B.2 LER No. 213/96-016

Event Description: Potentially inadequate RHR pump NPSH following a large- or medium-break LOCA

Date of Event: August 1, 1996

Plant: Haddam Neck

B.2.1 Event Summary

The Haddam Neck licensee determined that the net positive suction head (NPSH) available to a residual heat removal (RHR) pump during the sump recirculation phase of a loss-of-coolant accident (LOCA) would be inadequate for many emergency core cooling system (ECCS) configurations.[1] Inadequate NPSH will cause pump cavitation that, if severe or prolonged, will fail a pump. One RHR pump is used during the sump recirculation phase at Haddam Neck; use of RHR pump B would have almost certainly resulted in its failure due to low NPSH following a large- or medium-break LOCA. RHR pump A was also vulnerable to failure for some potential break locations and ECCS component unavailabilities. The estimated increase in the core damage probability (CDP) contribution for a 1-year period from inadequate RHR pump NPSH is 1.1×10^{-4}. This is above the nominal CDP for the same period of 3.7×10^{-5}. Uncertainties in the frequencies of large- and medium-break LOCAs (none have occurred), the reduced NPSH following such a LOCA, and the likelihood of pump failure with decreasing NPSH contribute to a substantial uncertainty in this estimate.

B.2.2 Event Description

On August 1, 1996, with the plant in cold shutdown, the Haddam Neck licensee determined that the RHR pump NPSH would not always be adequate during the sump recirculation phase of a LOCA. Past calculations that had been used to demonstrate adequate RHR pump NPSH were determined to have utilized an erroneous assumption that there would be sufficient overpressure in the containment to supply adequate suction pressure to meet the required NPSH.

The NPSH calculation estimates the pressure at the pump suction based on the temperature (and hence saturation pressure) of the sump water, the elevation difference between the free water surface in the containment sump and the pump suction, and the head loss through the flow path. The calculated pump suction pressure is compared to the minimum allowable pressure specified by the pump manufacturer to determine if adequate NPSH will exist following a LOCA. Inconsistent with Safety Guide 1, the original Haddam Neck calculation also considered containment overpressure and assumed that sufficient overpressure would exist in the containment to meet the required pump NPSH.

Analyses performed prior to submittal of the LER indicated that the assumed containment overpressure would not exist at all times during the sump recirculation phase following a large-break LOCA. These analyses indicated that if motor-operated sump valve RH-MOV-22 failed to open and the alternate sump recirculation

flow path through RH-V-808A was used, the containment pressure required for adequate RHR pump NPSH would probably not exist during recirculation.

Later analyses performed by the licensee and completed after the LER was submitted indicated that the NPSH problem existed independently of the sump recirculation flow path that was used and was therefore more serious than initially thought. During a telephone call on May 20, 1997, with ASP Program staff, licensee personnel provided additional information on the results of the later analyses. These analyses indicated that if RHR pump B was used during the recirculation phase, adequate NPSH would not exist for LOCA break sizes greater than 0.0046 m^2 (0.05 ft) (large- and medium-break LOCAs), independent of the sump recirculation flow path that was used. This condition would occur beginning ~1.5 h after the LOCA. If RHR pump A was used, adequate NPSH would not exist if RH-MOV-22 failed to open. If RH-MOV-22 successfully opened, NPSH would be adequate for cold-leg breaks, but would be ~80% of the required amount for hot-leg breaks.

B.2.3 Additional Event-Related Information

At Haddam Neck, post-LOCA ECCS operations are divided into three phases—injection, short-term recirculation, and long-term recirculation. During the injection phase (which is not a concern in this analysis), borated water is drawn from the refueling water storage tank (RWST) and injected into the reactor coolant system (RCS). The high-pressure safety injection (HPSI) pumps inject into the four cold legs, and the low pressure safety injection (LPSI) pumps inject into the reactor vessel head. The charging pumps are also used if offsite power is available.

When sufficient water has been ejected from the break, filling the containment sump (492,104 L (130,000 gal)], short-term recirculation is initiated. In this mode, the LPSI pumps are stopped, and one RHR pump is started. This pump takes suction from the sump and supplies water to the suction of one HPSI pump, which delivers water to two of the four cold legs. After a predetermined time has elapsed, two-path recirculation is initiated to prevent boric acid precipitation. In this alignment, one RHR pump again takes suction from the sump and supplies water to one charging pump, which delivers water at high pressure to the loop 2 cold leg. The RHR pump is also aligned to supply low-pressure water directly to the upper reactor vessel head (core deluge) during two-path recirculation. The procedures for initiating sump recirculation[2,3] are complex and involve the manipulation of many valves.

The Haddam Neck design is unusual in that it utilizes a single motor-operated valve (RH-MOV-22) to isolate the containment sump from the RHR pumps. This valve is opened when short-term recirculation is initiated. If RH-MOV-22 fails to open, procedure ES-1.3 (Ref. 2) instructs the operators to locally unlock and open a parallel manual valve, RH-V-808A, to provide recirculation flow. Haddam Neck procedures require sump switchover to be initiated quickly—in 10 min or less following a large-break LOCA.[4]

Additional information concerning this event and related events is included in Refs. 5 and 6.

B.2.4 Modeling Assumptions

This analysis assumes that, if RHR pump B is selected for sump recirculation or motor-operated valve RH-MOV-22 fails to open, adequate NPSH would not exist to support RHR pump operation following a large- or medium-break LOCA. As described above, break sizes above 0.05 ft^2 are of concern. This includes all large-break and some medium-break LOCAs [medium-break LOCAs include break areas between 0.00185 and 0.0185 m^2 (0.02 and 0.2 ft)]. Because data do not exist that would allow the medium-break LOCA initiating event category to be further divided to allow only break sizes greater than 0.0046 m^2 (0.05 ft^2) to be addressed, all medium-break LOCAs were assumed to result in low RHR pump NPSH (the inability to subdivide the medium-break LOCA category may add some conservatism to the analysis).

If RHR pump A is selected for sump recirculation and RH-MOV-22 successfully opens, the analysis assumes adequate NPSH would exist to support operation of that pump provided the LOCA occurred in the cold leg. If the LOCA occurs in the hot leg, operator throttling of discharge flow is assumed to be required to support long-term operation of the pump.[a] Recovery of recirculation flow through use of pump A is also assumed to be possible, if pump B is initially used.

The procedures for sump recirculation[2,3] instruct the operators to check pump current following RHR pump start to confirm that cavitation is not occurring and to throttle discharge flow if necessary. However, initial RHR pump start would occur when containment pressure is still high and when adequate NPSH is available. Although Refs. 2 and 3 also instruct the operators to monitor RHR pump current during recirculation, the licensee noted two factors in the May 20, 1997, telephone call that would complicate throttling and increase the likelihood that low RHR pump A NPSH will not be detected and corrected before pump damage occurs:

1. Two of the four HPSI discharge valves are closed during sump recirculation. If the LOCA occurred in an RCS loop associated with one of the two open valves (resulting in the loss of some HPSI flow out the break), there is essentially no range through which RHR flow can be adjusted to reduce cavitation and at the same time provide adequate decay heat removal from the core. The licensee believed that throttling would be very difficult in this situation. [This may be more of a concern following a cold-leg break, since HPSI flow is injected into the cold leg. However, because the licensee estimated a suction pressure for RHR pump A following a hot-leg break at ~80% of the vendor-specified NPSH, this analysis assumes the throttling concern applies to a hot-leg break as well. This may be pessimistic.]
2. Normally, cavitation is indicated by oscillating pump current. For this event, the licensee concluded that the operators would probably not observe oscillating current, but instead see a gradual reduction in pump current. This might lead them to open the discharge valves, exacerbating the cavitation problem.

---

[a]No information is available concerning the expected Haddam Neck RHR pump performance at reduced NPSH. However, Ref. 5 provided this information for another low-pressure, high-capacity pump—the containment spray pump at Maine Yankee. The manufacturer of that pump indicated that the pump could operate indefinitely at 95% of required NPSH and for 15 min at 75% of required NPSH. The pump manufacturer also stated that similar pumps are routinely operated for 1 to 3 min at 50% of required NPSH without sustaining damage. The Haddam Neck licensee estimated a suction pressure for RHR pump A following a hot-leg break at ~80% of the vendor-specified NPSH.

The Accident Sequence Precursor (ASP) Program typically considers the potential for core damage following four postulated initiating events in pressurized-water reactors: transient, loss of offsite power, small-break LOCA, and steam generator tube rupture. Supercomponent-based linked fault tree models are available for each of these postulated initiating events. The two initiating events that are of concern in this analysis (i.e., large- and medium-break LOCAs) are not currently modeled. However, for both of these initiating events, the unavailability of sump recirculation, which would occur following the loss of the RHR pumps as a result of cavitation, is assumed to result in core damage in all probabilistic risk assessments. Therefore, the significance of the event can be estimated directly from the probability of recirculation failure and the probability of a large- or medium-break LOCA in the unavailability period. The longest unavailability period used in an ASP analysis is 1 year.

An event tree depicting the potential sequences to core damage following a large- or medium-break LOCA is shown in Fig. B.2.1. The event tree is not chronological; it has been structured to reduce the number of sequences that must be addressed. The event tree includes the following branches:

Medium- or Large-Break LOCA Initiating Event (M/L LOCA). The initiating event is a large- or medium-break LOCA. The frequency of large- and medium-break LOCAs is estimated to be 2.7×10^{-4}/year and 5.0×10^{-4}/year, respectively. These values are based on a survey of large- and medium-break frequencies performed in support of the analysis of Turkey Point LER No. 250/94-005 in the 1994 precursor report (see Appendix H to Ref. 7 for additional information). The probability of a large- or medium-break LOCA in a 1-year period is therefore 7.7×10^{-4}.

Reactor Trip (RT). Failure of the reactor to trip is assumed to result in core damage for a medium-break LOCA (reactor trip success following a large-break LOCA is not required since void formation resulting from the break terminates the fission process). Consistent with the Integrated Reliability and Risk Analysis System (IRRAS)-based ASP models, a nonrecoverable failure to trip probability of 2.0×10^{-5} is utilized. This is weighted by the likelihood that the LOCA is a medium-break LOCA (0.65), resulting in an overall branch probability of 1.3×10^{-5}.

LPSI/HPSI Injection (INJECT). Failure of injection using the LPSI system results in a loss of short-term RCS makeup and core damage following a large-break LOCA. Consistent with the IRRAS-based ASP models, a failure probability of 9.4×10^{-4} is estimated for the two-train LPSI system. The Haddam Neck Individual Plant Examination[8] states that HPSI provides success following a medium-break LOCA. The HPSI and LPSI systems are both two-train systems, with similar failure probabilities (based on the system design, the HPSI system may be slightly more reliable). To simplify the analysis, the LPSI failure probability was used for the injection branch following both a large- and medium-break LOCA. This has no impact on the analysis results.

Operator Opens RH-MOV-22 for Recirc (RH-MOV-22). Failure of the motor-operated sump isolation valve to open for recirculation is assumed to result in core damage. Inadequate RHR pump NPSH exists in this case, independent of the RHR pump that is selected for recirculation. Consistent with the IRRAS-based ASP models, the probability of motor-operated valve RH-MOV-22 failing to open is estimated to be 3×10^{-3}. [Other potential RHR system failures, such as the common-cause failure of the RHR pumps, can also result

in failure of recirculation. These failures are unrelated to this event and contribute to a lesser extent to the overall failure of recirculation. They have not been addressed in this analysis.]

RHR Pump A Selected (SELECT A). Success for this branch implies that the operators initially select pump A for recirculation. The licensee stated that the operators were aware of flow restrictions that existed in the B RHR train and that the operators had stated in informal interviews that they would prefer to use the A pump when initiating recirculation. To reflect this, the analysis assumed that the A pump would be initially used with a probability of 0.75 (0.25 probability that RHR pump A would not be used).

RCS Cold-Leg Break (COLD LEG). Success for this branch implies that the LOCA occurred in one of the RCS cold legs. To recognize the greater likelihood of a break in a cold leg because of the larger number of cold leg pipe segments and welds,[a] this analysis assumes a probability of 0.6 that a LOCA will occur in a cold leg.

RHR Pump A Throttled (THROTTLE A). Failure to throttle RHR pump A discharge flow following a hot-leg break is assumed to result in pump failure due to cavitation. The probability of failing to throttle RHR pump flow was assumed to be 0.5 if the HPSI discharge valve associated with the faulted loop remained open (see factors 1 and 2 above). If the valve associated with the faulted loop was one of the two that was closed, the probability of failing to throttle RHR pump flow was assumed to be 0.12 (ASP recovery class R3, as described in Appendix A of Ref. 7; see factor 2 above). Combining these values with the probability that the HPSI valve associated with the faulted loop would be one of the two that was closed (0.5) results in an estimated branch failure probability of 0.31.

Recirculation Recovered (RECIRC). Sump recirculation can be recovered using RHR pump A following the failure of pump B, if pump B is initially selected for the recirculation function. Following the failure of the B pump, the operators would have to determine that cavitation was a potential cause of failure, and, if the break was in a hot leg, throttle the A pump discharge flow at the time the pump was started.[b] Two event tree branches address this possibility. The first branch is associated with the recovery of recirculation following a cold-leg break. A failure probability of 0.12 is assumed (ASP recovery class R3, as described in Appendix A of Ref. 7). The use of this probability recognizes the substantial burden and lack of specific procedural guidance that would exist following the failure of RHR pump B. The second branch is associated with the recovery of recirculation following a hot-leg break. The failure probability for this branch, 0.31, also recognizes the anticipated difficulties associated with throttling RHR pump discharge flow if the HPSI discharge valve associated with the faulted RCS loop remains open.

---

[a]Ref. 9 provides a discussion of the factors that influence the likelihood of pipe break.

[b]Procedure ECA-1.1, "Loss of Emergency Coolant Recirculation,"[10], instructs the operators to (1) reinitiate injection flow from the RWST in the event of a failure of recirculation and (2) not restart an RHR pump prior to consulting with the plant engineering staff.

B.2.5 Analysis Results

Sequences shown in Fig. B.2.1 that can result in core damage are described in Table B.2.1. Applying the branch probabilities (provided in the Modeling Analysis section) to the model for the event results in an estimated CDP for large- and medium-break LOCAs over a 1-year period of 1.1×10^{-4}. The nominal CDP over a 1-year period estimated using the ASP IRRAS models for Haddam Neck is 3.7×10^{-5}. The RHR pump NPSH problem increases this probability to 1.5×10^{-4}. This value is the conditional core damage probability (CCDP) for a 1-year period in which the potentially inadequate NPSH existed.

The dominant core damage sequence for the event involves

- a postulated large or medium hot-leg break (medium-break LOCAs are more likely);
- successful reactor shutdown, injection, and opening of RH-MOV-22;
- RHR pump A initially selected by the operators for sump recirculation; and
- failure to throttle RHR pump A discharge flow to provide adequate NPSH.

This sequence is highlighted on the event tree in Fig. B.2.1.

A greater than usual uncertainty is associated with this estimate. This uncertainty is dominated by the uncertainties in the frequency of a large- or medium-break LOCA (none have occurred), the available NPSH following such a LOCA, and the likelihood of pump failure with decreasing NPSH.

B.2.6 References

1. LER No. 213/96-016, Rev. 0, "Potential for Inadequate RHR Pump NPSH During Sump Recirculation," August 29, 1996.

2. Haddam Neck Procedure ES-1.3, "Transfer to Sump Recirculation," Rev. 14.

3. Haddam Neck Procedure ES-1.4, "Transfer to Two Path Recirculation," Rev. 13.

4. Transcript of December 4, 1996, Region 1 enforcement conference for Haddam Neck.

5. NRC Information Notice 96-55, *Inadequate Net Positive Suction Head of Emergency Core Cooling and Containment Heat Removal Pumps under Design Basis Accident Conditions*, October 22, 1996.

6. NRC Generic Letter 97-04, *Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps*, October 7, 1997.

7. R. J. Belles, J. W. Cletcher, D. A. Copinger, B. W. Dolan, J. W. Minarick, L. N. Vanden Heuvel, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.; and Science Applications International Corp., *Precursors to Potential Severe Core Damage Accidents: 1994, A Status Report*, U.S. NRC Report NUREG/CR-4674 (ORNL/NOAC-232),Vols. 21 and 22, December 1995.

8. *Haddam Neck Plant Individual Plant Examination for Severe Accident Vulnerabilities*, June 1993.

9. H. M. Thomas, "Pipe and Vessel Failure Probability," *Reliability Engineering*, Vol. 2, 1981, pages 83-124.

10. Haddam Neck Procedure ECA-1.1, "Loss of Emergency Coolant Recirculation," Rev. 11.

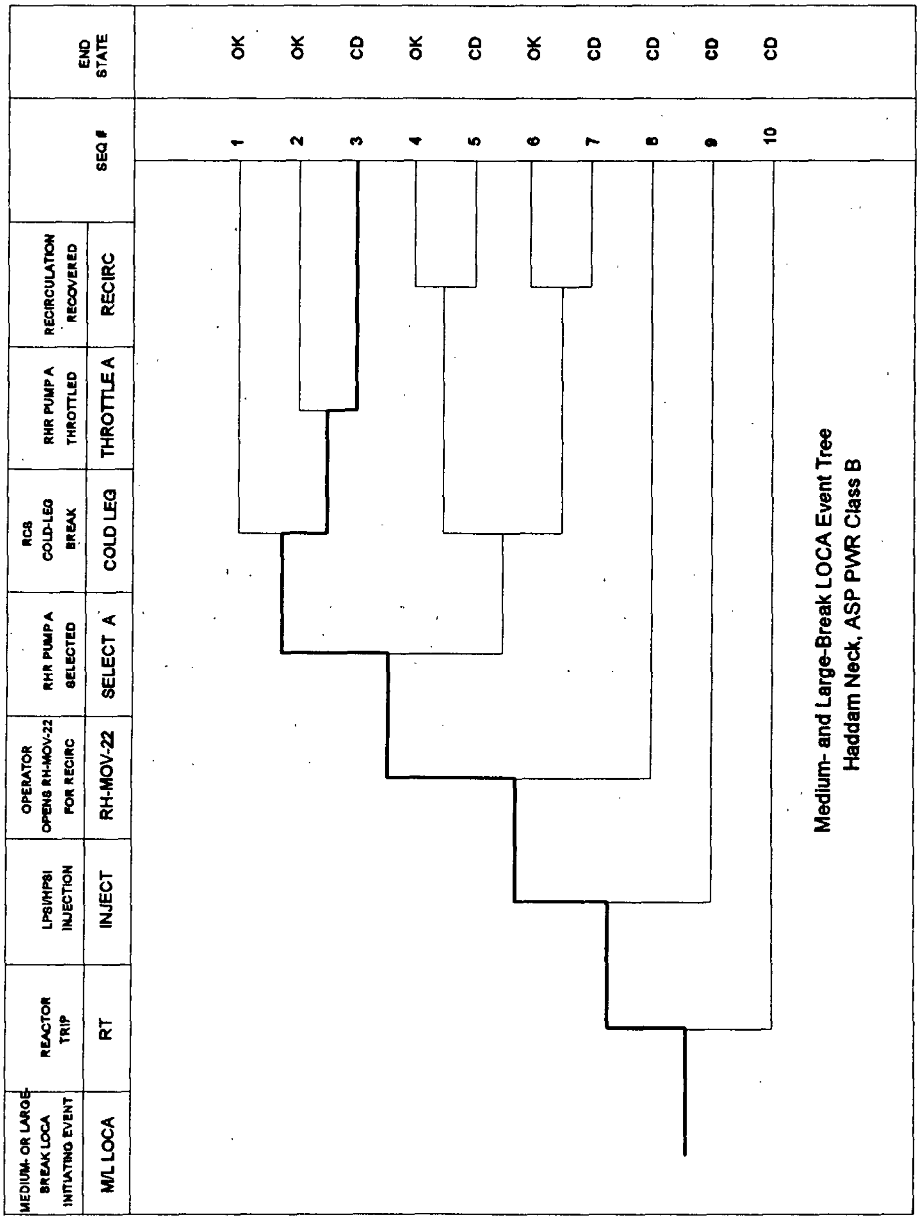

Fig. B.2.1. Dominant core damage sequence for LER No. 213/96-016.

Table B.2.1. Sequence descriptions for analysis event tree

Sequence	Description	Sequence probability
3	Large or medium hot-leg break, successful reactor shutdown and injection, RH-MOV-22 opens for sump recirculation, RHR pump A selected for recirculation, and failure to throttle RHR pump discharge flow for NPSH.	7.1 E-005
5	Large or medium cold-leg break, successful reactor shutdown and injection, RH-MOV-22 opens for sump recirculation, RHR pump B initially selected for recirculation, and failure to recover recirculation using pump A.	1.4 E-005
7	Similar to sequence 5 except a hot-leg break occurs.	2.4 E-005
8	Large- or medium-break LOCA, successful reactor shutdown and injection, and failure of RH-MOV-22 to open for sump recirculation.	2.3 E-006
9	Large- or medium-break LOCA, successful reactor shutdown and failure of injection.	7.2 E-007
10	Large- or medium-break LOCA and failure to shut down the reactor (failure to trip for a medium-break LOCA).	1.0 E-008