135.0 LER No. 315/99-031

Event Description: Valves Required to Operate Post-Accident Could Fail to Open Due to Pressure Locking/Thermal Binding

Date of Event: December 30, 1999

Plant: Donald C. Cook Nuclear Plant, Units 1 and 2

135.1 Event Summary

In LER 315/99-031 (Ref. 1), the licensee reported that a preliminary calculation review determined that valves which provide a suction path from the containment sump to the emergency core cooling system (ECCS) pumps and the valves which align residual heat removal (RHR) to the upper containment spray (CTS) header were susceptible to pressure locking following a postulated loss-of-coolant accident (LOCA). According to the LER, the calculated additional forces due to pressure locking were sufficient to exceed the capability of the respective valve actuators. Consequently, these valves may be incapable of opening under accident conditions.

The estimated increase in the core damage probability (CDP) over a one-year period (i.e., the importance) due to the pressure locking conditions is 3.6×10^{-5}/year. The uncertainty associated with the functionality of the valves in light of their potential to fail due to pressure locking contributes to the uncertainty in this frequency estimate.

135.2 Event Description

Pressure locking is a phenomenon in which water trapped in the bonnet cavity and in the space between the two disks of a parallel-disk gate valve or a flexible-wedge gate valve is pressurized above the pressure that was assumed when sizing the valve's motor operator. This prevents the valve operator from opening the valve when required. Water can enter a valve bonnet during normal valve cycling or when a differential pressure moves a disk away from its seat, creating a path to either increase fluid pressure or fill the bonnet with high-pressure fluid. A subsequent increase in the temperature of the fluid in the valve bonnet will cause an increase in bonnet cavity pressure due to thermal expansion of the fluid. Whether situations lead to a valve pressure locking scenario depends upon: (a) the fluid pressure when the bonnet cavity was filled, (b) temperature changes from when the fluid entered the bonnet cavity, and (c) the local line pressure compared with the bonnet cavity pressure at the time the motor-operated valve (MOV) is called upon to operate.

Thermal binding occurs due to different thermal expansion and contraction characteristics of the valve body and the disc. If the valve is closed while the system is hot, thermal binding can occur when the system cools due to the differences in thermal contraction.

References 2 and 3 provide additional details on the pressure locking phenomena and test and maintenance conditions that may lead to pressure locking.

According to Reference 1, at Cook, four valves of both units were identified as susceptible to pressure locking. They are: ICM-305, ICM-306, IMO-330, and IMO-331.

ICM-305 and ICM-306 are two normally closed MOVs located outside the reactor building in the two pipes between the RHR pump suction and containment recirculation sump. The RHR sump suction is connected to the refueling water storage tank (RWST) as well. The valves in the pipe from the RWST to the RHR pump suction are normally open. There are no check valves that would prevent RWST water from reaching the normally closed MOVs. Therefore, the upstream side of these MOVs will be in contact with water from the RWST. The other side of the MOVs communicates with the containment recirculation sump. During a LOCA or a feed-and-bleed cooling scenario, hot water will reach these MOVs. This hot water will heat up the valve body and the water trapped in the valve bonnet relatively rapidly. As a result, the pressure inside the valve bonnet will increase and pressure locking conditions will set in.

After this, thermal equilibration and valve bonnet depressurization will begin. That is, unless the valve is not demanded to open immediately, it will start cooling down and the pressure inside the valve would start dissipating gradually (Ref. 3). Thermal equilibration and valve bonnet depressurization will continue until the operator attempts to open this valve to establish sump recirculation.

IMO-330 and IMO-331 are the RHR to upper containment spray (CTS) shutoff valves. These valves are normally closed. In the event of a LOCA or feed-and-bleed cooling, depending upon the size of the LOCA or the rate of feed-and-bleed, containment spray may be demanded. The containment spray function is accomplished using the two containment spray pumps dedicated to that function. If both these pumps fail, then the RHR pumps can be used to perform the containment spray function. In order to use the RHR pumps to spray the containment, IMO-330 and IMO-331 must be opened.

135.3 Modeling Assumptions

Risk Impact of pressure locking in ICM-305 and ICM-306

In the event of a LOCA or a feed-and-bleed cooling scenario, valves ICM-305 and ICM-306 must be opened to establish sump recirculation. If these valves fail to open, then sump recirculation cannot be established. To distinguish between the time available for the valve bonnets to depressurize during different small LOCA scenarios, the small LOCA sequences were categorized as follows: reactor coolant pump (RCP) seal LOCAs, stuck-open power-operated relief valves (PORVs) and pressurizer safety valves, and small pipe breaks. The frequencies of each of the small LOCA groups were chosen to reflect the above categorization:

Sequence 1 - Small LOCAs (Stuck Open PORVs or SRVs)

- PORV or safety valve sticks open randomly or as a result of a transient, resulting in a small LOCA;
- Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST;
- Sump recirculation fails due to pressure locking of ICM-305 and ICM-306; and
- Cross-tie of the RWST from the affected unit to the unaffected unit fails.

Sequence 2 - Small LOCAs (RCP seal LOCAs)

- RCP seal LOCA occurs due to a random seal failure or due to loss of seal cooling;
- Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST;
- Sump recirculation fails due to pressure locking of ICM-305 and ICM-306; and
- Cross-tie of the RWST from the affected unit to the unaffected unit fails.

During the RCP seal LOCA and stuck-open PORV sequences identified above, the rate of loss of reactor coolant system (RCS) inventory is relatively low, and due to the relatively small size of the break and the presence of the ice condenser, the containment spray system should not divert a large quantity of the RWST water to the sump via the containment sprays.

For example, operating experience shows that during a stuck-open pressurizer safety valve or a PORV, the leak rates and the condition of the RCS allow the operators to depressurize and use RHR cooling. During the time period 1987-1995, there were two stuck open safety valve events, and during both these events, sump recirculation was not needed (Refs. 5, 6). During the event that occurred at Fort Calhoun (Ref. 5), approximately 21,500 gallons of RCS water was discharged from the RCS to the containment. This is much less than the discharge required to demand emergency core cooling system (ECCS) sump recirculation. During the event that occurred at Calvert Cliffs (Ref. 6), only 5000 gallons of reactor coolant discharged to the containment floor. During the TMI-2 event (3/28/79), a stuck open PORV released 271,000 gallons of RCS water to the sump. However, even during the TMI-2 event, sump recirculation was not demanded (Ref. 7). In addition to these events, during two RCP seal LOCA events (7, 8), the operators were able to successfully depressurize the RCS and establish RHR cooling. In the May 1975 event at Robinson Unit 2 (no LER, page I-3 of Ref. 7), a total of 132,500 gallons of RCS water was released to the containment sump before RHR cooling was established. The maximum leak rate was 500 gpm. During the event at Arkansas Nuclear One, Unit 1, (Ref. 8), approximately 60,000 gallons of water collected in the containment before RHR cooling was established. The maximum leak rate was 300 gpm. The containment pressure increased by 0.5 psi, at which time the reactor building containment coolers were put into service.

In light of the above information, it is reasonable to assume that (a) most likely sump recirculation would not be required for these events, and (b) even if sump recirculation were required, the rate of depletion of the RWST would allow a significant amount of time for the MOV bonnet pressures to dissipate (either, as discussed in detail below, through ambient heat loss as water in the adjacent piping cools down, or via packing leakage paths). Therefore, it is unlikely that the MOVs would fail due to pressure locking. Consequently, these two sequences were screened out from further analysis.

Sequence 3 - Feed-and-bleed cooling

- A transient or loss of offsite power event occurs;
- Auxiliary feedwater (AFW) fails, resulting in feed-and-bleed cooling;
- Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST;
- Sump recirculation fails due to pressure locking of ICM-305 and ICM-306; and
- Cross-tie of the RWST from the affected unit to the unaffected unit fails.

Transient or loss of offsite power event occurs. According to Reference 7, the frequency of a loss of offsite power is 0.046/ critical year; the frequency of a total loss of feedwater flow is 0.085/critical year; and the frequency of total loss of condenser heat sink events (power conversion system) is 0.12/critical year. This adds up to a total frequency of 0.25/critical year. For Cook Unit 1, the criticality factor is 0.79 (Ref. 7, Table H-3). Therefore, the frequency of a reactor trip with a loss of feedwater, offsite power, or the power conversion system is about 0.2/year (0.79 x 0.25).

AFW fails, resulting in feed-and-bleed cooling. From the Cook standardized plant analysis risk (SPAR) model, the failure probability of the AFW system is 1.1×10^{-4}. Therefore, the estimated frequency of a feed-and-bleed events requiring recirculation is $1.1 \times 10^{-4} \times 0.2$, or about 2.2×10^{-5}/year.

Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST. In the event of a small LOCA at a PWR, if the RCS can be depressurized using secondary heat removal and high pressure injection prior to depleting the RWST inventory, RHR cooling can be established and sump recirculation would not be needed. This success path is not modeled in the Cook IPE. That is, according to the Cook IPE, even though it has a RWST with an inventory of approximately 350,000 gallons, sump recirculation is required for all small LOCAs. Since this is overly conservative, and because: (a) this is a viable action for Cook plant, (b) the action is incorporated to the Cook plant emergency operating procedures, and (c) the operators are trained in the use of this EOP (Ref. 12), this analysis credited the capability to stabilize the RCS by depressurizing and establishing RHR cooling. Based on the SPAR model, this analysis used a probability of 0.004 for failing to cooldown the RCS and establish RHR cooling after a small LOCA.

Sump recirculation fails due to pressure locking of ICM-305 and ICM-306. During a feed-and-bleed cooling scenario, if sump recirculation is demanded, it will be demanded after several hours. When the feed-and-bleed function starts, the hot RCS water that collects in the sump would enter the RHR suction to the recirculation sump. When the hot water comes into contact with a valve, it will initially heat up the valve body and, in turn, the water trapped inside the valve bonnet. Note that the sump suction MOVs are located outside of the containment. Therefore, after the initial heat up, if time is available, the valves and the water column inside the pipe from the valve to the containment would start to cool down. During this period, the pressure inside the valve bonnets will dissipate. The pressure dissipation may occur due to leak paths through the valve gaskets. (Whether such leak paths existed is unknown at this time.) Therefore, this probability was assumed to be LOW.

Cross-tie of the RWST from the affected unit to the unaffected unit fails. In the event of sump recirculation failure, the RWST of the unaffected unit can be cross-tied to provide inventory to the RCS until RHR can be established. The Cook plant has two RWSTs, one dedicated to each unit, and these RWSTs have cross-tie capability. Technical Specifications require maintaining a minimum RWST inventory in a given unit, even when it is shut down to ensure its capability to feed the second unit's ECCS during a fire event. During a small break LOCA, in the event the suction from the containment recirculation sump fails due to the MOV failure, the cross-tie can be aligned to add borated water to the RCS. The additional RWST inventory of 350,000 gallons will provide ample time to continue depressurizing and cooling down during discharge flows that are typically encountered from stuck-open PORVs or pressurizer safety valves.

In the absence of significant details on the steps that the operators would follow to align the second unit's RWST, a probability of 0.34 was used for the failure probability for this action. In Accident Sequence Precursor (ASP) program analyses, a recovery probability of 0.34 has been used for those failures that appear recoverable during the period available at the failed equipment, rather than from the control room, given that the equipment was accessible (Ref. 9).

Using the frequencies and probabilities, the frequency of Sequence 3 was estimated as follows:

(Frequency of feed-and-bleed cooling scenarios: 2.2×10^{-5}/critical year) x
(Probability of requiring sump recirculation: 0.004) x
(Probability of failing sump recirculation due to pressure locking of the sump recirculation valves: LOW) x
(Probability of failing to establish the cross-tie from the unaffected unit: 0.34) = 3.0×10^{-8}/year x LOW probability

Since the product of 3.0×10^{-8} and a LOW probability will be below the ASP program precursor threshold of 1×10^{-6}, this sequence was screened out from further consideration.

Sequence 4 - Small LOCAs (pipe breaks)

- Small pipe break LOCA occurs;
- Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST;
- Sump recirculation fails due to pressure lockong of ICM-305 and ICM-306; and
- Cross-tie of the RWST from the affected unit to the unaffected unit fails.

Small pipe break LOCA occurs. Reference 7 indicates that the estimated frequency of a small LOCA attributed small pipe breaks is 5.0×10^{-4}/critical year.

Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST. Due to the reasons discussed in Sequence 3 above, a probability of 0.004 was used for this event.

Sump recirculation fails due to pressure locking of ICM-305 and ICM-306. At Cook plant, water in the RWST is used for injection into the core as well as for spraying the containment to mitigate containment pressure increases. As a result, the RWST may deplete relatively rapidly. However, each of the two Cook units is equipped with an ice condenser as well as a CTS system for containment heat removal. The ice condenser doors open at 0.5 psig. If the containment pressure exceeds 2.5 psig, the CTS system actuates. Reference 11 points out that for pipe breaks less than 2" (Reference 11 analyzed 1" and ½ " breaks), the sprays will not initiate until the ice depletes. Given that breaks greater than 2" are defined as medium LOCAs, it is reasonable to assume that for most small LOCAs, CTS will be demanded several hours after a small LOCA occurs. Due to the relatively long durations (several hours), the valve bonnets would have time to depressurize before the valves would be demanded. Therefore, this probability was assumed to be LOW.

Cross-tie of the RWST from the affected unit to the unaffected unit fails. For reasons discussed above for a feed-and-bleed cooling scenario, a probability of 0.34 was assumed for the probability of failure to establish the cross-tie from the unaffected unit.

Using the frequencies and probabilities, the frequency of Sequence 4 was estimated as follows:

(Frequency of small pipe break: 5.0×10^{-4}/critical year) x
(Criticality factor: 0.79) x
(Probability of requiring sump recirculation: 0.004) x
(Probability of failing sump recirculation due to pressure locking of sump recirculation valves: LOW) x
(Probability of failing to establish the cross-tie from the unaffected unit: 0.34) = 5.5×10^{-7}/year x LOW probability

Since the product of 5.5×10^{-7} and a LOW probability will be below the ASP program precursor threshold of 1×10^{-6}, this sequence was screened out from further consideration.

Sequence 5 - Medium or large LOCA

- Medium or Large LOCA occurs;
- Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST;
- Sump recirculation fails due to pressure locking of ICM-305 and ICM-306; and
- Cross-tie of the RWST from the affected unit to the unaffected unit fails.

Medium or large LOCA occurs. According to Reference 7, the frequency associated with large pipe breaks is 5.0×10^{-6}/critical year. The frequency of a medium pipe break is 4.0×10^{-5}/critical year. Therefore, the frequency of a medium or large LOCA is 4.5×10^{-5}/critical year.

Sump recirculation is required due to inability to establish RHR cooling prior to depleting RWST. For medium and large LOCAs, the RWST depletes relatively rapidly. Therefore, it was assumed that sump recirculation was essential for success. Therefore, this probability was assumed to be 1.0.

Sump recirculation fails due to pressure locking of ICM-305 and ICM-306. Per the Cook IPE (Ref. 4), only 30 minutes would be available between the occurrence of a medium LOCA and the need for sump recirculation. For a large LOCA, the time available would be even less. Therefore, it was assumed that there is insufficient time to equilibrate the pressures within the MOVs. No additional information was available regarding testing and maintenance practices which determine the window of vulnerability of these valves to pressure locking. It was assumed that the valves were vulnerable to pressure locking throughout the year. Consequently, the valves were assumed to fail with a probability of 1.0

Cross-tie of the RWST from the affected unit to the unaffected unit fails. For medium and large LOCAs, the RWST would deplete relatively rapidly. Therefore, it was assumed that there would be insufficient time available to establish the cross-tie. Hence, this probability was assumed to be 1.0.

Using the frequencies and probabilities, the frequency of Sequence 5 was estimated as follows:

(Frequency of medium or large LOCAs: 4.5×10^{-5}/critical-year) x
(Criticality factor: 0.79) x
(Probability of requiring sump recirculation: 1.0) x
(Probability of failing sump recirculation due to pressure locking sump recirculation valves: 1.0) x
(Probability of failing the cross-tie from the unaffected unit: 1.0) = 3.6×10^{-5}/year

The above frequency exceeds the ASP program precursor threshold of 1×10^{-6}. In addition, since the estimated frequencies of other sequences considered above and the frequencies associated with the pressure locking condition of valves IMO-330 and IMO-331 (discussed below) are well below 3.6×10^{-5}, this sequence is considered as the dominant contributor to risk.

Risk Impact of pressure locking in IMO-330 and IMO-331

IMO-330 and IMO-331 are the RHR to upper containment spray shutoff valves. These valves are normally closed. In the event of a LOCA or a feed-and-bleed cooling event, (depending upon the size of the LOCA or the rate of feed-and-bleed), containment spray may be demanded. The containment spray function is accomplished using the two containment spray pumps dedicated for that function. If both these pumps fail, then the RHR pumps can be used to perform the containment spray function. In order to use the RHR pumps to spray the containment, IMO-330 and IMO-331 must be opened.

Therefore, the sequence of interest is:

Sequence 6:

- Initiating event that requires containment spray occurs;
- Containment spray from the containment spray system fails; and

- Alternate spray from the RHR fails due to pressure locking of valves IMO-330 and IMO-331.

Initiating event that requires containment sump spray occurs. Each of the two Cook units is equipped with an ice condenser as well as a CTS system for containment heat removal. The ice condenser doors open at 0.5 psig. If the containment pressure exceeds 2.5 psig, the CTS system actuates. Reference 11 points out that for pipe breaks less than 2" (Reference 11 analyzed 1" and ½ " breaks) the sprays will not initiate until the ice depletes, adding to the sump inventory. Given that breaks greater than 2" are defined as medium LOCAs, it is reasonable to assume that CTS is essential for large and medium pipe breaks only. However, if it is conservatively assumed that all LOCAs except RCP seal LOCAs and stuck-open PORVs and pressurizer safety valves require CTS, using the frequencies associated with large pipe breaks (5.0 x 10^{-6}/critical year), medium pipe breaks (4.0 x 10^{-5}/critical year), small pipe breaks (5.0 x 10^{-4}/ critical year) the estimated total frequency of LOCAs that demand CTS is approximately 5.5 x 10^{-4}/critical year (Ref. 7, Table 3-1). The feed-and-bleed cooling scenario has a negligible contribution to this frequency.

Containment sump spray from the containment spray system fails. From the Cook IPE (Ref. 4), the probability of the CTS to inject is 2.5 x 10^{-4}/demand. The probability of CTS to perform recirculation was estimated to be 6.65 x 10^{-4}/demand. Therefore, the probability of failing CTS during either injection or recirculation is 9.1 x 10^{-4}/demand.

Alternate spray from the RHR fails due to pressure locking in IMO-330 and IMO-331. In the absence of additional information on testing and maintenance practices to determine the window of vulnerability of these valves due to pressure locking, it was assumed that the valves were vulnerable to pressure locking throughout the year. Consequently, the valves were assumed to fail with a probability of 1.0.

Using the frequencies and probabilities, the frequency of Sequence 6 was estimated as follows:

(Frequency of initiating events that require containment spray: 5.5 x 10^{-4}/critical-year) x
(Criticality factor: 0.79) x
(Probability of failing CTS: 9.1 x 10^{-4}) x
(Probability of failing alternate spray from RHR due to pressure locking: 1.0) = 4.0 x 10^{-7}/year

Since this frequency is below the ASP program precursor threshold of 1 x 10^{-6}, this sequence was screened out from further consideration.

135.4 Analysis of Results

The risk associated with this issue is dominated by Sequence 5. This sequence is highlighted in the attached event trees (figures 1 and 2). It consists of a postulated scenario in which MOVs ICM-305 and 306 fail to open due to pressure locking following a medium or a large LOCA. The estimated change in core damage frequency (ΔCDF) associated with this sequence was 3.6 x 10^{-5}/year. The frequencies of the other five sequences associated with ICM-305 and 306 as well as those associated with IMO-330 and

IMO-331 were negligible compared to this frequency. The uncertainty associated with the functionality of the valves in light of their potential to fail due to pressure locking contributes to the uncertainty in this frequency estimate.

135.5 References

1. LER 315/99-031, "Interim-Valves Required to Operate Post-Accident Could Fail to Open Due to Pressure Locking/Thermal Binding," January 31, 2000.

2. NUREG-1275, "Operating Experience Feedback Report - Pressure Locking and Thermal Binding of Gate Valves," Vol. 9, March 31, 1993.

3. NUREG/CR-4674, Vol. 23, "Precursors to Potential Severe Core Damage Accidents: 1996," December 1995.

4. *Donald C. Cook Nuclear Plant Units 1 and 2, Individual Plant Examination Revision 1*, October 1995.

5. LER 285/92-023, Rev. 0, "Reactor Trip Due to Inverter Malfunction and Subsequent Pressurizer Safety Valve Leak," August 3, 1992.

6. LER 317/94-007, Rev. 1, "Reactor Trip Caused by Closure of Turbine Stop Valves," August 18, 1994.

7. J. P. Poloski, et. al., *Rates of Initiating Events at U.S. Nuclear Power Plants: 1987-1995*, NUREG/CR-5750, February 1999.

8. LER 313/80-015, Rev. 2, "RCP Seal of RCP C Failure," April 13, 1981.

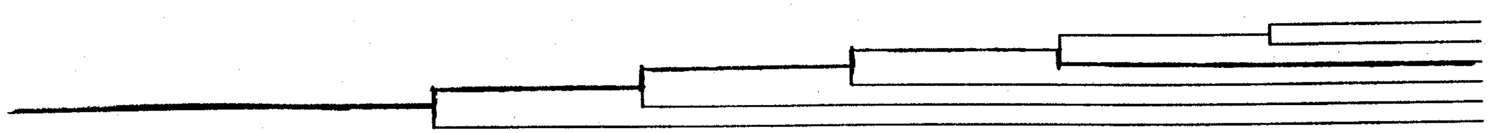
9. NUREG/CR-4674, Vol. 25, "Precursors to Potential Severe Core Damage Accidents: 1996," December 1997.

10. WASH-1400, Reactor Safety Study, 1975.

11. C.J. Shaffer and D.V. Rao, "Confirmatory Calculations of the D.C. Cook Sump Water Level," SEA 97-3703-A: 5, January 5, 1997.

12. Personal communications between Sunil D. Weerakkody, U.S. Nuclear Regulatory Commission and Brad Smalldridge, American Electric Power, March 16, 2000.

LARGE LOCA (>15 Centimeter)	REACTOR TRIP	ACCUMULATOR	LOW PRESSURE INJECTION	CONTAINMENT SPRAY INJECTION	LOW PRESSURE RECIRCULATION	CONTAINMENT SPRAY RECIRCULATION			
IE-LLOCA	RT-LLOCA	ACC	LPI	CSI-LL	LPR	CSR-LL		#	END-STATE

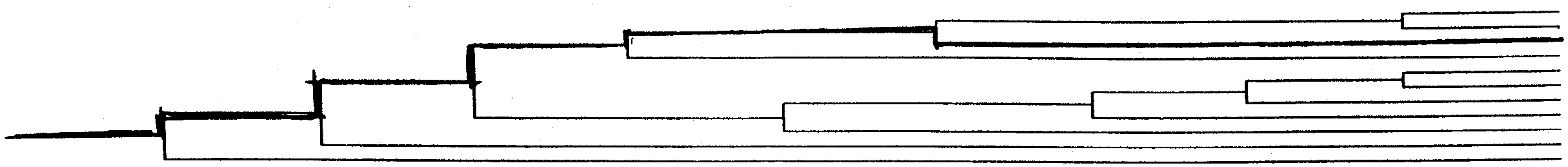


#	END-STATE
1	@
2	CD
3	CD
4	CD
5	CD
6	CD

LARGE LOCA EVENT TREE
DC COOK, UNITS 1 &2 PWR B

Figure 1 (Issue No. 135): Large LOCA Event Tree

MEDIUM LOCA	REACTOR TRIP	ACCUMULATOR	HIGH PRESSURE INJECTION	CONTAINMENT SPRAY INJECTION	RCS DEPRESSU-RIZATION	HIGH PRES. RECIRCU-LATION	LOW PRES. INJECTION	LOW PRES. RECIRCU-LATION	CONTAINMENT SPRAY RECIRCULATION	#	END-STATE
IE-MLOCA	RT	ACC	HPI	CSI-ML	OLI-ML	HPR	LPI	LPR	CSR-ML		



#	END-STATE	
1	@	Note-1
2	CD	
3	CD	
4	CD	Note-2
5	@	
6	CD	
7	CD	
8	CD	Note-3
9	CD	
10	CD	
11	CD	

MEDIUM LOCA EVENT TREE
DC COOK, UNITS 1 & 2 PWR B

Note 1: LPR (RHR) would spray thru its ring header into the containment. This header is different from the containment spray ring header. Thus, CSR-ML is a redundant approach.
Note 2: CS is needed during injection phase to prevent containment faillure due to overtemperature.
Note 3: A total of 20 Min. injection time is allowed. 5 Min. for detection, diagnostics, and action is permitted. 15 Min. for RWST depletion is allowed.

Figure 2 (Issue No. 135): Medium LOCA Event Tree