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March 2, 1987

Mr. Roy Woods
U.S. Nuclear Regulatory Commission
Reactor Safety Issues Branch
Division of Safety Review & Oversight
Phillips Building
7920 Norfolk Ave., MS-244
Bethesda, Maryland 20814

Dear Mr. Woods:

Re: FIN A-3829, Interfacing Systems LOCA at PWRs

Enclosed is a draft letter report covering additional work in the ISL Root Cause Analysis (Task 2B) and Core Damage Frequency Calculations (Task 3B).

Sincerely,

G. Bozoki

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GB/dm/l-rpt.
Enc.
cc: R. Fitzpatrick
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INTERFACING SYSTEMS LOCA AT PWRs

TASKS 2B AND 3B

DRAFT LETTER REPORT

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4. INITIATOR FREQUENCIES OF ISLs FOR VARIOUS PATHWAYS IN REPRESENTATIVE PWR PLANTS

4.1 General

The determination of the initiator frequencies of ISL on various pathways identified in Section 2 (of our previous letter report) is one of the most important part of our ongoing study of Interfacing Systems LOCA at PWRs. This section describes

a) the approach applied for modelling of the initiator frequencies,

b) the initiator models, the valve failure modes involved and the ways how they are acted upon by testing, and

c) the new frequency estimates for some valve failure modes (in Appendix B) and the quantification of the models.

4.2 Basic Approach

Originally, in modelling of the ISL initiators two possibilities were considered; to use Markovian or a simplified model. The Markovian model includes all the conceivable failure modes of the valves (e.g., design and installation errors, etc.), their change by the passage of time (e.g., aging) and how they are acted upon by testing, surveillance, operating and maintenance procedures and practices.

The simplified model considers the basic mechanism of accident initiation and includes only the most important failure modes of the valves, without their time dependence and makes drastic simplifications about the effect of testing, surveillance, operating and maintenance procedures and practices. While the natural wish of the analysts and their peers worked for the Markovian approach, it became clear that within the present time scale and supporting conditions one cannot pursue that line. Thus, for the present study, the simplified approach is chosen.

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According to this approach, similar pathways of the representative plants were grouped together. A generic model is worked out for the group. Then, the generic model is adapted to describe plant specific features of the pathways. The method allows to compare the effects of these features among the plants studied or with other plants having similar interfacing pathways.

4.3 Determination of Initiator Frequencies

4.3.1 Modelling of Multiple Failures for Valves in Series

This section discusses a generic failure model of valves (check valves or MOVs) in series. The model describes the basic mechanism of accident initiation of most of the pathways identified in Section 2 of our previous letter report. The formulae obtained can be adapted and evaluated easily under the test and surveillance conditions of a specific plant. Three valve configurations, a two-, a three-, and a four-unit system are analyzed.

a. Two-Valve in Series

Consider two valves in series. The valves are denoted by 1 and 2. Valve 1 is assumed to be the first isolation valve of interfacing systems. The failure frequency of the events, when both valves fail, can be written as:

$$\lambda_s(1,2) = \lambda(1)P(2|1) + \lambda(2)P(1|2) \equiv X_1 + X_2 , \qquad (1)$$

where $\lambda(1)$ and $\lambda(2)$ are the independent, random failure frequencies of valves 1 and 2, respectively.

$P(2|1)$ and $P(1|2)$ denote the conditional probabilities that valve 2 fails, given valve 1 failed and valve 1 fails, given valve 2 failed, respectively.

The conditional probabilities include both independent, random and demand type failures.

X_1 and X_2 denote the frequencies of failure combinations of two valves starting with failure of valves 1 or 2, respectively.

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It is easy to see that external conditions like presence or absence of RCS pressure in the space between the valves may significantly influence the "innate" failure rates and conditional probabilities of the valves. Its effect can be evaluated if, according to the notation of conditional probabilities, expression (1) is written in the following form:

$$\lambda_s(1,2)=[\bar{p}(X_1|\bar{p}) + p(X_1|p)] + [\bar{p}(X_2|\bar{p}) + p(X_2|p)] \ , \tag{1a}$$

where p is the probability that the space between the valves is pressurized by the RCS, and $\bar{p}=1-p$.

Since, $\bar{p}=1-p$, expression (1a) also can be written as:

$$\lambda_s(1,2)=(X_1|\bar{p}) + p[(X_1|p) - (X_1|\bar{p})] + (X_2|p) + p[(X_2|p) - (X_2|\bar{p})]. \tag{1b}$$

The formula can be simplified by considering that the term, $(X_2|\bar{p})$ is small compared to the other terms, since it describes failure rate and conditional probabilities when the second valve is not exposed to the RCS pressure. Consequently,

$$\lambda_s(1,2)=(X_1|\bar{p}) + p[(X_1|p) - (X_1|\bar{p})] + p(X_2|p). \tag{1c}$$

If the second valve is exposed to the RCS pressure the failure rate and conditional probabilities are very similar to those related to the first valve, when there is no pressure in the space between the valves, i.e., $p(X_2|p)=p(X_1|\bar{p})$.

Therefore:

$$\lambda_s(1,2)=(X_1|\bar{p}) + p(X_1|p) \ . \tag{1d}$$

The valve 1, in a state when its both sides are exposed to the RCS pressure, is expected to have smaller failure rate than in a state, when only its outer side is under RCS pressure. Thus, $(X_1|p)\leq(X_1|\bar{p})$ and the formula (1d) can be approximated as:

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$$\lambda_s(1,2) \leq (X_1|\bar{p})(1+p). \tag{1e}$$

The probability that the space between the valves is pressurized can be taken to be quite high ($\sim$1.0) because small leaks through valve 1 very quickly pressurize the space. Therefore, the failure frequency of two valves in series is:

$$\lambda_s(1,2) \leq 2(X_1|\bar{p}) \equiv 2\lambda(1)P(2|1) \ . \tag{2}$$

It is interesting to notice that the result is the same as if in Eq. (1) "symmetry" would be assumed, i.e., $\lambda(1)P(2|1)=\lambda(2)P(1|2)$. However, by referring simply to symmetry, the whole physical process would have been covered up.

The next step in the analysis is to evaluate the term $\lambda(1)P(2|1)$ by a simple multiple sequential failure model. The model introduces a chronological time ordering between the valve failures; the failure of valve 2 cannot proceed the occurrence of the failure of valve 1. The "innovation" in the model is the simultaneous treatment of random and demand type failure modes.

Let λ_1 and λ_2 denote the random type failure frequencies of valves 1 and 2, respectively. Let λ_d denote the demand type failure rate of valve 2. Then, the probability of "simultaneous" failure of two valves over a time interval t can be calculated by the following integral (exponentials are approximated by first order terms):

$$Q_{12} = \int_o^t \lambda_1 dt' \left(\int_{t'}^t \lambda_2 dt'' + \lambda_d \right) \tag{3}$$

$$= \frac{\lambda_1 \lambda_2 t^2}{2} + \lambda_1 \lambda_d t$$

(Note, that replacing λ_d by a beta factor, β, one arrives at an expression similar to the classical common mode failure formula. In sequential systems,

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the demand failure mode is similar to a β factor. Indeed, the time interval between a failure causing a demand and the second failure can be infinitely small. In this sense, two subsequent failures are equivalent with two really simultaneous failures. That is the reason why the common mode failure is not explicitly indicated in this simple model.)

Expression (3) is used to derive the failure (or hazard) rate for two valves:

$$\lambda_{12}'(t) = \frac{-1}{(1-Q_{12})}\frac{d}{dt}[1-Q_{12}], \quad (4)$$

$$= \frac{1}{1-Q_{12}}\frac{d}{dt}Q_{12} = \frac{d}{dt}Q_{12}, (Q_{12} << 1), \quad (4a)$$

$$= \lambda_1\lambda_2 t + \lambda_1\lambda_d. \quad (4b)$$

The average failure rate over a time period, T is given by

$$\langle\lambda_{12}'\rangle = \frac{1}{T}\int_0^T \lambda_{12}'(t)dt \quad (5)$$

$$= \frac{\lambda_1\lambda_2 T}{2} + \lambda_1\lambda_d \quad (5a)$$

By equating the term, $\lambda(1)P(2|1)$ to the average failure rate, $\langle\lambda_{12}'\rangle$, the the average failure frequency of two valves in series (see Eq. (2)) over a time period, T, is given by:

$$\langle\lambda_S^T(1,2)\rangle \leq 2\langle\lambda_{12}'\rangle = \lambda_1\lambda_2 T + 2\lambda_1\lambda_d \ . \quad (6)$$

If $\lambda_1 = \lambda_2$, one arrives at the expression:

$$\langle\lambda_S^T(1,2)\rangle = \lambda_1^2 T + 2\lambda_1\lambda_d. \quad (7)$$

This expression is used in some further applications.

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b. Three-Valve in Series

Consider now a configuration of three valves (1,2,3) in series. Again, valve 1 is assumed to be the first isolation valve. The failure frequency of the events, when three valves fail is:

$$\begin{aligned}\lambda_s(1,2,3) = {} & \lambda(1)P(2|1)P(3|12) + \lambda(2)P(1|2)P(3|21) + \\ & \lambda(1)P(3|1)P(2|13) + \lambda(2)P(3|2)P(1|23) + \\ & \lambda(3)P(1|3)P(2|31) + \lambda(3)P(2|3)P(1|32),\end{aligned} \tag{8}$$

where $\lambda(1)$, $\lambda(2)$, $\lambda(3)$ are the independent random failure frequencies of valves 1, 2, and 3, respectively.

$P(2|1)$ denotes the conditional probability that valve 2 failed given valve 1 failed. Similar terms denote similar events.

$P(3|12)$ is the conditional probability that valve 3 failed given valves 1 and 2 failed. Similar terms denote similar events.

The conditional probabilities describe both independent, random and demand type failures.

It is easy to see, RC pressure can be now not only in the space between valves 1 and 2, but also in the space between valves 2 and 3 if both valves, 1 and 2, fail. The pressure will affect the "innate" failure frequencies and probabilities of the valves. The possible number of pressure states of the inter-valve spaces are:

- 2 combinations of "non-pressurized spaces,"
- 1 combination, when the space between valves 1 and 2 is pressurized (the space between valves 2 and 3 cannot be pressurized before the preceding space is not pressurized), and
- 1 combination when both spaces are pressurized.

The total number of states are 4.

Each of the terms of Eq. (8) can be now expressed as "conditional" on the presence or absence of each of the four states. The process yields 6x2x4 = 48 terms. Most of the terms can be eliminated by physical considerations. After the elimination process, Eq. (8) can be written as

$$\lambda_s(1,2,3) \leq 6\lambda(1)P(2|1)P(3|12) \ . \tag{8a}$$

The result could be obtained also by symmetry consideration from Eq. (8) by substituting the first term for all the others. Obviously, the result is conservative.

The next step is to evaluate the frequency $\lambda(1)P(2|1)P(3|12)$ by a sequential model involving random and demand type failure modes.

Let λ_1, λ_2, and λ_3 denote the random type failure frequencies of valves 1, 2, and 3, respectively. Let λ_{d2} and λ_{d3} denote the demand type failure frequencies of valves 2 and 3, respectively. Then the probability of simultaneous failures of three valves over a time interval t can be calculated by the following integral (exponentials are approximated by first order terms):

$$Q_{123} = \int_o^t \lambda_1 dt' \left\{ \int_{t'}^t \lambda_2 dt'' \left[\int_{t''}^t \lambda_3 dt'' + \lambda_{d3} \right] + \lambda_{d2} \left[\int_{t''}^t \lambda_3 dt'' + \lambda_{d3} \right] \right\} =$$

$$= \frac{\lambda_1 \lambda_2 \lambda_3 t^3}{6} + \frac{\lambda_1 \lambda_2 \lambda_{d3} t^2}{2} + \frac{\lambda_1 \lambda_{d2} \lambda_3 t^2}{2} + \lambda_1 \lambda_{d2} \lambda_{d3} t \ . \tag{9}$$

The failure (hazard) rate is:

$$\lambda'_{123}(t) = \frac{d}{dt} Q_{123} = \frac{1}{2} \lambda_1 \lambda_2 \lambda_3 t^2 + \lambda_1 \lambda_2 \lambda_{d3} t + \lambda_1 \lambda_{d2} \lambda_3 t + \lambda_1 \lambda_{d2} \lambda_{d3} \ . \tag{10}$$

The average failure rate over a time period, T, is given by:

$$\langle \lambda'_{123} \rangle = \frac{1}{T} \int_o^T \lambda'_{123}(t) dt = \frac{\lambda_1 \lambda_2 \lambda_3 T^2}{6} + \frac{\lambda_1 \lambda_{d2} \lambda_3 T}{2} + \frac{\lambda_1 \lambda_{d2} \lambda_3 T}{2} + \lambda_1 \lambda_{d2} \lambda_{d3} \ . \tag{11}$$

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Again, by equating the term $\lambda(1)P(2|1)P(3|12)$ to the average failure rate $\langle\lambda'_{123}\rangle$, the average failure frequency of three valves in series (see Eq. (8)) over a time period, T, is given by:

$$\langle\lambda_S^T(1,2,3)\rangle \leq 6\langle\lambda'_{123}\rangle = \lambda_1\lambda_2\lambda_3T^2 + 3\lambda_1\lambda_2\lambda_{d3}T + 3\lambda_1\lambda_{d2}\lambda_3T + 6\lambda_1\lambda_{d2}\lambda_{d3}. \quad (12)$$

If $\lambda_1=\lambda_2=\lambda_3$ and $\lambda_{d2}=\lambda_{d3}=\lambda_d$ one arrives at the expression:

$$\langle\lambda_S^T(1,2,3)\rangle \leq \lambda_1^3T^2 + 6\lambda_1^2\lambda_dT + 6\lambda_1\lambda_d^2 . \quad (12a)$$

This expression is used in further applications.

c. Four-Valve in Series

It is easy to show that for four valves in series the failure frequency when four valves fail, can be written as

$$\lambda_s(1,2,3,4) \leq 24\lambda(1)P(2|1)P(3|12)P(4|123) \quad (13)$$

where $\lambda(1)$ is the independent failure frequency of the valves 1, 2, 3, and 4, and $P(2|1)$, $P(3|12)$, and $P(4|123)$ are conditional probabilities describing that a subsequent valve fail given that the preceding valves already failed. The conditional probabilities describe both independent, random, and demand type failures.

The integral which describes the probability of simultaneous failures of four valves over a time interval t is given by:

$$Q_{1234} = \int_0^t \lambda_1 dt' \int_{t'}^t \lambda_2 dt'' \int_{t''}^t \lambda_3 dt''' \left(\int_{t'''}^t \lambda_4 dt'''' + \lambda_{d4}\right) +$$

$$\int_0^t \lambda_1 dt' \lambda_{d2} \left[\int_{t''}^t \lambda_3 dt''' \left(\int_{t'''}^t \lambda_4 dt'''' + \lambda_{d4}\right)\right] +$$

$$\int_0^t \lambda_1 dt' \lambda_{d2} \left[\int_{t'}^t \lambda_3 dt'' \left(\int_{t''}^t \lambda_4 dt'' + \lambda_{d4}\right)\right] +$$

$$\int_0^t \lambda_1 dt' \lambda_{d3} \left(\int_{t'}^t \lambda_4 dt'' + \lambda_{d4}\right) = \frac{1}{24} \lambda_1 \lambda_2 \lambda_3 \lambda_4 t^4 +$$

$$\frac{1}{6} (\lambda_1 \lambda_2 \lambda_3 \lambda_{d4} t^3 + \lambda_1 \lambda_2 \lambda_{d3} \lambda_4 t^3 + \lambda_1 \lambda_{d2} \lambda_3 \lambda_4 t^3) +$$

$$\frac{1}{2} (\lambda_1 \lambda_2 \lambda_{d3} \lambda_{d4} t^2 + \lambda_1 \lambda_{d2} \lambda_3 \lambda_{d4} t^2 + \lambda_1 \lambda_{d2} \lambda_{d3} \lambda_4 t^2) +$$

$$\lambda_1 \lambda_{d2} \lambda_{d3} \lambda_{d4} t \ , \qquad (14)$$

where λ_1, λ_2, λ_3, and λ_4 denote the random type failure frequencies of valves 1, 2, 3, and 4, respectively. λ_{d2}, λ_{d3}, λ_{d4} denote the demand type failure frequencies of valves 2, 3, and 4, respectively.

In the same way as it was shown for the two and three valve configurations, the average failure frequency of four valves in series over a time period, T, can be expressed as:

$$\langle\lambda_s^T(1,2,3,4)\rangle \le \lambda_1 \lambda_2 \lambda_3 \lambda_4 T^3 + 4(\lambda_1 \lambda_2 \lambda_3 \lambda_{d4} T^2 + \lambda_1 \lambda_2 \lambda_{d3} \lambda_4 T^2 + \lambda_1 \lambda_{d2} \lambda_3 \lambda_4 T^2) +$$

$$12(\lambda_1 \lambda_2 \lambda_{d3} \lambda_{d4} T + \lambda_1 \lambda_{d2} \lambda_3 \lambda_{d4} T + \lambda_1 \lambda_{d2} \lambda_{d3} \lambda_4 T) + 24 \lambda_1 \lambda_2 \lambda_{d3} \lambda_{d4} \ . \qquad (15)$$

The formula obtained will be used for valve configurations when $\lambda_1 = \lambda_2 = \lambda_3$, and $\lambda_{d1} = \lambda_{d2} = \lambda_{d3} = \lambda_d$. For this case Eq. (15) has the following simplified form:

$$\langle\lambda_s^T(1,2,3,4)\rangle \le \lambda_1^3 \lambda_4 T^3 + 4(\lambda_1^3 \lambda_d T^2 + \lambda_1^2 \lambda_d \lambda_4 T^2 + \lambda_1^2 \lambda_d \lambda_4 T^2) + 12(2 \lambda_1^2 \lambda_d^2 \lambda_4 T) +$$

$$24 \lambda_1 \lambda_d^3 \ . \qquad (15a)$$

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4.3.2 Calculation of Initiator Frequencies for Accumulator, LPI, and HPI Pathways

At the majority of PWRs the LPI injection lines have a common inlet header to the RCS with the accumulator outlet lines. At PWRs of Westinghouse and Combustion Engineering designs this inlet header is even shared with the HPI system. At PWRs of Babcock and Wilcox design the HPIS injects to the reactor vessel via separate lines.

In all previous analyses of ISLs through the LPI (or HPI) lines the effect of the common inlet header was not taken into consideration. The ISL initiator frequencies were estimated assuming the LPI pathways to be independent from the accumulator system.

A thorough analysis of the check valve failure events occurring in the LPI, accumulator injection lines (see Appendix B for details) revealed the fact that the second (downstream) check valve in accumulator injection lines is rather prone to "failure to operate upon demand"(i.e., to non-complete seating) failure mode. The proneness to failures of this type is due to the combined effects of boric acid corrosion, boron deposition, and the valve being in a "see-saw" position between two overpressurized regions each of them subject to many pressure changes. Since the valve frequently falls in the "failed state," it behaves as a "kind of safety valve" with respect to the overpressurization of the common inlet header. Namely, whenever the first (upstream) isolation check valve to the RCS leaks (or in the worst case ruptures), in the majority of the cases, the second check valve will not prevent completely the propagation of the leakage (or pressure wave) to the accumulators.

Based upon the results of the check valve failure analysis, it was concluded, that in any study of ISLs going through the common injection inlet pathways, the proneness of accumulators second check valve to "failure to operate upon demand," failure mode has to be taken into account. It was inferred that depending upon the state, this check valve (whether it is seated or not) and the rate of the backflow through the first check valve the nature and frequency of ISLs through the LPI/HPI pathways will be significantly different.

a) If the valve is seated, there will be no "relief valve" effect. ISLs through the LPI/HPI pathways, even with moderate leak rate ($\leq$ 1000 gpm) will contribute to core damage and public health risk.

b) If the valve is open, the preferred direction of the ISLs will be through the accumulator and not through the LPI/HPI pathways. Should an ISL with small or moderate leak rate ($\leq$ 1000 gpm) still occur through these pathways, it will lead only to harmless overpressurization of low pressure piping. Since the accumulators are constantly monitored small leaks through the first check valve will have high potential for discovery and preventive actions.

   In the case of an ISL with high leak rate (check valve ruptures) the open accumulator check valve will cause an additional internal LOCA. Despite the increased confusion in the accident management, it will have the beneficial effect that it will turn large part of the RCS inventory available for recirculation. The advent of core damage will be delayed and public health risk will be decreased.

Thus, in the following calculations of ISL initiator frequencies both effects the "safety valve" effect of the accumulator check valve and the effect of the leak rate have been considered.

For lines having not shared inlets to the RCS, the initiator frequencies are calculated by considering the leak flow rate dependency of the leakage failure frequency of check valves. The leak rate dependency of the leakage failure frequency is described in Appendix B.

4.3.2.1 <u>ISL Initiator Frequencies for Accumulator Pathways</u>

In order to determine the ISL initiator frequencies for the accumulator pathways the exceedance frequency per year of experienced accumulator inleakage events (see also Section B.1.3) is plotted as a function of leakage flow rate through the accumulator injection lines. The plot is shown in Figure 4.1. The curve is fitted graphically with a straight line (on a log-log scale). A statistical estimate based on experienced event frequencies and assuming lognormal frequency distribution provided an average range factor of RF=10 for the curve. By using this range factor an other exceedance frequency per hour curve is constructed which represents mean values. The curve describing mean values can be taken now as a direct source to estimate ISL initiator frequencies.

The application of straight line fit for the observed values is supported by the generic experience, that "percolation type" physical processes, like leakage through two subsequent openings follows exceedance frequency distribution of Pareto type (i.e., a kind of power low).

To estimate ISL initiator frequencies for specific plant by using the curve, the most important parameter is to choose the appropriate leak flow rate value at which the estimate is carried out. For that purpose a reasonable choice is that leak flow rate, which fills up the "free volume" of the accumulators within a "critical time" deemed to be required for operator actions to treat safely an accumulator inleakage. Table 4.1 presents the free volumes of the accumulators for the selected PWRs. The table also shows some other relevant design characteristics of the accumulators for convenience. Table 4.2 lists the filling time of the free volumes for various leak rates. (The filling times presented in the table are conservative because it does not take into account the delay in the filling due to the compression of the N_2 gas.) As critical time, 10 minutes is selected for all the plants. This time is deemed to be long enough, for the operator to respond for the specific accumulator alarms (high pressure, high level) to take successful corrective actions. Table 4.3 gives the corresponding leak rates and the mean values of the leak rate exceedance frequencies per accumulator line year. The leak rate exceedance frequencies were obtained simply by "read-off" from the curve describing mean values in Figure 4.1.

In order to determine the ISL initiator frequencies from the generic curve, the listed exceedance frequencies should be only a little bit adjusted according to the plant specific parameters and plant specific test or

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surveillance conditions. The size of the lines is not important parameter because the experienced curve is based on failure events representing a relatively homogeneous sample of pipe size, 8"-14" diameter.

The value which is directly read off from the curve at an appropriately chosen leak flow rate is essentially Eq. (7) (see also Eq. (1) in Appendix B):

$$\langle\lambda_s^T(1,2)\rangle = 2\lambda_1(\frac{\lambda_2 T}{2} + \lambda_{d2}) \equiv 2\lambda_1 C \quad , \tag{7a}$$

where λ_1 is the frequency of leakage failure mode of the first check valve (near the RCS),

λ_2 denotes the same quantity for the accumulator outlet check valve,

λ_d is the frequency of check valve "fail to operate on demand" failure mode, enhanced by the special conditions just explained at the preceding section, and

C=.93 denotes an "effective leakage probability" for the accumulator outlet check valve.

At Indian Point 3 the check valves are leak tested after flow test at each RCS depressurization (~3 times/year). These leak tests are assessed to be 100% efficient for the present calculations. (Sensitivity calculations will be carried out later after all the representative plants have been visited.) Therefore, at Indian Point 3 the exceedance frequency, is not corrected for valve failures to reclose after cold shutdowns.

In contrast with Indian Point, at Oconee 3, leak tests are carried out only in time of nine month intervals. During this time period there are two cold shutdowns. Each cold shutdown creates a potential for additional reclose failures due to check valve demands. The probability that the first check valve "fails to operate (reclose) after demand" is: $\lambda_{d1}^{Mean} = 2.81(-4)$ (see Section B.2.5). Then, the corrections for the exceedance frequency are given by:

$E_A^{'} = \lambda_d C = 2.61(-4)$, due to the first cold shutdown, and

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$E_A'' = 2\lambda_d C = 5.22(-4)$, due to the second one.

The total correction per line averaged over the year is:

$$E_A^T = (E_A' + E_A'') = 7.84(-4)/ \;.$$

The correction is only 10% of the uncorrected value. Its value is presented also in Table 4.3.

The best conditions for failure detection of the first check valve are at Calvert Cliffs 1. The seat leakage of the first valve is continuously monitored with pressure sensors placed in the valve section between the two check valves of the accumulator lines. Thus, there is no need for correction of the exceedance frequency.

Based on the other relevant data in Table 4.3 the total initiator frequencies were calculated for each plant. The values obtained are presented also in Table 4.3.

The total initiator frequencies were determined also at leak rates which just exceeds the relief valve capacities of the accumulators. These frequencies represent the initiator frequencies for overpressurization of the accumulators. The value obtained are shown in the last row of Table 4.3.

The initiator frequencies serve as inputs for the accumulator ISL event tree. The event trees are described in Section 5.

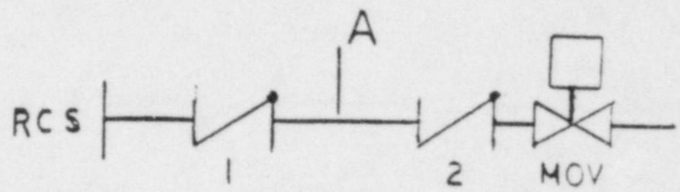
As one notices, the initiator frequencies are relatively high compared to the generic frequency of small LOCA initiators ($\sim 10^{-2}$/year). This is connected with the high frequency of accumulator inleakage events and with their good potential for discovery (see Item (b) in Section 4.3.2).

The initiator frequency valves, (I_A), presented in Table 4.1, serve as inputs for the accumulator ISL event trees. The event trees will be discussed in Section 5.

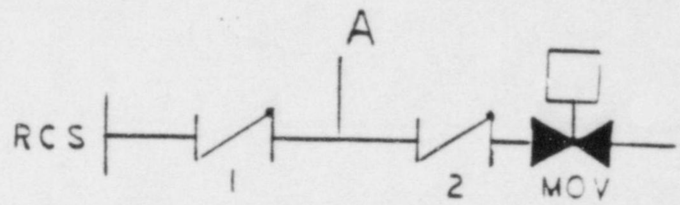
4.3.2.2 ISL Initiator Frequencies for LPI Pathways

The check valve arrangements on the interfacing LPI lines of the representative plants belong to the following basic configurations:

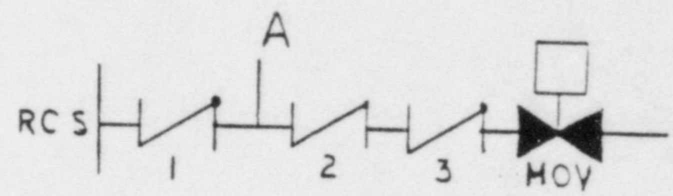
a. Two check valves and an open MOV.
Indian Point 3. (Valve descriptions are given in Tables 2.3.1 and 2.3.4)
Number of paths: 4



b. Two check valves and a closed MOV.
Oconee 3. (Valve description are given in Tables 2.4.1)
Number of paths: 2



c. Three check valves and a closed MOV.
Calvert Cliffs 1. (Valve description are given in Tables 2.5.1 and 2.5.4)
Number of paths: 4



The ISL initiator frequencies for these LPI pathways, I_{LPI}, is calculated by applying

a) the formalism developed in Section 4.3.2,

b) the dependency of the leakage failure frequency on the leak flow rate,

c) the condition that the accumulator check valve is frequently being in the failed state, and

d) the assumptions that ISLs, with leak flow less than the total relief valve capacity of the injection side of the LPI system do not lead to overpressurization of the low pressure piping, but contribute to the small LOCAs, and ISLs with leak flow below the total capacity of the charging system are easily treatable and therefore negligible events.

Before entering into the description of the calculation we reiterate the remark made on the common cause failure behavior of the quantity λ_d in the formalism developed in Section 4.3.2. The formalism does not include terms explicitly identified as accounting for common cause failures of the components. In sequential systems where the system is modelled as combination of operating and standby components, the λ_d represents the demand failure of the standby components. Thus, if there is a combination of an operating and standby component, any failures of both components will occur at the same time because of the way the system is designed, independently from the type of failure of the operating component, whether it is independent or common cause failure. Therefore, it is superfluous to introduce separate terms for common cause failures. It is only required that the numerical value of λ_d should be appropriately selected.

4.3.2.2.1 <u>Calculation of I_{LPI} at Indian Point 3</u>

The formula applicable to calculate the average failure rate of the check valve configurations in the LPI pathways is described by Eq. (6), which is repeated here for convenience.

$$\langle\lambda_s^T(1,2)\rangle = 2\lambda_1(\frac{\lambda_2 T}{2} + \lambda d) .$$

All the quantities in this equation have been defined earlier.

The formula can be also applied to calculate the average frequency of double check valve failure events which are not accompanied by check valve failure in the accumulator line $(1,2,\overline{A})$. This can be done simply by multiplying the failure frequency (λ_1) of the first check valve by (1-C), where C is "the effective leakage failure probability" of the accumulator outlet check valve. Thus, $\lambda_1(1-C)$ will denote the frequency of the first check valve failures, when the accumulator check valve is closed.

The average frequency of the events $(1,2,\overline{A})$, therefore, can be written as:

$$\langle\lambda_s^T(1,2,\overline{A})\rangle = 2\lambda_1(\frac{\lambda_2 T}{2} + \lambda_{d2})(1-C) \equiv \langle\lambda_s^T(1,2)\rangle(1-C) , \qquad (17)$$

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and if $\lambda_2 = \lambda_1$,

$$\langle \lambda_s^T(1,2,\overline{A}) \rangle = (\lambda_1^2 T + 2\lambda_1 \lambda_{d2})(1-C) \qquad (17a)$$

At Indian Point there are four similar lines and the reactor is at power about 72% of the total time. Thus, the total average frequency of potential ISL initiators with (remember that $C = .97$, and $\lambda_1 = \lambda_1 C$) and without simultaneous accumulator inleakage will be:

$$I_{LPI}(1,2,A) = .72 x 4 x \langle \lambda_s^T(1,2) \rangle \qquad (18)$$

and

$$I_{LPI}(1,2,\overline{A}) = .72 x 4 x \langle \lambda_s^T(1,2,\overline{A}) \qquad (18a)$$

$$= .72 x 4 x \langle \lambda_s^T(1,2) \rangle (1-C),$$

respectively.

Quantification of I_{LPI} (Indian Point 3)

Expressions (18) and (18a) were evaluated numerically as a function of the leak flow rate through the shared LPI/HPI/Accumulator inlet by using the leakage failure exceedance curve given in Figure B.2 of Appendix B.

By using the curve data as medians, λ_1^{Median}, and by assuming lognormal failure frequency distribution and range factors slowly varying from RF:10 to RF:14 in the leak flow rate interval of 100-2000 gpm, the mean leakage frequency, λ_1^{Mean}, and the expectation of its square $\langle \lambda_1^2 \rangle = (\lambda_1^{Mean})^2 + var.$, have been calculated (e.g., at leak flow rate of 100 gpm:

$$\lambda_1^{Median} = 1.58(-3)/yr,\ RF=10,\ \lambda_1^{Mean} = 4.20(-3)/yr,\ \text{and}\ \langle \lambda_1^2 \rangle = 1.25(-4)/yr^2).$$

The mean frequency of "valve fail to operate on demand" failure mode was taken to be $\lambda_{d2} = 2.81(-4)$/demand (see Appendix B.1.2).

At the Indian Point 3 plant the check valve disc being in the open position is precluded by the leak test performed after every cold shutdown. (This is a considered assessment. It is understood, in such a way, that the

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check valves are closed as tight as their leak flow is smaller than a limiting flow rate defined in the tech. specs. and test requirements. A survey of the test performances will be discussed later.)

The average time interval between cold shutdown at Indian Point 3 is T=1/3 year.

The results obtained by the quantification are shown in Figure 4.2 to be compared with the results of other plants.

Initiation frequency data at important leak flow rates are also given in Table 4.4. Those values which are selected as inputs for LPI event trees are indicated in the last column of the table.

The first value is the frequency of double check valve failure events without accumulator inleakage where the leak flow rate is larger than the maximum makeup flow (~98 gpm), but less than the total capacity of LPI relief valves at the injection side (740 gpm). These events are not considered to cause overpressurization of the LPI piping, but may result in small LOCA. (Double check valve failure events in this category, which are associated with accumulator inleakage are considered to be mild and negligible.)

The second value is the sum of the frequencies of the following events:

a) Double check valve failure events without accumulator inleakage, where the leak flow rate is larger than the total capacity of LPI relief valves at the injection side. These are considered to cause overpressurization.

b) Double check valve failures with accumulator inleakage, where the leak flow rate at the shared inlet of the LPI/HPI/Accumulator System exceeds the capacity of the LPI relief valves (740 gpm) in spite of the flow diversion to the accumulator.

These events represent the majority of overpressurization events. (The "critical leak flow" was estimated by considering that only a fraction, F of the incoming flow reaches the relief valves. The fraction is equal to the ratio of the cross sections of the LPI and accumulator pipes:

$$F = \left(\frac{6"}{10"}\right)^2 = .36 \ .$$

Thus, the critical flow rate is: $\frac{740}{.36} \approx 2100$ gpm.)

4.3.2.2.2 Calculation of I_{LPI} at Oconee 3

An ISL would occur through an LPI line at Oconee 3 if two check valves and a normally closed MOV were in an "open" failure state. The frequency of these events can be calculated by applying Eq. (12) to the case. At the application, one has to use the appropriate failure modes of both types of valves, check valves, and MOVs and the specific testing policy of the valves. The testing policy of the valves is discussed first.

At Oconee 3, there is a leak testing equipment (a rig) to carry out the ISL tests at nine month intervals. (The efficiency of the test process will be discussed later after having seen the equipment, procedures, and discussion with plant personnel during an oncoming plant visit.) These tests which are intended to verify that the check valves of the ECCS system properly reseat after cold shutdown, are considered to be efficient. However, there are usually two cold shutdowns during the nine month leak testing period when the LPI lines are flow tested and the MOVs are stroked. After cold shutdowns the check valves may be stuck open and also the MOVs may remain in failed state (do not operate on demand), These conditions should be taken into account in the calculation of the initiator frequencies. For calculational simplicity, it is assumed that cold shutdowns are performed in three month intervals. It means that during a nine month period there will be two cold shutdowns with potential of undetected valve reclose failures. Since the initiator frequencies are given on a basis "per reactor year,", the failure model will be evaluated for four time periods of three months long and the results will be summed to obtain the yearly ISL frequency. It is easy to see that

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- in the first time period, just after the ISL test (and cold shutdown), there is no need to correct the terms in Eq. (12),
- in the second time period (after a cold shutdown), in addition to the terms in Eq. (12), corrections have to be made for the potentially non-reclosed valves,
- in the third time period (after cold shutdown) the correction is doubled for check valves (the MOV stays the same), and
- the fourth time period is the same as the first because this period begins also after ISL test.

The expressions to be quantified are (based on Eq. (12)):

<u>1st Time Period</u> (0-3 months), t = 1/4 year, T = 3/4 year;

$$t\langle\lambda_s^T(1,2,3)\rangle \leq t(\lambda_1^2\lambda_3T^2 + 3\lambda_1^2\lambda_dT + 3\lambda_1\lambda_d\lambda_3T + 6\lambda_1\lambda_d^2) \quad (19)$$

for events with accumulator inleakage and

$$t\langle\lambda_s^T(1,2,3,\overline{A})\rangle = t\langle\lambda_s^T(1,2,3)\rangle(1-C) \quad (19a)$$

for events without accumulator inleakage.

The meaning and numerical values of the variables are given below in the description of quantification.

<u>2nd Time Period</u> (3-6 months), T = 1/4 year;

The same frequency contribution as above plus the correction. The correction is calculated by counting all the possible failure combinations caused by "valve fails to operate on demand" failure mode;

$$\langle\lambda_s^T(1,2,3)\rangle^{corr} = (2\lambda_d\lambda_1\lambda_3T + 4\lambda_d^2\lambda_3 + 2\lambda\lambda_d^2 + 2\lambda_d^3) \quad (20)$$

for events with accumulator inleakage and

$$\langle\lambda_s^T(1,2,3,\overline{A})^{corr} = \langle\lambda_s^T(1,2,3)\rangle(1-C) \qquad (20a)$$

for events without accumulator inleakage.

<u>3rd Time Period</u> (6-9 months).

The same contribution as in the second time period plus twice this correction term because the frequency of "valve fails to operate on demand" failure mode doubles (accumulates).

<u>4th Time Period</u> (9-12 months).

The contribution from this time period is exactly the same as that of the first one.

<u>Quantification of I_{LPI}</u> (Oconee 3)

In the formulae above

λ_1 is the leakage failure frequency of the check valves.
λ_d is the check valve "fails to operate on demand" failure frequency. The same quantity is used also for "MOV fails to operate on demand" failure mode (see also Section B.2.5).
λ_3 is the sum of the frequencies of MOV failures which lead to inadvertent open state of normally closed MOVs.

1. The formulae were evaluated as a function of the leakage flow rate. The leakage frequencies were taken from the frequency exceedance curve (Figure B.2). The same procedure was used for obtaining mean, etc., failure frequencies as that of applied for the Indian Point 3 calculations.

2. The frequency of "valve fail to operate on demand" is also the same as that was used for the Indian Point 3 calculations (see also Section B.1.2.3);

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λ_d^{Mean} = 2.81(-4)/demand. The expectation of its square is:

$$\langle\lambda_d^2\rangle = (\lambda_d^{Mean})^2 + \text{var.} = 2.05\times10^{-7}/\text{demand}^2.$$

The expectation of its third power is obtained by the generic formula valid for lognormal distributions:

$$\langle\lambda_d^3\rangle = [\frac{\langle\lambda_d^2\rangle}{\lambda_d^{Mean}}]^3 = 3.88\times10^{-10}/\text{demand}^3.$$

3. The sum of the mean frequencies of MOV failures leading to inadvertent open state of normally closed MOV is obtained from the following contributors:

a) MOV disc rupture (B.2.1)	1.20×10^{-3}/year
b) MOV internal leakage (B.2.2)	4.85×10^{-3}/year
c) MOV disc failing open while indicating closed (B.2.3)	1.07×10^{-4}/year
d) MOV transfer open (B.2.4, Seabrook value)	8.1×10^{-4}/year
e) Inadvertent SI signal	6.4×10^{-2}/year*
	7.10×10^{-2}/year

*This value is taken from the Indian Point 3 PRA as a generic value for estimating the frequency of inadvertent SI signal. The Oconee PRA assumes a more moderate value of 1×10^{-2}/year.

4. The quantity, 1-C is equal to 0.07.
Since there are two LPI lines and the plant is at power 86% of the time, the initiator frequencies were obtained by the expression:

$$I_{LPI} = .86\times2\times\sum_{i=1}^{4}(\text{quarterly contribution})_i \quad . \qquad (21)$$

The results obtained are shown in Figure 2 as a function of the leak rate for both cases, with and without accumulator inleakage. The coincidence of the Oconee 3 "with accumulator inleakage" curve with Indian Point 3 "without accumulator inleakage curve" is merely accidental.

More precise values are presented in Table 4.4 at relevant leak flow rates. The final initiator frequencies selected as inputs for event trees at appropriate leak flow rates are given also in Table 4.4.

The selection consideration was similar to that described at the Indian Point 3 calculation.

4.3.2.2.3 Calculation of I_{LPI} at Calvert Cliffs 1

At Calvert Cliffs an ISL occurs through the LPI lines if three check valves and a normally closed MOV were in an open failure state. The frequency of the events can be calculated by applying Eq. (15a) to the case. At the application, one has to use the appropriate failure modes of both types of valves, check valves, and MOVs.

The check valve testing policy of Calvert Cliffs 1 is varied; continuous leak/pressure indication of the first check valve and additionally leak test on each inboard check valve at each refueling outages. Leak test is performed quarterly during plant operation and flow test during refueling outages on outboard check valves. The MOVs are stroke tested quarterly and cycled per month.

Since the test interval for the components ranges from zero to 1.5 year in the quantification of Eq. (15a), the basic time period, T, over which the average multiple valve failure frequency is calculated was chosen to be T=1/4 year. The value selected seems to be conservative, considering that the leak/pressure indication and an additional safety valve would detect the failures of the first check valve.

There are four lines and the reactor is at power of 88% of the time, the initiator frequencies were evaluated by using Eq. (15a) as a function of the leak rate:

$$I_{LPI}(1,2,3,4) = .88 \times 4 \times \langle \lambda_s^T(1,2,3,4) \rangle \qquad (21)$$

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for events with accumulator inleakage and

$$I_{LPI}(1,2,3,4,\overline{A}) = .88 \times 4 \times \langle \lambda_s^T(1,2,3,4) \rangle (1-C) \qquad (21a)$$

for events without accumulator inleakage.

The procedure of the calculation was the same as it was applied in the previous cases.

The sum of the mean frequencies of MOV failures leading to inadvertent open state of normally closed MOV is obtained by using the list given at the quantification of Oconee 3 initiators. The only difference is that the demand rate "at MOV failing open while indicating closed" failure mode is taken to be 12/year, resulting in λ_3 = 7.22(-2)/year.

The results of the calculation are shown on Figure 4.3 as a function of the leak rate. The ISL frequencies seem to be indeed small because of the high check valve redundancy. More accurate initiation frequencies at relevant leak flow rates are given in Table 4.4. Table 4.4 indicates also the selected values for small LOCA and overpressurization initiators. The selection criteria were similar to those applied at Indian Point.

4.3.2.3 ISL Initiator Frequencies for HPI Pathways

The basic valve arrangements of the interfacing HPI lines do not differ from those already described for the LPI. Thus, the calculation of average multiple valve failure frequencies for individual lines essentially repeats the approach applied at the I_{LPI} calculations. Small complication arises only for systems where various valve arrangements occur together as in the HPI system of Indian Point 3.

4.3.2.3.1 Calculation of I_{HPI} at Indian Point 3

The HPI system in this plant has:

A) Four lines whose valve arrangement is of the type: three check valves and an open MOV. These lines have shared inlets with the LPI/Accumulator System to the cold legs of the RCS.

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B) Four lines whose valve arrangement is of the type: two check valves and an open MOV. These lines have no shared inlets with the accumulator.

C) Two lines whose valve arrangement is of the type: two check valves and a closed MOV.

There is a relief valve for these lines with a set point of 1500 psia and estimated capacity of 580 gpm. Valve descriptions are given in Table 2.3.3.

1. Calculation of average multiple check valve failure frequencies for group A lines.

The leak and stroke test of the check valves on these lines are different. The first check valve (upstream) stroke and leak tested at each cold shutdown. The other check valves are stroke tested at each cold shutdown, but leak tested at every refueling. The average valve failure frequencies per line were calculated for both of the cases, with and without accumulator inleakage by using the expressions:

$$3[\langle\lambda_s^T(1,2,3)\rangle] \leq 3(\lambda_1^3 T^2 + 6\lambda_1^2\lambda_d T + 6\lambda_1^2\lambda_d T + 6\lambda_1\lambda_d^2) \,, \qquad (22)$$

and

$$3[\langle\lambda_s^T(1,2,3,\bar{A})\rangle] \leq [\langle\lambda_s^T(1,2,3,) \rangle (1-C)] \,. \qquad (22a)$$

The time interval selected for the quantification was T=1/3 year, the average cold shutdown period, applicable for the first check valve. However, to make correction for the asymmetric in the leak and stroke test interval (1.5 year) of the other check valves, the average failure frequencies were multiplied by three.

The definition of the quantities appearing in these expressions have been defined earlier. The frequency values were quantified as a function of the leak flow rate through the first check valve.

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2. Evaluation of average multiple check valve failure frequencies for group B lines.

The check valves on these lines are stroke and leak tested only a each refueling period. Thus, the average multiple check valve failure frequencies were calculated with a time period of T=1.5 years. The lines do not have shared inlet with the accumulator.

The average failure frequency of two check valves is calculated with the formula by the formerly explained way:

$$\langle \lambda_s^T(1,2) \rangle = (\lambda_1^2 T + 2\lambda_1 \lambda_d) \quad .$$

3. Evaluation of average multiple check valve failure frequencies for group C lines.

The check valves on these lines are stroke and leak tested also at each refueling period (T=1.5 years). The MOVs are locked closed during normal operation. Therefore, from the MOV failure modes (see the list at B.2) the "MOV disk rupture," "MOV internal leakage," "MOV left open while indicating closed" failure modes, and "MOV does not operate on demand" failure modes were selected as appropriate ones. The sum of the failure frequencies of the first three failure mode is λ_3 = 6.16(-3)/year.

The average multiple failure frequency was calculated by the expression:

$$\langle \lambda_s^T(1,2,M) \rangle = (\lambda_1^2 \lambda_3 T^2 + 3\lambda_1^2 \lambda_d T + 3\lambda_1^2 \lambda_d + 6\lambda_1 \lambda_d) \quad , \qquad (23)$$

where all the quantities were defined previously.

Taking into account that the reactor is at power about 72% of the total time, the initiator frequencies were evaluated for each group of lines, A, B, and C separately with the following expressions.

For line group A, in the case when there is accumulator inleakage

$$I^{A}_{HPI} = .72x4x3<\lambda^{T}_{s}(1,2,3)>(1-C) , \qquad (24)$$

and in the case when there is no accumulator inleakage

$$I_{HPI} = .72x4x3<\lambda^{T}_{s}(1,2,3)>(1-C) . \qquad (24a)$$

For line group B (no inlet shared with the accumulator)

$$I_{HPI} = .72x4x<\lambda^{T}_{s}(1,2)> , \qquad (25)$$

and for line group C (no inlet shared with the accumulator

$$I_{HPI} = .72x2x<\lambda^{T}_{s}(1,2,M)> . \qquad (26)$$

The results were plotted as a function of the leak flow rate at the line inlets in Figure 4.3. The figure shows the dominant contributors are the flow paths having no common inlets with the accumulator.

Numerical value of the "line group frequencies" at several important leak flow rates are presented in Table 4.5. The table shows, each line group contribute to both, the overpressurization and for small LOCAs. The selection of values is based on the same leak rate considerations which were explained at the description of LPI initiators. The data in the last column of Table 4.5 indicate the final values selected for further analysis.

4.3.2.3.2 Calculation of I_{HPI} at Calvert Cliffs 1

The valve arrangement of the HPI lines at Calvert Cliffs 1 is similar to that of the LPI lines: three check valves and a closed MOV. (The valve descriptions are given in Table 2.5.3.) The number of lines is 4.

The testing policy of the isolation check valves is also similar continuous leak pressure indication of the first check valve (common with the accumulator and LPI lines), leak test quarterly during plant operation of a outboard check valve, flow test during refueling outages. Additionally, leak test on each inboard check valves at each refueling.

The position of the MOVs is under continuous surveillance. They are stroke tested quarterly and after cycling upon SI signal their closed position is monthly verified. There is also a relief valve at header of the branch lines with a setpoint of 1485 psia and an estimated capacity of about 580 gpm.

There was no reason to use other parameters to calculate the multiple valve failure frequencies than it was used in the case of the LPI. Thus, the Calvert Cliffs frequency vs. leak flow rate curves in Figure 4.3 relate not only to the LPI but also to the HPI system.

Since the relief valve setpoint and capacities are different, the leak flow requirements will be also different for the two systems. Correspondingly, the selected values for small LOCA and overpressurization initiators will be different. These values are presented in Table 4.5 where also the data on Indian Point 3 are also shown.

4.3.3 ISL Initiator Frequencies For RHR Suction Paths

For all three plants the three single RHR suction lines (Tables 2.3.3, 2.4.2, 2.5.2) is separated by two specially built MOVs in series. The basic model of two valves in series described in Section 4.3.1 is essentially applicable to calculate the average failure frequency of each of these valve arrangement if the MOV failure modes are appropriately selected. For some of the valve arrangements preclude certain failure modes and test policies and practices are also different at each plant. Therefore the initiator frequencies are calculated on a plant specific basis.

There is a generic problem in the calculation of the initiator frequencies for the RHR suction paths, namely how to take into account in the model the role of the suction side relief valve. The approach applied for the check valves, when the initiation frequencies are evaluated as a function of the leak rate cannot be applied. The reason for this is that leakage failure frequency data similar to those of the check valves are not available for MOVs. The use of check valve data, as surrogates, can be very misleading.

In order to overcome this problem, the following approach has been adopted in the calculation of initiation frequencies:

Failure combinations involving "MOV internal leakage" failure mode are considered to be representing failure events when the inleakage into the RHR system is below the relief valve capacity. Failure combinations, however, involving "MOV disk rupture" with other MOV failure modes (not MOV internal leakage) are considered to contribute to the overpressurization frequency of the RHR suction line (i.e., inleakage into the suction line is assumed to be higher than the relief valve capacity).

4.3.3.1 Calculation of I_s at Indian Point 3

In Appendix B.2 six different failure modes are listed for a typical MOV. From these three failure modes (1) MOV failing open while indicating closed, (2) MOV transfer open, and (3) MOV gross external leakage are not considered.

At Indian Point 3 the MOVs are stroke and leak (disk integrity) tested at each cold shutdown. The leak test rules out the possibility of leaving the valve open, while the control room has a signal indicating a closed position. (If both valves had failed open valve disks, this condition would be detected during plant startup.) "MOV transfer open" failure mode cannot happen either, because at this plant not only the power breakers are locked in the off position but even the fuse disconnect is normally kept open during normal plant operation. Gross external leakage would result in a LOCA inside the containment with the HP and LP recirculation paths remaining open. It would cause no overpressurization. The frequency of this failure mode (B.2.6) is very small, so its failure combinations are assumed to be negligible.

Since Indian Point 3 is at power about 72% of the time the overpressurization frequency of the suction line is calculated by the expression (see also Eq. (7)):

$$T_s(\text{Rupture}) = .72x(\lambda_R^2 T + 2\lambda_R \lambda_d) , \quad (27)$$

where λ_R denotes the mean frequency of the "MOV disk rupture" failure mode (B.2.1) and

λ_d denotes "MOV fails to operate on demand" failure mode (B.2.5).

The time parameter, T = (1/3)year, is the average time period between cold shutdowns.

The result of the quantification is:

I_s(Rupture = 9.80(-7)/year .

Similarly, the frequency of "leakage" events is calculated by the expression:

$$I_s(\text{Leakage}) = .72x(\lambda_L^2 T + \lambda_R \lambda_L T + 2\lambda_L \lambda_d) , \quad (28)$$

where λ_L denotes the "MOV internal leakage" failure mode (B.2.2).

λ_L and λ_d denote the same failure modes as were defined above.

The frequencies of various failure modes used in the quantification are given in Appendix B.

The quantification yields:

I_s(Leakage) = 1.80(-5)/year .

The values, I_v(Rupture and I_v(Leakage) are presented also in Table 4.6 for comparison with other initiation frequencies obtained for other plants.

4.3.3.2 Calculation of I_s at Oconee 3

The MOVs of the RHR suction line at Oconee 3 are located inside the containment. Thus, the "MOV external leakage" failure mode is not considered in the analysis. As it was mentioned in the previous section, this failure mode would result only in an inside LOCA of low occurrence frequency. The simultaneous occurrence of "MOV fail open, while indicating closed" failure event is expected to be recognized during plant heatup and is not further considered. At Oconee 3 the two MOVs are:

- stroke tested at each cold shutdown and
- •• leak (disk integrity) tested at every nine months.

Since the leak tests are carried out less frequency than the stroke tests, the "MOV fails open, while indicating closed" (demand type) failure mode would increase after each cold shutdown during the nine month period between two leak tests.

The initiator frequencies are evaluated for four time periods of three months long and the results will be summed to obtain the yearly ISL frequencies. The terms to be quantified are:

<u>1st Time Period</u> (0-3 months) t = 1/4 year.

Terms of rupture type (since valve ruptures are detected by the stroke test: T = 1/4 year).

$$F_R^1 = t(\lambda_R^2 T + 2\lambda_R \lambda_d) \tag{29}$$

Terms of leakage type (since disk integrity is tested only in each nine month period: T = 3/4 year).

$$F_L^1 = t(\lambda_L^2 T + \lambda_L \lambda_R T + 2\lambda\lambda_d) \tag{30}$$

In these expressions λ_R, λ_L, and λ_d denote "MOV rupture," "MOV leakage," "MOV fails to operate on demand" failure frequencies, respectively.

<u>2nd Time Period</u> (3-6 months) t = 1/4 year.

The same frequency contributions, F_R^1, F_s plus the corresponding corrections:

$$F_R^2 = F_R^1 + \text{Corr.}_R^1 \quad \text{and} \quad F_L^2 = F_L^1 + \text{Corr.}_L^1 \ .$$

In the first expressions, the correction terms of rupture type (T = 1/4 year) are:

$$\text{Corr.}_R^1 = t(2\lambda_R\lambda_g + \lambda_R\lambda_T\frac{T}{2}) \quad . \tag{31}$$

In the second expression, the correction terms of leakage type (T = 1/4 year) are:

$$\text{Corr.}_L^1 = t(2\lambda_L\lambda_g + \lambda_g\lambda_T + \lambda_L\lambda_T\frac{T}{2}) \quad . \tag{32}$$

In the correction terms λ_g and λ_T denote the frequencies of "MOV fails open, but indicating closed," and "MOV transfer open" failure modes, respectively. "MOV transfer open" failure mode is considered only for the second (downstream) MOV, since the upstream valve is always subjected to the full RCS pressure. "MOV transfer open" failure events may arise at Oconee 3, because according to our knowledge, the fuse disconnect is not kept open normally.

<u>3rd Time Period</u> (6-9 months) t = 1/4.

The same frequency contributions as in the previous period and additional increase of demand type failure terms:

$$F_R^3 = F_R^2 + \text{Corr.}_R^2 \quad \text{and} \quad F_L^3 = F_L^2 + \text{Corr.}_L^2 \quad .$$

In the first expression the additional correction term of rupture type (T = 1/4 year) is:

$$\text{Corr.}_R^2 = 4(2\lambda_R\lambda_g) \tag{33}$$

In the second expression the additional correction term of leakage type (T = 1/4 year) is:

$$\text{Corr.}_L^2 = t(2\lambda_R\lambda_g) \tag{34}$$

4th Time Period (9-12 months).

The same terms as in the first time period. The frequencies of various failure modes used in the quantification are given in Appendix B.

The quantification provides the following frequency contributions:

	Rupture	Leakage
1st time period:	$F_R^1 = 1.29(-7)$/qu.yr.,	$F_L^1 = 1.38(-5)$/qu.yr.
2nd time period:	$F_R^2 = 6.79(-7)$/qu.yr.,	$F_L^2 = 1.61(-5)$/qu.yr.
3rd time period:	$F_R^3 = 7.43(-7)$/qu.yr.,	$F_L^3 = 1.65(-5)$/qu.yr.
4th time period:	$F_R^4 = F_R^1 = 1.29(-7)$/qu.yr.,	$F_L^4 = F_L^1 = 1.38(-5)$/qu.yr.
Total	$F_R = \sum_{i=1}^{4} F_R^i = 1.68(-6)$/yr.,	$F_L = \sum_{i=1}^{4} F_L^i = 6.02(-5)$/yr.

The initiation frequencies (by using 86% capacity factor for Oconee 3) are:

I_s(Rupture) = $.86xF_R = 1.44(-6)$/year and
I_s(Leakage) = $.86xF_L = 5.18(-5)$/year.

These values are given also in Table 4.6.

4.3.3.3 Calculation of I_s at Calvert Cliffs 1

The isolation valve arrangement on the RHR suction line at Calvert Cliffs 1 (Shutdown Cooling Line) is different from those of the other two plants. One of the isolation MOVs is located outside the containment. This requires to consider the "MOV external leakage" failure mode for that valve for such failure event would lead an ISL bypassing the containment even though actual overpressurization would not occur.

An interesting feature of the Calvert Cliffs isolation valve system that a relief valve is located between the two MOVs, inside the containment. While it has the potential for continuous leakage monitoring, its set point (~2485 psia) is much higher than the normal operating pressure of the RCS (~2250 psia). Therefore, in the present study no credit is given to this possibility.

The MOVs are stroke and leak tested at every refueling. There are about on the average four cold shutdowns per year. After cold shutdowns, however, in order to avoid "MOV failing open while indicating closed" failure mode manual checks are carried out by using calibrated wrench, to check whether the valves are indeed closed (have the prescribed torque). The maintenance crew (usually consisting of two persons) knows that these valves are "sacred" at the plants and the potential consequence of a failure to close these valves is severe. The mean human error probability that the crew will leave open the valves (or initiate restoring valve position) is estimated to be $2x10^{-3}$/d. Thus, the combination of this human failure with the "MOV failing open but indicated closed" failure (λ_g = 1.04(-4)/year, B.2.3) would be about $2x10^{-7}$/year. Therefore, it is taken to be negligible.

"MOV transfer open" failure mode is considered only for the second (downstream) MOV because this valve is not under high pressure difference and the fuse disconnects of the MOVs at this plant normally not kept open.

Calvert Cliffs 1 is at power about 88% of the time. Thus, the rupture and leakage initiator frequencies are calculated by the following expressions:

$$I_s(\text{Rupture}) = .88x(\lambda_R^2 T + 2\lambda_R \lambda_d + \lambda_R \lambda_T \frac{T}{2}) \qquad (35)$$

and

$$I_s(\text{Leakage}) = .88x(\lambda_L^2 T + 2\lambda_L \lambda_d + \lambda_L \lambda_T \frac{T}{2} + \lambda_R \lambda_L T) \ . \qquad (36)$$

The time T is taken to be T = 1/4 year because MOV disk ruptures would be detected at cold shutdown. In these expressions λ_R, λ_L, λ_d, and λ_T denote the "MOV rupture," "MOV internal leakage," "MOV fails to operate on demand," and "MOV transfer open" failure frequencies, respectively.

Quantification yields for the initiation frequencies:

I_s(Rupture) = 1.45(-6)/year and
I_s(Leakage) = 1.89(-5)/year.

The frequency of ISLs bypassing the containment by the "MOV external leakage failure mode" is estimated by the expressions:

$I_{Direct}(\text{Rupture}) = .88x(\lambda_R \lambda_0 T/2)$

for cases when the first MOV ruptures and the second leaks profusely, and

$I_{Direct}(\text{Leakage}) = .88x(\lambda_L \lambda_0 t/2)$

for cases when the first MOV is leaking only. In these expressions λ_0 denotes the frequency of "MOV external leakage" failure mode (see B.2.6). Quantification if performed by assuming that T = 8 hours, a very conservative case that the external leakage of the MOV would not be detected. The values obtained are:

I_{Direct}(Rupture) = 4.22(-10)/year and
I_{Direct}(Leakage) = 1.84(-9)/year.

All of the above data are presented also in Table 4.6 for comparison. The coincidence of the I_s(Rupture) values for Oconee 3 and Calvert Cliffs 1 is completely accidental.

4.3.4 Letdown

The letdown line is used to continuously remove reactor coolant for level control and/or RC chemistry treatment.

4.3.4.1 Indian Point Unit 3

Reactor coolant is withdrawn from the intermediate leg of the RC piping through a manual and two air-operated fail closed stop valves, LCV-459 and LCV-460. Three letdown orifices are provided the reduce the letdown flow pressure from RCS operating (2235 psig) to the CVCS operating pressure (225-275 psig). Normally one orifice is in operation allowing normal letdown flow at optimum level. One of the other two orifices is for backup and the other is to increase letdown flow when required to the maximum capacity of the CVCS. A relief valve is provided on the inside containment section of the low pressure piping to protect it in the event that either the letdown control valves fail open, the flow orifice may rupture or any of the low pressure block valves (201, 202) may fail in the closed position. These failure modes combined with the failure of the relief valve may result in a pipe rupture. In case the relief valve opens the result is a small LOCA inside the containment. Failure rates for air-operated valves fail to remain open or fail in the open position has been obtained from the data base included in the Oconee PRA and has the value of λ_{Valve} = 2.01-03/year. The orifice rupture rate has been obtained from the data base provided in the Calvert Cliffs PRA, $\lambda_{Orifice}$ = 2.63-04/year. Similarly, the failure rate for a relief valve to open on demand is λ_{RV} = 3.0-04/d. The total average failure rate at Indian Point resulting in a pipe rupture is

$$\langle\overline{\lambda}_{Letdown}\rangle = (\lambda_{Valve} + \lambda_{Orifice}) * \lambda_{RV} = 6.82\text{-}07/\text{year}$$

The opening of the relief valve results in a small LOCA inside the containment and its average failure rate is

$$\langle\overline{\lambda}_{Letdown}\rangle = \lambda_{Valve} + \lambda_{Orifice} = 2.28\text{-}03/\text{year} .$$

4.3.4.2 Oconee Unit 3

The letdown flow from the RCS is routed through the normally used 3A LD cooler. Two MO block valves are provided on this line, HP-1 and HP-3, inside the containment. There is a redundant cooler and associated block valves (3B,

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HP-2 and HP-4). Outside the containment there are two air-operated HP stop valves (HP-5, HP-6) upstream of the pressure reducing orifice and the letdown flow control valve (HP-7) parallel with the orifice. The HP/LP boundary is located outside the containment including the relief valve on the LP piping. Failures, such as orifice rupture, demineralized inlet valves fail closed or letdown flow control valve fail open leading to overpressurization of the LP piping results in a small LOCA outside the containment, even if the relief valves open. The failure modes to be considered are the same as previously discussed in Section 4.3.2.4.1.

$$\lambda_{Valve} = 2.01\text{-}03/\text{year}$$

$$\lambda_{Orifice} = 2.63\text{-}04/\text{year} \ .$$

The average failure rate for the letdown system including small LOCA events due to overpressurization and consequent opening of the relief valve is

$$\langle\bar{\lambda}_{Letdown}\rangle = \lambda_{Valve} + \lambda_{Orifice} = 2.28\text{-}03/\text{year} \ .$$

4.3.4.3 Calvert Cliffs Unit 2

Coolant letdown from the cold leg first passes through the regenerative heat exchanger and then through the letdown control valves. The valves, controlled by the pressurizer level control system, control the letdown flow to maintain proper pressurizer level. An excess flow check valve is installed before the control valves to limit the letdown flow in abnormal circumstances. RC pressure is reduced to CVCS operating pressure in one of the air-operated letdown control valve. A relief valve on the low pressure side prevents the overpressurization of the LP piping.

The average failure rate of the letdown system can be obtained using general valve and orifice failure data as in the previous section and estimated as:

$$\langle\bar{\lambda}_{Letdown}\rangle = 2.28\text{-}03/\text{year} \ .$$

4.3.5 References

1. "Indian Point Probabilistic Safety Study," Power Authority of the State of New York and Consolidated Edison Company of New York, 1982.

2. "Oconee PRA, A Probabilistic Risk Assessment of Oconee Unit 3," NSAC-60, June 1984.

3. "Interim Reliability Evaluation Program: Analysis of the Calvert Cliffs Unit 1 Nuclear Power Plant," NUREG/CR-3511, March 1984.

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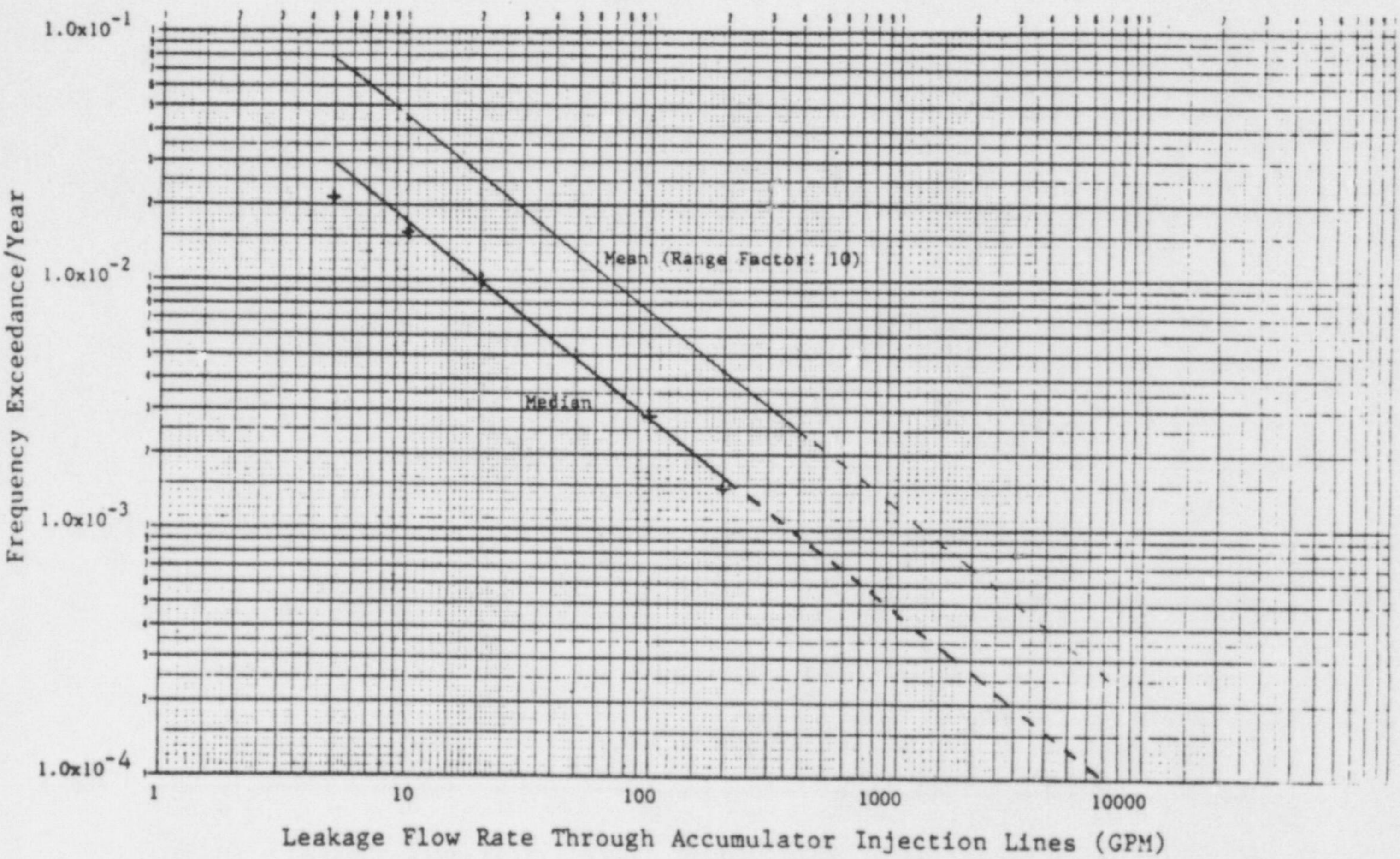

Figure 4.1 Frequency of accumulator inleakage events.

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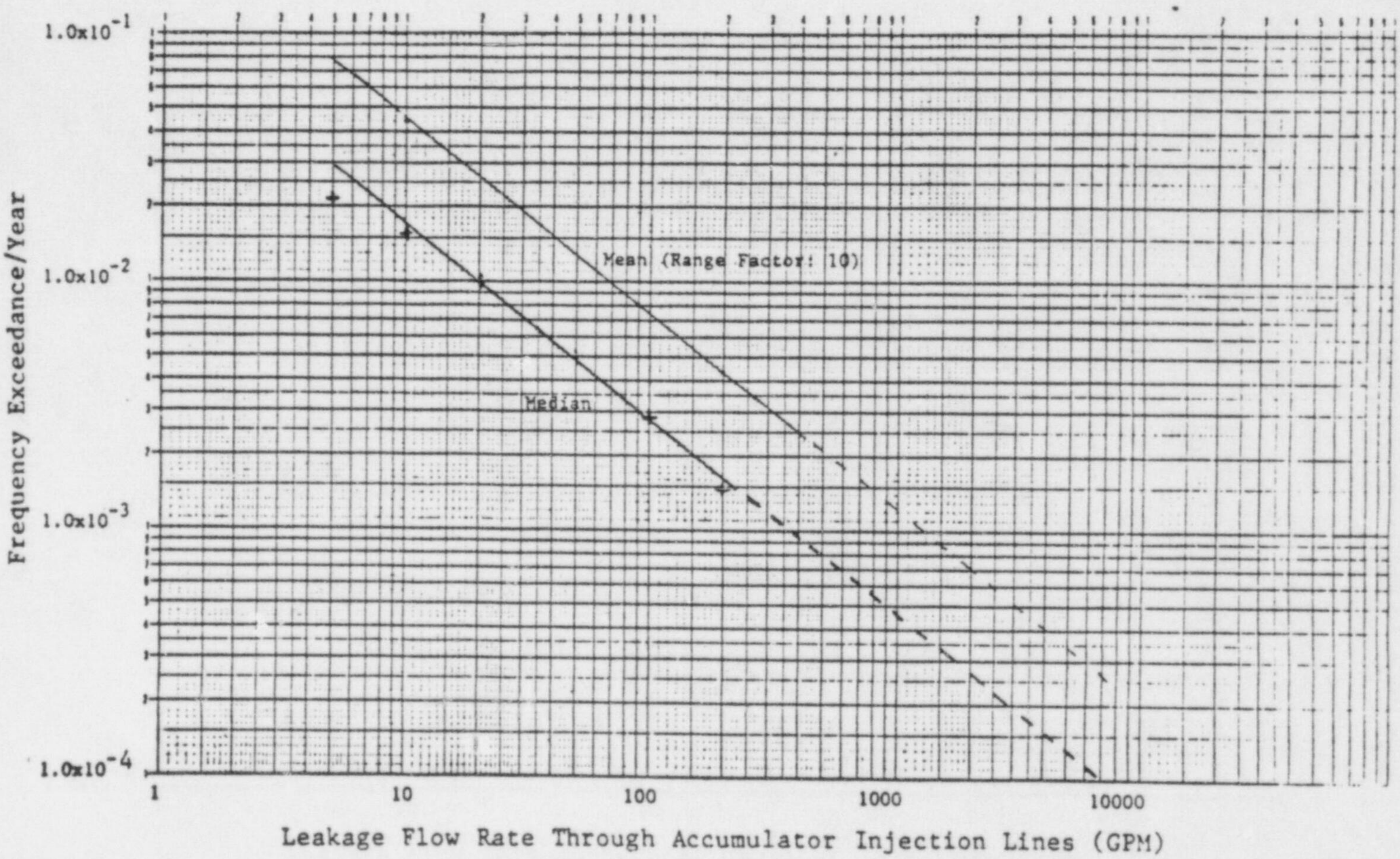

Figure 4.1 Frequency of accumulator inleakage events.

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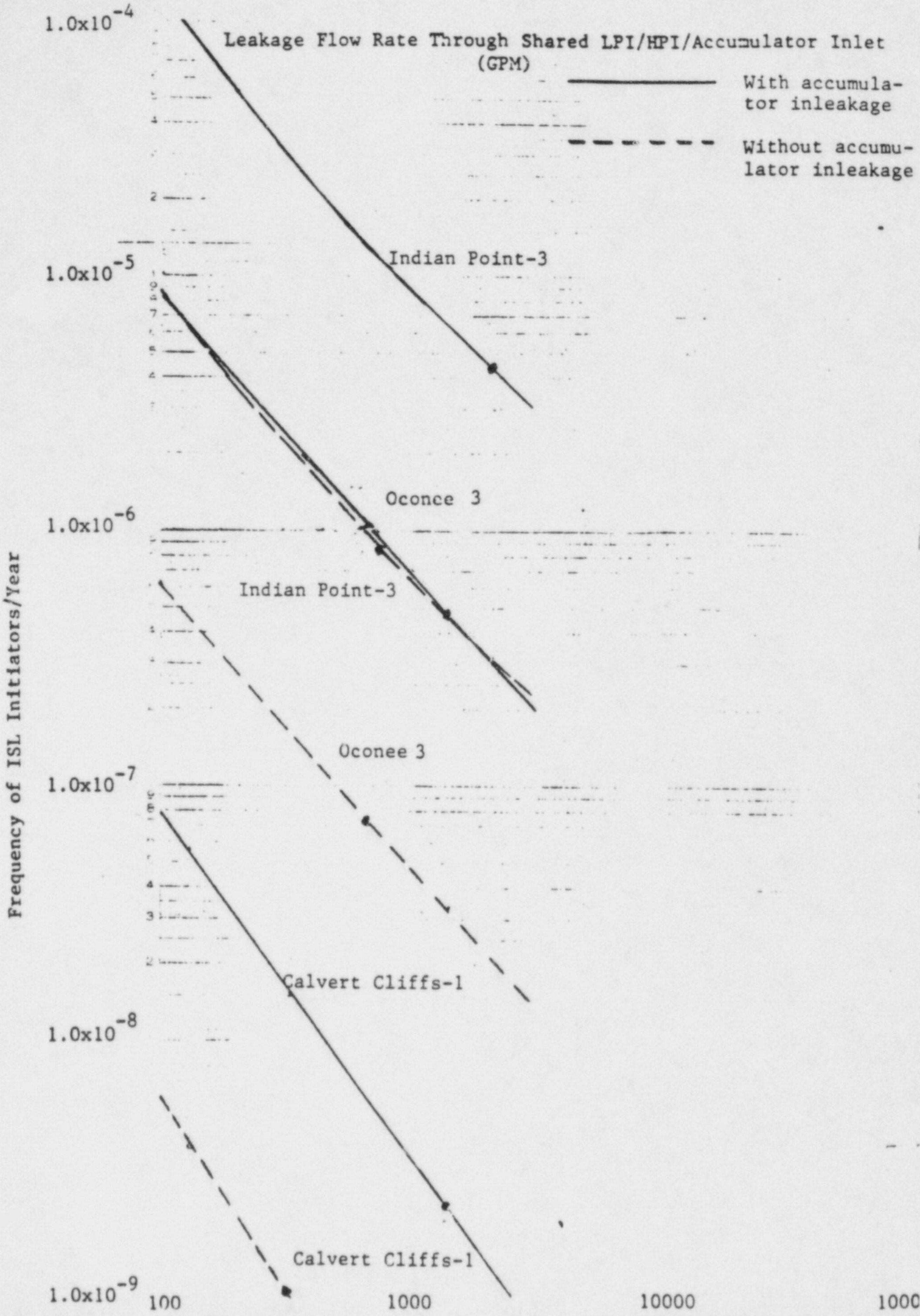

Figure 4.2 Frequency of ISL initiators through LPI lines vs. leak rate.

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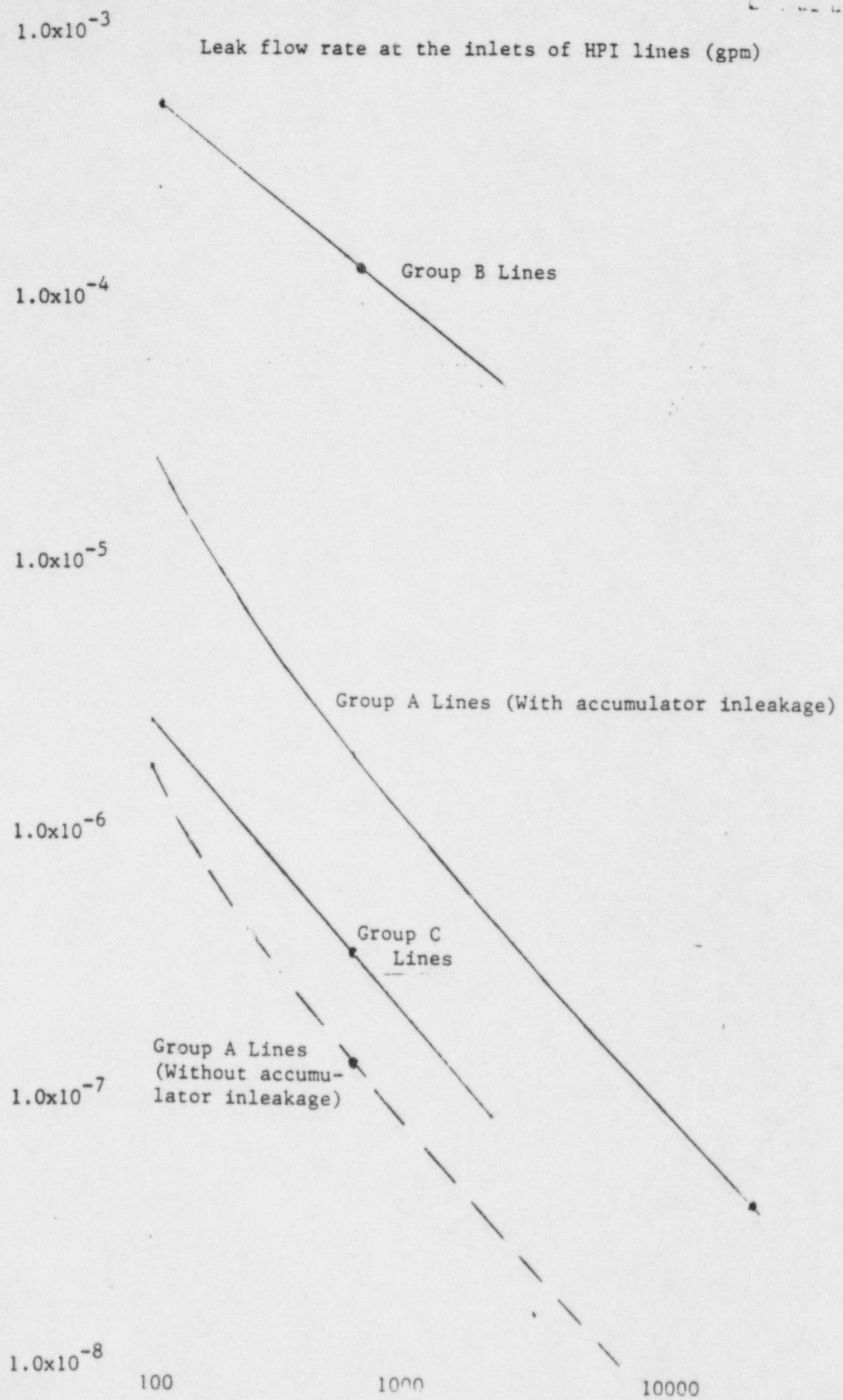

Figure 4.3 Frequency of ISL initiators through HPI lines vs. leak rate - Indian Point 3.

Table 4.1
Some Design Characteristics of The Accumulators
(Core Flooding Tanks) at The Selected PWRs

Design Characteristics	Indian Point-3	Oconee-3	Calvert Cliffs-1
Number of accumulators	4	2	4
Design pressure (psig)	700	700	250
Operating pressure (psig)	650	600	200
Tank total volume (gallon)	8230	10547	14960
Water volume (gallon)	5240	7780	8325
"Free" volume (gallon)	~3000	~2800	~6650
Number of relief valves	1	1	1
Relief valve size	1"	1"	1"
Relief valve setpoint	700	~700	250
Relief valve capacity (est.) (gpm)	710	710	425
Drain line (accessible) and size (inch)	1 (1")	1 (1")	1" (1")
Drainage capacity (gpm)	~1250	~1250	~1250

Table 4.2
Filling Time of Accumulator's "Free" Volumes
For Various Leak Rates*

Indian Point-3		Oconee-3		Calvert Cliffs-1	
Leak Rate (gpm)	Time (min)	Leak Rate (gpm)	Time (min)	Leak Rate (gpm)	Time (min)
100	30	100	28	100	66
200	15	200	14	200	33
300	10	280	10	300	22
500	6	467	6	500	13
740	4	700	4	665	10
1000	3	1000	~3	1000	~7

*Leak rates underlined correspond to the "critical time" necessary to the operator to take successful corrective actions.

Table 4.3
ISL Initiation Frequencies For Accumulator Pathways
With Some Relevant Parameters Used in The Calculation

	Indian Point-3	Oconee-3	Calvert Cliffs-1
Reactor at power	.72	.86	.88
Number of lines, Size (inch)	4 10	2 14	4 12
Leak rate (gpm) at the "critical time, 10 min.,"	300	280	665
Leakage exceedance frequency at above leak rate (per line-year)	3.1(-3)	3.3(-3) *	1.7(-3)
ISL initiation frequency at above leak rate I_A (per year)	8.93(-3)	7.02(-3)	5.98(-3)
ISL frequency at accumulator relief valve capacity	4.64(-3) (710 gpm)	4.10(-3) (710 gpm)	**

*Correction: $E_A^T = 7.84(-4)$.

**Not calculated (relief valve capacity is smaller than 665 gpm).

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Table 4.4
ISL Initiation Frequencies for LPI Pathways

Plant	Number of Lines	Leak Rate @ The Shared LPI/HPI/Accum. Inlet (gpm)	LPI Inleakage Frequencies With Accumulator Inleakage (Per Year)	W/O Accumulator Inleakage (Per Year)	I_{LPI} Initiator Frequencies Selected For Further Analysis (Per Year)
Indian Point 3	4	98+	1.27(-4)	8.86(-6)	8.86(-6)
		740++	1.19(-5)	8.33(-7)	
		~2100+++	4.50(-6)	3.20(-7)	5.33(-6)
Oconee 1	2	100+	8.84(-6)	6.19(-7)	6.19(-7)
		660++	1.03(-6)	7.23(-8)	
		1370+++	4.86(-7)	3.40(-8)	5.58(-7)
Calvert Cliffs 1	4	130+	5.60(-8)	3.92(-9)	3.92(-9)
		330++	1.50(-8)	1.05(-9)	
		~1400+++	2.35(-9)	1.65(-10)	3.40(-9)

+Leak rate equal to the maximum charging flow rate.
++Capacity of relief valves at injection side.
+++Leakage required to exceed the capacity of relief valves given accumulator inleakage.

Table 4.5
ISL Initiation Frequencies for HPI Pathways

Plant	Number of Lines	Leak Rate @ The Inlets of HPI Lines (gpm)	HPI Inleakage Frequencies With Accumulator Inleakage (Per Year)	HPI Inleakage Frequencies W/O Accumulator Inleakage (Per Year)	I_{HPI} Initiator Frequencies Selected For Further Analysis (Per Year)
Indian	4	98+	2.60(-5)	1.81(-6)∇	
Point	Group A	580++	2.05(-6)	1.44(-7)*	Small LOCA
3		14600++	4.30(-8)*	3.00(-9)	Sum of ∇ 5.52(-4)
	4	98+	No shared	5.47(-4)∇	Overpressurization
	Group B	580++	inlet	1.38(-4)*	Sum of * = 1.39(-4)
	2	98+	No shared	2.76(-6)∇	
	Group C	580++	inlet	3.51(-7)*	
Calvert	4	130+	5.60(-8)	3.92(-9)	3.92(-9)
Cliffs		580++	8.84(-9)	6.18(-10)	
1		28420+++	<1.0(-10)*	<<1.0(-10)	7.18(-10)

+Leak rate equal to the maximum charging flow rate.
++Capacity of relief valves at injection side.
+++Leak rate required to exceed the capacity of relief valves given accumulator inleakage.
Calculated as: Leak rate at relief valve capacity/flow diversion ratio at the shared inlet.
Flow diversion ratio: $\frac{\text{Cross section of LPI line}}{\text{Cross section of acc. line}}$
Indian Point 3: Flow diversion ratio: .04
Calvert Cliffs 1: Flow diversion ratio: .02

Table 4.6
ISL Initiation Frequencies For RHR Suction Pathways

Plant	I_S (Per Year) Leakage+	Rupture++
Indian Point-3	1.80(-5)	9.80(-7)*
Oconee-3	5.18(-5)	1.44(-6)*
Calvert Cliffs-1	1.89(-5)	1.45(-6)*
Direct leakage from external MOV	1.84(-9)	4.22(-10)*

*Selected for further analysis.
+Leakage defines leak rates smaller than the capacity of suction side relief valve.
++Rupture defines leak rates higher than the relief valve capacity.

5. CORE DAMAGE FREQUENCIES AND EVENT TREES

The event trees have been constructed in such a way that for any given initiator the end states correspond to an initiating event of the respective PRA studies of the particular plant.[1-2-3] In this manner all events are classed as small or large LOCAs, inside or outside the containment building with a respective conditional core damage frequency derived from the plant PRAs. The effect of ISL on Safety systems required to mitigate a LOCA has also been considered in determining the conditional core damage frequency. Table 5.1 lists all conditional core damage frequencies as derived from the plant specific PRA studies. The main results of this study, the core damage frequencies due to ISLs are listed in a summary format in Tables 5.2 through 5.6 for the three plants.

One of the major assumptions in this study is that small LOCAs bypassing the containment would eventually lead to core damage. In order to mitigate LOCAs bypassing the containment the operator has to rely on the water supply available in the RWST. Once the RWST is depleted additional source of water must be found.

The time available to establish makeup to the RWST varies depending on the size of the break and the available equipment and could range from 3-4 minutes (~6" break no LP, no HP systems), to a few (~12) hours (~1" break HP available).[4] The makeup to the RWST would be based on an "ad hoc" arrangement, and consequently was not modelled. Core damage was assumed to occur when the RWST has been depleted. In Sections 5.1 through 5.5 the event trees for all interfacing systems are discussed along with the additional assumptions used to establish the core damage frequencies. Section 5.6 briefly describes the method used to derive the conditional core damage frequencies from the plant specific PRAs. The core damage frequencies are presented in Section 5.7. In Appendix C assumptions used to quantify operator performances are discussed and Appendix D presents a brief summary of the thermal-hydraulic aspect of ISL events.

5.1 LP Injection

The event trees for the three plants are shown on Figures 5.1 and 5.2.

An overpressurization event of the LP injection lines at Calvert Cliffs & Oconee cannot be isolated causing a LOCA bypassing the containment. Even though at Oconee one LP injection train might be unaffected, the loss of recirculation capability leads to core damage once the RWST water supply runs out. The Indian Point arrangement is different from the other plants, because a large portion of the system is routed inside the containment and in addition there is isolation capability on each injection line. It is very likely that an overpressurization event of the LP injection line at Indian Point will result in a LOCA inside the containment. The injection line is designed such, that the operator has the capability to terminate the blowdown of the primary coolant by closing at least one of the two high pressure rated MOVs. In addition to the major pipe break event, the top events are (a) pipe break location, inside/outside containment building, and (b) operator diagnoses the event and attempts to terminate it. In case of a small break the probability of a pipe break inside the containment was estimated at .9. This probability was based on engineering judgment after reviewing the piping design and actual layout of the LP injection piping. In case of a small break inside the containment, the primary concern is that depending on the actual break location the HP recirculation capability might be disrupted increasing the core damage frequency due to an unisolated small LOCA without recirculation.

Thermal-hydraulic calculations[4] have indicated (see Appendix D for a brief summary) that there is ample time available (2-3 hours) to the operator to diagnose a small LOCA event. It is assumed that at least one of the two isolation MOVs would operate and would terminate the blowdown of the primary coolant.

The NREP cognitive error function (see Appendix C) has been used to determine the probability of an operator error, 9×10^{-4}, having ~2 hours available to recognize and isolate a small LOCA through the LP injection lines.

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The core damage frequency for terminated small LOCAs has been determined using the unavailability of the HP injection system.

A small break outside the containment on the recirculation line connecting the LP outlet to the suction side of the HP pumps would disable the normally closed isolation valves. The RWST would drain through the pipe break and the HP pumps would be unavailable leading to core damage regardless of the isolation capability.

A large LOCA inside the containment would disable one LP injection line making the LP pumps unavailable, leading to core damage. It is assumed that the isolation capability would be lost during a large LOCA, because the isolation MOVs are not designed for high flow and high temperature conditions.

5.2 SI Discharge

The event tree (Figure 5.3), for the SI line overpressurization event is relatively simple at Calvert Cliffs. There is no isolation capability, therefore, a pipe break (small LOCA) would eventually lead to core damage, when the RWST water supply is depleted.

At Indian Point some low pressure portion of the SI piping is inside the containment making the event tree somewhat more complicated (Figure 5.4). In addition, an open MOV on each injection line can isolate a LOCA event. Given an overpressurization accident the relief valve common to both train will open leading to a small LOCA inside the containment. If the leak does not exceed the relief valve capacity, than the core damage frequency is what associated with small LOCA. The integrity of both injection train is intact and can be used to mitigate the accident. If the leak is larger than the relief valve capacity the integrity of the piping boundary may be lost. If the pressure boundary is damaged at the train isolating check valves (858A or B), then the other train may loose enough flow through the break making the HP system unavailable. This leads to CD even if the blowdown is terminated by the operator (no makeup capability).

If the pipe break is located outside (with a probability of .1) and is not terminated, CD will result, because of the lost recirculation capability. In addition, the RWST could most likely be drained through the damaged train making the progress of this accident much faster (reduced RWST inventory). In order to terminate the accident outside the containment on the HP pump discharge line, the operator has to (a) be able to diagnose the problem, (b) terminate the RC blowdown with the SI high pressure isolation MOV, and (c) be able to isolate the damaged HP train and stop the RWST drain. The available time is judged to be 30-60 minutes. Considering the complexity of the accident and the short available time the probability of an error in the operator's action is taken as .1 (the HEP for post-diagnosis activities are taken as 1.0; see Appendix C).

The CD frequency associated with the small outside LOCA, terminated by the operator has been calculated using HP system unavailability with one train in a definite failed mode.

5.3 RHR Suction

The event trees for all three plants are very similar and are shown in Figures 5.5 and 5.6. The main difference at Calvert Cliffs is that the pressure isolation boundary is located outside the containment leading to LOCAs always bypassing the containment. At Indian Point and Oconee the initiator or overpressurization event may cause a pipe break either inside or outside the containment. The first top event is to decide if the event is a small (<6") or large break. The location of the pipe break is of utmost importance and the second top event determines if this is a break inside the containment or bypassing it. The probability of a pipe break outside the containment at Indian Point has been based on field observations and was estimated at .5. The length of the LP piping are approximately equal on both sides of the containment wall, there are few pipe turns and bends and relatively few weld locations. These observations support an equal conditional pipe break probability for the inside and outside LP pipe segments. At Oconee the line just beyond LP-2 is designed for 200 psi. It connects inside the containment to a low pressure pipe designed for 388 psi. There is also a relief valve (388 psi setpoint), which could not relieve the

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full pressure. The relief valve and the 200 psi line are the most likely failure points. The probability that pipe break occurs inside the containment was estimated, based on these considerations at .9. If the overpressurization is such that the relief valve is lifted and the leak does not exceed the relief valve capacity the end result is a small LOCA inside the containment. Each plant has an additional low pressure rated, normally closed valve on the suction line after the two closed MOV. The assumption has been made that a major pipe break outside the containment would disable this valve. However, for small breaks, this third isolation valve would maintain the pressure boundary. In either case small or large LOCAs outside the containment eventually lead to core damage, because recirculation is unavailable and the RWST water supply is limited. Naturally the time available to find additional water supply would mainly depend on the size of the break. This ranges, depending on on the available equipment, from a few minutes (large LOCA, no makeup capability) to a few hours (small LOCA, HP available).

5.4 Letdown Lines

Figures 5.7 and 5.8 shows the event trees for the letdown lines. The primary top event asks whether the operator can recognize the nature of the accident and what action might be taken. The time available, even when the HP system is unavailable, is about 1-2 hours before core damage starts. The blowdown can be terminated by closing the high pressure rated letdown stop valves. The probability of the operator not able to recognize and terminate the accident, 1.2×10^{-3}, was determined from the NREP cognitive error function (Appendix C). In this accident substantial amount of primary coolant may be lost requiring makeup capability using the HP pumps. The core damage frequency associated with terminated small LOCAs reflects the unavailability of the HP system.

At Indian Point, in addition to operator action, a top event representing inside or outside break location is also included. The probability of a letdown pipe to rupture outside the containment, .5, has been estimated as previously described in 5.3.

5.5 Accumulators

The event tree for the accumulator system is shown on Figure 5.9. The accumulators are well instrumented including high pressure and high-low level alarms. The operator can easily recognize and diagnose a small ISL event with ample time available to terminate it. Therefore, below a critical leak rate (see Section 4.3.2.1) ISL's are essentially non-events. If the leak rates are above the critical level the time available for operator action is in the order of a few minutes. It has been assumed that initially the operator would try to maintain the water level in the accumulator by draining the excess leakage. The operator error associated with the draining action is based on the lower bound HEP values of Figure C.1 (Appendix C). For Oconee no remote draining capability has been identified eliminating the possibility of this action. If the back leakage is in excess of the drain and relief capacity a major pipe rupture may occur. The operator may be able to terminate the ISL event by closing the high pressure rated MOV on the accumulator outlet lines, which is deenergized open in normal operation requiring local action at the valve MCC. The probability of an operator error, including the probability of an MOV failure to close on demand has been estimated at 3.0×10^{-3} using generic MOV data with the error recognition function. In case of a major pipe or tank rupture the event is equivalent to the large LOCA DBA of the FSAR with one accumulator not being available. All the plant specific PRAs discuss and quantify this event.

5.6 Conditional Core Damage Frequencies (CCDF)

The CCDF values have been derived from the plant specific PRAs.[1-3] All ISL events result in a small or large LOCA, inside or outside the containment. In addition, the effect of the initiating event (ISL) on some of the safety systems required to mitigate the accident has to be also considered.

5.6.1 Indian Point (Reference 2)

In the following events the operator is unable to isolate the primary coolant leak and a failure in one of the required safety systems leads to core damage.

1. Large LOCA Inside Containment - 8.4-03.

   This sequence is basically dominated by sequences AEFC and ALFC, which reflects the failure of the LP injection or recirculation functions (Table 1.3.6.1-4 of Reference 1).

2. Small LOCA Inside Containment - 5.7-03.

   The Indian Point PRA has three LOCA classes (large, medium, and small). In this study the medium and small LOCA has been grouped into one (small loca <6"). In this case the dominant sequences are again related to the injection and recirculation functions (see Table 1.3.6.2-4 and 1.3.6.3-4 of Reference 1).

ISL events terminated by the operator result in core damage only if the makeup capability to the RCS is lost.

3. Small LOCA Inside/Outside, Terminated - 1.7-04.

   In this case the operator is able to terminate the loss of the primary coolant, but it is assumed that makeup is still required to prevent core damage using the HP injection system. This value essentially represents the HP system unavailability and corresponds to the SEFC and AEFC sequences in Table 1.3.6.2-4, Seq. 13-HH-1 failure and Table 1.3.6.3-4, Seq. 35-HH-2 failure.

4. Small LOCA Inside/Outside HP Train Affected - 5.74-03.

   The ISL event may affect one HP injection train. The unavailability of the HP system may be recalculated in terms of the unavailabilities of the dominant contributors with one train in a failed mode. The dominant contributors with the original quantifications are found in pages 1.6-461 through 1.6-467 of Reference 1.

5.6.2 Oconee (Reference 2, Volume 4)

1. Large LOCA Inside Containment - 1.03-02.

Large break LOCA events are contained in Bin V and VI. Bin V sequences include all those initiating events where core melt results due to failure in the injection phase (AU sequence). Bin VI correspond to failures in the recirculation phase (AX sequence). The dominant cutset listing for Bin V and Vi including the initiator value are in Chapter D.2.7 and D.2.8 of Reference 2, Volume 4, Appendix D.

2. Small LOCA Inside Containment - 2.1-03.

The dominant sequences leading to core melt are primarily related to the unsuccessful operation of the HP injection and/or recirculation system. These sequences are contained in Bin I (SU_s and SY_sX_s) and Bin II (SX_s). Again, the dominant cutsets along with the initiator are listed in Chapter D.2.1.1, D.2.1.3 and D.2.3.3 of Volume 4, Appendix D of Reference 2.

3. Terminated Small LOCA Inside/Outside - 1.6-04.

The HP system unavailability has been derived using the SU_s sequence of Bin I.

5.6.3 Calvert Cliffs (Reference 3)

1. Large LOCA Inside - 2.8-02.

The quantification of all large LOCA sequences, indicated on Figure 5.4 of Reference 3, is listed in Appendix C, Table C.9 of the same.

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reference. The CCDF due to large LOCA has been calculated based on the initiator value listed in Figure 4.1 of Chapter 4.

2. Small LOCA Inside - 1.3-03.

   Similarly to the previous case, the quantified sequences, which are listed in Figure 5.6, were renormalized using the initiator value from Figure 4.1. The numerical values of the sequence probabilities are also listed in Appendix C, Table C.9 of Reference 3.

3. Terminated, Small LOCA Inside/Outside - 7.5-05.

   The HP system unavailability has been derived using the S_2D'' sequence with the corresponding initiator.

5.7 Core Damage Frequency (CDF)

The plant and system specific CDFs are listed in Tables 5.2a through 5.4b. In Tables 5.2a, 5.3a, and 5.4a only ISL events resulting in overpressurization are shown. If the system is equipped with a relief valve than overpressurization occurs only if the leak is in excess of the capacity of this valve. The opening of the relief valve results in a small LOCA inside the containment and the associated CDF values are listed in Tables 5.2b, 5.3b, and 5.4b.

A summary of the total CDF due to ISL, both inside and outside the containment, is shown in Table 5.5 with the respective CDF values (due to LOCAs) from the plant specific PRAs.

It can easily be seen that the total CDF due to overpressurization is less sensitive to low values of the major pipe rupture probability parameter. This is mainly reflecting the assumption that small LOCAs bypassing the containment would eventually result in core damage. Therefore, small LOCA events will be the dominant contributors to CDF when the major pipe rupture probability is small.

The most important result of this study, CDF due to ISLs bypassing containment are listed in Table 5.6. This again reflects the dominance of small LOCA events at low P(Rupture).

The total contribution of these events to CDF due to LOCAs is rather small (~1%), but naturally they are one of the most significant type of contributors to risk resulting from core damage.

5.8 References

1. "Indian Point Probabilistic Safety Study," Power Authority of the State of New York and Consolidated Edison Company of New York, 1982.

2. "Oconee PRA, A Probabilistic Risk Assessment of Oconee Unit 3," NSAC-60, June 1984.

3. "Interim Reliability Evaluation Program: Analysis of the Calvert Cliffs Unit 1 Nuclear Power Plant," NUREG/CR-3511, March 1984.

4. "Dominant Accident Sequences in Oconee-1 Pressurized Water Reactor," NUREG/CR-4140, April 1985.

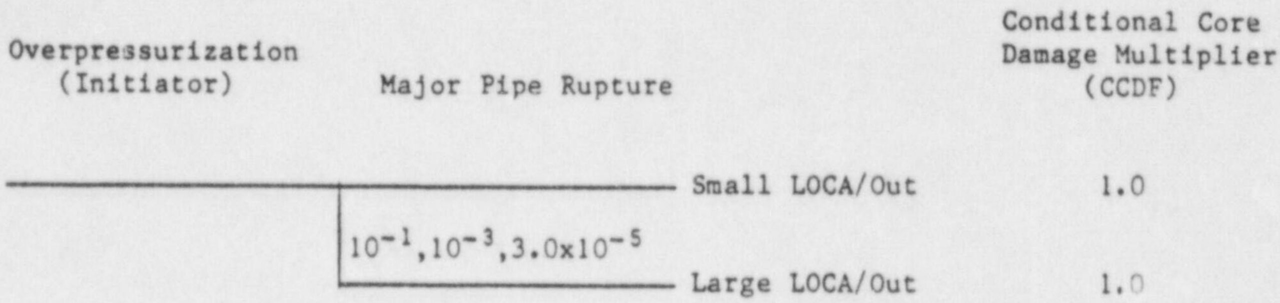


Figure 5.1 ISL Event Trees - LP injection, Oconee and Calvert Cliffs stations.

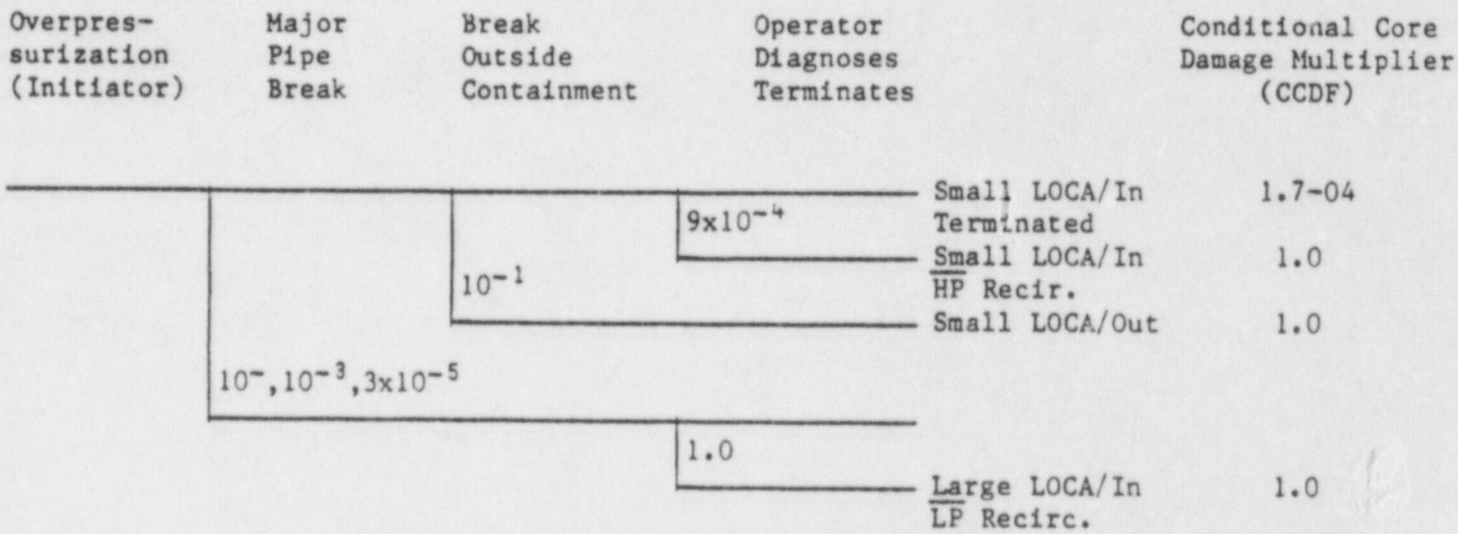


Figure 5.2 ISL Event Trees - LP injection, Indian Point Station.

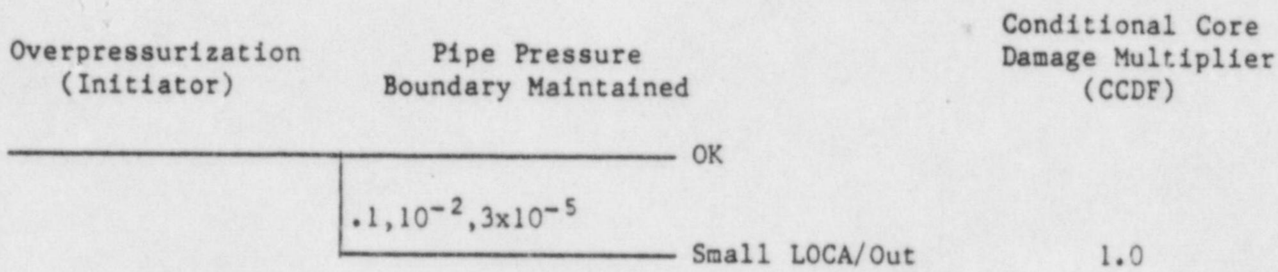
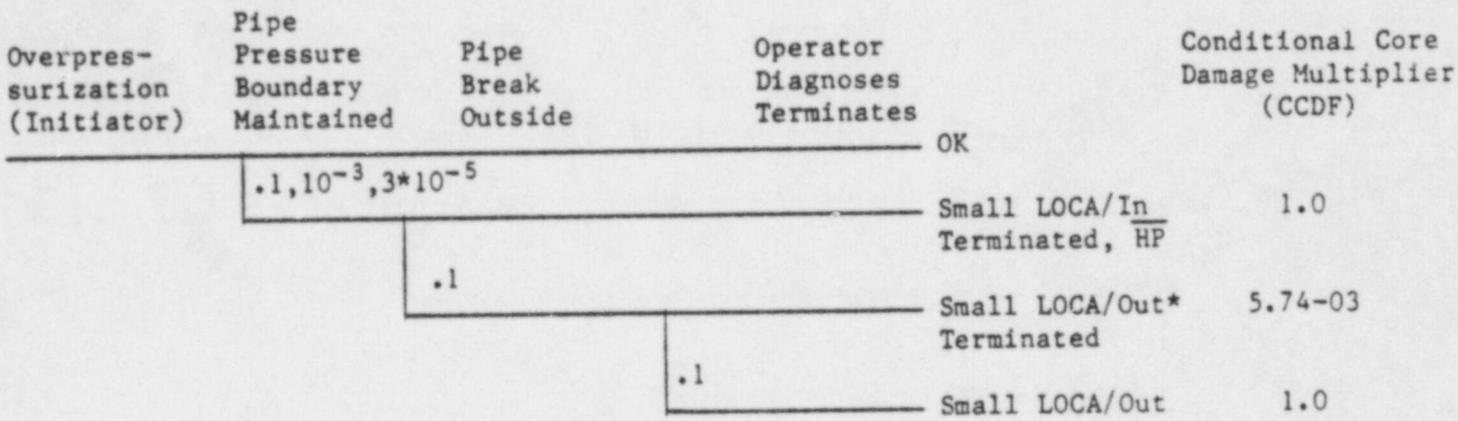


Figure 5.3 ISL event tree - SI discharge, Calvert Cliffs station.



*CCDF calculated with one side in failed mode.

Figure 5.4 ISL event tree - SI discharge, Indian Point Station.

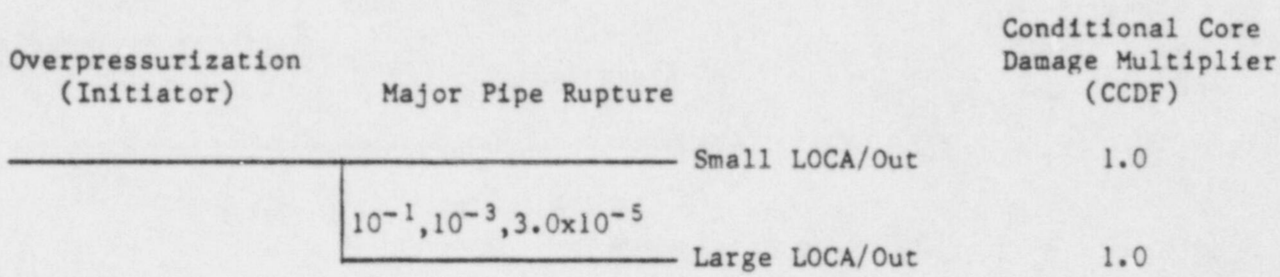


Figure 5.5 ISL event trees - RHR suction, Calvert Cliffs Station.

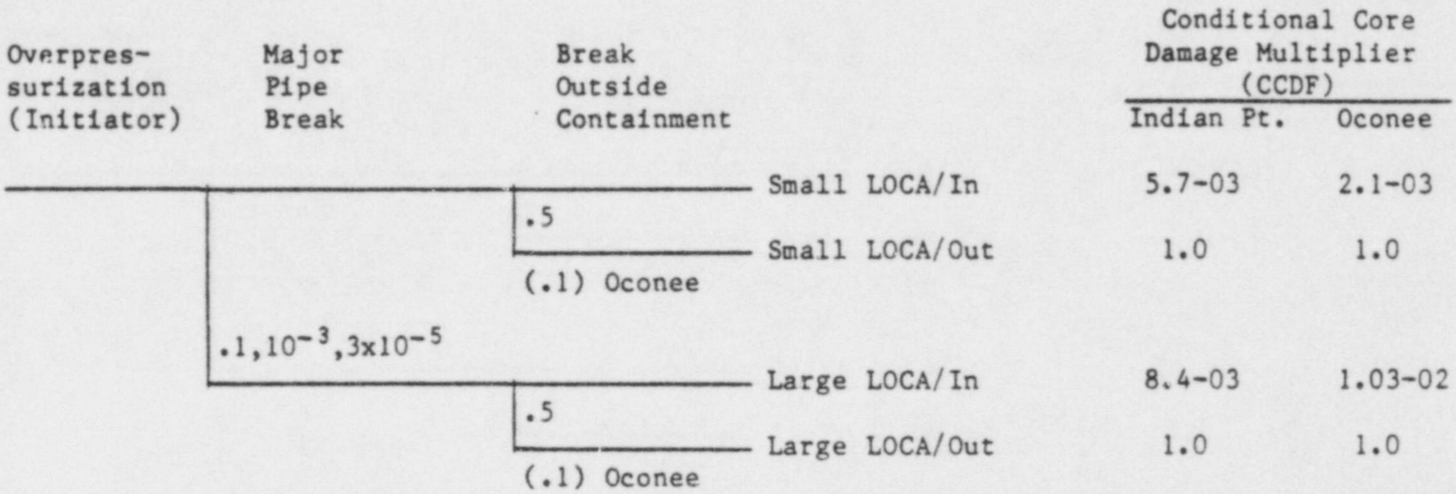


Figure 5.6   ISL event trees - RHR suction, Indian Point and Oconee Stations.

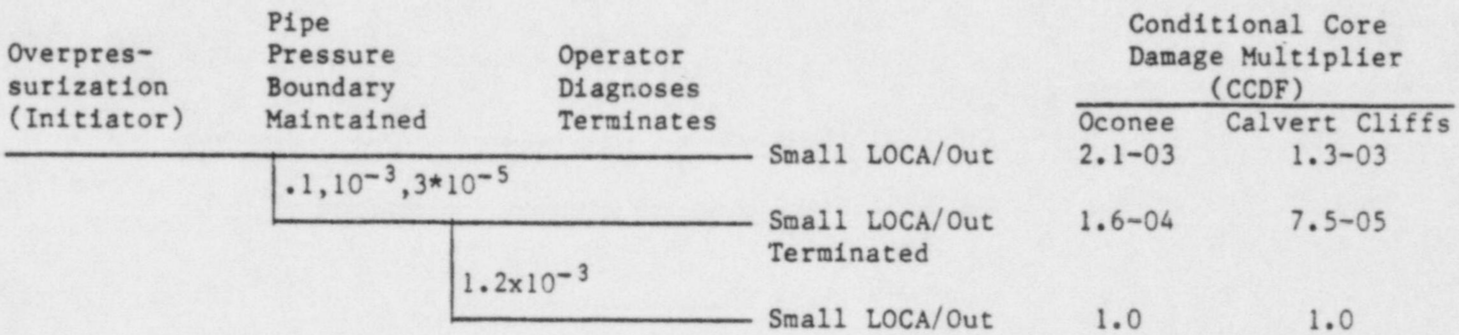
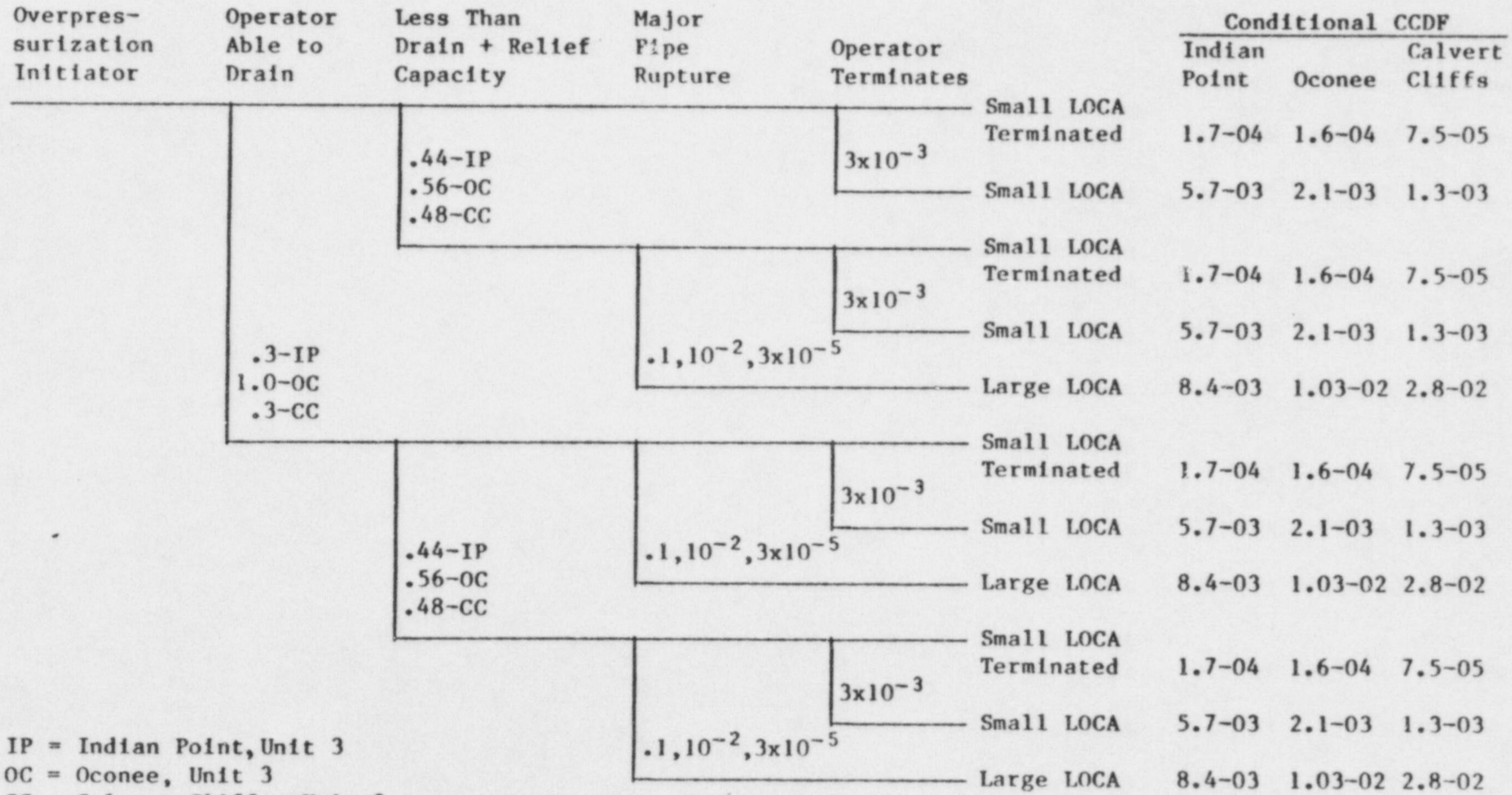


Figure 5.7 ISL event trees - Letdown lines, Oconee and Calvert Cliffs Stations.



IP = Indian Point, Unit 3
OC = Oconee, Unit 3
CC = Calvert Cliffs, Unit 2

Figure 5.9 ISL event trees - Accumulators.

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Table 5.1
Conditional Core Damage Frequencies for LOCAs

	Indian Point	Oconee	Calvert Cliffs
No Operator Action			
Large LOCA Inside Containment	8.4-03	1.03-02	2.8-02
Small LOCA Inside	5.7-03	2.10-03	1.3-03
Large LOCA Outside	1.0	1.0	1.0
Small LOCA Outside	1.0	1.0	1.0
LOCA Terminated by Operator			
Small LOCA Inside	1.7-04	1.6-04	7.5-05
Small LOCA Outside	1.7-04	1.6-04	7.5-05
Special Case			
Small LOCA Inside One Train of HP System Not Available	5.74-03		

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Table 5.2a
Core Damage Frequency
Indian Point

System	Overpressurization Initiator	P(Rupture)	Sum of Event*CCDF	CDF/Year
LPI	5.33-06	1.00-01	1.91-01	1.02-06
		1.00-03	1.02-01	5.44-07
		3.00-05	1.01-01	5.38-07
SI*	1.39-04	1.00-01	9.12-02	1.27-05
		1.00-03	9.12-04	1.27-07
		3.00-05	2.74-05	3.81-09
RHR Suction	9.80-07	1.00-01	5.03-01	4.93-07
		1.00-03	5.03-01	4.93-07
		3.00-05	5.02-01	4.92-07
Letdown* (Includes relief valve opening)	2.28-03	1.00-01	7.73-05	1.76-07
		1.00-03	7.73-07	1.76-09
		3.00-05	2.31-08	5.77-11
Accumulators	4.64-03	1.00-01	6.85-04	3.18-06
		1.00-03	1.39-04	6.45-07
		3.00-05	1.35-04	6.26-07
TOTAL (CDF due to overpressurization)		1.00-01		1.76-05
		1.00-03		1.81-06
		3.00-05		1.66-06

Note: P(Rupture) = Probability of a major pipe rupture.
*For this system P(Rupture) = Probability of pipe pressure boundary NOT maintained.

Table 5.2b
Core Damage Frequency Without Overpressurization
Indian Point

System	Initiator*	CCDF (Small LOCA)	CDF/Year
LPI	3.53-06	5.7-03	2.01-08
SI	4.13-04	5.7-03	2.35-06
RHR	1.70-05	5.7-03	9.69-08
Total (CDF w/o overpressurization)			2.47-06

*No overpressurization relief valves open.

Table 5.3a
Core Damage Frequency
Oconee

System	Overpressuriztaion Initiator	P(Rupture)	Sum of Event*CCDF	CDF/Year
LPI	5.58-07	1.00-01	1.00	5.58-07
		1.00-03	1.00	5.58-07
		3.00-05	1.00	5.58-07
RHR Suction	1.44-06	1.00-01	1.00-01	1.44-07
		1.00-03	1.00-01	1.44-07
		3.00-05	1.00-01	1.44-07
Letdown* (Includes relief valve opening)	2.28-03	1.00-01	1.36-04	3.10-07
		1.00-03	1.36-06	3.10-09
		3.00-05	4.08-08	9.30-11
Accumulators	4.10-03	1.00-01	1.18-03	4.84-06
		1.00-03	1.76-04	7.72-07
		3.00-05	1.60-04	6.81-07
TOTAL (CDF due to over-pressurization)		1.00-01		5.85-06
		1.00-03		1.43-06
		3.00-05		1.38-06

Note: P(Rupture) = Probability of a major pipe rupture.
*For this system P(Rupture) = Probability of pipe pressure boundary NOT maintained.

Table 5.3b
Core Damage Frequency Without Overpressurization
Oconee

System	Initiator*	CCDF (Small LOCA)	CDF/Year
LPI	6.10-08	2.1-03	1.28-10
RHR	5.04-05	2.1-03	1.06-07
Total (CDF w/o over-pressurization)			1.07-07

*No overpressurization relief valves open.

Table 5.4a
Core Damage Frequency
Calvert Cliffs

System	Overpressurization Initiator	P(Rupture)	Sum of Event*CCDF	CDF/Year
LPI	3.40-09	1.00-01	1.00	3.40-09
		1.00-03	1.00	3.40-09
		3.00-05	1.00	3.40-09
SI*	7.18-10	1.00-01	1.00-01	7.18-11
		1.00-03	1.00-03	7.18-13
		3.00-05	3.00-05	2.15-14
RHR Suction	1.45-06	1.00-01	1.00	1.45-06
		1.00-03	1.00	1.45-06
		3.00-05	1.00	1.45-06
Letdown* (Includes relief valve opening)	2.28-03	1.00-01	1.27-04	2.90-07
		1.00-03	1.27-06	2.90-09
		3.00-05	3.81-08	8.69-11
Accumulators	5.98-03	1.00-01	1.85-03	1.11-05
		1.00-03	9.65-05	5.77-07
		3.00-05	7.92-05	4.74-07
TOTAL (CDF due to overpressurization)		1.00-01		1.28-05
		1.00-03		2.03-06
		3.00-05		1.93-06

Note: P(Rupture) = Probability of a major pipe rupture.
*For this system P(Rupture) = Probability of pipe pressure boundary NOT maintained.

Table 5.4b
Core Damage Frequency Without Overpressurization
Calvert Cliffs

System	Initiator*	CCDF (Small LOCA)	CDF/Year
LPI	5.2-10	1.3-03	6.76-13
SI	3.2-09	1.3-03	4.16-12
RHR	1.75-05	1.3-03	2.27-08
Total (CDF w/o overpressurization)			2.27-08

*No overpressurization relief valves open.

Table 5.5
Core Damage Frequency
Summary

Plant	P(Rupture)	Total CDF Due to Overpres-surization	Total CDF Without Overpres-surization	Total CDF/Year	CDF* in PRA (/Year)
Indian Point	1.00-01	1.76-05	2.47-06	2.01-05	1.18-04
	1.00-03	1.81-06		4.28-06	
	3.00-05	1.6[illegible]-06		4.13-06	
Oconee	1.00-01	5.85-06	1.07-07	5.96-06	1.59-05
	1.00-03	1.45-06		1.54-06	
	3.00-05	1.38-06		1.49-06	
Calvert Cliffs	1.00-01	1.28-05	2.27-08	1.28-05	3.34-05
	1.00-03	2.03-06		2.05-06	
	3.00-05	1.93-06		1.95-06	

*Due to LOCA only.

Table 5.6
Core Damage Frequency Due to ISL
Bypassing Containment

Plant	P(Rupture)	Total CDF/Year ISL Outside Containment	CDF* in PRA (/Year)
Indian Point	1.00-01	1.27-06	1.18-04
	1.00-03	1.03-06	
	3.00-05	1.02-06	
Oconee	1.00-01	1.49-06	1.59-05
	1.00-03	7.05-07	
	3.00-05	7.02-07	
Calvert Cliffs	1.00-01	2.04-06	3.34-05
	1.00-03	1.45-06	
	3.00-05	1.45-06	

*Due to LOCA only.

APPENDIX B: Analysis of Valve Failure Data

This appendix provides the documentation of valve failure data used to calculate the initiator frequencies of Interfacing System LOCAs (ISLs) in various pathways. It describes the approach used in the derivation of new failure rates and gives the sources for those which were previously determined.

B.1 Check Valve Failure Rates

In the initiation of an ISL through ECCS injection lines, essentially three check valve failure modes are considered:

1. Check valve gross reverse leakage,
2. Check valve failure to operate on demand, and
3. Check valve disc rupture.

The following subsection discusses the data sources for each of the failure modes.

B.1.1 Check Valve Gross Reverse Leakage

B.1.1.1 General

In spite of the fact that various nuclear industry data sources have failure rate values for this failure mode, a cursory survey of the data showed, that the available data are not suitable for ISL analysis. The available data are related to a conglomerate of check valves of different type, size and make, which are built into various reactor systems. It was recognized at the start of the study, that the knowledge of the specific value of gross reverse leakage failure rate of check valves in the RCS/ECCS interface plays a crucial role in the ISL analysis. It was also recognized, that small or large leak flow rate result in markedly different accident developments. Therefore, it was clear that specific information was required about the frequency of exceeding certain leakage flows through the valves and that information needed to be able to be extracted from available data.

In order to satisfy above requirements, special data collection and analysis were performed and are described below.

B.1.1.2 Data Collection

A computer search was conducted in the LER data base for check valve failures occurring in the RCS/ECCS interface. The events selected were reported in Tables 3.1 and 3.3. Since then, the "efficiency" of the event selection has been cross-checked by conducting a similar search in the Nuclear Power Experience data source, which is an LER-based compilation of failure events. This new search and a comparison with the results of an independent search conducted at Pickard, Lowe and Garrick, Inc. for the Seabrook Station Risk Management and Emergency Planning Study (PLG-0432),[1] proved that our search process was highly efficient.

The cross-check covered the time period from 1972 to the end of 1985. The failure events selected are shown in Table B.1. The format of Table B.1 is somewhat different from the format of Table 3.1 and 3.3. The present format was developed to serve our further analysis. It contains the NPE number for facilitating better event identification, the name of the specific ECCS system involved (Accumulator, LPI, HPI) and direct or indirect information about the leak rate. The latter involves such evidences as: the rate of boron concentration changes and rate of pressure reduction in the accumulators. The table also contains the estimated leak rates. The approach used to estimate the leak rate was essentially similar to that of Ref. 1: the utilization of the direct or indirect flow rate information. If there were no such information available, the similarity to other occurrences for which the leak rates were known was applied.

An inspection of Table B.1 shows, that the majority of failure events are failures of the check valves in the accumulator outlet lines. This apparent bias might be due to the continuous monitoring of the accumulators, or it might reflect a particularly severe environment acting on the valves. An additional difficulty related to the interpretation of the leakage flow rates derived from accumulator inleakages. Accumulator inleakages from the RCS represent leakage through two check valves in series, where the less leaking valve dominates (the other valve may even be wide open). Thus, the leakage flow rate values derived from RC leakage into the accumulators are essentially lower limits for these quantities. In order to clarify the causes of the apparent bias and extract maximum information from the data, the following event analysis was carried out.

B.1.1.3 Event Analysis

B.1.1.3.1 Event Categories

The failure events of Table B.1 were grouped into four categories:

1. Events whose description contains evidence of RC leakage into the accumulators. These events are considered to be accumulator inleakages through two failed check valves in series; A(2). The total number of A(2) events is: $N_{A(2)} = 28$. (It represents 56 check valve failures.)

2. Accumulator leakage events, whose description contains evidence only about one leaking check valve; A(1). (The water source is assumed not to be the RCS.) The total number of A(1) events is: $N_{A(1)} = 8$.

3. Leakage events of check valves in the common injection header of accumulator, LPI and HPI lines. Accumulator inleakages are not associated with these events. The leakages are directed into the LPI/HPI systems. These events are denoted by: LP. The total number of check valves in LP events is: $N_{LP} = 2$.

4. Leakage events of check valves on other HPI lines not associated with the accumulator injection header. These events are denoted by HP. There is only one such event in Table B.1; representing three check valve leakage failures: $N_{HP} = 3$.

Since our main concern is to find an explanation for the high frequency of failure events associated with the accumulators, the events in the first three groups are subject to further analyses.

B.1.1.3.2 Interpretation of Accumulator Leakage Events, A(2)

Succeeding steps in the data analysis require some further understanding about the possible origins of events A(2). For that purpose the schematic of the check valve arrangements at the RCS/Accumulator, LPI, HPI interface is presented in Figure B.1. The figure indicates the pressure conditions at the interface under ideal normal reactor operations when the check valves are perfect. P_1, P_2, and P_3 denote the pressures in the RCS, in the accumulator and in the LPI, HPI systems, respectively.

We are interested in the pressure conditions in the piping section between the check valves CV1, CV2, and CV3. (An additional check valve CV4 is also there if the design is such that the HPI line joins the LPI header downstream from CV3.)

It is easy to see that, when the check valves are operating, the pressure between the valves is that of the accumulator, P_2. Since $P_1>P_2>P_3$, (where P_2, the pressure of N_2 filling in the accumulator is much higher than P_3, the hydrostatic pressure of the RWST) the pressure differences across the check valves CV1 and CV3 (and CV4) keep these valves closed. However, the accumulator outlet check valve, CV2 is essentially open. Consequently, the seat of this check valve is exposed to various damaging affects of the highly borated water of the accumulator. Under unfavorable temperature conditions boron can be deposited onto the seat or hinges of the valve disc. The affects of boric acid are different at the other check valves. At CV1, whose temperature is about the same as that of the RCS, boric acid stays in solution. At CV3 (and CV4), the effect of boric acid is much smaller than at CV2, because these check valves are closed.

Consider now what happens when a back-leakage develops through CV1. (An original "disc failing open" failure mode of CV1 must be excluded from consideration, because CV1 and other similar "front line" check valves are leak tested after RCS depressurization to ensure disc seating.) The sudden, ruling pressure in the space between the valves will become P_1, and the valve CV2 will close. CV3 (and CV4) will close even tighter because of the increased pressure difference across their discs. CV1 will have RCS pressure on both sides of its disc. At the same time, the check valves CV2 and CV3 (and CV4) will be exposed to the RC temperature. This is the situation, when CV2, CV3, and CV4 are operating. Due to the damaging effects of boric acid or boron deposition it is highly probable, however, that CV2 will not reclose.

Check valves also have a failure mode of "failure to operate (reseat) on demand" (see more about in in Section 1.2). The effects of boric acid may significantly enhance this probability for CV2. The effect of boric acid on CV3 (and CV4) is expected to be much less, because CV3 (and CV4) are always kept closed (unless they fail).

If CV2 recloses, it may develop backward leakage randomly in time with the same failure rate as previously CV1 had, because its disc is exposed now to the same differential pressure as previously CV1 was.

The level, pressure, temperature, and boric acid concentration of the accumulator is under constant surveillance. CV2 has high probability that is will not reclose completely upon demand. Consequently, even small leaks through CV1, have high potential for discovery.

Thus, it can be concluded, that the combination of two effects, the constant surveillance of the accumulators and the high probability that CV2 fails to operate on demand because of boric acid effects, provides a reasonable explanation for the high occurrence frequency of accumulator events, A(2).

The frequency of these events can be described by the expression given below (for more details see Section 4.3 of the main text, discussing the determination of ISL initiator frequencies for LPI pathways):

$$\lambda_{A(2)} = 2\lambda_1\left(\frac{\lambda_2 T}{2} + \lambda_{d2}\right) \equiv 2\lambda_1 C \qquad (1)$$

where, λ_1 and λ_2 the gross backward leakage failure rates of check valves CV1 and CV2, respectively,

λ_{d2} is the enhanced failure probability of CV2 to operate on demand, T is normally the time interval between the leak tests of CV1, when there is no other means to discover valve failures. Since the accumulators are constantly monitored, it is, T=0.

The quantity C, may be considered as "an effective leakage failure probability" of CV2.

λ_{d2} is expected to be much higher than the first term in the parenthesis. Thus, C is practically equal to the enhanced failure probability of CV2 to operate on demand.

B.1.1.3.3 Interpretation of Accumulator Leakage Events, A(1)

In order to interpret the origin of these events we refer again to the valve configuration shown in Figure B.1. Consider the case, when CV1 is perfectly seated. Leakage into the accumulator through CV2 still can occur, if:

a) for some reasons, the N_2 pressure in the accumulator, P_2 falls below the hydrostatic pressure of the RWST, P_3 (i.e., $P_3 > P_2$) and CV2 does not reclose upon this challenge, or

b) for some reasons, e.g., due to inadvertent initiation of the HPI pumps the pressure in the space between the valves suddenly increases such that $P_3 > P_2$ and CV2 does not operate upon this demand. Since these failure events are not associated with RC inleakage into the accumulators they are not analyzed further.

B.1.1.3.4 Interpretation of Leakage Events, LP

For the interpretation of these events we refer again to Figure B.1. We recall the situation described in Section B.1.1.3.2, when CV1 leaks and CV2 is operating. i.e., CV2 recloses upon demand and does not develop leakage randomly. If there is no safety valve connected to the space between the valves, the overpressurization of the space between the valves is hard to detect. Leakage tests on CV1 leads to the discovery of the valve failure.

Consider now the case when both check valves, CV1 and CV2 are operating, but CV3 or CV4 leaks ($P_2>P_3$). It is hard to detect the failure because successive check valves upstream in the injection lines will probably reclose. As in the former case, leakage test leads to the discovery of the failures.

The frequency of LP events, i.e., the frequency of check valve back leakage failures which are not accompanied by check valve failure in the accumulator line, can be described by the expression:

$$\lambda_{LP} = \lambda_1(1-C), \qquad (2)$$

where λ_1 is the leakage failure rate of the individual check valves (considered to be the same for each check valve, CV1, CV3, or CV4) and C is the "effective leakage failure probability of CV2" defined in expression (1).

Additional failure combinations of CV1 and CV3, or CV1 and CV4 are discussed in Section 4.3, of the main text, where the ISL initiator frequencies are calculated.

B.1.1.4 Data Reduction

B.1.1.4.1 General

The following approach has been applied in the data reduction:

1) Expressions (1) and (2) are equated to the maximum occurrence frequencies of events A(2) and LP. The obtained system of equations is solved for the "effective leakage probability," C of the accumulator check valve, CV2.

2) Expressions (1) and (2) are equated to the experienced frequences of events A(2) and LP in various leak rate groups. By solving the equations for the leakage failure rate, a leakage exceedance frequency versus leak rate curve is calculated.

B.1.1.4.2 Determination of the Effective Leakage Probability, C for the Accumulator Check Valve, CV2

The maximum occurrence frequencies (frequency/hour) of events A(2) and LP are determined by using expressions (1) and (2), respectively, as follows:

$$\lambda_{A(2)}^{max} = 2\lambda_1^{max} C = \frac{2N_{A(2)}}{T_A} , \tag{I}$$

and

$$\lambda_{HP}^{max} = \lambda_1^{max}(1-C) = \frac{N_{LP}}{T_{LP}} , \tag{II}$$

where λ_1^{max} denotes the maximum LP leakage failure frequency,

$N_{A(2)}$ and N_{LP}, are the total number of failure events of event categories (1) and (3) (see Section B.1.1.3.1),

T_A and T_{LP} the total number of check valve $\geq$ hours for check valve populations in accumulator and LPI lines, respectively at all PWRs.

The solution of the system of equations (I) and (II) for C, is:

$$C = \frac{N_{A(2)}}{N_{A(2)} + N_{LP}k} , \tag{III}$$

where $k = T_A/T_{LP}$, $N_{A(2)} = 28$, $N_{LP} = 2$ (from Section B.1.1.2.1).

The total number of check valve hours, $T_{A(2)}$ and T_{LP} are given in Table B.2, as:

$T_{A(2)} = 2.369 \times 10^7$ and $T_{LP} = 2.266 \times 10^7$.

Additional details about the determination of total number of check valve hours are discussed in Section B.1.1.4.4.

From the data above the "effective leakage probability" of the accumulator check valve, CV2 is (k=1.045):

$$C = .93 \tag{III'}$$

As it was explained in Section B.1.1.3.2, C is practically equal to the probability of "failure to operate on demand" of CV2. The value is high because of the presence of the boric acid. The valve obtained is in agreement with the expectation.

The significance of the high value of C for the initiation of ISLs through LPI lines is important. It means that CV2 behaves as a kind of safety valve and the preferred direction of the ISL will be through the accumulator and not through the LPI (or HPI) pathways.

B.1.1.4.3 Calculation of a Leakage Exceedance Frequency Versus Leak Flow Rate

The leakage events, A(2) can LP, were grouped into five leak flow ranges. For each group, a frequency per hour value is calculated by using the total check valve hours given above. By equating expressions (1) and (2) to the frequencies of the i-th leak flow range one obtains the following system of equations:

$$\lambda_{A(2)}^{(i)} = 2\lambda_1(i)C = \frac{2n_{A(2)}^{(i)}}{T_A} \qquad \text{(I')}$$

$$\lambda_{LP}(i) = \lambda_1(i)(1-C) = \frac{n_{LP}(i)}{T_{LP}} \qquad \text{(II')}$$

Here, $\lambda_1(i)$ denotes the leakage failure frequency of a check valve in the i-th leak flow range and $n_{A(2)}(i)$ and $n_{LP}(i)$ are the number of leakage events of event categories (1) and (3) in the i-th leak flow range.

Solving the system of equations (I') and (II') for $\lambda_1(i)$, one obtains:

$$\lambda_1(i) = \frac{1}{T_{LP}} \left(n_{LP}(i) + \frac{n_{A(2)}^{(i)}}{k}\right)$$

Considering, that k=1.0,

$$\lambda_1(i) = \frac{1}{T_{LP}} (n_{LP}(i) + n_{A(2)}(i)) \qquad \text{(III')}$$

Table B.3 shows the sum of leakage events and the leakage failure frequencies calculated according to formula (III') for the five leak flow ranges. Table B.3 shows also the corresponding cumulative frequency values. The cumulative frequency values are also plotted as a function of the leak flows in Figure B.2.

The cumulative frequency values are fitted graphically with a straight line (on a log-log scale) to facilitate inter- or extrapolation. The application of straight line fit is supported by the generic experience, that "percolation type" physical process, like leakage through two openings, follow exceedance frequency distributions of Pareto type (i.e., a kind of power low).

It has to be recognized that the curve in Figure B.2 is only a first approximation for a more precise leak exceedance frequency versus relative leak rate curve, which should be based on single valve leakage data and more homogeneous check valve sizes.

For further applications of the exceedance leak frequency data, a stretched statistical range factor (ratio of the 95th to the 5th percentile of lognormal probability density function), RF=10 is assigned to them (stretched from RF=4). This large value accounts for the uncertainty in the classification and leak flow rate grouping of the data, estimation of the total exposure time and applicability of the approach used for event interpretation and data reduction.

B.1.1.4.4 <u>Total Exposure Times of Check Valves in Accumulator and LPI Lines</u>

This section provides some additional information about the determination of total exposure times for check valves in the accumulator and LPI lines.

Table B.2 details the accumulator and LPI check valve hours for each PWR considered and presents the total exposure times, $T_{A(2)}$ and T_{LP}. Usually the FSARs of various PWRs were used to obtain the number of check valves in the relevant lines. The total time from start of commercial operation of the individual plants was taken as "time of exposure per check valve." This was done because corrosion effects (e.g., corrosion due to boric acid) continuously degrade the internals of the valves.

B.1.2 Check Valve Failure to Operate on Demand

B.1.2.1 General

The situation, concerning the usefulness of the available data sources on "check valve failure to operate on demand" failure mode, was similar to that of the reverse leakage failure mode discussed in Section B.1.1.1. The data sources do not specify "failure to open" and "failure to close" modes separately and there is no data on the subsets of check valves in the interfacing lines.

B.1.2.2 Data Collection

From a larger set of failure events collected with the search process described in Section B.1.1.2 a subset was selected which is considered to be representative for check valve fails to reclose stuck open mode. The events are listed in Table B.4, whose format is similar to Table B.1. From all the events listed the LPI and HPI events are taken to estimate the probability of the failure mode. The total number of failed check valves involved in these events are 9.

The corresponding success data (number of demand) are developed on the LPI check valve population and plant age. The HPI check valve population in the interfacing lines is assumed to be equal to that of the LPI. An average of 10 system wide demands per year is considered for the success estimate.

B.1.2.3 Data Reduction

The total number of check valve years for LPI check valves from Table B.2 is 2.587×10^3. This value based on the above considerations results in the following total number of check valve demands in the LPI and HPI interfacing lines: Check valve demands (LPI and HPI) = $2 \times 10 \times 2.587 \times 10^3 = 5.174 \times 10^4$.

The corresponding probability of failure to reclose on demand is

$$\lambda_d^{\text{Median}} = \frac{9}{5.174 \times 10^4} = 1.74 \times 10^{-4} \text{ per demand.}$$

The range factor assigned to characterize the uncertainty is RF=5. Thus,

$\lambda_D^{\text{Mean}} = 2.81 \times 10^{-4}$ per demand, and the expectation value of its square is:

$$\langle \lambda_D^2 \rangle = (\lambda_D^{\text{Mean}})^2 + \text{var.} = 2.05 \times 10^{-7} \text{ per demand}^2 .$$

The result obtained is in agreement with that of obtained in Ref. 1 applying different basic data:

$\lambda_d(\text{Median}) = 1.58 \times 10^{-4}$ per demand.

B.1.3 Check Valve Disc Rupture

Till the end of 1985 the nuclear industry had not reported any check valve disc rupture events. The closest failure event to this category is what happened at Davis Besse-1 (NPE # VII.A.273, IE Info. Notice 80-41) when a disc and arm had separated from the body in an LPI isolation check valve. The PSA Procedures Guide[2] lists an estimated value based on expert opinions for the disc rupture failure rate, as 1.0×10^{-7}/hour. The guide's value practically coincides with the exceedance frequency of the maximum experienced leak flow (200 gpm) in Figure B.2. Since there is no experienced event for this failure made in the nuclear industry, the leakage failure rates applied in this study are considered as conservative upper bounds for the disc rupture frequency.

B.2 Motor-Operated Valve Failure Rates

The following failure modes of MOVs are considered in the calculation of ISL initiator frequencies:

1. MOV disc rupture.
2. MOV internal leakage.
3. MOV disc failing open while indicating closed.
4. MOV transfer open.
5. MOV failure to close on demand.
6. MOV gross (external) leakage.

The subsection below discusses the data sources for each of the failure modes.

B.2.1 MOV Disc Rupture

Available data sources had no data on this catastrophic MOV failure mode based on experienced data. A LER search for this failure mode at PWRs could not identify any such event. However, a search conducted for the study of ISLs at BWR[3] found five events in which valve disc was separated from the stem. The MOV disc rupture failure rate estimated in that study is: 1.37×10^{-7} per hour. This value is applied also in the present calculations.

B.2.2 MOV Internal Leakage

This failure mode represents failures in which MOV leaks because of seat wear or other reasons. The failure mode is assumed to result in limited leakage through the valve. An LER search performed to identify such failures in motor-operated isolation valves. Three events were found in RHR suction valves. These are special valves with double discs (see Table 3.2). The total number of RHR suction valve-hours was calculated by using the number of reactor years of Table B.2 and RHR suction valve population of two or four per reactor for plants starting commercial operation before or after 1981. The total number of RHR suction valve-hours is 8.743×10^{6}. Therefore, the internal leakage failure rate for MOV events divided by the number of valve hours is

$3.43x10^{-7}$ per hour. Estimated range factor, RF=5. The corresponding mean value, λ_{MOV}^{Mean}: $4.85x10^{-3}$ per year. The expectation value of its square, $\langle\lambda_{MOV}^{2}\rangle = (\lambda_{MOV}^{Mean})^2 + var. = 6.12x10^{-5}$ per year^2.

B.2.3 MOV Disc Failing Open While Indicating Closed

This type of failure mode may arise at MOVs, which are not equipped with stem-mounted limit switches from gear drive disengagement. At valves which are equipped with limit switches it arises from failure of the stem or other internal connections or failure of a limit switch (including improper maintenance such as reversing indication). The failure may occur after the valve being opened. As a result, the valve is leaking while the indication in the control room signals that the valve is closed. It is expected, that this failure mode is giving rise small leakage.

The failure rate applied in this study is taken from the Seabrook PSA,[4] where it was obtained from data reported in NPE. The mean frequency of "failure of an MOV to close on demand and indicate closed" is $1.07x10^{-4}$/demand.

B.2.4 MOV Transfer Open

"MOV transfer open" failure mode defines such MOV failure, when a closed MOV inadvertently opens due to failures of valve control circuits and power supplies or due to human errors during test or maintenance.

In the Seabrook PSA[4] the failure rate of this failure mode was estimated by using generic data to be $9.2x10^{-8}$ per hour. Table 4.4 has two events which can be classified as "MOV transfer open" failures for RHR suction valves. Taking the total RHR suction valve-hours, $T=8.743x10^{6}$ and these two events, one obtains a median failure rate of: $2.29x10^{-7}$ per hour. Estimated range factor: RF=5.

B.2.5 MOV Failure to Operate on Demand

MOV failure to operate on demand represents MOV failures in which a closed MOV suddenly opens upon demand, e.g., as various kind of shocks like pressure wave, sudden stress increases due to mechanical or thermal causes. This failure mode of MOV is a failure mode of "dependent" type and different from the retainer rupture failure mode of MOVs, which is a failure mode of random type.

An LER search to identify such events was futile. Therefore, in the calculation of ISL initiator frequencies instead of a guessed estimate the corresponding "check valve failure to operate on demand" (see Section B.1.2) failure rate is used as bounding value.

B.2.6 MOV External Leakage/Rupture

This failure mode of the MOVs is the most visible and detectable. The failure rate is given in various data sources. The data sources, however, do not provide information about the exceedance frequency of the failure as a function of the leak flow rate. A cursory review of some failure event reports showed that there is no appropriate information in the event descriptions about the leak rate. The LER search for failures of MOVs in the interfacing lines did not detect the occurrence of this failure mode. Thus, for the present report the generic value given in NUREG/CR-1363[3] for PWRs is taken. The failure frequency of MOV external leakage/rupture mode is 1.0×10^{-7} per hour. As first approximation to the variation of this value with the leak flow rate, the exceedance frequency vs. leak flow rate curve for check valves (Section B.1.1.4.3) is used.

B.3 References

1. "Seabrook Station Risk Management and Emergency Planning Study," PLG-0432, December 1985.

2. R. A. Bari et al., "Probabilistic Safety Analysis Procedures Guide," NUREG/CR-2815, August 1985.

3. L. Chu, S. Stoyanov, R. Fitzpatrick, "Interfacing Systems LOCA at BWRs," Draft Letter Report, July 1986.

4. "Seabrook Station Probabilistic Safety Assessment," PLG-0300, December 1983.

5. W. H. Hubble, C. F. Miller, "Data Summaries of LERs of Values," June 1980.

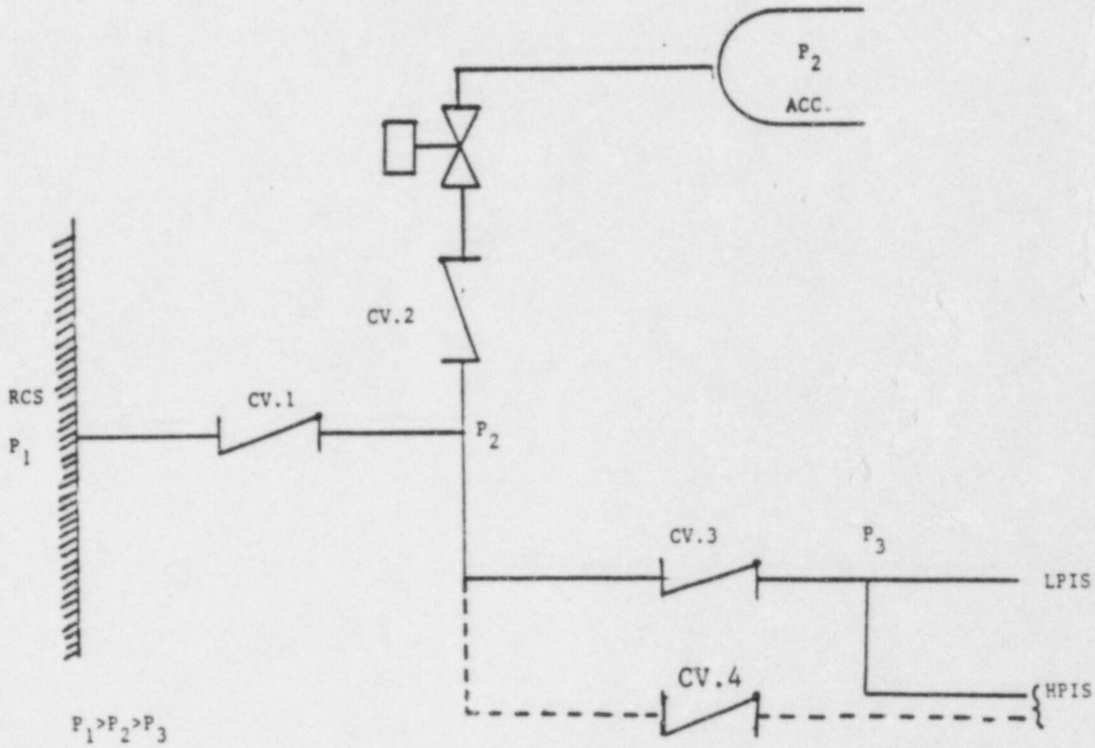

Figure B.1 Schematic of the valve arrangement at the RCS/ Accumulator, LPIs, HPIs interface. (An alternative joint of the HPI line to the LPI header is indicated by a broken line.)

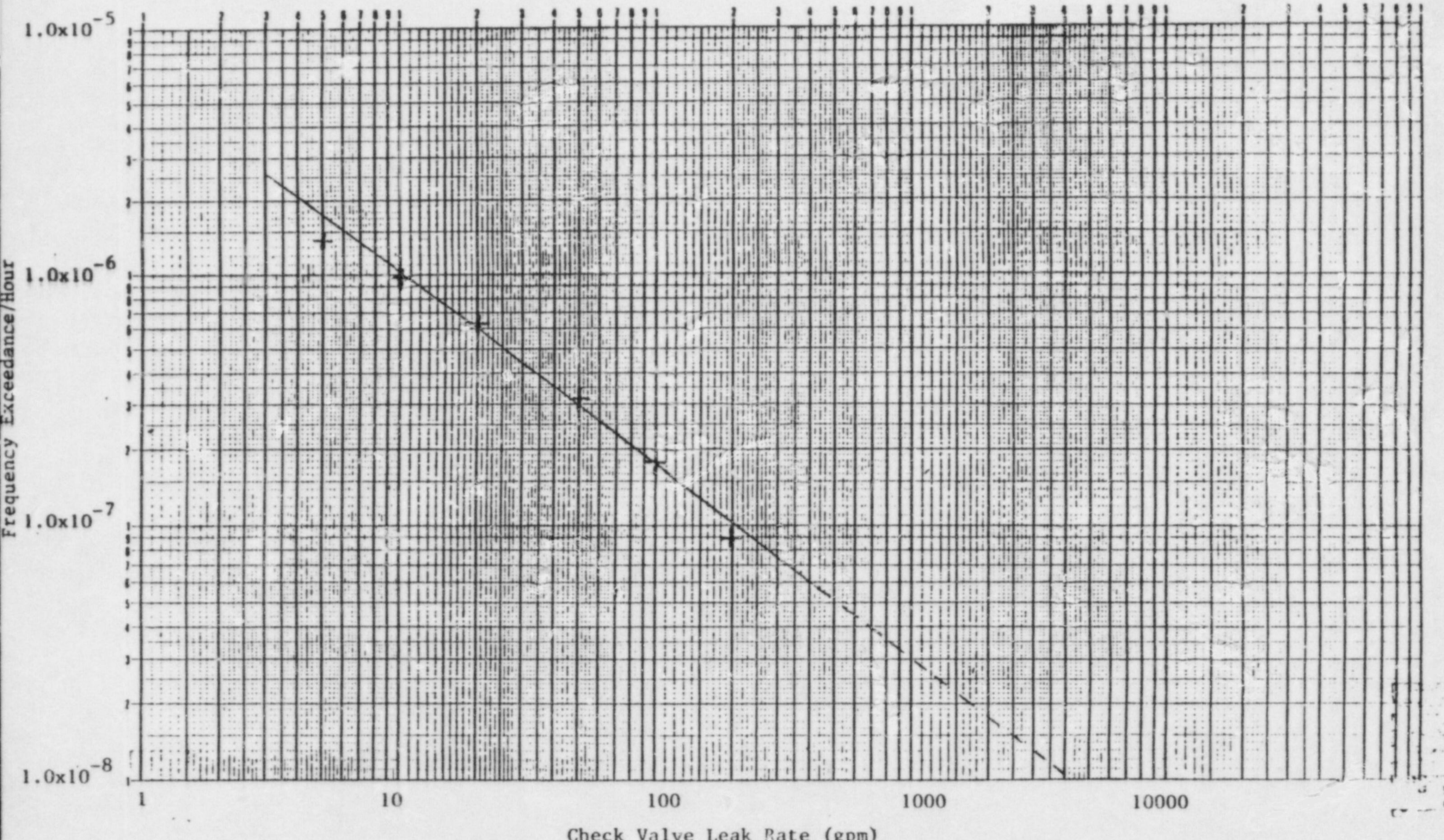

Figure B.2 Frequency of RCS/Accumulator, LPI pressure isolation check valve leakage events.

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Table B.1

Summary of Operating Events, Emergency Core Cooling System Isolation Check Valves, Leakage Failure Mode

Reference (NPE #)	Plant	Date	ECCS System	Event Description	Number of Check Valves Failed	Estimated Leak Rate (gpm)
VII.A.13	Palisades	5/72	ACC	Leakage into SI tank. The internals of a check valve on the outlet of an SI tank was incorrectly assembled.	1	$\gamma<5$
VII.A.25	Main Yankee	12/72	ACC	Leakage into SI tank. A small piece of weld slag had lodged under the seal of the outlet check valve allowing back leakage. Dilution: 1700 ppm (limit is 1720 ppm).	1	$\gamma<5$
VII.A.32	Turkey Point	5/73	HPI	One of the three check valves in the SI lines developed a leakage of 1/3 gpm. Two other check valves showed only slight leakage. Failure of soft seats.	3	$\gamma\leq.33$
VII.A.63	Ginna	9/74	ACC	Leakage of a check valve caused boron dilution in ACC. "A" (from 2250 ppm to 1617 ppm).	1	$\gamma<20$
VIII.A.85	Surry 1	8/75	ACC	Check valve did not seat. ACC ("IC") level increased. Leakage rate: ≈6 gpm.	1	$\gamma<10$
VII.A.126	Zion 2	10/75	ACC	Wrong size gasket installed in the check valve for ACC. "A". Leak rate: ≈.25 gpm.	1	$\gamma\leq.25$
VII.A.105	Robinson 2	1/76	ACC	Accumulator ("B") inleakage through leaking outlet check valve.	1	$\gamma<20$
V.A.122	Zion 1	6/76	ACC	Inleakage to ACC. "1D" from RCS.	2	$\gamma<20$
VII.A.114	Surry 1	7/76	ACC	Two check valves in series (1-SI-128, 130) leaked causing boron dilution in ACC. "B".	2	$\gamma<10$
VII.A.120	Surry 2	8/76	ACC	Boron dilution (from 1950 ppm to 1893) in SI ACC. "C" caused by leaking check valves (2-SI-145, 147).	2	$\gamma<10$
VII.A.225	Millstone 2	4/77	ACC	Inleakage of RC through outlet check valves to SI tank "4". Low boron concentration. Five occurrences in 1977.	2×6	$\gamma<20$
VIII.A.182	Calvert Cliffs 2	9/78	ACC	Outlet check valves for SI tanks 21B and 22B leaked. Boron concentration reduction from 1724 and 1731 ppm to 1652 and 1594 ppm in one month period.	4	$\gamma<10$ $\gamma<10$

Table B.1 (Continued)

Reference (NPE #)	Plant	Date	ECCS System	Event Description	Number of Check Valves Failed	Estimated Leak Rate (gpm)
VII.A.262	Crystal River 3	7/80	ACC	Check valve CFV-79 to core flood tank failed. The isolation valve to the N_2 system was open for N_2 mixing. ≈500 gallon liquid entered the N_2 system and ≈20 gallons was released. The corresponding activity released estimated as 1.07 mCi.	1+1	$100 < \gamma < 200$
VII.A.273 IE Info. Notice 80-41	Davis Besse 1	10/80	ACC	RHR system isolation check valve CF-30 leaked back excessively. Valve disk and arm had separated from the valve body. Bolts and locking mechanism were missing. Core flood tank overpressurized.	2	$50 < \gamma < 100$
VII.A.291	Surry 2	1/81	ACC	Accumulator ("C") boron diluted. Check valve (1-SI-144) leaked. Flushing system improperly set up, resulting in charging system pressure to exist on the downstream side of the check valve.	1	$\gamma < 10$
VII.A.301	Palisades	3/81	ACC	Leakage of RC into the SI tank (T-823).	2	$\gamma < 5$
VII.A.306	McGuire 1	4/81	ACC	Accumulator "A" outlet check valves IN-159 and IN-160 were leaking. RCS pressure: 1800 psig. Acc. pressure: 425 psig. Water level above alarm setpoint.	2	$\gamma < 10$
VII.A.307	McGuire 1	4/81	ACC	Similar events with Accs. "C" and "D".	2×2	$\gamma < 10$ $\gamma < 10$
VII.A.343	Point Beach 1	10/81	LPI	RCS/LPI isolation check valve (1-853C) leaks in excess of acceptance criteria (>6 gpm).	1	$\gamma < 10$
VII.A.384	Calvert Cliffs 1 & 2	7/82	ACC	Acc. outlet check valve at Unit 1 leaked due to deterioration of the disk sealing o-ring. The o-ring material has been changed on all check valves of Unit 1 and 2 1/2 SI-215, 225, 235, and 245.	2	$\gamma \leq 200$
VII.A.403	Surry 2	9/82	ACC	Acc. outlet check valve (2-SI-144) leaked RCS water into tank "C" during a pipe flush resulting in low boron concentration.	1	$\gamma < 20$
VII.A.396	Palisades	9-12/82	ACC	Minor leakage into SI tank (compounded by level indication failure) via check valve leakages.	2	$\gamma < 5$

Table B.1 (Continued)

Reference (NPE #)	Plant	Date	ECCS System	Event Description	Number of Check Valves Failed	Estimated Leak Rate (gpm)
VII.A.407	McGuire 1	5/83	ACC	RCS water inleakage through outlet check valves IN-170 and IN-171, resulting in low boron concentration in CLA "B".	2	$20<\gamma<50$
VII.A.437	Farley 2	9/83	LPI/ HPI	SI check valve to loop 3 cold leg was excessively leaking, incomplete contact between the valve disk and seat.	1	$50<\gamma<100$
LER 84-001	Oconee 1	3/84	ACC	Accumulator ("A") inleakage through leaking valves. Administrative deficiency, no management control over a known problem (since 8/83).	2	$\gamma<5$
V.F.0043 LER 84-012	Palisades	7/84	ACC	Accumulator inleakage through leaking check valves CK-3146 and CK-3116.	2	$\gamma<5$
VII.A.452	St. Lucie 2	12/84	ACC	Inleakage to SI tank. Seal plate cocked, valve seat compensating joint ball galled.	2	$20<\gamma<50$
VII.A.456	Calvert Cliffs 1 & 2	1/85	ACC	Inleakage to safety injection tanks through check valve, o-ring material degradation (Unit 1 = 1.6 gpm, Unit 2 = 27.2 gpm).	2	$\gamma<5$ $20<\gamma<50$
VII.A.457	McGuire 1	4/85	ACC	Low accumulator boron concentration.	2	$\gamma<5$
LER 85-007	Palisades	6/85	ACC	Inleakage from the RCS. Low level boron concentration.	2	$\gamma<5$
VII.A.474	Palisades	11/85	ACC	Accumulator (SIT-82D) inleakage from RCS Boron dilution (see Note 1).	2	$\gamma<5$

Note 1: The Palisades unit has a chronic accumulator inleakage problem.

Table B.2
Accumulator and LPI Check Valve Exposure Data

Plant Name	Start of Commercial Operation	Number of Years	Number of Accumulator Check Valves	Total Number of Accumulator Check Valve-Hrs. (10^5 Hours)	Number of LPI Check Valves	Total Number of LPI Check Valve-Hrs. (10^5 Hours.)
Arkanasas Nuclear One 1	December 1974	11.08	4	3.882	4	3.882
Crystal River 3	March 1977	8.83	4	3.094	4	3.094
Davis-Besse 1	November 1977	8.16	4	2.859	4	2.859
Oconee 1	July 1973	12.50	4	4.380	4	4.380
Oconee 2	March 1974	11.83	4	4.145	4	4.145
Oconee 3	December 1974	11.08	4	3.882	4	3.882
Rancho Seco	April 1975	10.75	4	3.767	4	3.767
Three Mile Island 1	September 1974	11.33	4	3.970	4	3.970
Three Mile Island 2	December 1978	7.08	4	2.481	4	2.481
Arkansas Nuclear One 2	March 1980	5.83	8	4.086	8	4.086
Calvert Cliffs 1	May 1975	10.67	8	7.478	12	11.217
Calvert Cliffs 2	April 1977	8.75	8	6.132	12	9.198
Fort Calhoun	September 1973	12.33	8	8.641	2	2.160
Millstone 2	December 1975	10.08	8	7.064	16	10.596
Maine Yankee	December 1972	13.08	6	6.875	9	10.312
Palisades	December 1971	14.08	8	9.867	2	2.467
St. Lucie 1	December 1976	7.08	8	6.363	8	6.363
Beaver Valley 1	April 1977	8.75	6	4.599	6	4.599
D. C. Cook 1	August 1975	10.42	8	7.302	4	3.651
D. C. Cook 2	July 1978	7.50	8	5.256	4	3.651
Indian Point 2	July 1974	11.50	8	8.059	9	8.954
Indian Point 3	August 1976	9.42	8	6.602	9	7.427
Joseph M. Farley 1	December 1977	8.08	6	4.247	6	4.247
Kewaunee	June 1974	11.58	4	4.058	4	4.058
North Anna 1	June 1978	7.58	6	3.984	8	5.312
Prairie Island 1	December 1973	12.08	4	4.233	3	3.175
Prairie Island 2	December 1974	11.08	4	3.882	3	2.588
Point Beach 1	December 1970	15.08	4	5.284	3	3.523
Point Beach 2	October 1972	13.25	4	4.643	3	3.095
R. E. Ginna 1	March 1970	15.83	4	5.547	-	---
H. B. Robinson 2	March 1971	14.83	6	7.795	2	2.598
Salem 1	June 1977	8.50	8	5.957	6	4.668
Surry 1	December 1972	13.08	6	6.875	6	6.875
Surry 2	May 1973	12.67	6	6.659	6	6.659
Trojan	May 1976	9.67	8	6.777	6	5.083
Turkey Point 3	December 1972	13.08	6	6.875	2	2.292
Turkey Point 4	September 1973	12.33	6	6.481	2	2.160
Yankee Rowe	June 1971	14.50	2	2.540	-	---
Zion 1	December 1973	12.08	8	8.466	14	14.816
Zion 2	September 1974	11.33	8	7.940	14	13.895
McGuire 1	December 1981	4.08	8	2.859	14	5.003
Sequoyah 1	July 1981	4.50	10	3.942	14	5.519
Sequoyah 2	June 1982	3.58	10	3.136	14	4.390
San Onofre	January 1968	18.0	-	---	3	4.730
Haddam Neck	January 1968	18.0	-	---	3	4.730
TOTAL				2.369(2)		2.266(2)

Table B.3
Statistical Data on Leakage Events of Pressure Isolation Check Valves to Accumulators and LPI Systems

Leak Rate (gpm)	Number of Leakage Events (A(2) + LP)	Frequency of Occurrence (per hour)	Frequency of Exceedance (per hour)
5	8	3.53(-7)	1.32(-6)
10	8	3.53(-7)	9.71(-7)
20	7	3.03(-7)	6.18(-7)
50	3	1.32(-7)	3.09(-7)
100	2	8.83(-8)	1.77(-7)
200	2	8.83(-8)	8.83(-8)

Table B.4

Summary of Operating Events, Emergency Core Cooling System, Isolation Check Valves, "Failure to Operate on Demand" Failure Mode

Reference (NPE #)	Plant	Date	ECCS System	Event Description	Number of Check Valves Failed
VII.A.175	San Onofre 1	5/78	LPI	Tilting disk check valve failed to close with gravity. It was installed in a vertical rather than a horizontal pipeline.	1
VII.A.270	Sequoyah 1	9/80	HPI	SI check valve 63-635 was found to be stuck open. It was caused by interference between the disk nut lockwire tack weld and the valve body.	1
VII.A.285	Salem 1	12/80	HPI	SI check valve failed to close during a test. It is an interface between RCS hot leg and SI pumps. Valve was found to be locked open due to boron solidification during the last refueling.	1
VII.A.294	Oconee 1	2/81	LPI	Reactor vessel LPI loop "B" isolation valve (GCF-12) leaked excessively during LOCA leak test. The valve disk had become frozen at the pivot in a cocked position. Buildup of deposit in the gap between the hinge and disc knob caused the freezing.	1
VII.A.302	Oconee 3	3/81	LPI	Similar to event at Unit 1 (valve involved is 3 CF-13).	1
VII.A.310	McGuire 1	5/81	ACC	Leak test damaged acc. check valves - seat type changed.	2
VII.A.311	McGuire 1	5/81	ACC	Acc. check valves failed.	2
VII.A.315	Point Beach 1	7/81	LPI	RCS/LPI isolation check valves 1-853 C and D were found to be stuck in the full open position. High leakage rate.	2
VII.A.392	ANO-2	10/82	HPI	SI isolation check valves 2 SI-13C and 2 SI-13B stuck in the open position during test requested by IE Notice 81-30. Disk stud protruded above nut, disk misaligned.	2

APPENDIX C: Operator Diagnosis and Post-Diagnosis Performance

Human behavior in response to an event, especially an abnormal event in a nuclear power plant, can be considered in three phases of activity: (1) observation of the event, (2) recognizing and/or diagnosing it, and (3) responding to it. Errors in each of these phases can be considered separately. However, there is much interaction between the various phases. In particular, phases 1 and 3 are very much controlled by phase 2 - the diagnosing stage. Failures in this stage are the most significant and basically constitute failures in cognitive behavior. The term cognitive behavior refers to the behavior that comprises structuring information, conceptualizing root causes and developing a response.

In regard to an abnormal event in a nuclear power plant cognitive behavior on the part of the operator consists of identifying the nature of the event, identifying the necessary safety-related responses and deciding how those responses can be implemented in terms of system operation. The main basis for estimating the reliability of operator action is primarily determined by the available time for that particular event before core damage occurs.

The numerical models for diagnosing an abnormal event by the control room team and carrying out the appropriate activities has been based on work described in Reference 1 (Handbook of HRA). Figure C.1 shows the basic diagnosis model, the probability of operations team diagnosis error in case of an abnormal event. The median joint human error probability (HEP) shows the probability of a team not diagnosing an abnormal event by a given elapsed time. The other lines represent the lower and upper error factors. The probability vs time curve was developed on the basis of a clinical speculation presented in Reference 2 at an National Reliability Evaluation Program data workshop. A hypothetical response time probability curve has been constructed using the general approach suggested in Reference 3 assuming lognormality for time to diagnosis rather than that the probability of failure is a logarithmic function of time.

In case the event is generally not practiced by the operators except in the initial training, the handbook[1] recommends the use of the upper bound joint HEP curve.

In this study a combination of upper bound HEP_{UB} and median HEP_M has been used (HEP_{UB} + $HEP_M/2$) reflecting on the fact, that even though LOCA events are well practiced, ISL events are not specifically recognized in the written procedures especially not on the system level.

For post-diagnosis performance the handbook recommends using single HEP values, which are applicable to activities to be carried out by the control room team following diagnosis of the problem. It is certain that actions will always be taken by the operators in response to an abnormal event, but only after the condition has been diagnosed will the operators refer to the appropriate written procedures (if any) to cope with the event.

In case of an ISL the initial signals are somewhat misleading indicating either a typical inside or outside LOCA event. The determination of the particular location of the break due to the ISL is extremely important, since systems required to mitigate the LOCA event might be affected.

In general, system specific ISL procedures are not available to the operator, but the loss-of-coolant phase is covered by the LOCA procedures.

Once the nature of the event has been correctly diagnosed an HEP of .2 has been used for carrying out post-diagnosis activities. The recommended HEP value of .05 is based on availability of well written specific procedures. However, for ISL events system specific procedures generally do not exist and an increased HEP value is judged to be more appropriate.

References

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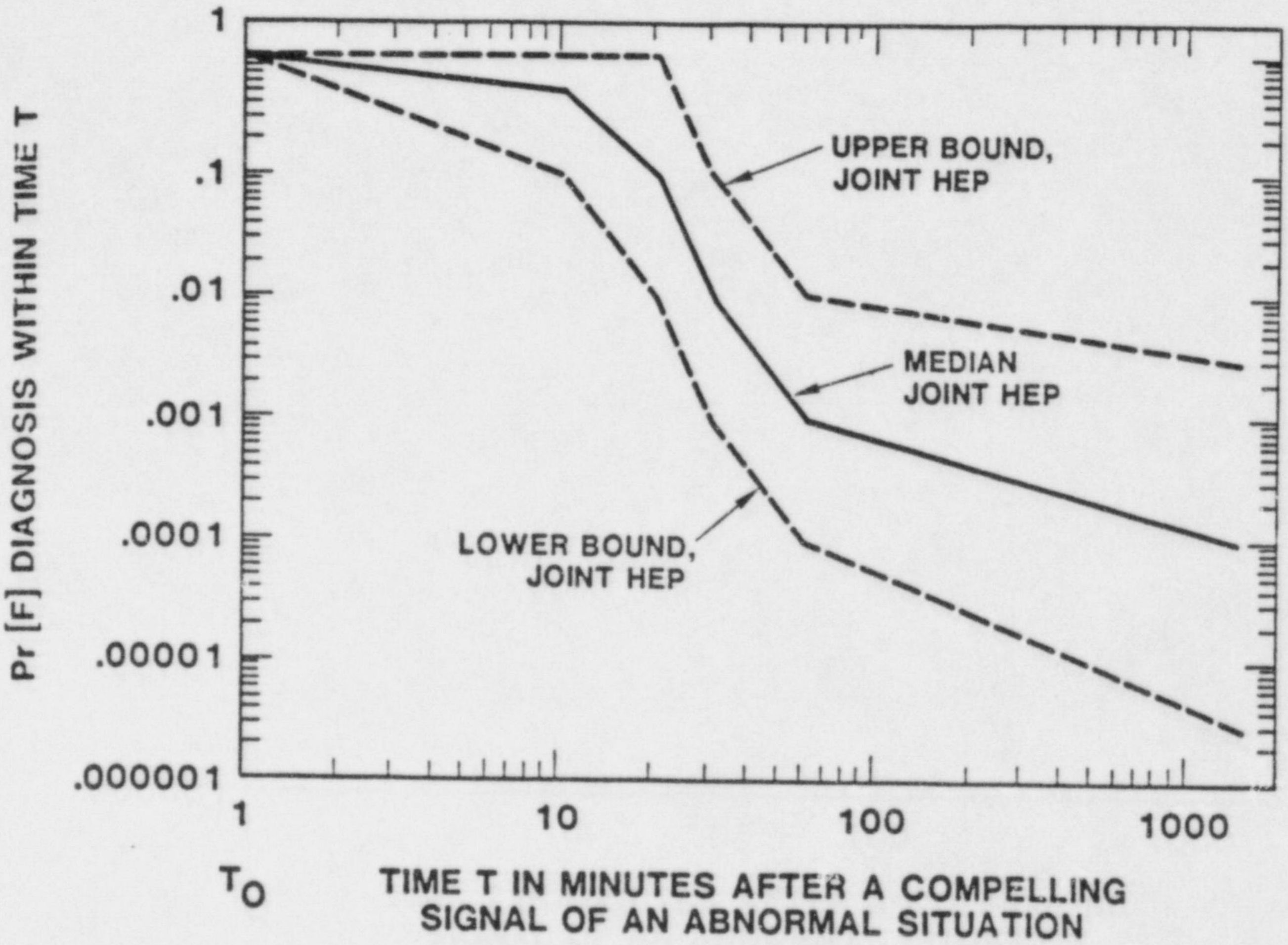

Figure C.1 Time curve for operator action.

APPENDIX D: Thermal-Hydraulic Aspects of Interfacing LOCAs

Interfacing LOCA bypassing the containment has been deterministically studied for typical cases[1] to assess the effect on core damage.

The LOCA sequence assumes the failure of the pressure boundary at isolating check valves and/or motor-operated gate valves. The low pressure system is overpressurized by the primary coolant and the system boundary fails outside the containment (pipe rupture or pump seal blowout, etc.). Depending on the mode of failure and its particular location, a large or small break LOCA can occur. In the following a brief summary of the deterministic calculations is given for these type of accident sequences.

D.1 Large and Medium LOCA (>2")

The transient is initiated by a large low pressure pipe break resulting in an extremely severe accident sequence.[1] Figures D.1 through D.3 describe the thermal-hydraulic history of this accident. Four parametric cases have been calculated. The base case indicates an accident sequence where no ECC injection is available. If the failure is such that pumped ECC injection is prevented, core damage is certain as indicated on Figure 2 even if accumulators are available. Core damage would occur at ~8 minutes after the break. The other parametric cases indicate that stable core cooling can be established with a minimum of one HPI pump available until the RWST inventory is depleted, which is in the order of 1-12 hours (Figure D.3). Long term cooling is a major concern since the water supply from the RWST is limited. In addition, recirculation system may be unavailable due to the postulated failure in the low pressure RHR system.

D.2 Small LOCA (<2")

The primary system in accident sequences with initial break size less than 2" in diameter will remain pressurized by one HPI pump (see Figure D.4). The reactor coolant system is refilled and subcooling is achieved. Core average temperature is determined by system-wide energy balance (Figure D.5) and in all cases the system would slowly cool until the RWST water supply is exhausted, which may be extended by throttling the HPI flow. Conditions for low pressure recirculation cooling are not met before the RWST supply runs out (8-15 hours). Long term cooling may also be of some concern, because the postulated failure could affect the capability of the HP and/or LP recirculation system.

References

1. J. F. Dearing et al., "Dominant Accident Sequences in Oconee-1 PWR," NUREG/CR-4140, Los Alamos National Laboratory, April 1985.

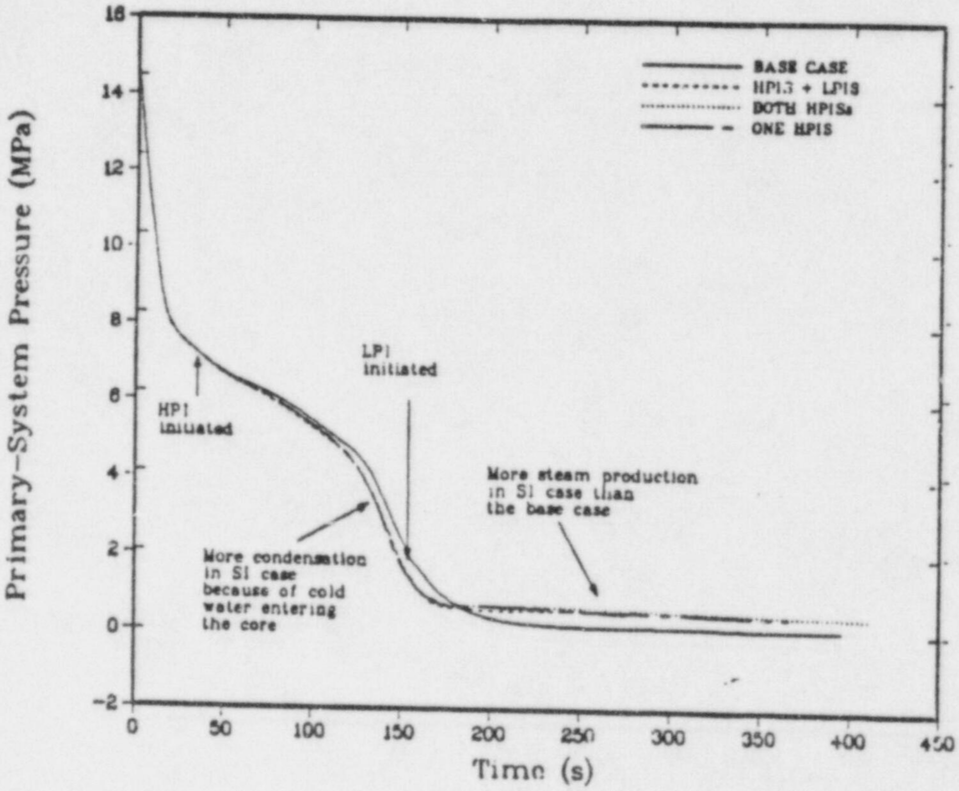

Figure D.1 Primary system pressure during V sequence base and parametric cases.

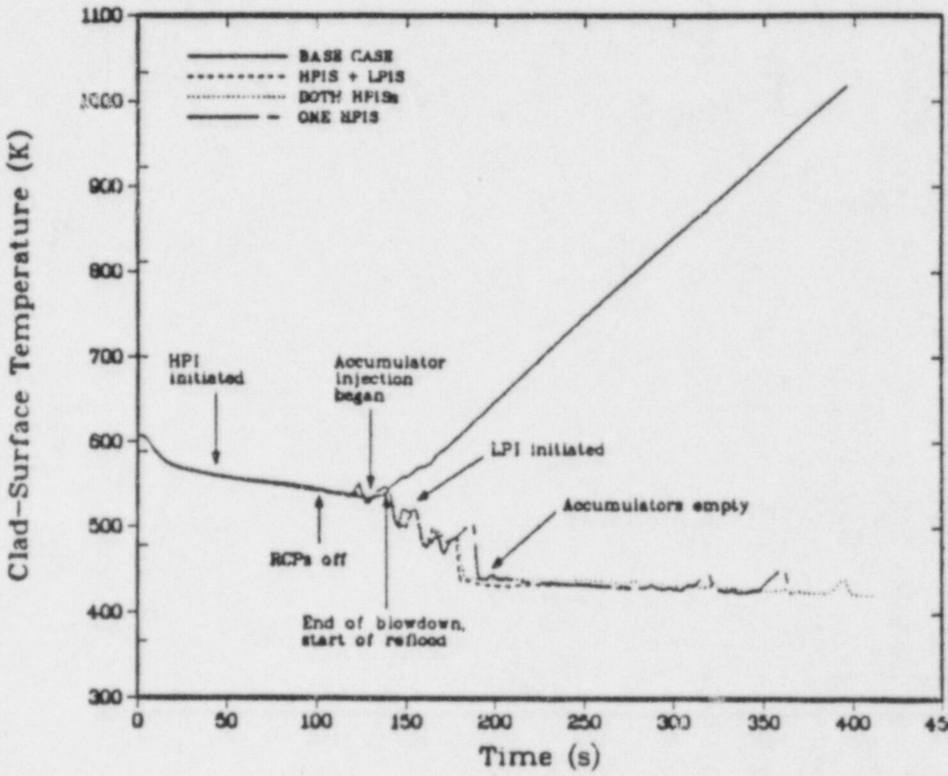

Figure D.2 Maximum cladding temperature of average rod during V sequence base and parametric cases.

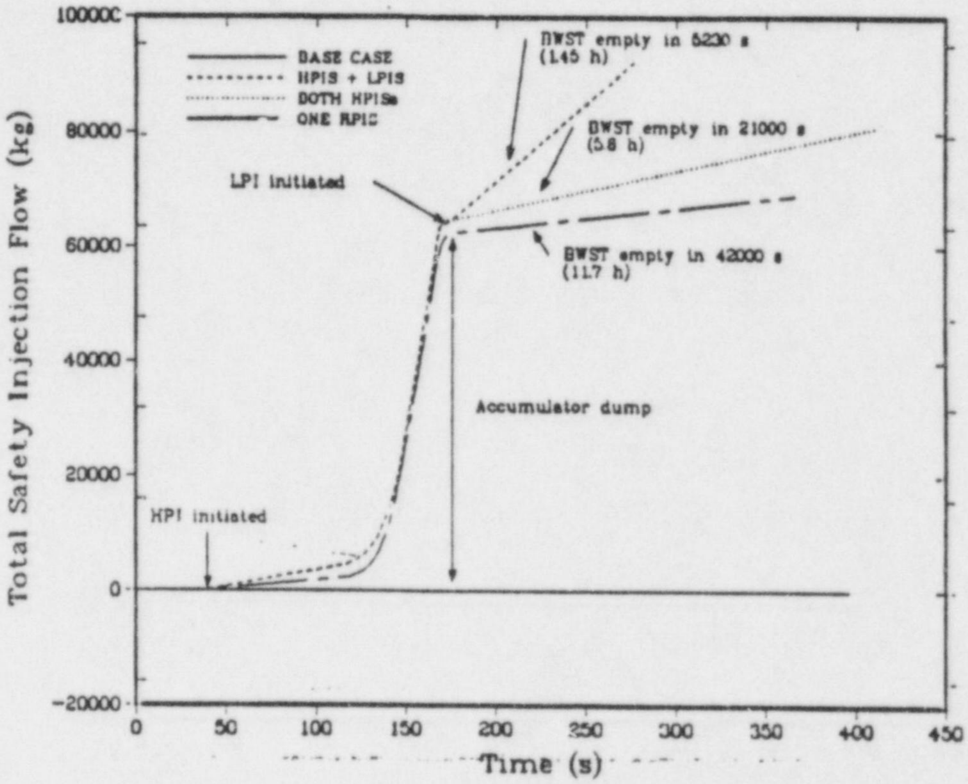

Figure D.3 Duration of effective core cooling during V sequence base and parametric cases.

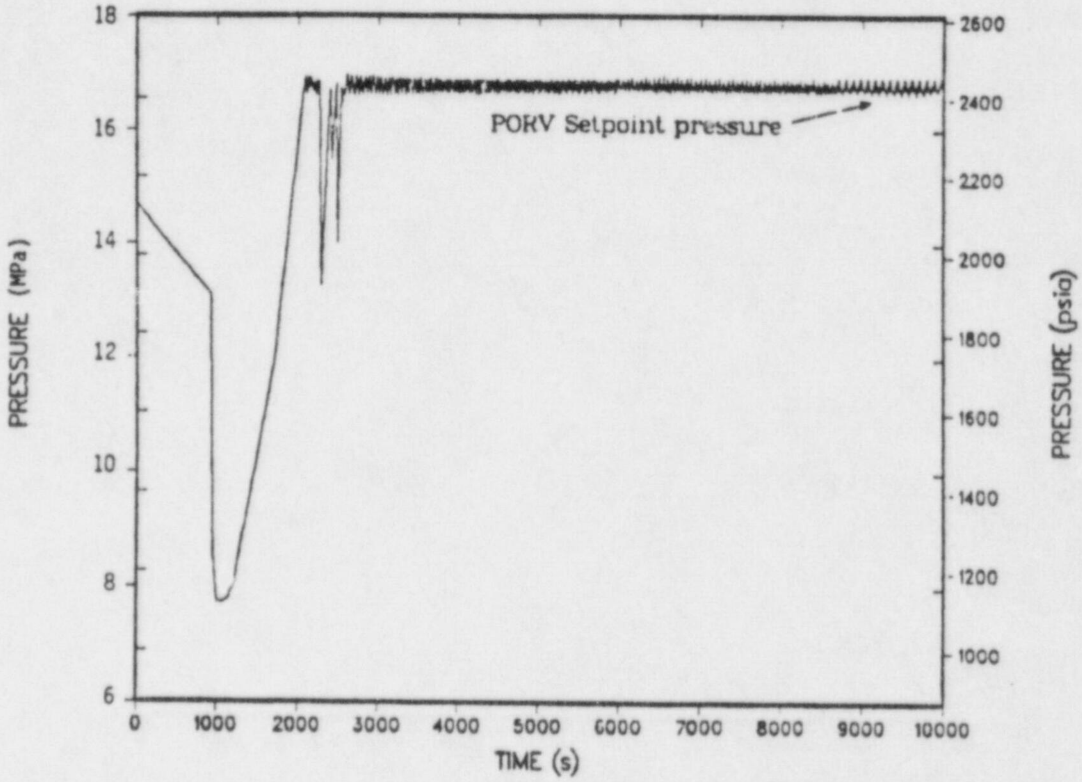

Figure D.4 Pressurizer pressure, 11-mm diam. (0.43") break case.

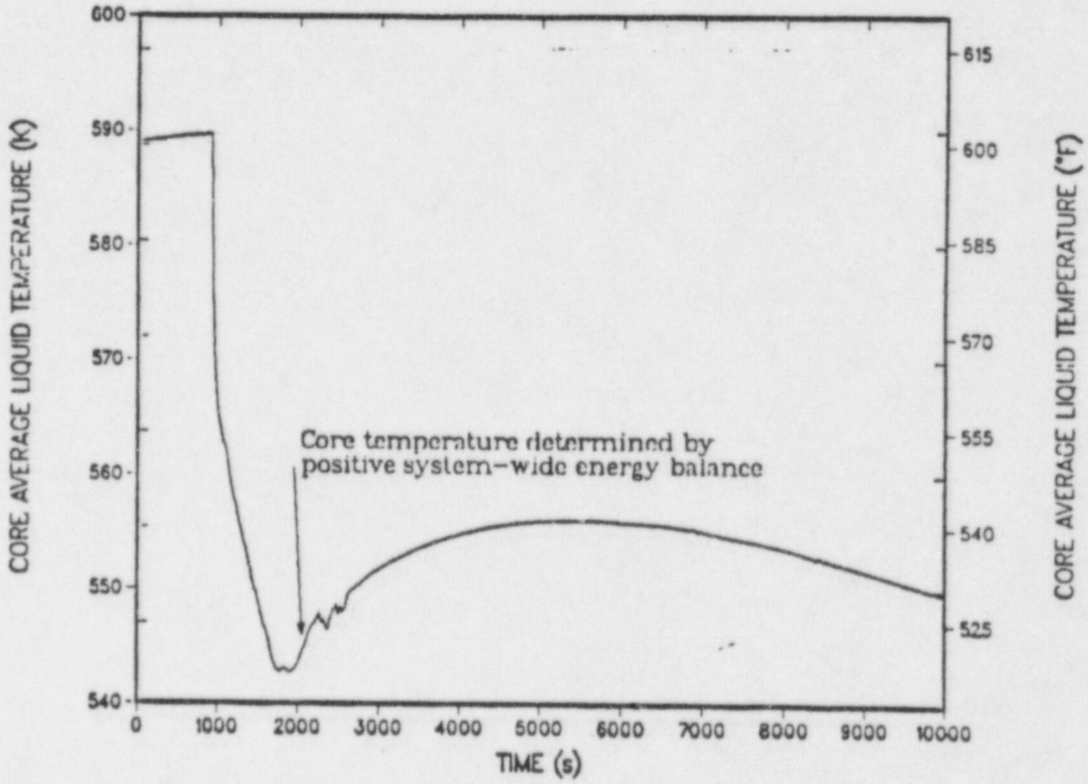

Figure D.5 Core average liquid temperature, 11-mm diam. (0.43") break case.

6. EFFECTS OF SOME CORRECTIVE ACTIONS ON CORE DAMAGE FREQUENCY

In order to reduce the core damage frequency due to ISLs, numerous options appear to be available. From these options, however, corrective actions with perspective of implementation are rather limited. In the present section, those corrective actions will be discussed which have been deemed to be implementable without excessive difficulties.

The corrective actions considered are essentially plant specific ones. The reason for this is that one or two plants already have certain safety features against ISLs, while others do not.

In the following calculations, the effects of the remedial actions on the initiator frequencies of LOCAs and overpressurization, as well as on the core damage frequencies are presented.

6.1 Corrective Actions at Indian Point 1

At Indian Point 3 leak tests are performed on the isolation valves (check valves as well as MOVs) after each cold shutdown. Thus, there is no reason to increase the frequency of leak tests. However, as the calculations below demonstrate, there is room for safety improvement by implementing the following corrective actions.

1. Application of pressure sensors (or equivalent continuous leak sensor devices) between the first (RCS side) and second isolation valves on each of the LPI/HPI/RHR pathways. (This is a feature, which can be found at the common LPI/HPI/Accumulator inlet at Calvert Cliffs 1.)

2. Improving the ability of operators for ISL recognition and accident management.

3. Application of a "pipe fuse" (or equivalent plant feature) in the RHR suction line after the two MOVs, as it is implemented at Oconee 3.

4. Establishing a procedure for RWST makeup in case of an ISL.

Table 6.1 presents the base case results to be compared with the results of each corrective action separately and combined.

6.1.1 Application of Permanent Pressure Sensor Between The First Two Isolation Valves on Each LPI/HPI/RHR Line

The advantage of the pressure sensor is that whenever the first isolation valve leaks an overpressurization alarm would call the attention of the operator to make preventive action in time. Its effect causes the time dependent terms to vanish in expressions describing initiator frequencies. Table 6.2 shows the pathway by pathway results if the permanent pressur sensors are implemented. (The results reflect the assumption that the pressure sensors will not fail.) The last column gives the core damage reduction values relative to the base case. The effect of the continuous leak testing is to reduce the total CDF associated with ISL bypassing the containment by a factor of ~2.

6.1.2 Improving The Ability of Operators For ISL Management

After the plant visit and having read the LOCA procedure of Indian Point 3, our impression was that it would be very useful to improve the ability of operators to manage an ISL accident. This would be easily achieved by training on control room simulators. However, Table 6.3 shows the effect of considering improved operator actions in the ISL event trees is negligible.

6.1.3 Application of a "Pipe Fuse" in The RHR Suction Pathway

The advantage of the implementation of this corrective feature is that it allows to convert a containment bypassing LOCA to a LOCA inside the containment. Its merit is related rather to risk reduction and not to overall reduction of core damage. It results in the decrease of about a factor of two of the core damage frequency value associated with the "ISL outside containment" case in Table 6.4.

6.1.4 Establishing RWST Makeup Procedure

One of the basic assumptions in this study is that small LOCA bypassing the containment (LOCA/outside) would eventually lead to core damage (CCDF=1). The operator has to rely on the water supply available in the RWST. The makeup to the RWST is generally based on "ad hoc" arrangements depending on the type of accidents and the available water supply. If this procedure can be formalized with respect to the various ISL scenarios, the CDF associated with small LOCA/outside would greatly be reduced (effectively reflecting only HP unavailability and typically CCDF~10^{-3}).

Table 6.5 lists the corresponding CDF values and it can clearly be seen that the total CDF/outside is reduced by more than a factor of ~10. Two important conclusions can be drawn: 1) small LOCAs dominate the total CDF/outside, and 2) the most effective corrective action is to insure long term water supply.

Table 6.6 provides the results if all of the above corrective actions would be implemented. A comparison with the base case shows significant advantage by implementing all of the above corrective actions.

6.2 Corrective Actions at Oconee 3

At Oconee 3 the leak tests of the isolation check valves and MOVs are performed at halfway between refueling (nine month intervals). After cold shutdown (there are two during the leak test period) the isolation valves may remain in failed states (open). Therefore, for this plant the simplest remedial action is to increase the frequency of the leak test. In addition, there are other options. The list of recommendations are:

1. Leak test of the isolation valves (check and MOVs) after each cold shutdown.

2. Application of permanent pressure sensors between the first and the second isolation valves on each LPI/RHR pathways.

3. Improving the ability of operators for ISL recognition and accident management.

4. Rerouting the drain lines of certain relief valves back to the containment.

5. Establishing RWST makeup procedure.

Table 6.7 provides the results to be compared with the results of each corrective action separately and combined.

6.2.1 Leak Test of The Isolation Valves After Each Cold Shutdown

With the implementation of leak tests after each cold shutdown, the possibility of leaving isolation valves open can be eliminated. In addition, the MOV in the LPI lines should be open during RCS pressurization. After reaching system pressure and before rods are withdrawn the MOV should be closed.

At the RHR suction MOVs, after leak tests the fuse disconnect should be kept open to isolate the 480 ac power during plant operation. This is implemented at Indian Point 3 against any spuriously generated shorts in the control cables of the MOV breaker.

Table 6.8 lists the results of the calculation. The results are obtained by omitting the "quarterly correction terms" introduced into the expressions describing the LPI/RHR initiators at Oconee 3.

6.2.2 Application of Permanent Pressure Sensors Between The First and Second Isolation Valves on Each LPI/RHR Pathways

The application of pressure sensors (or other equivalent leak sensor devices) have the same effect as it was explained at Indian Point 3. Table 6.9 shows the results for each pathway.

6.2.3 Improving The Ability of Operators For ISL Recognition and Accident Management

Table 6.10 presents the results of this corrective action.

6.2.4 Rerouting The Drain Lines of Certain Relief Valves Back to The Containment

The drain lines of the LPI and letdown relief valves relieve into tanks located outside containment. The consequences of this fact is that small LOCAs though these relief valves are essentially containment bypassing ISLs. By rerouting the drain lines from these relief valves back to the containment (e.g., to the Pressurizer Relief Tank) containment bypassing LOCAs would be converted to LOCAs inside containment. Thus, health risk would be reduced. Table 6.11 contains the results of this correction action.

6.2.5 RWST Makeup Procedure

Establishing RWST makeup procedures have significant effect in reducing total CDF/outside as it was explained at Indian Point 3. Table 6.12 lists the results of this corrective action.

The combined effect of corrective action 2, 3, 4, and 5 is shown in Table 6.13.

6.3 Corrective Actions at Calvert Cliffs 1

At Calvert Cliffs there is a permanent pressure sensor at the common LPI/HPI/Accumulator inlet. There is also a relief valve between the MOVs on the RHR suction line. However, its set point is set to high.

Thus, for Calvert Cliffs the list of corrective action is as follows:

1. Application of permanent pressure sensors also between the last check valves and the closed MOV on the LPI/HPI lines and also between the two MOVs in the RHR suction line.

2. Improving the ability of operators for ISL recognition and accident management.

3. Rerouting the drain lines of LPI/HPI/RHR/Letdown relief valves back to the containment.

4. RWST makeup procedure.

Table 6.14 summarizes the results to be compared with the results of each corrective action separately and combined.

6.3.1 Application of Additional Permanent Pressure Sensors

In the base case calculations for the LPI/HPI lines full credit was not given to the effect of the pressure sensor at the shared inlet, because the other check valves and the MOVs on these lines are not surveilled continuously. Also, no credit was given to the effect of the relief valve between the two MOVs on the RHR suction line.

Table 6.15 contains the relevant data if the additional permanent pressure sensors would be implemented along with open fuse disconnects of 480 ac power bus to the RHR suction MOVs.

6.3.2 Improvement of The Ability of Operators For ISL Recognition and Accident Management

Table 6.16 shows the results of this corrective action.

6.3.3 Rerouting The Drain Lines of LPI/HPI/RHR/Letdown Relief Valves Back to The Containment

The advantage of rerouting the drain lines of these relief valves back to the containment has mainly health risk reducing significance. Table 6.17 presents the relevant data.

6.3.4 RWST Makeup Procedure

Table 6.18 presents the results of calculations including the effects of formalized RWST makeup procedure.

The combined effect of corrective actions 1, 2, ., and 4 is shown in Table 6.19.

Table 6.1
Core Damage Frequency - Indian Point
Base Case

System	Initiator	P(Rupture)	CDF/Year Base
<u>A - Overpressurization</u>			
LPI	1.71-06	1.00-01	3.26-07
		1.00-03	1.74-07
		3.00-05	1.73-07
SI	6.98-05	1.00-01	6.36-06
		1.00-03	6.36-08
		3.00-05	1.91-09
RHR Suction	9.80-07	1.00-01	4.93-07
		1.00-03	4.93-07
		3.00-05	4.93-07
Letdown	6.82-07	1.00	1.50-10
Accumulators	4.64-03	1.00-01	3.18-06
		1.00-03	8.89-07
		3.00-05	8.66-07
<u>B - Without Overpressurization</u>			
LPI	9.88-06		5.63-08
SI	5.52-04		3.15-06
RHR	1.70-05		9.69-08
Letdown	2.28-03		1.30-05
<u>Total CDF</u>			
A - Overpressurization		1.00-01	1.04-05
		1.00-03	1.62-06
		3.00-05	1.53-06
B - Without Overpressurization			1.63-05
A and B		1.00-01	2.67-05
		1.00-03	1.79-05
		3.00-05	1.78-05
Total CDF With ISL Outside		1.00-01	7.17-07
		1.00-03	6.63-07
		3.00-05	6.61-07

Table 6.2
Core Damage Frequency - Indian Point
Continuous Leak/Pressure Monitoring

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	9.90-07	1.00-01	1.89-07	3.26-07	.58
		1.00-03	1.01-07	1.74-07	.58
		3.00-05	1.00-07	1.73-07	.58
SI	2.04-06	1.00-01	1.86-07	6.36-06	.03
		1.00-03	1.86-09	6.36-08	.03
		3.00-05	5.57-11	1.91-09	.03
RHR Suction	4.85-07	1.00-01	2.44-07	4.93-07	.50
		1.00-03	2.44-07	4.93-07	.50
		3.00-05	2.44-07	4.93-07	.50
Letdown	No change	1.00		1.50-10	1.00
Accumulators	No change	1.00-01		3.18-06	1.00
		1.00-03		8.89-07	1.00
		3.00-05		8.66-07	1.00
B - Without Overpressurization					
LPI	1.50-06		8.55-09	5.63-08	.15
SI	6.81-06		3.88-08	3.15-06	.01
RHR	1.49-06		8.49-09	9.69-08	.09
Letdown	No change			1.30-05	1.00
Total CDF					
A - Overpressurization		1.00-01	3.80-06	1.04-05	.37
		1.00-03	1.24-06	1.62-06	.76
		3.00-05	1.21-06	1.53-06	.79
B - Without Overpressurization			1.31-05	1.63-05	.80
A and B		1.00-01	1.69-05	2.67-05	.63
		1.00-03	1.43-05	1.79-05	.80
		3.00-05	1.43-05	1.78-05	.80
Total CDF With ISL Outside		1.00-01	3.34-07	7.17-07	.47
		1.00-03	3.41-07	6.63-07	.52
		3.00-05	3.41-07	6.61-07	.52

Table 6.3
Core Damage Frequency - Indian Point
Operator Training

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	3.25-07	3.26-07	.99
		1.00-03	1.73-07	1.74-07	.99
		3.00-05	1.71-07	1.73-07	.99
SI	No change	1.00-01	6.29-06	6.36-06	.99
		1.00-03	6.29-08	6.36-08	.99
		3.00-05	1.89-09	1.91-09	.99
RHR Suction	No change	1.00-01	No change	4.93-07	1.00
		1.00-03	No change	4.93-07	1.00
		3.00-05	No change	4.93-07	1.00
Letdown	No change	1.00	1.19-10	1.50-10	.79
Accumulators	No change	1.00-01	2.54-06	3.18-06	.79
		1.00-03	8.14-07	8.89-07	.92
		3.00-05	7.97-07	8.66-07	.92
B - Without Overpressurization					
LPI	No change		No change	5.63-08	1.0
SI	No change		No change	3.15-06	1.0
RHR	No change		No change	9.69-08	1.0
Letdown	No change		No change	1.30-05	1.0
Total CDF					
A - Overpressurization		1.00-01	9.65-06	1.04-05	.93
		1.00-03	1.54-06	1.62-06	.95
		3.00-05	1.46-06	1.53-06	.95
B - Without Overpressurization			1.63-05	1.63-05	1.00
A and B		1.00-01	2.59-05	2.67-05	.97
		1.00-03	1.78-05	1.79-05	.99
		3.00-05	1.78-05	1.78-05	.99
Total CDF With ISL Outside		1.00-01	6.55-07	7.17-07	.91
		1.00-03	6.61-07	6.63-07	.99
		3.00-05	6.61-07	6.61-07	.99

Table 6.4
Core Damage Frequency - Indian Point
RHR Suction, Inside Break Enhanced

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01		3.26-07	1.00
		1.00-03		1.74-07	1.00
		3.00-05		1.73-07	1.00
SI	No change	1.00-01		6.36-06	1.00
		1.00-03		6.36-08	1.00
		3.00-05		1.91-09	1.00
RHR Suction	No change	1.00-01	1.03-07	4.93-07	.21
		1.00-03	1.03-07	4.93-07	.21
		3.00-05	1.03-07	4.93-07	.21
Letdown	No change	1.00		1.50-10	1.0
Accumulators	No change	1.00-01		3.18-06	1.00
		1.00-03		8.89-07	1.00
		3.00-05		8.66-07	1.00
B - Without Overpressurization					
LPI	No change			5.63-08	1.00
SI	No change			3.15-06	1.00
RHR	No change			9.69-08	1.00
Letdown	No change			1.30-05	1.00
Total CDF					
A - Overpressurization		1.00-01	9.97-06	1.04-05	.96
		1.00-03	1.23-06	1.62-06	.76
		3.00-05	1.14-06	1.53-06	.75
B - Without Overpressurization			1.63-05	1.63-05	1.00
A and B		1.00-01	2.63-05	2.67-05	.99
		1.00-03	1.75-05	1.79-05	.98
		3.00-05	1.74-05	1.78-05	.98
Total CDF With ISL Outside		1.00-01	3.25-07	7.17-07	.45
		1.00-03	2.70-07	6.63-07	.41
		3.00-05	2.69-07	6.61-07	.41

Table 6.5
Core Damage Frequency - Indian Point
RWST Makeup Procedure

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	1.73-07	3.26-07	.53
		1.00-03	4.33-09	1.74-07	.02
		3.00-05	2.67-09	1.73-07	.01
SI	No change	1.00-01	6.29-06	6.36-06	.99
		1.00-03	6.29-08	6.36-08	.99
		3.00-05	1.89-09	1.91-09	.99
RHR Suction	No change	1.00-01	5.44-08	4.93-07	.11
		1.00-03	6.07-09	4.93-07	.01
		3.00-05	5.60-09	4.93-07	.01
Letdown	No change	1.00	1.16-10	1.50-10	.77
Accumulators	No change	1.00-01		3.18-06	1.0
		1.00-03		8.89-07	1.0
		3.00-05		8.66-07	1.0
_ - Without Overpressurization					
LPI	No change			5.63-08	1.0
SI	No change			3.15-06	1.0
RHR	No change			9.69-08	1.0
Letdown	No change			1.30-05	1.0
Total CDF					
A - Overpressurization		1.00-01	9.70-06	1.04-05	.94
		1.00-03	9.62-07	1.62-06	.60
		3.00-05	8.77-07	1.53-06	.57
B - Without Overpressurization			1.63-05	1.63-05	1.0
A and B		1.00-01	2.60-05	2.67-05	.98
		1.00-03	1.73-05	1.79-05	.96
		3.00-05	1.72-05	1.78-05	.96
Total CDF With ISL Outside		1.00-01	5.65-08	7.17-07	.08
		1.00-03	4.29-09	6.63-07	.01
		3.00-05	3.78-09	6.61-07	.01

Table 6.6
Core Damage Frequency - Indian Point
Combination of Corrective Actions

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI		1.00-01	9.97-08	3.26-07	.31
		1.00-03	1.79-09	1.74-07	.01
		3.00-05	8.26-10	1.73-07	.005
SI		1.00-01	1.84-07	6.36-06	.03
		1.00-03	1.84-09	6.36-08	.03
		3.00-05	5.51-11	1.91-09	.03
RHR Suction		1.00-01	7.70-09	4.93-07	.02
		1.00-03	2.81-09	4.93-07	.01
		3.00-05	2.77-09	4.93-07	.01
Letdown		1.00	1.16-10	1.50-10	.77
Accumulators		1.00-01	2.54-06	3.18-06	.79
		1.00-03	8.14-07	8.89-07	.92
		3.00-05	7.97-07	8.66-07	.92
B - Without Overpressurization					
LPI			8.55-09	5.63-08	.15
SI			3.88-08	3.15-06	.01
RHR			8.49-09	9.69-08	.01
Letdown			1.30-05	1.30-05	1.0
Total CDF					
A - Overpressurization		1.00-01	2.83-06	1.04-05	.27
		1.00-03	8.20-07	1.62-06	.51
		3.00-05	8.01-07	1.53-06	.52
B - Without Overpressurization			1.31-05	1.63-05	.80
A and B		1.00-01	1.59-05	2.67-05	.60
		1.00-03	1.39-05	1.79-05	.77
		3.00-05	1.39-05	1.78-05	.77
Total CDF With ISL Outside		1.00-01	5.78-09	7.17-07	.01
		1.00-03	8.90-10	6.63-07	.001
		3.00-05	8.42-10	6.61-07	.001

Table 6.7
Core Damage Frequency - Oconee
Base Case

System	Initiator	P(Rupture)	CDF/Year Base
A - Overpressurization			
LPI	7.68-08	1.00-01	7.68-08
		1.00-03	7.68-08
		3.00-05	7.68-08
RHR Suction	1.44-06	1.00-01	1.48-07
		1.00-03	1.47-07
		3.00-05	1.47-07
Letdown	2.28-03	1.0	5.93-07
Accumulators	4.10-03	1.00-01	4.83-06
		1.00-03	7.21-07
		3.00-05	6.81-07
B - Without Overpressurization			
LPI	6.22-07		6.22-07
RHR	5.04-05		1.06-07
Total CDF			
A - Overpressurization		1.00-01	5.65-06
		1.00-03	1.54-06
		3.00-05	1.50-06
B - Without Overpressurization			7.31-07
A and B		1.00-01	6.38-06
		1.00-03	2.27-06
		3.00-05	2.23-06
Total CDF With ISL Outside		1.00-01	1.44-06
		1.00-03	1.44-06
		3.00-05	1.44-06

Table 6.8
Core Damage Frequency - Oconee
Leak Test After Each Cold Shutdown

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	9.68-09	1.00-01	9.68-09	7.68-08	.12
		1.00-03	9.68-09	7.68-08	.12
		3.00-05	9.68-09	7.68-08	.12
RHR Suction	1.02-06	1.00-01	1.05-07	1.48-07	.71
		1.00-03	1.04-07	1.47-07	.71
		3.00-05	1.04-07	1.47-07	.71
Letdown	No change	1.0		5.93-07	1.00
Accumulators	2.75-03	1.00-01	3.24-06	4.83-06	.67
		1.00-03	4.84-07	7.21-07	.67
		3.00-05	4.57-07	6.81-07	.67
B - Without Overpressurization					
LPI	8.07-08		8.07-08	6.22-07	.13
R	1.85-05		3.88-08	1.06-07	.37
Total CDF					
A - Overpressurization		1.00-01	3.95-06	5.65-06	.70
		1.00-03	1.19-06	1.54-06	.77
		3.00-05	1.16-06	1.50-06	.78
B - Without Overpressurization			1.20-07	7.31-07	.16
A and B		1.00-01	4.07-06	6.38-06	.64
		1.00-03	1.31-06	2.27-06	.58
		3.00-05	1.28-06	2.23-06	.58
Total CDF With ISL Outside		1.00-01	7.85-07	1.44-06	.55
		1.00-03	7.85-07	1.44-06	.55
		3.00-05	7.85-07	1.44-06	.55

Table 6.9
Core Damage Frequency - Oconee
Continuous Leak/Pressure Testing

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	6.57-10	1.00-01	6.57-10	7.68-08	.01
		1.00-03	6.57-10	7.68-08	.01
		3.00-05	6.57-10	7.68-08	.01
RHR Suction	5.80-07	1.00-01	5.95-08	1.48-07	.40
		1.00-03	5.91-08	1.47-07	.40
		3.00-05	5.91-08	1.47-07	.40
Letdown	No change	1.0		5.93-07	1.00
Accumulators	No change	1.00-01		4.83-06	1.00
		1.00-03		7.21-07	1.00
		3.00-05		6.81-07	1.00
B - Without Overpressurization					
LPI	2.90-09		2.90-09	6.22-07	.004
RHR	1.77-06		3.72-09	1.06-07	.03
Total CDF					
A - Overpressurization		1.00-01	5.49-06	5.65-06	.97
		1.00-03	1.37-06	1.54-06	.89
		3.00-05	1.33-06	1.50-06	.89
B - Without Overpressurization			6.62-09	7.31-07	.01
A and B		1.00-01	5.49-06	6.38-06	.86
		1.00-03	1.38-06	2.27-06	.61
		3.00-05	1.34-06	2.23-06	.60
Total CDF With ISL Outside		1.00-01	6.54-07	1.44-06	.46
		1.00-03	6.54-07	1.44-06	.46
		3.00-05	6.54-07	1.44-06	.46

Table 6.10
Core Damage Frequency - Oconee
Operator Training

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	7.68-08	7.68-08	1.00
		1.00-03	7.68-08	7.68-08	1.00
		3.00-05	7.68-08	7.68-08	1.00
RHR Suction	No change	1.00-01	1.48-07	1.48-07	1.00
		1.00-03	1.47-07	1.47-07	1.00
		3.00-05	1.47-07	1.47-07	1.00
Letdown	No change	1.0	3.88-07	5.93-07	.65
Accumulators	No change	1.00-01	4.82-06	4.83-06	.99
		1.00-03	7.00-07	7.21-07	.97
		3.00-05	6.60-07	6.81-07	.97
B - Without Overpressurization					
LPI	No change		6.25-07	6.22-07	1.0
RHR	No change		1.06-07	1.06-07	1.0
Total CDF					
A - Overpressurization		1.00-01	5.43-06	5.65-06	.96
		1.00-03	1.31-06	1.54-06	.85
		3.00-05	1.27-06	1.50-06	.85
B - Without Overpressurization			7.31-07	7.31-07	1.0
A and B		1.00-01	6.16-06	6.38-06	.97
		1.00-03	2.04-06	2.27-06	.90
		3.00-05	2.00-06	2.23-06	.89
Total CDF With ISL Outside		1.00-01	1.23-06	1.44-06	.86
		1.00-03	1.23-06	1.44-06	.86
		3.00-05	1.23-06	1.44-06	.86

Table 6.11
Core Damage Frequency - Oconee
Rerouting Relief Valve Drain Lines

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01		7.68-08	1.00
		1.00-03		7.68-08	1.00
		3.00-05		7.68-08	1.00
RHR Suction	No change	1.00-01		1.48-07	1.00
		1.00-03		1.47-07	1.00
		3.00-05		1.47-07	1.00
Letdown	No change	1.0	3.65-07	5.93-07	.62
Accumulators	No change	1.00-01		4.83-06	1.00
		1.00-03		7.21-07	1.00
		3.00-05		6.81-07	1.00
B - Without Overpressurization					
LPI	No change		1.31-09	6.22-07	.002
IR	No change		1.06-07	1.06-07	1.00
Total CDF					
A - Overpressurization		1.00-01	5.42-06	5.65-06	.96
		1.00-03	1.31-06	1.54-06	.85
		3.00-05	1.27-06	1.50-06	.85
B - Without Overpressurization			1.07-07	7.31-07	.15
A and B		1.00-01	5.53-06	6.38-06	.87
		1.00-03	1.42-06	2.27-06	.63
		3.00-05	1.38-06	2.23-06	.62
Total CDF With ISL Outside		1.00-01	5.87-07	1.44-06	.41
		1.00-03	5.87-07	1.44-06	.41
		3.00-05	5.87-07	1.44-06	.41

Table 6.12
Core Damage Frequency - Oconee
RWST Makeup Procedure

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	7.83-09	7.68-08	.10
		1.00-03	2.38-10	7.68-08	.003
		3.00-05	1.64-10	7.68-08	.002
RHR Suction	No change	1.00-01	1.85-08	1.48-07	.13
		1.00-03	3.18-09	1.47-07	.02
		3.00-05	3.03-09	1.47-07	.02
Letdown	No change	1.0	3.65-07	5.93-07	.62
Accumulators	No change	1.00-01		4.83-06	1.00
		1.00-03		7.21-07	1.00
		3.00-05		6.81-07	1.00
B - Without Overpressurization					
LPI	No change		1.31-09	6.22-07	.002
R	No change		1.06-07	1.06-07	1.00
Total CDF					
A - Overpressurization		1.00-01	5.23-06	5.65-06	.93
		1.00-03	1.09-06	1.54-06	.71
		3.00-05	1.05-06	1.50-06	.70
B - Without Overpressurization			1.07-07	7.31-07	.15
A and B		1.00-01	5.33-06	6.38-06	.84
		1.00-03	1.20-06	2.27-06	.53
		3.00-05	1.16-06	2.23-06	.52
Total CDF With ISL Outside		1.00-01	3.89-07	1.44-06	.27
		1.00-03	3.67-07	1.44-06	.26
		3.00-05	3.67-07	1.44-06	.26

Table 6.13
Core Damage Frequency - Oconee
Combination of Corrective Actions

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI		1.00-01	6.69-11	7.68-08	.001
		1.00-03	2.04-12	7.68-08	.00002
		3.00-05	1.40-12	7.68-08	.00001
RHR Suction		1.00-01	7.43-09	1.48-07	.05
		1.00-03	1.28-09	1.47-07	.01
		3.00-05	1.22-09	1.47-07	.01
Letdown		1.0	3.65-07	5.93-07	.62
Accumulators		1.00-01	4.82-06	4.83-06	.99
		1.00-03	7.00-07	7.21-07	.97
		3.00-05	6.60-07	6.81-07	.97
B - Without Overpressurization					
'PI			6.09-12	6.22-07	0.0
.IR			3.72-09	1.06-07	.04
Total CDF					
A - Overpressurization		1.00-01	5.19-06	5.65-06	.92
		1.00-03	1.07-06	1.54-06	.70
		3.00-05	1.03-06	1.50-06	.68
B - Without Overpressurization			3.72-09	7.31-07	.01
A and B		1.00-01	5.19-06	6.38-06	.81
		1.00-03	1.07-06	2.27-06	.47
		3.00-05	1.03-06	2.23-06	.46
Total CDF With ISL Outside		1.00-01	3.71-07	1.44-06	.26
		1.00-03	3.65-07	1.44-06	.25
		3.00-05	3.65-07	1.44-06	.25

Table 6.14
Core Damage Frequency - Calvert Cliffs
Base Case

System	Initiator	P(Rupture)	CDF/Year Base
A - Overpressurization			
LPI	1.07-09	1.00-01	1.07-09
		1.00-03	1.07-09
		3.00-05	1.07-09
SI	6.21-10	1.00-01	6.21-11
		1.00-03	6.21-13
		3.00-05	1.86-14
RHR Suction	1.48-06	1.00-01	1.48-06
		1.00-03	1.48-06
		3.00-05	1.48-06
Letdown	2.28-03	1.0	3.99-07
Accumulators	5.98-03	1.00-01	1.11-05
		1.00-03	5.77-07
		3.00-05	4.74-07
B - Without Overpressurization			
LPI	3.94-09		3.94-09
SI	3.93-09		3.93-09
RHR	1.75-05		1.75-05
Total CDF			
A - Overpressurization		1.00-01	1.30-05
		1.00-03	2.46-06
		3.00-05	2.35-06
B - Without Overpressurization			1.75-05
A and B		1.00-01	3.05-05
		1.00-03	2.00-05
		3.00-05	1.99-05
Total CDF With ISL Outside		1.00-01	1.92-05
		1.00-03	1.92-05
		3.00-05	1.92-05

Table 6.15
Core Damage Frequency - Calvert Cliffs
Continuous Leak/Pressure Monitoring

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	2.68-11	1.00-01	2.68-11	1.07-09	.03
		1.00-03	2.68-11	1.07-09	.03
		3.00-05	2.68-11	1.07-09	.03
SI	5.96-12	1.00-01	5.96-13	6.21-11	.01
		1.00-03	5.96-15	6.21-13	.01
		3.00-05	1.79-16	1.86-14	.01
RHR Suction	5.93-07	1.00-01	5.93-07	1.48-06	.40
		1.00-03	5.93-07	1.48-06	.40
		3.00-05	5.93-07	1.48-06	.40
Letdown	No change	1.0		3.99-07	1.0
Accumulators	No change	1.00-01		1.11-05	1.0
		1.00-03		5.77-07	1.0
		3.00-05		4.74-07	1.0
B - Without Overpressurization					
LPI			3.22-11	3.94-09	.01
SI			1.75-11	3.93-09	.005
RHR			1.81-06	1.75-05	.1
Total CDF					
A - Overpressurization		1.00-01	1.21-05	1.30-05	.93
		1.00-03	1.57-06	2.46-06	.64
		3.00-05	1.47-06	2.35-06	.62
B - Without Overpressurization			1.81-06	1.75-05	.1
A and B		1.00-01	1.39-06	3.05-05	.46
		1.00-03	3.38-06	2.00-05	.17
		3.00-05	3.28-06	1.99-05	.17
Total CDF With ISL Outside		1.00-01	2.63-06	1.92-05	.14
		1.00-03	2.63-06	1.92-05	.14
		3.00-05	2.63-06	1.92-05	.14

Table 6.16
Core Damage Frequency - Calvert Cliffs
Operator Training

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	1.07-09	1.07-09	1.0
		1.00-03	1.07-09	1.07-09	1.0
		3.00-05	1.07-09	1.07-09	1.0
SI	No change	1.00-01	6.21-11	6.21-11	1.0
		1.00-03	6.21-13	6.21-13	1.0
		3.00-05	1.86-14	1.86-14	1.0
RHR Suction	No change	1.00-01	1.48-06	1.48-06	1.0
		1.00-03	1.48-06	1.48-06	1.0
		3.00-05	1.48-06	1.48-06	1.0
Letdown	No change	1.0	1.94-07	3.99-07	.48
Accumulators	No change	1.00-01	8.73-06	1.11-05	.79
		1.00-03	5.33-07	5.77-07	.93
		3.00-05	4.53-07	4.74-07	.96
B - Without Overpressurization					
LPI	No change		3.94-09	3.94-09	1.0
SI	No change		3.93-09	3.93-09	1.0
RHR	No change		1.75-05	1.75-05	1.0
Total CDF					
A - Overpressurization		1.00-01	1.04-05	1.30-05	.80
		1.00-03	2.21-06	2.46-06	.90
		3.00-05	2.13-06	2.35-06	.90
B - Without Overpressurization			1.75-05	1.75-05	1.0
A and B		1.00-01	2.79-05	3.05-05	.92
		1.00-03	1.97-05	2.00-05	.99
		3.00-05	1.96-05	1.99-05	.99
Total CDF With ISL Outside		1.00-01	1.90-05	1.92-05	.99
		1.00-03	1.90-05	1.92-05	.99
		3.00-05	1.90-05	1.92-05	.99

Table 6.17
Core Damage Frequency - Calvert Cliffs
Rerouting Relief Valve Drain Lines

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01		1.07-09	1.00
		1.00-03		1.07-09	1.00
		3.00-05		1.07-09	1.00
SI	No change	1.00-01		6.21-11	1.00
		1.00-03		6.21-13	1.00
		3.00-05		1.86-14	1.00
RHR Suction	No change	1.00-01		1.48-06	1.00
		1.00-03		1.48-06	1.00
		3.00-05		1.48-06	1.00
Letdown	No change	1.0	1.71-07	3.99-07	.43
Accumulators	No change	1.00-01		1.11-05	1.00
		1.00-03		5.77-07	1.00
		3.00-05		4.74-07	1.00
B - Without Overpressurization					
LPI	No change		5.12-12	3.94-09	.001
SI	No change		5.11-12	3.93-09	.001
RHR	No change		2.27-08	1.75-05	.001
Total CDF					
A - Overpressurization		1.00-01	1.27-05	1.30-05	.98
		1.00-03	2.23-06	2.46-06	.90
		3.00-05	2.13-06	2.35-06	.90
B - Without Overpressurization			2.28-08	1.75-05	.001
A and B		1.00-01	1.28-05	3.05-05	.42
		1.00-03	2.25-06	2.00-05	.11
		3.00-05	2.15-06	1.99-05	.11
Total CDF With ISL Outside		1.00-01	1.50-06	1.92-05	.01
		1.00-03	1.50-06	1.92-05	.01
		3.00-05	1.50-06	1.92-05	.01

Table 6.18
Core Damage Frequency - Calvert Cliffs
RWST Makeup Procedure

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI	No change	1.00-01	1.08-10	1.07-09	.10
		1.00-03	2.46-12	1.07-09	.002
		3.00-05	1.42-12	1.07-09	.001
SI	No change	1.00-01	8.07-14	6.21-11	.001
		1.00-03	8.07-16	6.21-13	.001
		3.00-05	2.42-17	1.86-14	.001
RHR Suction	No change	1.00-01	1.50-07	1.48-06	.10
		1.00-03	3.49-09	1.48-06	.002
		3.00-05	1.97-09	1.48-06	.001
Letdown	No change	1.0	1.71-07	3.99-07	.43
Accumulators	No change	1.00-01		1.11-05	1.00
		1.00-03		5.77-07	1.00
		3.00-05		4.74-07	1.00
B - Without Overpressurization					
LPI	No change		5.12-12	3.94-09	.001
SI	No change		5.11-12	3.93-09	.001
RHR	No change		2.27-08	1.75-05	.001
Total CDF					
A - Overpressurization		1.00-01	1.14-05	1.30-05	.88
		1.00-03	7.51-07	2.46-06	.31
		3.00-05	6.47-07	2.35-06	.28
B - Without Overpressurization			2.28-08	1.75-05	.001
A and B		1.00-01	1.14-05	3.05-05	.38
		1.00-03	7.74-07	2.00-05	.039
		3.00-05	6.70-07	1.99-05	.034
Total CDF With ISL Outside		1.00-01	1.73-07	1.92-05	.009
		1.00-03	2.65-08	1.92-05	.001
		3.00-05	2.50-08	1.92-05	.001

Table 6.19
Core Damage Frequency - Calvert Cliffs
Combination of Corrective Actions

System	Initiator	P(Rupture)	CDF/Year Perturbed	CDF/Year Base	CDF Pert / CDF Base
A - Overpressurization					
LPI		1.00-01	2.71-12	1.07-09	.003
		1.00-03	6.16-14	1.07-09	.00005
		3.00-05	3.56-14	1.07-09	.00003
SI		1.00-01	7.75-16	6.21-11	1.2-05
		1.00-03	7.75-18	6.21-13	1.2-05
		3.00-05	2.32-19	1.86-14	1.2-05
RHR Suction		1.00-01	6.00-08	1.48-06	.04
		1.00-03	1.39-09	1.48-06	.001
		3.00-05	7.89-10	1.48-06	.001
Letdown		1.0	1.71-10	3.99-07	.43
Accumulators		1.00-01	8.73-06	1.11-05	.79
		1.00-03	5.33-07	5.77-07	.93
		3.00-05	4.53-07	4.74-07	.96
B - Without Overpressurization					
LPI			4.19-14	3.94-09	1.0-05
SI			2.28-14	3.93-09	5.8-06
RHR			2.35-09	1.75-05	1.3-04
Total CDF					
A - Overpressurization		1.00-01	8.96-06	1.30-05	.69
		1.00-03	7.06-07	2.46-06	.29
		3.00-05	6.25-07	2.35-06	.27
B - Without Overpressurization			2.35-09	1.75-05	1.3-04
A and B		1.00-01	8.96-06	3.05-05	.29
		1.00-03	7.08-07	2.00-05	.04
		3.00-05	6.27-07	1.99-05	.03
Total CDF With ISL Outside		1.00-01	6.24-08	1.92-05	.003
		1.00-03	3.75-09	1.92-05	.0002
		3.00-05	3.17-09	1.92-05	.0002