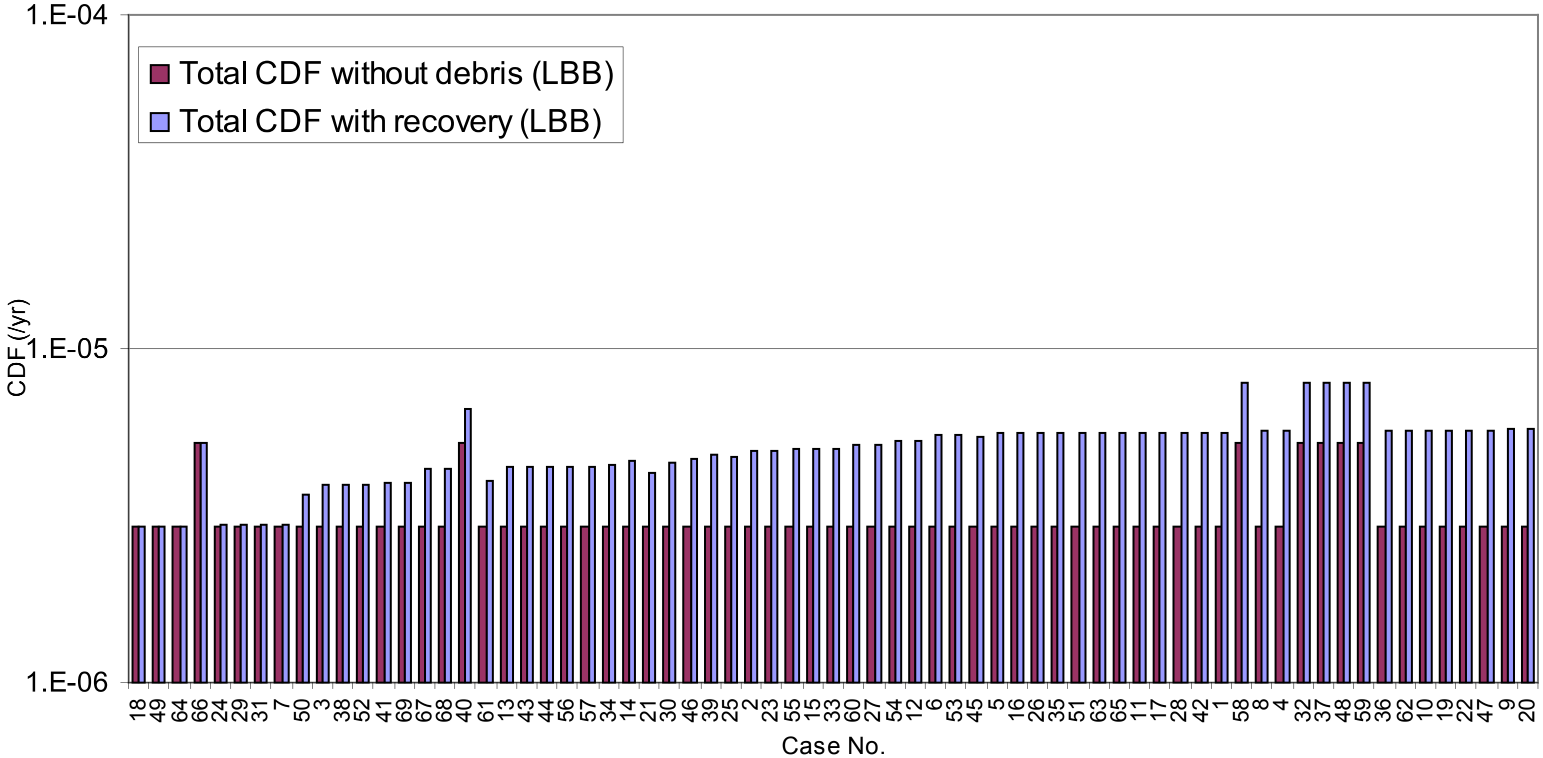
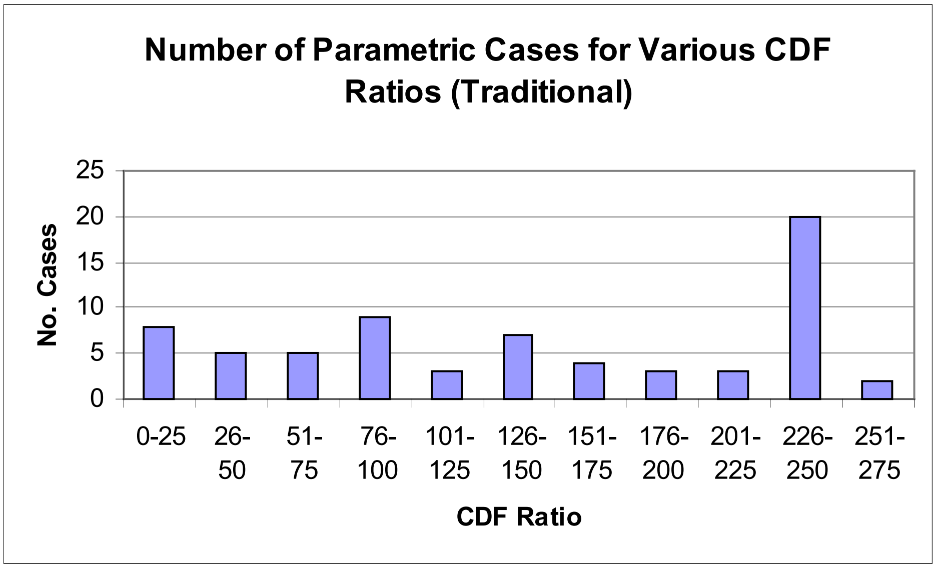


Figure 8. Change in CDF From Debris-Induced Loss of Recirculation Sump Flow. Based on LBB LOCA Initiating Event Frequencies.



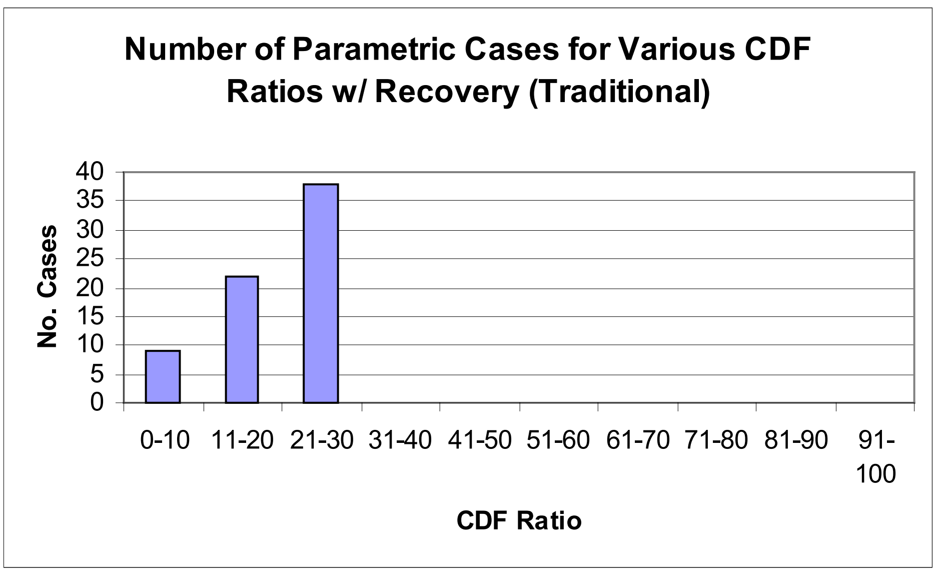


Figure 9. **Effect of Debris-Induced Loss of Recirculation Sump Flow on CDF Expressed in Terms of CDF Ratio: Traditional Initiating Event Frequencies. CDF Ratio with Debris Effects but Without Recovery (Top) and with Recovery (Bottom).**

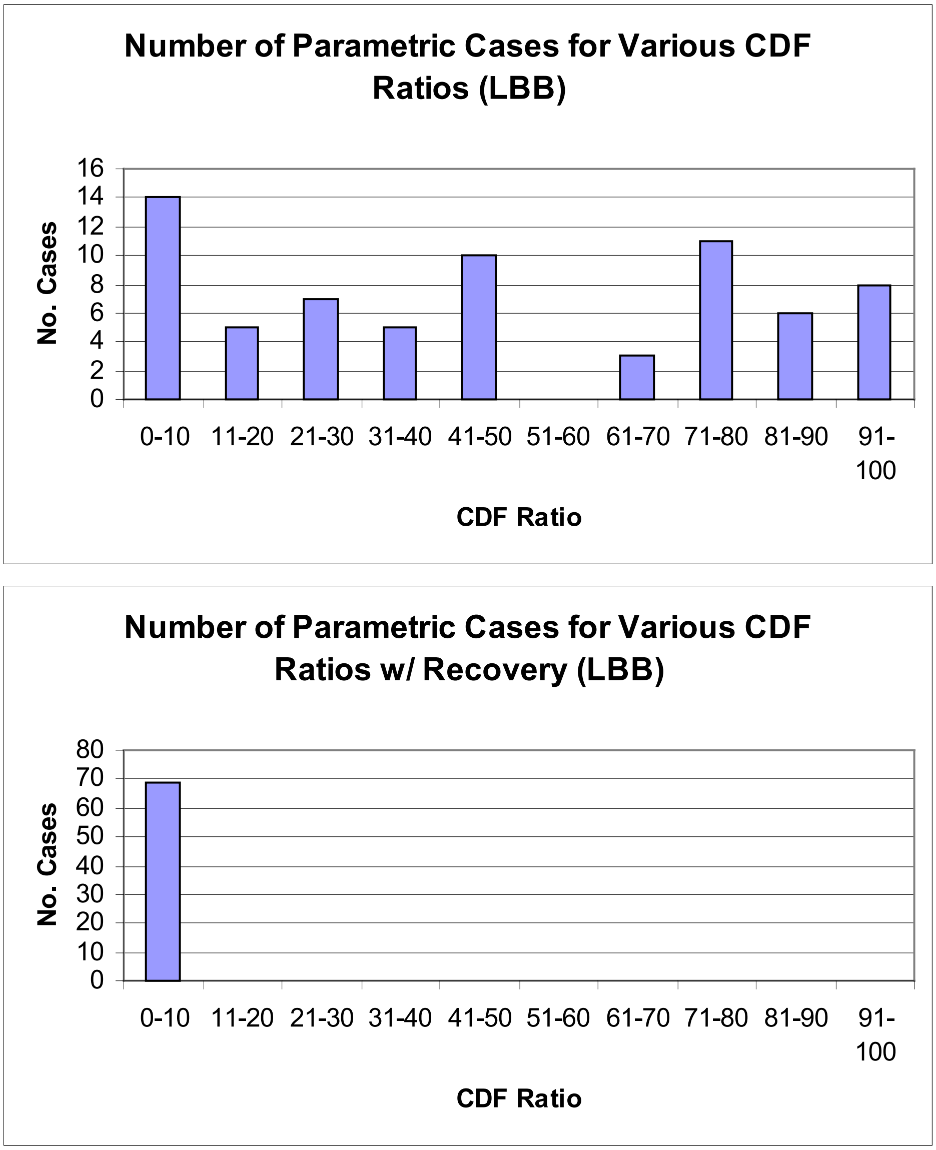


Figure 10. Effect of Debris-Induced Loss of Recirculation Sump Flow on CDF Expressed in Terms of CDF Ratio: LBB Initiating Event Frequencies. CDF Ratio with Debris but without Recovery (Top) and with Recovery (Bottom).

Table 1. Contributions of Each Accident Sequence to the Baseline and Modified CDF

Traditional

	LLOCA	MLOCA	SLOCA (S3)	SLOCA (S2)	PORV	LOFW	TOTAL
No Debris	3.60E-06	2.20E-06	1.10E-06	1.00E-06	2.20E-06	4.20E-07	1.05E-05
With Recovery	1.64E-04	3.29E-05	1.39E-06	1.29E-06	2.21E-06	4.20E-07	2.02E-04
Delta CDF	1.60E-04	3.07E-05	2.92E-07	2.92E-07	5.81E-09	5.80E-10	1.91E-04
CDF Ratio	45	15	1	1	1	1	19

LBB

	LLOCA	MLOCA	SLOCA (S3)	SLOCA (S2)	PORV	LOFW	TOTAL
No Debris	2.59E-08	4.18E-08	2.42E-08	4.60E-07	2.20E-06	4.20E-07	3.17E-06
With Recovery	1.18E-06	6.25E-07	3.06E-08	5.95E-07	2.21E-06	4.20E-07	5.06E-06
Delta CDF	1.15E-06	5.84E-07	6.42E-09	1.35E-07	5.81E-09	5.80E-10	1.88E-06
CDF Ratio	45	15	1	1	1	1	2

ATTACHMENT A
QUANTIFYING RECOVERY OF DEBRIS-INDUCED LOSS OF ECCS RECIRCULATION FOR PWRS

1.0. Introduction

This attachment addresses probabilistic considerations related to LOCA conditions resulting from a pipe break-initiating event, from a transient condition involving a stuck-open PORV, or from operator actions to establish feed-and-bleed cooling in response to loss of main and auxiliary feedwater. The probabilistic data and potential recovery actions described here apply potentially to all of these types of LOCA conditions.

These probabilistic failure data are useful for evaluating recovery from debris-induced loss of ECCS recirculation at PWRs. The data have been used to evaluate recovery at a facility representative of all PWRs, modeled here as a typical PWR cooling system, as was done in NUREG /CR-6771. Potential recovery actions include adjustment of ECCS flows to regain recirculation capability, and reswitching of ECCS from recirculation back to injection.

2.0. Maintain Recirculation Mode With Possible Operator Intervention to Adjust ECCS Flows or Clear Blockage

Figure 1 shows a fault tree logic model for the event tree heading, "ECCS Recirc with Loss NPSH Margin." As indicated, the loss of ECCS recirculation requires that the ECCS pumps fail to operate with loss of NPSH margin (Event A), combined with operator failure to restore and maintain recirculation cooling. (While detailed data is lacking, there is some evidence that extended pump operation may occur with loss of NPSH–verification of this by testing must be done before it is accepted as a reliable mitigation of sump blockage.) Operators can restore recirculation cooling by one of two general methods. In one method, a reduction in sump flow is made to reduce the pressure drop across the sump system, thereby increasing ECCS pump NPSH. The reduction in sump flow can be accomplished by turning off sprays,[1] turning off redundant ECCS core injection trains, throttling ECCS core injection flow, or cycling the pumps in plants that have self-cleaning strainers. In the second method, the blockage is cleared by using the backflush system installed at some plants.[2]

Quantification of the top event in Fig. 1, discussed in more detail later, includes consideration of several operator events. Also, quantification of the top event is dependent on the specific conditions of a given accident. For example, times available for operator actions may vary considerably among postulated accident types.

3.0. Reestablish ECCS Injection

If recirculation cannot be maintained or reestablished, it may be possible to reswitch from recirculation back to the injection mode of cooling. To accomplish this mitigation strategy at most plants, it would be necessary to reswitch ECCS equipment from the recirculation lineup to an injection lineup and at the same time refill the RWST with borated water. An alternative to reestablishing ECCS injection may be available at certain multiple-unit sites where RWSTs or ECCS pumps for individual units are cross-connected.[3] The use of cross-connections between multiple units is discussed more thoroughly in Section 3.3.

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[1] Plants with a subatmospheric containment design remove post-LOCA decay heat from the reactor core via the containment spray system. Therefore, for these types of plants, it would not be possible to turn off all sprays and at the same time maintain core cooling.

[2] Details related to the design and operation of PWR backflush systems were not available for this study.

[3] Only one multiple unit site was identified where hardware (piping and valves) connected unit-specific RWSTs and portions of the unit-specific ECCS. Cross-connections of this type would allow the affected unit to draw borated water from an unaffected unit's RWST.

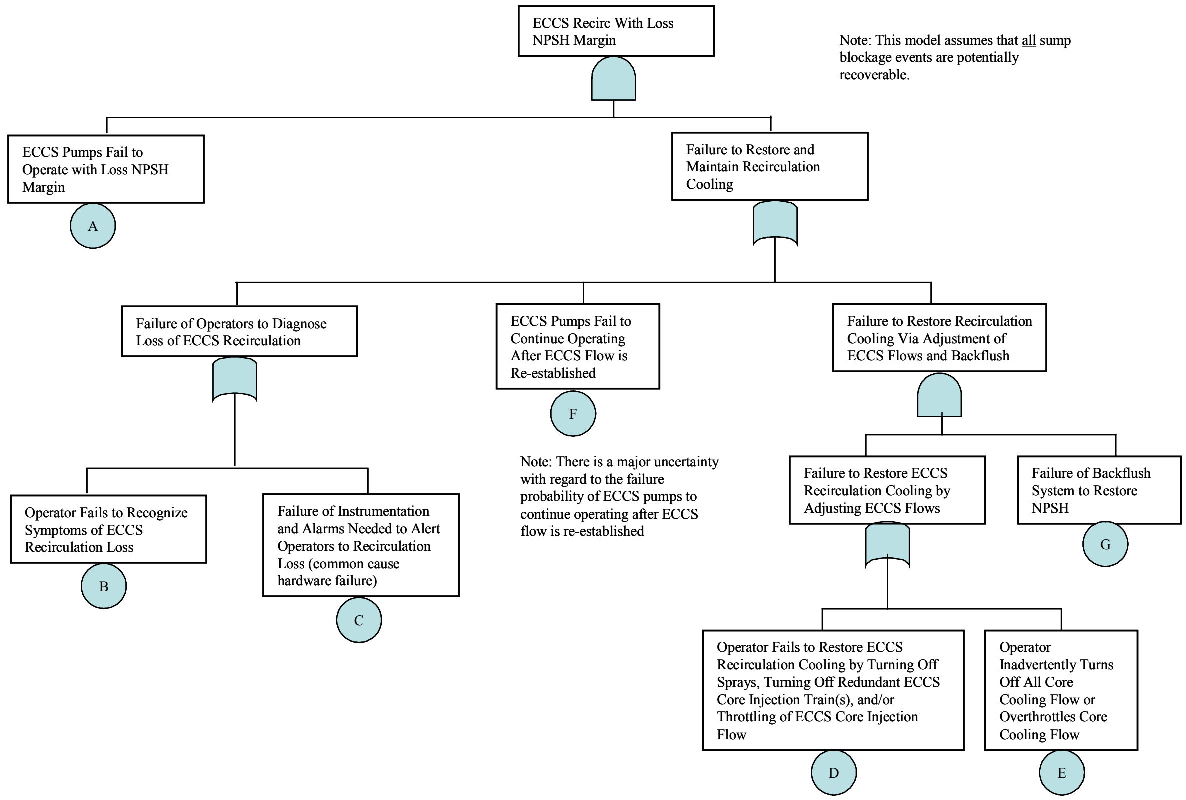

Figure 1. Simplified Logic Model for Event Tree Heading "ECCS Recir. with Loss NPSH Margin."

Success of this mitigation strategy would also require suitable operator procedures and training, as well as appropriate indication of debris-related problems. The timing of reswitching is also critical, as it must ensure that core cooling is restored in time to prevent core damage. Because of this timing issue, certain sizes and types of a LOCA may make it impractical or impossible for operators to accomplish reswitching before core damage occurs. Figure 2 displays important considerations related to reestablishment of ECCS injection. The quantification of events in Fig. 2 is discussed later.

If ECCS injection were to be reestablished and continued indefinitely, overfill of containment would eventually be of concern. If reestablishment of ECCS injection were to be successful, it is expected that operators would attempt RCS cool down and depressurization to prepare for eventual use of RHR shutdown cooling. However, at many PWRs, the same LPI pumps that are used to draw suction from the ECCS sumps are the same pumps that are used for RHR shutdown cooling. This design feature is important because the LPI/RHR pumps may have been damaged from debris effects and thus might not be available for RHR shutdown cooling. The potential for debris-related damage to ECCS pumps is a major uncertainty in this analysis.

3.1. Reswitching of ECCS from Recirculation Back to Injection

Figure 3 is a simplified schematic of the high-pressure injection (HPI) and low-pressure injection (LPI) portion of the ECCS system at a representative 2-loop plant. This figure displays the valve positions during recirculation. Specifically, sump suction valves SM-V1, SM-V2, SM-V3, and SM-V4 are open while RWST suction valves RW-V1, RW-V2, RW-V3, RW-V4, RW-V5, and RW-V6 are closed. Reswitching of the HPI and LPI systems to injection mode would require that the sump be isolated and the RWST be

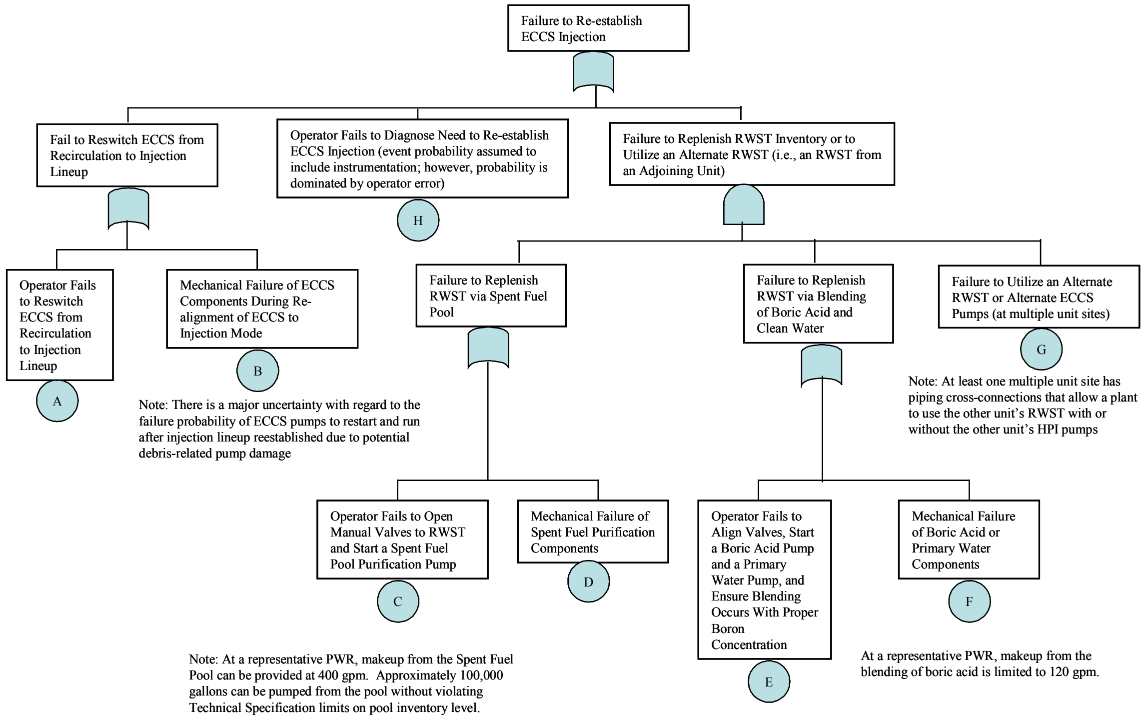

Figure 2. Important Considerations Related to Reestablishment of ECCS Injection.

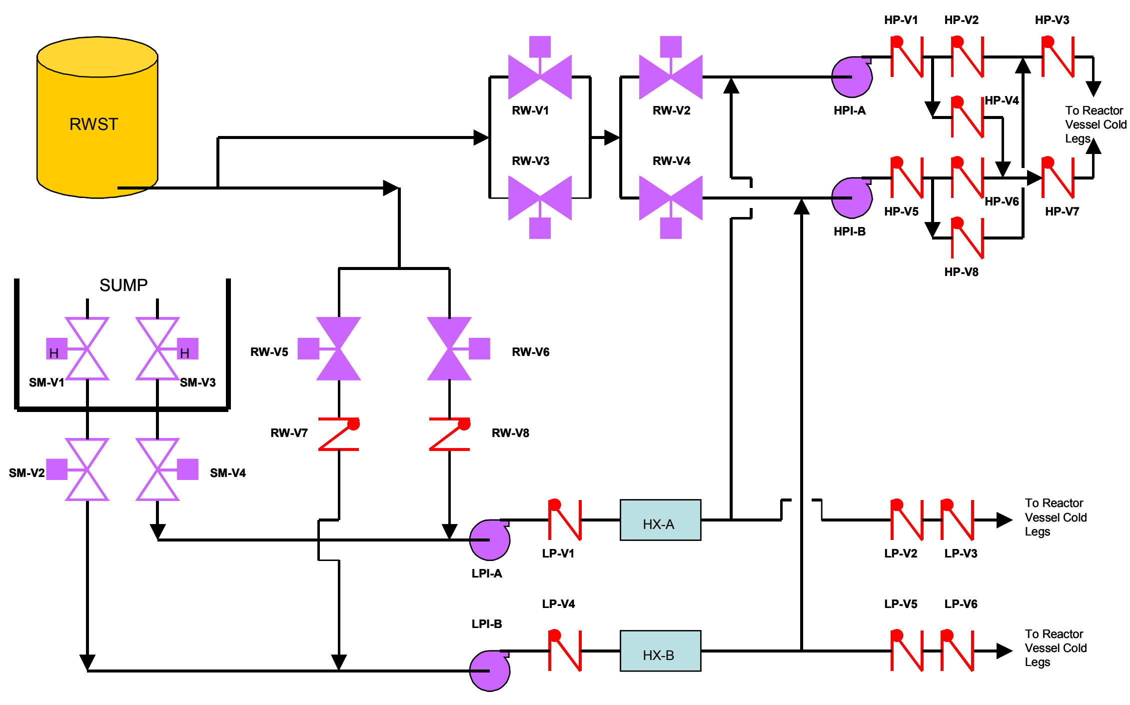

Figure 3. ECCS System of Typical 2-Loop Plant (Valve Lineups Reflect Recirculation Positions).

aligned to at least one injection train (LPI or HPI, depending on the type of LOCA). For simplicity, Fig. 3 does not show the containment spray system.[4]

Table 1 summarizes the dominant contributors to mechanical failure of ECCS reswitching for the ECCS system shown in Fig. 3. Here it is assumed that one injection train (LPI or HPI) must be restored and that the pumps must be turned off during the reswitching process. As noted in this table, the estimates of pump failure probabilities (fail to restart and run) may be significantly underestimated because the pumps may have been damaged from debris effects, which are not accounted for by the available generic failure data.[5] Aside from this caveat, the probability that mechanical failure will defeat either HPI or LPI is estimated to be approximately 1E-03. Note that common cause events that fail both LPI and HPI are not included because successful LOCA mitigation is assumed to require LPI for LLOC and MLOCA and HPI for the remaining events.

At some plants the HPI pumps can draw suction directly from the containment sumps during recirculation, while the design shown in Fig. 3 involves piggybacking of HPI pumps onto the discharge of the LPI pumps. In any case, required hardware actions associated with reswitching are expected to be comparable for both types of plant design.

3.2. Refill of the RWST

Water used for RWST refill must be borated. Modern PWRs have “unrodded cores,”– they use chemical shim (borated water) to control reactivity and use rods only for fine level control and for scram. The use of chemical shim instead of insertion of rods for reactivity control prevents perturbations in flux and power that would result from the insertion of rods.

Below hot zero power (saturation temperature at the pressure of the steam generator secondaries, about 540°F), PWRs cannot always maintain shutdown margin (1% subcritical) on rods alone, assuming the most reactive gang of rods fails to insert, and boration must be increased to maintain shutdown margin as the primary is cooled down. The actual shutdown margin available from the rods is dependent on the time of core life (i.e., amount of fuel burnup).

System configurations at a number of PWRs were reviewed to identify potential means to transfer borated water into the RWST during post-accident conditions. Two typical methods were identified. One method involves the transfer of borated water from the spent fuel pool, while the other involves the mixing of water from the purification system and boric acid stored in chemical, volume, and control system (CVCS) boric acid tanks.

Transfer of borated water from the spent fuel pool to the RWST can be accomplished via the spent fuel purification pumps, as shown in Fig. 4. The spent fuel pool is normally filled to a level above the plant Technical Specification limit. At a representative PWR, the spent fuel pool level is normally 20 in. above the Technical Specification limit, which corresponds to an available “excess” spent fuel pool water inventory of approximately 108,000 gal. Because the suction of the purification pumps is typically 4 feet below the normal pool level, the purification system at this plant might be able to provide at least 260,000 gal. of borated water from the spent fuel pool (assuming adequate purification pump NPSH). RWSTs typically hold in the range of 250,000 to 450,000 gal, depending on the particular plant.

Emergency makeup of fresh (unborated water) into the spent fuel pool could be used to restore the pool level, though the overall boron concentration of the pool water would be correspondingly reduced. Emergency pool makeup might be accomplished, for example, by the use of fire hoses or by emergency

[4] As previously noted, plants with a subatmospheric containment design remove post-LOCA decay heat from the reactor core via the containment spray system. Figure 3 does not represent plants with a subatmospheric containment design.

[5] Potential damage is probably of most concern for pumps that draw suction directly from the sump, which in the sample plant are the LPI pumps.

Table 1. Important Mechanical Failure Contributors to Reswitch of HPI and LPI From Sump to RWST Suction

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
1	(a) [SM-V1 and SM-V3] (MOVs) and (b) [SM-V2 and SM-V4] (hydraulic valves)	Fail to Close Common Cause	(0.08) *(3E-03) = 2E-04	Reclose sump suction valves 3E-03 per demand for MOVs, 2E-03 for hydraulic valves per Table 6 of Ref. (1); treat all four valves as similar with individual failure probability of 3E-03, apply MGL factor of 0.08 for 4 of 4 valves per Ref. (2) Note: Depending on plant design and specific accident conditions, failure of the sump suction valves to reclose may not necessarily disable the reswitching of ECCS. The pumps might still be able to draw suction from the RWST once the RWST suction valves have been reopened. Without detailed analyses, it was assumed that pump suction from the RWST would fail if sump suction is not isolated to at least one injection train.
2	RW-V1 and RW-V3 (MOVs)	Fail to Open Common Cause	(0.1)*(3E-03) = 3E-04	Reopen RWST suction valves to HPI pumps MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
3	RW-V2 and RW-V4 (MOVs)	Fail to Open Common Cause	(0.1)*(3E-03) = 3E-04	Reopen RWST suction valves to HPI pumps MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
4	HPI-A and HPI-B (pumps)	Fail to start and run Common Cause	(0.1)*(4E-03) = 4E-04	Restart HPI pumps Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; *this may significantly underestimate the failure probability because the pumps may have been damaged from debris effects which are not accounted for by these failure data*; multiply 4E-03 by screening Beta factor of 0.1
5	(HP-V1 and HP-V5) or (HP-V3 and HP-V7) (check valves) Also 6 combinations of 3 check valves failures and 6 combinations of 4 check valve failures from group of check valves HP-V1 through HP-V8	Fail to Open Common Cause	(0.1)*(5E-05)*2 + (0.02)*5E-05*6 + (0.008)*5E-05*6= 2E-05	Reopen HPI pump discharge flow paths Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1 times 2 possible combinations of 2 check valves For combinations of 3 and 4 check valve failures, use screening Beta factors given in Ref. (3) which are 0.02 and 0.008, respectively For 6 groups of 3 check valve failures, failure probability is 0.02*5E-05*6= 6E-06 For 6 groups of 4 check valve failures, failure probability is 0.008*5E-05*6= 2E-06

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
6	RW-V5 and RW-V6 (MOVs)	Fail to Open Common Cause	(0.1)*(3E-03) = 3E-04	Reopen RWST suction valves to LPI pumps MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
7	RW-V7 and RW-V8 (check valves)	Fail to Open Common Cause	(0.1)*(5E-05) = 5E-06	Reopen RWST suction valves to LPI pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
8	(LP-V1 and LP-V4) or (LP-V1 and LP-V5) or (LP-V1 and LP-V6) or (LP-V2 and LP-V4) or (LP-V2 and LP-V5) or (LP-V2 and LP-V6) or (LP-V3 and LP-V4) or (LP-V3 and LP-V5) or (LP-V3 and LP-V6) (check valves)	Fail to Open Common Cause	(0.1)*(5E-05)*9 = 5E-05	Reopen LPI pump discharge flow paths Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1 times 9 possible combinations
9	LPI-A and LPI-B (pumps)	Fail to start and run	(0.1)*(4E-03) = 4E-04	Restart LPI pumps Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; *this may significantly underestimate the failure probability because the pumps may have been damaged from debris effects which are not accounted for by these failure data*; multiply 4E-03 by screening Beta factor of 0.1
Total Failure Probability for Reswitch of HPI			~1E-03	Sum of Failure Group (Cut Set) Nos. 1 through 5
Total Failure Probability for Reswitch of LPI			~1E-03	Sum of Failure Group (Cut Set) No. 1 and Nos. 6 through 9
References: (1) Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, EGG-SSRE-8875, February 1990. (2) Procedures for Treating Common Cause Failures in Safety and Reliability Studies, EPRI NP-5613, NUREG/CR-4780, 1988. (3) Millstone Unit 2 Individual Plant Examination, December 30, 1993.				

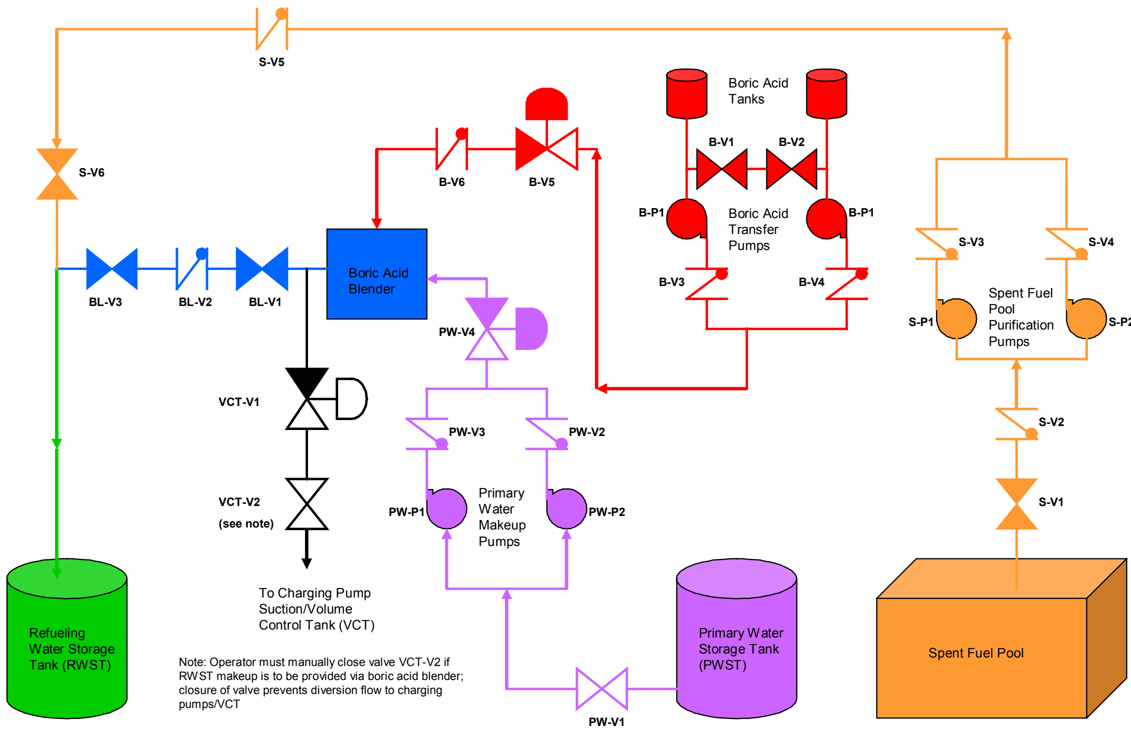

Figure 4. Typical Methods Available for Refill of the RWST.

makeup from the service water system. It is unlikely that either of these options is proceduralized. In addition, makeup from the service water system typically requires installation of a spool piece. However, if makeup of the spent fuel pool inventory can be accomplished, the purification pumps would be able to transfer additional borated water into the RWST. Given an initial replenishment of the RWST with spent fuel pool water, sufficient time likely may be available to restore the pool level. This analysis has assumed that restoration of pool level would be successful for subsequent transfers of borated water to the RWST.

Use of the fuel pool pumps for makeup requires that operators open manual valves S-V1 and S-V6, and start a purification pump (see Fig. 4). Given a fuel pool purification pump design rating of 400 gpm, the “excess” spent fuel pool inventory of 108,000 gal. can be transferred into the RWST in about 4.5 h. Simultaneous operation of both purification pumps should increase the flow rate, through by an unknown amount.

Table 2 summarizes the dominant contributors to mechanical failure of RWST refill per the components shown in Fig. 4. As indicated, refill of the RWST from the spent fuel pool (SFP) has a mechanical failure probability of approximately 2E-03, while refill via the mixing of borated water has a slightly higher mechanical failure probability of 3E-03.

The other alternative for RWST makeup is more complex, because it involves the mixing of primary grade water and boric acid prior to transfer into the RWST. Clean water from the primary water storage tank is blended with boric acid from the boric acid tanks (Fig. 4). The operators must adjust flow rates to ensure a proper blend of clean water and boric acid (approximately 2000-ppm boron). Using this method, makeup to the RWST can be provided at a flow rate of 120 gpm at a representative plant. This relatively low flow rate may not be sufficient for all types of LOCA conditions. A plant-specific analysis would be necessary to determine the adequacy of this makeup method for a specific plant and specific postulated LOCA conditions.

Table 2. Important Mechanical Failure Contributors to Refill of RWST

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
Method A: Transfer Inventory from Spent Fuel Pool to RWST				
1	S-V1 (manual valve)	Fail to Open	5E-04	Open manual suction isolation valve to spent fuel purification pumps 5E-04 per demand per Table 1 of Ref. (1); does not include human action needed to operate valve, but is instead assumed to represent a "frozen" valve that operators cannot readily open
2	S-V2 (check valve)	Fail to Open	5E-05	Open suction path to spent fuel purification pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)
3	S-P1 and S-P2 (pumps)	Fail to start and run Common cause	(0.1)*(4E-03) = 4E-04	Start and run at least one spent fuel purification pump Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; multiply 4E-03 by screening Beta factor of 0.1
4	S-V3 and S-V4 (check valves)	Fail to Open Common cause	(0.1)*(5E-05) = 5E-06	Open discharge path from spent fuel purification pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
5	S-V5 (check valve)	Fail to Open	5E-05	Open discharge path from spent fuel purification pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)
6	S-V6 (manual valve)	Fail to Open	5E-04	Open manual isolation valve in discharge path of spent fuel purification pumps 5E-04 per demand per Table 1 of Ref. (1); does not include human action needed to operate valve, but is instead assumed to represent a "frozen" valve that operators cannot readily open
Total Failure Probability for Transfer of Spent Fuel Pool Inventory			~2E-03	Sum of Failure Group (Cut Set) Nos. 1 through 6
Method B: Mix Borated Water Via Boric Acid Transfer and Purification Pumps				
7	B-P1 and B-P2 (pumps)	Fail to start and run Common cause	(0.1)*(4E-03) = 4E-04	Start and run at least one boric acid transfer pump Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; multiply 4E-03 by screening Beta factor of 0.1
8	B-V3 and B-V4 (check valves)	Fail to Open Common cause	(0.1)*(5E-05) = 5E-06	Open discharge path from boric acid transfer pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
9	B-V5 (control valve)	Fail to Operate	2E-04	Control flow of boric acid into boric acid blender Pneumatic valve failure data of 1E-05/h per Table 1 of Ref. (1); total failure probability is 2.4E-04 based on 24 h mission time

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
10	B-V6 (check valve)	Fail to Open	5E-05	Open discharge path from boric acid transfer pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)
11	PW-P1 and PW-P2 (pumps)	Fail to start and run Common cause	(0.1)*(4E-03) = 4E-04	Start and run at least one primary water makeup pump Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; multiply 4E-03 by screening Beta factor of 0.1
12	PW-V3 and PW-V4 (check valves)	Fail to Open Common cause	(0.1)*(5E-05) = 5E-06	Open discharge path from primary water makeup pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
13	BPW-V4 (control valve)	Fail to Operate	2E-04	Control flow of primary (clean) water into boric acid blender Pneumatic valve failure data of 1E-05/h per Table 1 of Ref. (1); total failure probability is 2.4E-04 based on 24 h mission time
14	BL-V1 (manual valve)	Fail to Open	5E-04	Open manual discharge isolation valve from boric acid blender 5E-04 per demand per Table 1 of Ref. (1); does not include human action needed to operate valve, but is instead assumed to represent a "frozen" valve that operators cannot readily open
15	BL-V2 (check valve)	Fail to Open	5E-05	Open discharge path from boric acid blender Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)
16	BL-V3 (manual valve)	Fail to Open	5E-04	Open manual discharge isolation valve from boric acid blender 5E-04 per demand per Table 1 of Ref. (1); does not include human action needed to operate valve, but is instead assumed to represent a "frozen" valve that operators cannot readily open
17	VCT-V2 (manual valve)	Fail to Close	5E-04	Close manual discharge isolation valve from boric acid blender to volume control tank (VCT) 5E-04 per demand per Table 1 of Ref. (1); does not include human action needed to operate valve, but is instead assumed to represent a "frozen" valve that operators cannot readily close
Total Failure Probability for Mixing Borated Water Via Boric Acid Transfer and Purification Pumps			~3E-03	Sum of Failure Group (Cut Set) Nos. 7 through 17
References: (1) Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, EGG-SSRE-8875, February 1990.				

3.3. Use of RWST and/or ECCS Pump Cross-Connections at Multiple Unit Sites

An alternative to reestablishing ECCS injection may be available at multiple-unit sites if RWSTs or ECCS pumps for individual units can be cross-connected. A survey of available multi-unit documentation resulted in the identification of one dual unit site that has these types of cross-connections.[6] As shown in Fig. 5, the two RWSTs at this plant are cross-connected so that either Unit 1 or Unit 2 HPI pumps can take suction from the other unit's RWST. This cross-connection was included in the plant design to help protect against the possibility that a main steam line break could place the associated RWST out of service. It should be noted that action could put the RWST for the unaffected unit out of technical specifications. However, in an emergency situation it would be up to the licensee's judgment whether to use this option.

Each of the four pneumatically-operated cross-tie valves (RW-V8, 9, 10, 11) will automatically open given a steam line break signal from either unit. In addition, these four valves can be remotely opened from the main control room with hand switches.

Figure 5 also shows that the Unit 1 and Unit 2 HPI systems at this plant can be cross-tied such that the discharge of one unit's HPI pumps can be aligned to supply core cooling to the opposite unit. Manual valve HP-V-XTIE must be opened to establish this alignment.

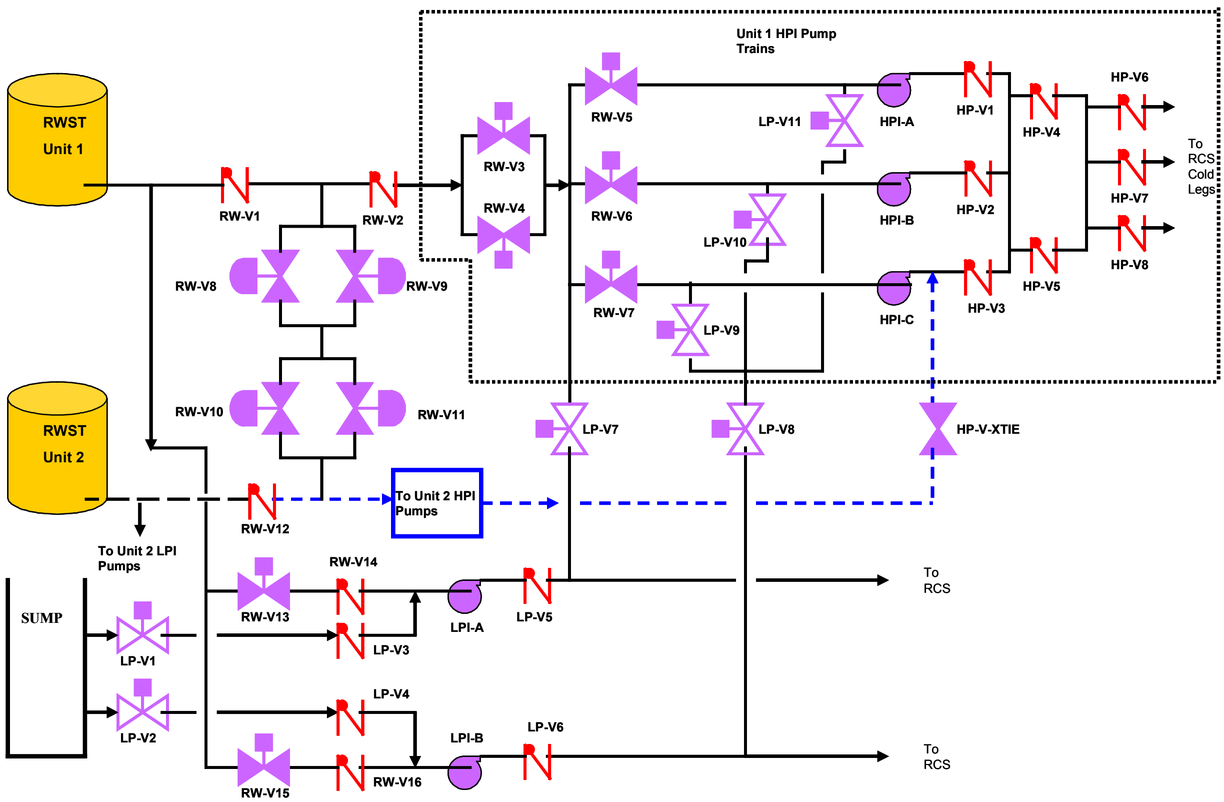

Figure 5. RWST Cross-Connections at a Particular Dual Unit PWR (Valve Lineups Reflect Recirculation Positions).

[6] While cross-connections were identified at only one multiple unit site, it is possible that cross-connections may exist at some other multiple unit sites as well. A more accurate survey would require detailed system-level information for each multiple unit site. Only a limited amount of site-specific system information was available for this study.

In the scenarios of interest in this study, debris-induced loss of ECCS recirculation, the use of the opposite unit's RWST would involve either

1. reswitching the affected unit's HPI system from recirculation to injection and opening the RWST cross-connect path, or
2. opening manual valve HP-V-XTIE and using the opposite unit's HPI pumps and RWST for core cooling.

In the first approach, all necessary actions can be accomplished from the control room, whereas the second approach requires an action outside the control room to open a manual valve. On the other hand, the second approach would utilize HPI pumps that have not been exposed to debris-related conditions, and thus these alternate HPI pumps may operate with a higher reliability than the HPI pumps affected by debris. Because the alternate RWST can supply only the HPI pumps, either approach may be inadequate for successful mitigation of large and medium LOCAs.

Table 3 summarizes the dominant mechanical failure contributors related to use of the alternate RWST in conjunction with reswitching the affected unit's HPI pumps from recirculation to injection mode. Here it is assumed that one injection train of HPI must be restored and that the HPI pumps must be turned off during the reswitching process. As noted in this table, the estimates of pump failure probabilities (failure to restart and run) may be significantly underestimated because the pumps may have been damaged from debris effects which are not accounted for by the available generic failure data. Aside from this, the probability that mechanical failure will defeat HPI is estimated to be approximately 1E-03. A comparable hardware failure probability is expected from the other approach – opening manual valve HP-V-XTIE and using both the opposite unit's HPI pumps and RWST for core cooling. As previously noted, opening of the manual valve involves an additional operator action outside the control room.

Table 3. Important Mechanical Failure Contributors Related to Use of Alternate RWST and Reswitching HPI to Injection (multiple unit sites)

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
1	RW-V12 (check valve)	Fail to Open	5E-05	Open suction path from Unit 2 RWST to cross-connection piping network Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)
2	RW-V8 and RW-V9 (pneumatic valves)	Fail to Open Common cause	(0.1)*(1E-03) = 1E-04	Open a required portion of the cross-connection path between Unit 1 and 2 RWSTs Pneumatic valve failure data 1E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
3	RW-V10 and RW-V11 (pneumatic valves)	Fail to Open Common cause	(0.1)*(1E-03) = 1E-04	Open a required portion of the cross-connection path between Unit 1 and 2 RWSTs Pneumatic valve failure data 1E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
4	RW-V2 (check valve)	Fail to Open	5E-05	Open suction path to HPI pumps Check valve failure data 5E-05 per demand from Table 1 of Ref. (1)

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
5	RW-V3 and RW-V4 (MOVs)	Fail to Open Common Cause	(0.1)*(3E-03) = 3E-04	Reopen RWST suction valves to HPI pumps MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1
6	RW-V5, RW-V6, and RW-V7 (MOVs)	Fail to Open Common Cause	(0.02)*(3E-03) = 6E-05	Reopen RWST suction valves to HPI pumps MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor given in Ref. (3) for 3 components which is 0.02
7	HPI-A, HPI-B, and HPI-C (pumps)	Fail to start and run Common Cause	(0.02)*(4E-03) **=** 8E-05	Restart HPI pumps Pump failure data of 3E-03 fail to start and 3E-05/h for run per Table 1 of Ref. (1); total failure probability per pump is about 4E-03 based on 24 h mission time; *this may significantly underestimate the failure probability because the pumps may have been damaged from debris effects which are not accounted for by these failure data*; multiply pump failure probability by screening Beta factor given in Ref. (3) for 3 components which is 0.02
8	HP-V1, HP-V2, and HP-V3 (check valves)	Fail to Open Common Cause	(0.02)*(5E-05) = 1E-06	Reopen HPI pump discharge flow paths Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor given in Ref. (3) for 3 components which is 0.02
9	HP-V4 and HP-V5 (check valves)	Fail to Open Common Cause	(0.1)*(5E-05) = 5E-06	Reopen HPI pump discharge flow paths Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor screening Beta factor of 0.1
10	HP-V6, HP-V7, and HP-V8 (check valves)	Fail to Open Common Cause	(0.02)*(5E-05) = 1E-06	Reopen HPI pump discharge flow paths Check valve failure data 5E-05 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor given in Ref. (3) for 3 components which is 0.02
11	LP-V1 and LP-V7 (MOVs)	Fail to Close Common Cause	(0.1)*(3E-03) = 3E-04	Reclose sump suction valves MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factor of 0.1 Note: Depending on the plant design and specific accident conditions, failure of the sump suction valves to reclose may not necessarily disable the reswitching of ECCS. The pumps might still be able to draw suction from the RWST once the RWST suction valves have been reopened. Without detailed analyses, it was assumed that pump suction from the RWST would fail if sump suction is not isolated to at least one injection train

Failure Group (Cut Set) No.	Components in Group	Failure Mode	Failure Probability Estimate for Group	Basis for Group Failure Probability Estimate
12	LP-V2, LP-V8, LP-V9, LP-V10, LP-11 (MOVs)	Fail to Close Common Cause	(0.008)*(3E-03) = 2E-05	Reclose sump suction valves MOV failure data 3E-03 per demand from Table 1 of Ref. (1); multiply valve failure probability by screening Beta factors given in Ref. (3) for 4 components which is 0.008 Note: Depending on the plant design and specific accident conditions, failure of the sump suction valves to reclose may not necessarily disable the reswitching of ECCS. The pumps might still be able to draw suction from the RWST once the RWST suction valves have been reopened. Without detailed analyses, it was assumed that pump suction from the RWST would fail if sump suction is not isolated to at least one injection train
Total Failure Probability for Use of Alternate RWST (HPI only)			~1E-03	Sum of Failure Group (Cut Set) Nos. 1 through 12
References: (1) Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs, EGG-SSRE-8875, February 1990. (3) Millstone Unit 2 Individual Plant Examination, December 30, 1993.				

4.0. Quantification of Human Actions

The quantification of human actions associated with recovery of ECCS recirculation loss was accomplished largely by use of the methodology presented in *Accident Sequence Evaluation Program Human Reliability Analysis Procedure*, NUREG/CR-4772, 1987 (Ref. 4). Accident Sequence Evaluation Program (ASEP) methodology has been used in a number of reactor probabilistic risk studies.

The use of the ASEP methodology was focused on two tables presented in the ASEP document. Information extracted from these tables is reproduced below in Tables 4 and 5. A mean value for each entry was calculated and added to Tables 4 and 5. These mean values were subsequently used as input data for generating HRA estimates.

The human error probabilities (HEPs) listed in Table 5 are for independent actions or independent sets of actions in which the actions making up the set can be judged to be completely dependent. The task types referred to in Table 5, "dynamic" and "step-by-step" are defined in the ASEP document as follows:

> *"Dynamic task – one that requires a higher degree of interaction between the people and the equipment in a system that is required by routine, procedurally guided tasks. Dynamic tasks may include decision-making, keeping track of several functions, controlling several functions, or any combination of these. A post-accident task may be classified as a dynamic task if the written emergency operating procedure is so poorly written that it is difficult to follow with ease. The operator's tasks in coping with an abnormal event may be classified either as dynamic or step-by-step tasks. Pre-accident tasks are usually classified as step-by-step tasks, e.g., restoration of valves (to their normal operating states) after maintenance."*

> *"Step-by-step task – a routine, procedurally guided set of steps performed one step at a time without a requirement to divide one's attention between the task in question and other tasks. With high levels of skill and practice, a step-by-step task may be performed reliably without recourse to written procedures, e.g., repairing a faucet or the sequential performance of memorized immediate emergency actions. However, in such cases, the likelihood of errors of omission is increased. Pre-accident tasks or post-accident tasks may be classified as step-by-step tasks. "*

Table 4. Nominal Estimated HEPs and Error Factors (EFs) for Diagnosis Within Time "T" by Control Room Personnel of an Abnormal Single Event (Based on Data From Table 8-2 of ASEP HRA Guidance Document)

Diagnosis Time (T) (min)	Median	Error Factor	Mean
1	1.0	--	1.0
10	0.1	10	2.7E-01
20	0.01	10	2.7E-02
30	0.001	10	2.7E-03
60	0.0001	30	8.5E-04
1500	0.00001	30	8.5E-05

Table 5. Nominal Estimated HEPs for Post-Accident, Post-Diagnosis Actions (Based on Data From Table 8-5 of ASEP HRA Guidance Document)

Action Category	Median	Error Factor	Mean
(1) Perform a critical skill- or rule-based action correctly when no procedures are available	1.0	--	1.0
(2) If sufficient information available to perform a more detailed task analysis, use data tables in Chapter 20 of NUREG/CR-1278 adjusted for effects of dependence, stress, and other performance shaping factors (PSFs), and error recovery factors (RFs)	Variable	Variable	Variable
(3) Perform a critical action as part of a step-by-step task done under moderately high stress (applies to original performer of action)	0.02	5	3.2E-02
(4) Perform a critical action as part of a dynamic task done under moderately high stress or a step-by-step task done under extremely high stress (applies to original performer of action)	0.05	5	8.1E-02
(5) Perform a critical action as part of a dynamic task done under extremely high stress (applies to original performer of action)	0.25	5	4E-01
(10) Perform a post-diagnosis immediate emergency action for the reactor vessel/containment critical parameters when (a) it can be judged to have been committed to memory, (b) it can be classified as skill-based actions, and (C) there is a backup written procedure. It is assumed that no immediate recovery factor (RF) from a second person for each such action.	0.001	10	2.7E-03
The following items (6) through (9) are adjustment factors that account for the influence of recovery factors and other operators			
(6) Verify the correctness of a critical action as part of a step-by-step task done under moderately high stress	0.2	5	3.2E-01
(7) Verify the correctness of a critical action as part of a dynamic task done under moderately high stress or a step-by-step task done under extremely high stress	0.5	5	8.1E-01
(8) Verify the correctness of a critical action as part of a dynamic task done under extremely high stress	0.5	5	8.1E-01
(9) If there are error recovery factors (RFs) in addition to the use of human redundancy in items (6), (7), and (8), the influence of these RFs must be assessed separately.	Variable	Variable	Variable

To apply the ASEP methodology to debris-induced loss of recirculation, Table 6 has been constructed. This table contains human reliability analysis (HRA)-related events contained in Figs. 1 and 2. Note that the mean values for HRA elements in Tables 4 and 5 are used in Table 6. Also, where recovery factors (RFs) were credited for a given set of multiple operator actions in Table 6, these recovery factors were applied to the combined set of actions instead of being applied to individual actions.

5.0. Summary of Quantification Estimates for Figures 1 and 2 Logic Models

Table 7 summarizes the point-estimate quantification of events associated with the logic models shown in Figs. 1 and 2. The largest areas of uncertainty are associated with the quantification of human actions, and the failure probability of ECCS pumps to restart and run after ECCS flows are reestablished.

The top-level events are quantified by following the Boolean logic in Figs. 1 and 2, with some additional considerations. In Fig. 1, the probability of event E is assumed to be captured within the probability of failure for event D. The combined probabilities then give a probability of failure to continue ECCS recirculation of 0.46 for LLOCA and 0.16 for MLOCA events. For SLOCA, OPEN pressure relief valve (PRV), and LOFW Events, the probability of failure is 0.025. Quantification of the failure to reestablish ECCS injection is not straight forward because of the requirement to refill the RWST. While Fig. 2 suggests three potential paths to refill the RWST, it does not indicate the time limitations required. For conservatism, it is assumed that for LLOCA events the operators will have time to try only one refill option, using the boric acid pumps. For all other events it is assumed that the operators will have time to attempt the other options. The probability of failure to reestablish ECCS injection is 0.87 for LLOCA events, 0.37 for MLOCA events, and 0.045 for SLOCA, OPEN_PRV, and LOFW events.

6.0. Review of Individual Plant Examinations for Additional Failure Data

To further assess human actions relevant to PWR debris-induced loss of recirculation, a survey was made of human reliability analyses contained in a number of Individual Plant Examinations (IPEs). The results of this survey are summarized in the following paragraphs.

The Palo Verde IPE quantified the failure of operators to refill the RWST during a small LOCA. While the Palo Verde emergency operations procedures require frequent verification of the RWST level, they do not direct operators to perform a particular action if the tank level becomes low. The IPE assumed the operators would not consider the need for RWST refill until high-pressure recirculation fails. Assuming RWST refill via the spent fuel pool and boric acid makeup (BAM) system, the licensee estimated a human failure probability of 3E-01. Note that this failure probability does not appear to include any actions needed to realign ECCS pumps from recirculation to injection lineups.

The Comanche Peak IPE also quantified an operator action to align a source of makeup water to the RWST. The quantification of this event assumes that operators will be aware of the loss of recirculation capability many hours before recirculation is required. (The procedure directs the operators to verity this capability, but the IPE does not indicate how this is to be accomplished – one way might be inadequate containment water level.) The IPE assigned a human failure probability of 1E-01 to this action.

The Indian Point 3 IPE quantified an operator action to refill the RWST during a steam generator tube rupture (SGTR). Here it is assumed that either the operators are unable to terminate leakage from the reactor coolant system (RCS) so that an RWST low-low level alarm is reached at about 9 h, or RCS depressurization is successful but residual heat removal (RHR) shutdown cooling fails. Procedural guidance is in place to direct operators to refill the RWST under these conditions. The IPE assigned a failure probability of 1.75E-01 to successfully refill of the RWST. This failure probability does not include actions to realign ECCS pumps from recirculation to injection lineups, as an ECCS recirculation lineup is never made.

Table 8 summarizes the preceding IPE human reliability data pertinent to ECCS reswitching.

Table 6. Quantification of HRA-Related Events

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
Figure 1, Large LOCA					
B	Operator fails to recognize symptoms of ECCS recirculation loss	10	Diagnosis	2.7E-01	Table 4, second entry (mean value)
D	Operator fails to restore ECCS recirc. by turning off sprays and/or redundant core injection trains, and/or throttling of core injection flow	Extremely high stress	Post-diagnosis Dynamic	3E-01	Assume extremely high stress because of large LOCA and very limited time for action Operator fails to perform required actions: Table 5, Item (5) = 4E-01 Credit for recovery: recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = (4E-01)*(8.1E-01) = 3E-01
E	Operator inadvertently turns off all core cooling flow or overthrottles core cooling flow	-	-	-	Assume that this failure mode has been accounted for above in Event "D," including potential recovery by supervisors and other operators of interruption or overthrottling flow
Total HRA failure probability estimate, Figure 1, Large LOCA				**6E-01**	
Figure 1, Medium LOCA					
B	Operator fails to recognize symptoms of ECCS recirculation loss	20	Diagnosis	2.7E-02	Table 4, third entry (mean value)
D	Operator fails to restore ECCS recirc. by turning off sprays and/or redundant core injection trains, and/or throttling of core injection flow	Extremely high stress	Post-diagnosis Dynamic	3E-01	Assume extremely high stress because of medium LOCA and very limited time for action Operator fails to perform required actions: Table 5, Item (5) = 4E-01 Credit for recovery: recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = (4E-01)*(8.1E-01) = 3E-01
E	Operator inadvertently turns off all core cooling flow or overthrottles core cooling flow	-	-	-	Assume that this failure mode has been accounted for above in Event "D," including potential recovery by supervisors and other operators of interruption or overthrottling flow
Total HRA failure probability estimate, Figure 1, medium LOCA				**3E-01**	

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
Figure 1, Small LOCA					
B	Operator fails to recognize symptoms of ECCS recirculation loss	30	Diagnosis	2.7E-03	Table 4, fourth entry (mean value)
D	Operator fails to restore ECCS recirc. by turning off sprays and/or redundant core injection trains, and/or throttling of core injection flow	Moderately high stress	Post-diagnosis Dynamic	6E-02	Assume moderately high stress because of small LOCA with additional time for action compared to large and medium LOCAs Operator fails to perform required actions: Table 5, Item (4) = 8.1E-02 Credit for recovery: recovery factor (RF) Table 5, Item (8) = 8.1E-01 Overall failure probability = (8.1E-02)*(8.1E-01) = 6E-02
E	Operator inadvertently turns off all core cooling flow or overthrottles core cooling flow	-	-	-	Assume that this failure mode has been accounted for above in Event "D," including potential recovery by supervisors and other operators of interruption or overthrottling flow
Total HRA failure probability estimate, Figure 1, small LOCA				**1E-01**	Round up failure probability estimate from 6.3E-02 to 1E-01
Figure 2, Large LOCA					
H	Operator fails to diagnose need to reestablish ECCS injection	10	Diagnosis	2.7E-01	Table 4, second entry (mean value)
A	Operator fails to reswitch ECCS from recirculation to injection lineup	Extremely high stress	Post-diagnosis Step-by-step	3E-01	Assume extremely high stress because of large LOCA and very limited time for action Four critical actions: (1) turn off ECCS pumps, (2) close sump suction valves, (3) reopen RWST suction valves, (4) restart ECCS pumps Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery: recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 4*(8.1E-02)* (8.1E-01) = ~3E-01

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
C	Operator fails to open manual valves to RWST and start a SPF purification pump	Extremely high stress	Post-diagnosis Step-by-step	2E-01	Assume extremely high stress because of large LOCA and very limited time for action Three critical actions: (1) open manual valve S-V1 (nuclear plant operator), (2) open manual valve S-V6 (nuclear plant operator), (3) start a SFP purification pump (control room operator) Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery of action (3): recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 3*(8.1E-02)*(8.1E-01) = ~2E-01
E	Operator fails to align valves, start a boric acid and primary water pump and ensure blending occurs with proper boron concentration	Extremely high stress	Post-diagnosis Step-by-step	3E-01	Assume extremely high stress because of large LOCA and very limited time for action Four critical actions: (1) open manual valve BL-V1 (nuclear plant operator), (2) open manual valve BL-V3 (nuclear plant operator), (3) close manual valve VCT-V2 (nuclear plant operator), (4) start a primary water and boric acid transfer pump (control room operator) Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery of action (4): recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 4*(8.1E-02)*(8.1E-01) = ~3E-01
G	Failure to utilize an alternate RWST and/or alternate ECCS pumps (at multiple unit sites)			1.0	At the one plant identified with suitable cross-connections, only HPI pumps would be available for core cooling; even if the operators were to be successful in aligning HPI, the resulting flow is likely to be inadequate for mitigation of a large LOCA
Figure 2, Medium LOCA					
H	Operator fails to diagnose need to reestablish ECCS injection	20	Diagnosis	2.7E-02	Table 4, third entry (mean value)

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
A	Operator fails to reswitch ECCS from recirculation to injection lineup	Extremely high stress	Post-diagnosis Step-by-step	3E-01	Assume extremely high stress because of medium LOCA and very limited time for action Four critical actions: (1) turn off ECCS pumps, (2) close sump suction valves, (3) reopen RWST suction valves, (4) restart ECCS pumps Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery: recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 4*(8.1E-02)*(8.1E-01) = ~3E-01
C	Operator fails to open manual valves to RWST and start a SPF purification pump	Extremely high stress	Post-diagnosis Step-by-step	2E-01	Assume extremely high stress because of medium LOCA and very limited time for action Three critical actions: (1) open manual valve S-V1 (nuclear plant operator), (2) open manual valve S-V6 (nuclear plant operator), (3) start a SFP purification pump (control room operator) Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery of action (3): recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 3*(8.1E-02)*(8.1E-01) = ~2E-01
E	Operator fails to align valves, start a boric acid and primary water pump and ensure blending occurs with proper boron concentration	Extremely high stress	Post-diagnosis Step-by-step	3E-01	Assume extremely high stress because of medium LOCA and very limited time for action Four critical actions: (1) open manual valve BL-V1 (nuclear plant operator), (2) open manual valve BL-V3 (nuclear plant operator), (3) close manual valve VCT-V2 (nuclear plant operator), (4) start a primary water and boric acid transfer pump (control room operator) Operator fails to perform each required action: Table 5, Item (4) = 8.1E-02 Credit for recovery of action (4): recovery factor (RF) Table 5, Item (7) = 8.1E-01 Overall failure probability = 4*(8.1E-02)*(8.1E-01) = ~3E-01

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
G	Failure to utilize an alternate RWST and/or alternate ECCS pumps (at multiple unit sites)			1.0	At the one plant identified with suitable cross-connections, only HPI pumps would be available for core cooling; even if the operators were to be successful in aligning HPI, the resulting flow is likely to be inadequate for mitigation of a medium LOCA
Figure 2, Small LOCA					
H	Operator fails to diagnose need to reestablish ECCS injection	30	Diagnosis	2.7E-03	Table 4, fourth entry (mean value)
A	Operator fails to reswitch ECCS from recirculation to injection lineup	Moderately high stress	Post-diagnosis Step-by-step	4E-02	Assume <u>moderately high stress</u> because of small LOCA with additional time for action compared to large and medium LOCAs Four critical actions: (1) turn off ECCS pumps, (2) close sump suction valves, (3) reopen RWST suction valves, (4) restart ECCS pumps Operator fails to perform each required action: Table 5, Item (3) = 3.2E-02 Credit for recovery: recovery factor (RF) Table 5, Item (6) = 3.2E-01 Overall failure probability = 4*(3.2E-02)*(3.2E-01) = ~4E-02
C	Operator fails to open manual valves to RWST and start a SPF purification pump	Moderately high stress	Post-diagnosis Step-by-step	3E-02	Assume <u>moderately high stress</u> because of small LOCA with additional time for action compared to large and medium LOCAs Three critical actions: (1) open manual valve S-V1 (nuclear plant operator), (2) open manual valve S-V6 (nuclear plant operator), (3) start a SFP purification pump (control room operator) Operator fails to perform each required action: Table 5, Item (3) = 3.2E-02 Credit for recovery: recovery factor (RF) Table 5, Item (6) = 3.2E-01 Overall failure probability = 3*(3.2E-02)*(3.2E-01) = ~3E-02

HRA Event No.	Event Desc.	Time Available (min) and/or Stress Level	Type	Quantification (mean value)	Basis for Quantification, Notes
E	Operator fails to align valves, start a boric acid and primary water pump and ensure blending occurs with proper boron concentration	Moderately high stress	Post-diagnosis Step-by-step	4E-02	Assume moderately high stress because of small LOCA with additional time for action compared to large and medium LOCAs Four critical actions: (1) open manual valve BL-V1 (nuclear plant operator), (2) open manual valve BL-V3 (nuclear plant operator), (3) close manual valve VCT-V2 (nuclear plant operator), (4) start a primary water and boric acid transfer pump (control room operator) Operator fails to perform each required action: Table 5, Item (3) = 3.2E-02 Credit for recovery: recovery factor (RF) Table 5, Item (6) = 3.2E-01 Overall failure probability = 4*(3.2E-02)*(3.2E-01) = ~4E-02
G	Failure to utilize an alternate RWST and/or alternate ECCS pumps (at multiple unit sites)	Moderately high stress	Post-diagnosis Step-by-step	5E-02 (only one plant example known at this time)	Assume use of alternate RWST with affected unit's HPI pumps (only one plant example known at this time) Assume moderately high stress because of small LOCA with additional time for action compared to large and medium LOCAs Five critical actions: (1) turn off ECCS pumps, (2) close sump suction valves, (3) open Unit 1-2 RWST cross-tie valves (4) reopen RWST suction valves to affected unit's HPI pumps, (5) restart HPI pumps Operator fails to perform each required action: Table 5, Item (3) = 3.2E-02 Credit for recovery: recovery factor (RF) Table 5, Item (6) = 3.2E-01 Overall failure probability = 5*(3.2E-02)*(3.2E-01) = ~5E-02

Table 7. Overall Summary of Quantification Estimates for Figures 1 and 2 Logic Models

Event	Description	Accident Condition	Failure Probability Estimate	Basis for Quantification, Notes
Figure 1				
A	ECCS Pumps Fail to Operate with Loss NPSH Margin	Large LOCA Medium LOCA Small LOCA	0.8 0.5 0.4	Engineering judgment
B	Operator Fails to Recognize Symptoms of ECCS Recirculation Loss	Large LOCA Medium LOCA Small LOCA	2.7E-01 2.7E-02 2.7E-03	Table 6 (ASEP)
C	Failure of Instrumentation and Alarms Needed to Alert Operators to Recirculation Loss	All	2.4E-04	Common cause failure, conservatively represented by failure of a power supply to a single instrumentation train; per Table 4 of Ref. (1), failure rate of 1E-05/h *24 h mission time= 2.4E-04
D	Operator Fails to Restore ECCS Recirculation by Turning Off Sprays, Turning Off Redundant ECCS Core Injection Train(s), Throttling of ECCS Core Injection Flow, or Cycling Pumps	Large LOCA Medium LOCA Small LOCA	3E-01 3E-01 6E-02	Table 6 (ASEP) Probability is dominated by operator actions.
E	Operator Inadvertently Turns Off All Core Cooling Flow or Overthrottles Core Cooling Flow	-	-	Assumed to be included in quantification for event D
F	ECCS Pumps Fails to Continue Operating After ECCS Flow is Reestablished	All	4E-04 (HPI or LPI)	Table 1- Estimate may be significant underestimate of failure probability due to potential for debris-related pump damage
G	Failure of Backflush System to Restore NPSH	Plants with backflush systems	1E-2	Engineering judgment due to unavailability of system details
		All Others	1.0	
Figure 2				
A	Operator Fails to Reswitch ECCS from Recirculation to Injection Lineup	Large LOCA Medium LOCA Small LOCA	3E-01 3E-01 4E-02	
B	Mechanical Failure of ECCS Components During Realignment of ECCS to Injection Mode	All	1E-03 (HPI) 1E-03 (LPI)	Table 1 - Major uncertainty regarding probability of failure of pumps to restart and run
C	Operator Fails to Open Manual Valves to RWST and Start a Spent Fuel Purification Pump	Large LOCA Medium LOCA Small LOCA	2E-01 2E-01 3E-02	Table 6 (ASEP)
D	Mechanical Failure of Spent Fuel Purification Components	All	2E-03	Table 2
E	Operator Fails to Align Valves, Start a Boric Acid Pump and a Primary Water Pump, and Ensure Blending Occurs with Proper Boron Concentration	Large LOCA Medium LOCA Small LOCA	3E-01 3E-01 4E-02	Table 6 (ASEP)

Event	Description	Accident Condition	Failure Probability Estimate	Basis for Quantification, Notes
F	Mechanical Failure of Boric Acid and Primary Water Components	All	3E-03	Table 2
G	Failure to Utilize an Alternate RWST or Alternate ECCS pumps (at multiple unit sites)	All	1.0 for most plants (see note) 5E-02 for at least one multiunit plant (see note)	Most plants do not appear to have this capability, thus no credit given (failure probability of 1.0 assigned) For one multi-unit plant with identified cross-connections, estimate failure probability of 5E-02 for small LOCAs, assuming use of alternate RWST with affected unit's HPI pumps (see Table 6)
H	Operator Fails to Diagnose Need to Reestablish ECCS Injection	Large LOCA Medium LOCA Small LOCA	2.7E-01 2.7E-02 2.7E-03	Table 6 (ASEP)

Table 8. IPE Human Reliability Data Pertinent to ECCS Reswitching

Accident Condition	Aspects of Reswitching Addressed	Human Error Probability	Data Source, Notes
Small LOCA	Refill RWST	3E-01	Palo Verde IPE (p. 7-45) Procedures do not specify that a particular action be taken given low RWST inventory
Not clear, appears to be LOCA	Refill RWST	1E-01	Comanche Peak IPE (p. 3-198) Assumes operators aware of recirculation loss for many hours prior to needing RWST refill
SGTR	Refill RWST	1.75E-01	Indian Point 3 (p. H-101)
Note: All of the above reliability data appear to be limited to one aspect of ECCS reswitching, namely refill of the RWST. The other major aspect of reswitching, namely realignment of ECCS equipment from recirculation to injection lineups, is not addressed.			

6.1. Depressurization of RCS and use of Shutdown Cooling (SDC) with Makeup

For medium and small LOCAs, it might be possible to depressurize the RCS and establish shutdown cooling (SDC) while maintaining sufficient makeup flow to the RCS. The Indian Point IPE quantified the human error portion of RCS depressurization and RHR SDC alignment for very small LOCAs and SGTR (p. H-87). The estimated human error probability was 9E-04. However, this estimate assumes that sump recirculation is never reached, but instead RHR shutdown cooling is achieved prior to RWST depletion.

6.2. Recovery of Main Feedwater

One mitigation strategy for loss of feedwater (LOFW) sequences is the recovery of feedwater so that feed and bleed could be terminated, thereby obviating the need for sump recirculation cooling. It is assumed that main feedwater may have the potential for recovery.

The Indian Point 3 IPE (p. H-115) notes that there are no procedures that explicitly instruct operators to attempt feedwater recovery unless main feedwater, auxiliary feedwater, and feed and bleed have been lost. Given this set of failures, operators are instructed to depressurize the steam generators and align flow from the main feedwater's condensate system. The IPE estimated the failure probability of this action to be 3.7E-01 because of the relatively short time (17 min) available for diagnosis (feed and bleed was assumed to fail early). It is possible that additional time might be available to operators if failure of feed and bleed occurs hours later when sump recirculation is attempted.

References

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2. Procedures for Treating Common Cause Failures in Safety and Reliability Studies, EPRI NP-5613, NUREG/CR-4780, 1988.
3. Millstone Unit 2 Individual Plant Examination, December 30, 1993.
4. Accident Sequence Evaluation Program Human Reliability Analysis Procedure, NUREG/CR-4772, 1987.
5. Indian Point 3 Nuclear Power Plant Individual Plant Examination, June 30, 1994.
6. Palo Verde Individual Plant Examination, April 7, 1992.
7. Comanche Peak Steam Electric Station Individual Plant Examination, August 1992.