A PRESSURIZED THERMAL SHOCK EVALUATION OF THE CALVERT CLIFFS UNIT 1 NUCLEAR POWER PLANT

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6.0. PTS INTEGRATED RISK FOR CALVERT CLIFFS UNIT 1 AND POTENTIAL MITIGATION MEASURES

6.1. Introduction

The preceding three chapters have outlined the procedures employed to estimate the three fundamental parameters (transient frequency, thermal-hydraulic history, and the conditional probability of vessel failure) required to quantify the PTS risk associated with a transient in Calvert Cliffs Unit 1. This chapter discusses the means by which these three influences are integrated to yield an estimated frequency of vessel failure (through-wall crack penetration). Section 6.2 describes the risk integration process and identifies the dominant risk sequences, as well as the relative risk of different classes of transients, and Section 6.3 discusses the effects of potential corrective actions.

6.2. Risk Integration

6.2.1. General Approach and Results

The frequency of a through-the-wall crack associated with each sequence identified in Chapter 3.0 is obtained by multiplying the sequence frequency by the appropriate conditional possibility of a through-the-wall crack presented in Chapter 5.0. The results of this exercise are presented in Table 6.1 for two conditions: (1) 32 effective full power years (EFPY), or $\underline{RT}_{NDT} + 2\sigma = 251°F$, where $\underline{RT}_{NDT}$ is the nil-ductility reference temperature, and (2) the point in time when $\underline{RT}_{NDT} + 2\sigma = 270°F$.*

*The 270°F $\underline{RT}_{NDT}$ data are presented to provide information on plant risk when the NRC screening criteria are reached. The axial weld screening value was used rather than the 300°F circumferential weld value since the analysis clearly indicated that the circumferential welds did not significantly contribute to the PTS risk. It should be noted that Calvert Cliffs Unit 1 is not expected to reach the screening criteria during the present licensed life of the plant.

Table 6.1. Summary of risk integration

Sequence Number†	Estimated Sequence Frequency (yr^{-1})	Transient Number Used for Conditional Failure Probability†	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Sequence Conditional Failure Probability	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Through-the-Wall Crack Frequency (yr^{-1})	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Rank Ordering of Risk Due to PTS	$RT_{NDT} + 2\sigma = 270°F$ Sequence Conditional Failure Probability	$RT_{NDT} + 2\sigma = 270°F$ Through-the-Wall Crack Frequency (yr^{-1})
1.1	2.8E-4	1.1	3.0E-8	8.4E-12			
1.2	3.7E-6	1.2	9.0E-8	3.3E-13			
1.3	3.8E-6	1.3	6.0E-7	2.3E-12		4.9E-6	1.9E-11
1.4	3.8E-6	1.4	3.3E-6	1.3E-11		1.7E-5	6.5E-11
1.5	3.4E-7	1.5	3.0E-5	1.0E-11		1.2E-4	4.1E-11
1.6	2.4E-7	1.6	5.1E-5	1.2E-11			
1.7	7.7E-9	1.7	1.9E-4	1.5E-12		4.8E-4	3.7E-12
1.8*	4.0E-8	1.8	2.5E-4	1.0E-11		6.2E-4	2.5E-11
2.1	3.8E-3	2.1	2.0E-7	7.6E-10	5	1.4E-6	5.3E-9
2.2	5.0E-5	2.1	2.0E-7	1.0E-11		1.4E-6	7.0E-10
2.3	5.1E-5	2.4	1.7E-5	8.7E-10	4	6.8E-5	3.5E-9
2.4	5.1E-5	2.4	1.7E-5	8.7E-10	3	6.8E-5	3.5E-9
2.5	4.6E-6	2.5	7.6E-6	3.5E-11		3.2E-5	1.5E-10
2.6	3.2E-6	2.6	8.2E-6	2.6E-11		3.4E-5	1.1E-10
2.7	8.7E-8	2.7	1.8E-4	1.6E-11		4.5E-4	3.9E-11
2.8	1.0E-7	2.8	2.3E-6	2.3E-13		1.1E-5	1.1E-12
2.9*	5.0E-7	2.7	1.8E-4	9.0E-11	8	4.5E-4	2.3E-10
3.1	8.5E-4	B**	<1E-9	<8.5E-13			
3.2	1.1E-5	B	<1E-9	<1.1E-14			
3.3	1.1E-5	B	<1E-9	<1.1E-14			
3.4	1.1E-5	B	<1E-9	<1.1E-14			
3.5	1.0E-6	3.5	8.0E-7	8.0E-13			
3.6	7.0E-7	3.6	7.2E-6	5.0E-12		3.6E-5	2.5E-11
3.7	5.5E-6	B	<1E-9	<5.5E-15			
3.8	3.7E-6	B	<1E-7	<3.7E-13			
3.9	3.7E-7	B	<1E-7	<3.7E-14			
3.10*	7.0E-7	3.10	6.7E-5	4.7E-11	9		
4.1	1.1E-2	B	<1E-9	<1.1E-11			
4.2	1.5E-4	B	<1E-9	<1.5E-13			
4.3	1.5E-4	B	<1E-9	<1.5E-13			
4.4	1.5E-4	B	<1E-9	<1.5E-13			
4.5	1.3E-5	B	<1E-7	<1.3E-12			

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Table 6.1. (Continued)

Sequence Number	Estimated Sequence Frequency (yr^{-1})	Transient Number Used for Conditional Failure Probability†	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Sequence Conditional Failure Probability	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Through-the-Wall Crack Frequency (yr^{-1})	32 EFPY ($RT_{NDT} + 2\sigma = 251°F$) Rank Ordering of Risk Due to PTS	$RT_{NDT} + 2\sigma = 270°F$ Sequence Conditional Failure Probability	$RT_{NDT} + 2\sigma = 270°F$ Through-the-Wall Crack Frequency (yr^{-1})
4.6	9.5E-6	4.6	2.0E-7	1.9E-12		1.0E-6	9.5E-12
4.7	5.0E-5	B	<1E-7	<5.0E-12			
4.8	6.5E-7	B	<1E-7	<6.5E-14			
4.9	6.7E-7	B	<1E-6	<6.7E-13			
4.10	5.0E-6	B	<1E-6	<5.0E-12			
4.11	7.2E-5	B	<1E-7	<7.2E-12			
4.12	9.7E-7	B	<1E-7	<9.7E-14			
4.13*	6.2E-6	4.13	6.0E-6	3.7E-11	10		
5.1	5.4	B	<1E-12	<5.4E-12			
5.2	4.6E-2	B	<1E-11	<4.6E-13			
5.3	1.2E-3	B	<1E-11	<1.3E-14			
5.4	2.3E-3	B	<1E-11	<2.3E-14			
5.5	6.2E-5	B	<1E-11	<6.0E-16			
5.6	1.0E-2	B	<1E-11	<1.0E-13			
5.7	7.6E-4	B	<1E-11	<7.6E-15			
5.8	1.5E-4	B	<1E-11	<1.5E-15			
5.9	4.1E-5	B	<1E-11	<4.1E-16			
5.10	1.5E-4	B	<1E-11	<1.5E-15			
5.11	1.0E-5	B	<1E-11	<1.0E-16			
5.12	2.5E-6	B	<1E-11	<2.5E-17			
5.13	7.0E-7	B	<1E-11	<7.0E-18			
5.14	1.5E-4	B	<1E-11	<1.5E-15			
5.15	1.0E-5	B	<1E-11	<1.0E-16			
5.16	2.5E-6	B	<1E-11	<2.5E-17			
5.17	6.8E-7	B	<1E-11	<6.8E-18			
5.18	1.5E-4	B	<1E-11	<1.5E-15			
5.19	1.0E-5	B	<1E-11	<1.0E-16			
5.20	2.5E-6	B	<1E-11	<2.5E-17			
5.21	3.7E-5	B	<1E-11	<3.7E-16			

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Table 6.1. (Continued)

Sequence Number†	Estimated Sequence Frequency (yr^{-1})	Transient Number Used for Conditional Failure Probability†	32 EFPY (RT_{NDT} + 2σ = 251°F) Sequence Conditional Failure Probability	32 EFPY (RT_{NDT} + 2σ = 251°F) Through-the-Wall Crack Frequency (yr^{-1})	32 EFPY (RT_{NDT} + 2σ = 251°F) Rank Ordering of Risk Due to PTS	RT_{NDT} + 2σ = 270°F Sequence Conditional Failure Probability	RT_{NDT} + 2σ = 270°F Through-the-Wall Crack Frequency (yr^{-1})
5.22	2.6E-6	B	<1E-11	<2.6E-17			
5.23	5.0E-7	B	<1E-9	<5.0E-16			
5.24	1.8E-7	B	<1E-9	<1.8E-16			
5.25	9.0E-6	B	<1E-10	<9.0E-16			
5.26	6.6E-7	B	<1E-7	<6.6E-14			
5.27	1.3E-7	B	<1E-7	<1.3E-14			
5.28	4.4E-4	B	<1E-11	<4.4E-15			
5.29	8.0E-6	B	<1E-11	<8.0E-17			
5.30	2.0E-6	B	<1E-11	<2.0E-17			
5.31	6.8E-2	B	<1E-11	<6.8E-13			
5.32	9.0E-4	B	<1E-11	<9.0E-15			
5.33	9.0E-4	B	<1E-11	<9.0E-15			
5.34	9.0E-4	B	<1E-11	<9.0E-15			
5.35	6.0E-5	B	<1E-11	<6.0E-16			
5.36	3.4E-3	B	<1E-9	<3.4E-12			
5.37	2.0E-6	B	<1E-9	<2.0E-15			
5.38	1.0E-6	3.6	7.2E-6	7.2E-12			
5.39*	2.0E-6	B	<1E-9	<2.0E-15			
5.40*	3.3E-6	B	<1E-8	<3.3E-14			
5.41*	4.6E-5	B	<1E-9	<4.6E-14			
5.42*	9.0E-5	B	<1E-8	<9.0E-13			
5.43*	5.8E-5	4.13	6.0E-6	3.5E-10	7		
6.1	2.8E-4	B	<1E-9	<2.8E-13			
6.2	1.0E-5	B	<1E-9	<1.0E-14			
6.3	1.4E-2	B	<1E-9	<1.4E-11			
6.4	1.3E-4	B	<1E-9	<1.3E-13			
6.5	2.6E-6	B	<1E-9	<2.6E-15			
6.6	1.1E-5	B	<1E-9	<1.1E-14			

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Table 6.1. (Continued)

			32 EFPY ($RT_{NDT} + 2\sigma$ = 251°F)			$RT_{NDT} + 2\sigma$ = 270°F	
Sequence Number†	Estimated Sequence Frequency (yr^{-1})	Transient Number Used for Conditional Failure Probability†	Sequence Conditional Failure Probability	Through-the-Wall Crack Frequency (yr^{-1})	Rank Ordering of Risk Due to PTS	Sequence Conditional Failure Probability	Through-the-Wall Crack Frequency (yr^{-1})
6.7	1.8E-4						
6.8	3.6E-6	B	<1E-9	<3.6E-15			
6.9	8.0E-7						
6.10	9.0E-6						
6.11	3.0E-5	B	<1E-9	<3.0E-14			
6.12	2.4E-7	B	<1E-9	<2.4E-16			
6.13	3.7E-7						
6.14	2.2E-6	B	<1E-9	<2.2E-15			
6.15	4.4E-7	B	<1E-9	4.4E-16			
6.16	1.2E-7	B	<1E-9	1.2E-16			
6.17	6.0E-7	B	<1E-9	6.0E-16			
6.18	1.0E-4	B	<1E-9	1.0E-13			
6.19	1.0E-6	6.19	5E-6	5.0E-12			
7.1	1.0E-3	B	<1E-9	<1.0E-12			
7.2	9.0E-6	B	<1E-7	<9.0E-13			
7.3	4.3E-7	B	<1E-7	<4.3E-14			
7.4	1.2E-5	B	<1E-7	<1.2E-12			
7.5	3.3E-7	B	<1E-7	<3.3E-14			
7.6	6.0E-7	B	<1E-7	<6.0E-14			
7.7	2.0E-6	B	<1E-7	<2.0E-13			
7.8	1.5E-7	B	<1E-7	<1.5E-14			
7.9*	2.0E-7	B	<1E-7	<2.0E-14			
8.1	1.0E-3	8.1	4.0E-7	4.0E-10	6	2.2E-6	2.2E-9
8.2	3.0E-4	8.2	1.5E-4	4.5E-8	1	2.9E-4	8.7E-8
8.3	5.0E-6	8.3	5.9E-3	3.0E-8	2	8.0E-3	4.0E-8
8.4	2.5E-2	B	<1E-10	<2.5E-12			

*Residual sequences.

†See Chapter 3 for definition of sequence numbers.

**Bounding calculation used for the sequence.

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As noted in Chapter 4.0, a limited number (12) of event sequences were calculated in detail using the LANL thermal-hydraulic analysis code TRAC. These sequences in turn served as a basis for estimating the thermal-hydraulic histories of approximately 115 sequences. Fracture-mechanics failure probabilities were assigned to each sequence from one of the following three data sources presented in Chapter 5.0:

(1) Direct Analysis of Sequence - If the minimum temperature of the sequence dropped below 350°F and the sequence did not fall into Category 2 below, a specific fracture-mechanics calculation was performed for that sequence. The conditional vessel failure probability reported in Chapter 5.0 for the specific calculation is used in Table 6.1 and the sequence number is repeated in column 3 to indicate that the numbers presented are based on specific calculations for that sequence.

(2) Assignment of Value from a Separate Sequence - In Chapter 4.0 and Appendix J, several sequences were identified as having essentially the same thermal-hydraulic profiles as another sequence. In this case a fracture-mechanics calculation was performed for only one sequence and the same failure probability was assigned to the other sequences in the group. In Table 6.1 the case number of the calculated sequence is listed in column 3 to identify it as representing the sequence listed in column 1.

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(3) Value Obtained from a Bounding Calculation - Many of the over 100 sequences involved relatively minor cooling of the primary system. Rather than perform a separate calculation for each of these sequences, a series of bounding calculations were performed. As discussed in Chapter 5.0, these bounding calculations assumed a step decrease in temperature along with full pressure. A bounding calculation result was used to represent a sequence if: (1) the minimum temperature for the sequence was greater than 350°F and (2) the use of a bounding calculation did not lead to a significant contribution to the total estimated plant risk due to PTS events. The use of a bounding calculation was considered to be an over-estimation of the risk and thus the probabilities entered in Table 6.1 for these sequences are preceded by a "<" sign. The use of a bounding calculation for a sequence is indicated by the letter "B" in column 3 of the table.

The total plant risk due to PTS is obtained by summing the individual estimated risks associated with each sequence or residual group as presented in Table 6.1. This total risk value was determined to be ~8 x 10^{-8} per reactor year (RY) at 32 EFPY and ~1.4 x 10^{-7} per reactor year when the limiting weld reaches an $\underline{RT}_{NDT} + 2\sigma$ value of 270°F.

6.2.2. Dominant Risk Sequences

A review of the rank ordering of the individual sequence risks given in Table 6.1 shows that the total plant risk due to PTS is dominated by five sequences (2.1, 2.3, 2.4, 8.2, and 8.3). These sequences represent

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approximately 97% of the total plant risk due to PTS at 32 EFPY as determined by this study. The risk associated with each of the five transients is presented in Table 6.2 and plotted in Figure 6.1 as a function of $\underline{RT}_{NDT}$. It is interesting to note that as $\underline{RT}_{NDT}$ increases, the relative contribution to the total risk from the LOCAs which result in loop flow stagnation (as in sequences 8.2 and 8.3) decreases, while the relative contribution due to small steam-line breaks (as in sequences 2.1, 2.3, and 2.4) increases. In the following paragraphs each sequence is discussed with respect to thermal-hydraulic characteristics, frequency of occurrence, conditional failure probability and relative change with increasing $\underline{RT}_{NDT}$ values.

Sequence 8.2

Sequence 8.2 is basically a small-break LOCA with a loss of natural circulation. This stagnation condition can be achieved by several means but would appear most frequently to be due to the occurrence of the small-break LOCA at a hot 0% power condition (low core decay heat). In Chapter 4.0 it was assumed that this sequence would lead to loop stagnation. Since this assumption led to a dominant sequence, it was necessary to actually perform the calculation of the thermal-hydraulic properties for this sequence. (See results of TRAC calculations in Appendix F.) The TRAC calculation confirmed the previous assumption and loop flow stagnation was predicted to occur within a few hundred seconds after event initiation.

The downcomer temperatures calculated by TRAC for sequence 8.2 were somewhat higher than those calculated by Theophanous and presented in

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Table 6.2. Summary of risk vs EFPY, F_o, and RT_{NDT} for dominant risk sequences

EFPY	9.2	16.8	24.4	32	41.2	53.0
F_o, 10^{19} n/cm^2	1.52	3.03	4.55	6.06	7.88	10.24
$RT_{NDT} + 2\sigma$, °C*	79	99	112	122	132	143
Sequence Number	Through-the-Wall Crack Frequency (yr^{-1})					
2.1				7.6E-10	5.3E-9	2.3E-8
2.3		1.0E-11†	1.5E-10	8.5E-10	3.5E-9	1.2E-8
2.4		1.0E-11	1.5E-10	8.5E-10	3.5E-9	1.2E-8
8.2	1.5E-10	3.6E-9	1.8E-8	4.5E-8	8.7E-8	1.8E-7
8.3	1.8E-9	9.5E-9	2.0E-8	3.0E-8	4.0E-8	5.0E-8
Total	2.0E-9	1.3E-8	3.8E-8	8.0E-8	1.4E-7	3.0E-7

*Temperature headings in °F are 174, 210, 233, 252, 270, and 289, respectively.

†Read: 1.0×10^{-11}.

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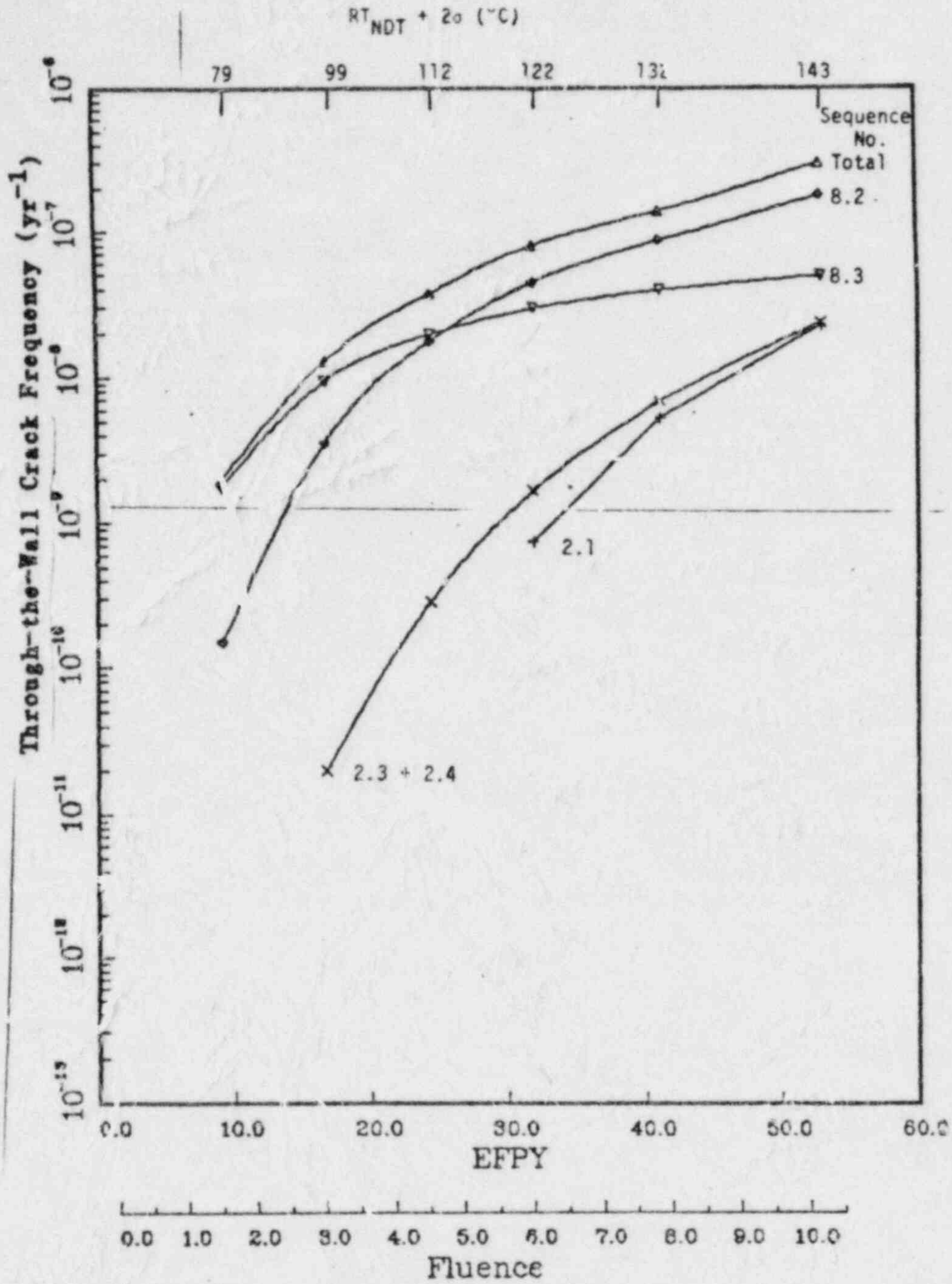

Figure 6.1. Risk associated with five dominant sequences.

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Chapter 4.0. However, the TRAC analysts have pointed out that TRAC cannot correctly account for the reverse flow and stratification conditions expected when HPI water flows into a stagnated cold leg. As a result, it was assumed that TRAC would over-predict the downcomer temperature, and the temperature profile provided by Theophanous was taken to be the best estimate of temperature conditions for this transient.

The cooldown process for this transient is dominated by the constant inflow of relatively cold HPI water into the stagnated cold loops. The minimum temperature is 125°F and it occurs at the 2-hour analysis time limit. The temperature will continue to slowly drop beyond the 2-hour time period, but an increase in the failure probability at times greater than 2 hours is not expected.

Sequence 8.3

The principal difference between sequences 8.3 and 8.2 is a difference in pressure during the latter part of the transient. In sequence 8.3 the LOCA event is terminated by isolation of the break. Due to the nature of this event, no credit was taken for controlling the repressurization and thus the system quickly reaches a high-pressure condition. The minimum

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temperature for this sequence is essentially the same as that for sequence 8.2, but the final pressure is considerably higher than that for sequence 8.2.

The event frequency determined for this sequence is almost two orders of magnitude smaller than the event frequency for sequence 8.2, but the higher pressure results in a conditional failure probability increase of almost a factor of 30 at 32 EFPY.

Sequence 2.1

This sequence is a small steam-line break at hot 0% power, and it has the highest event frequency of the five dominant sequences. However, the severity of the transient is substantially less than that for sequence 8.2 or for sequence 8.3. The minimum temperature for sequence 2.1 is ~250°F, which is to be compared with a minimum temperature of ~125°F for sequence 8.2. Thus, the conditional failure probability is lower. However, as the $\underline{RT}_{NDT}$ value increases, the conditional failure probability increases much more rapidly than it does for sequence 8.2 or sequence 8.3. For situations involving very high $\underline{RT}_{NDT}$ values, it is perceived that this sequence could become the dominant transient.

Sequence 2.3

This sequence is also a steam-line break at hot 0% power, the principal difference between this sequence and sequence 2.1 being that this sequence

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(2.3) has the additional failure of the operator not controlling the repressurization. The additional failure reduces the event frequency by about two orders of magnitude; however, the effects of this failure produce a much more severe transient due to the increased repressurization rate (minimum temperature is the same as sequence 2.1). This results in an increase in the conditional failure probability of two orders of magnitude over that for sequence 2.1. Thus the integrated risk associated with transients 2.1 and 2.3 are approximately the same.

Sequence 2.4

In the analyses performed in Chapters 3.0 and 4.0, sequences 2.3 and 2.4 were treated as identical sequences. The only difference between them is that sequence 2.4 includes the additional failure of the operator not controlling the auxiliary feedwater flow to the steam generator on the intact steam line. This additional failure was determined to have little effect on the thermal-hydraulic conditions in the downcomer region, and, as noted in Tables 6.1 and 6.2, the PTS risks for the two sequences are the same.

6.2.3. Relative Importance of Each Category of Sequences as Initiating Events

In the previous section the individual dominant sequences were identified and discussed. In this section results are presented for categories of sequences. Eight initiating event categories have been developed in previous sections. These categories are:

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(1) Large main steam-line break at hot 0% power.

(2) Small main steam-line break at hot 0% power.

(3) Large main steam-line break at full power.

(4) Small main steam-line break at full power.

(5) Small-break LOCA (<0.016 ft^2) at full power.

(6) Small-break LOCA (<0.016 ft^2) at hot 0% power.*

(7) Small-break LOCA (>0.016 ft^2 and <0.05 ft^2) at full power.

(8) Steam generator overfeed.†

The risk associated with each of these eight categories is plotted in Figure 6.2, along with that for an additional category (No. 9) that includes 11 residual groups.

6.3. Effects of Potential Risk Reduction Measures

The effects of potential mitigating actions were examined as a part of this study. This section is not intended as a list of recommendations but is provided to give information on the relative value of actions which could be taken provided a need to reduce the integrated risk due to PTS is identified.

*This category has previously been defined as small-break LOCAs which lead to loop stagnation. Since this category was found to be dominated by small-break LOCAs at hot 0% power, the category title was changed to better describe the sequences within the category.

†Includes main feedwater overfeed events (which are the only reactor trip sequences that do not fall into one of the other event categories) plus auxiliary feedwater overfeed events.

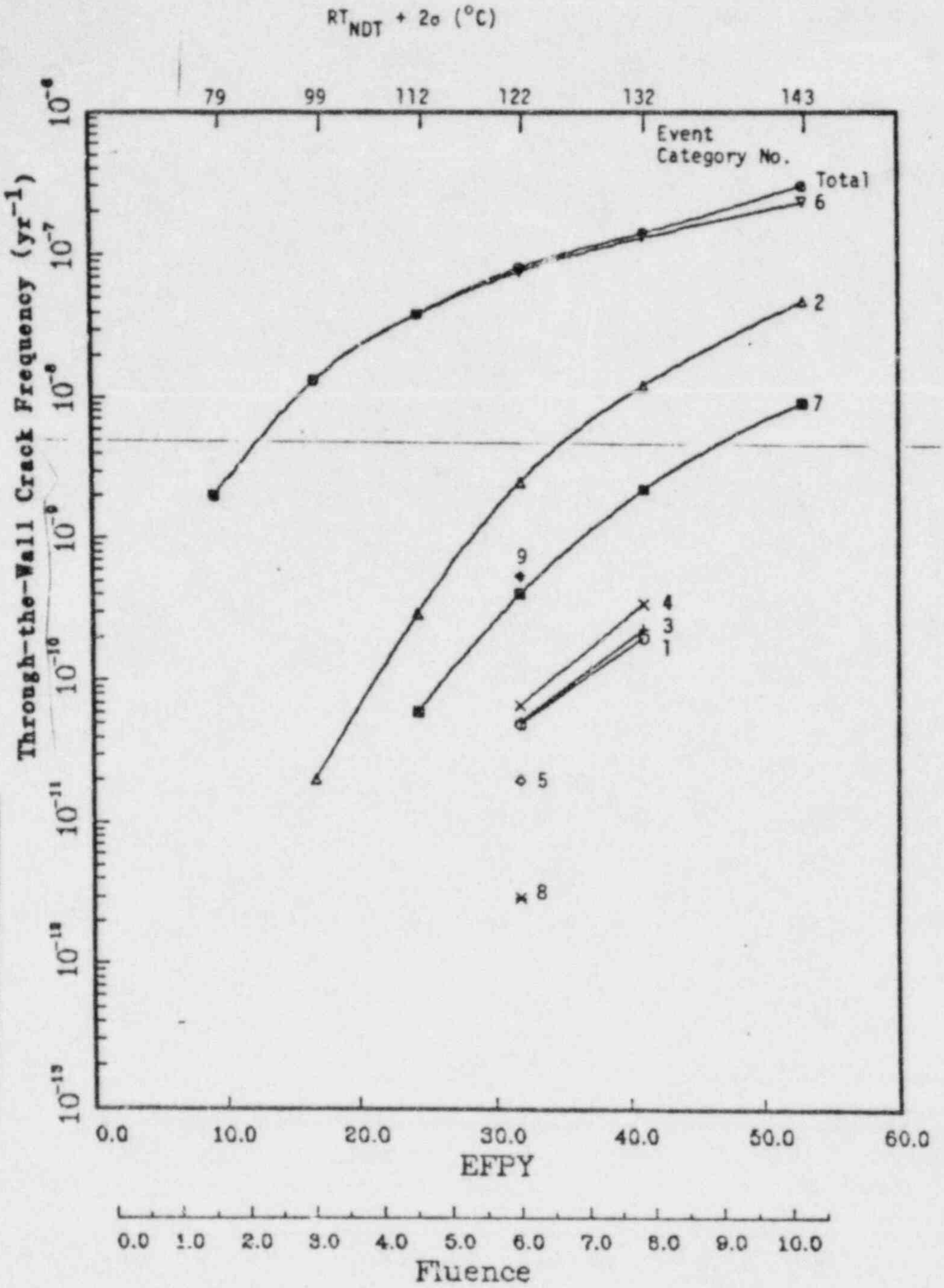

Figure 6.2. Risk associated with each category of events.

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In the pressurized thermal shock evaluation of the Oconee plant,[1] seven reduction measures were examined:

(1) Limitation on primary system repressurization,

(2) Introduction of a high steam generator trip system,

(3) Reduction of neutron fluence rate,

(4) Heating of the HPI water,

(5) In-service inspection of vessel,

(6) Annealing of vessel, and

(7) Improvement of operator training.

Limiting repressurization was not examined in this study for Calvert Cliffs Unit 1 since the low head HPI system already slows the repressurization, and the practicality of introducing an automatic restraint on repressurization is not clear. The other six measures were examined for Calvert Cliffs Unit 1. In addition, one other risk reduction action, that of maintaining RCP operation during a secondary side overcooling transient, was examined. These seven corrective actions are discussed below.

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6.3.1. Introduction of a High Steam Generator Trip System

Calvert Cliffs Unit 1 does not have a system that automatically terminates feedwater flow when a designated high steam generator level is reached. The principal effect of such a system would be early termination of an overfeed event. In the thermal-hydraulic analysis performed for this study, no credit was taken for termination of feedflow for the overfeed events. Thus feedflow continued until there was insufficient water in the hot well to maintain flow. Under this assumption, the maximum overfeed condition is obtained; however, the consequence of this maximum overfeed was negligible. Thus the introduction of a high steam generator trip of feedwater pumps would have no effect on risk reduction.

6.3.2. Reduction of Neutron Fluence Rate

The benefits obtained from reducing the neutron fluence rate in the vessel wall by factors of 2, 4, and 8 were evaluated. Since fluence has a cumulative impact on the vessel $\underline{RT}_{NDT}$ value, reducing the fluence rate will retard the effective rate of aging. This can have a significant effect on risk reduction. It was found that the fluence rate reduction factors of 2, 4, and 8 resulted in risk reduction factors of approximately 3, 11, and 27, respectively, at 32 EFPY.

6.3.3. Heating of the HPI Water

In the Oconee analysis it was determined that heating the HPI water would provide only a small risk reduction since the vent valves ensured that the warm water would always be mixed with colder HPI water before reaching the vessel wall.

For Calvert Cliffs Unit 1 the situation is substantially different. Since the plant does not have vent valves, the dominant risk sequences 8.2 and 8.3 are greatly impacted by the temperature of the HPI water. A 40°F increase in the HPI water temperature would translate to a 30°F warmer downcomer temperature at the 2-hour time period. This 30°F warmer downcomer temperature decreased the conditional failure probabilities associated with sequences 8.2 and 8.3 by factors of 10 and 2.5, respectively, at 41 EFPY ($\underline{RT}_{NDT} + 2\sigma = 270°F$). This resulted in a total risk reduction factor of 3.8 at 41 EFPY.

6.3.4. In-Service Inspection of Vessel

In the Oconee analysis[1] it was assumed that in-service inspection would reveal 90% or 99% of the surface flaws with depths equal to or greater than 6 mm. It was further assumed that all flaws found would be repaired. If before the in-service inspection, no calculated failures were attributed to initial flaws with depths less than 6 mm, then the 90% and 99% inspection would reduce the conditional probability of failure, P(F E), by factors of 0.1 and 0.01, respectively. This assumption led to an overall reduction in the probability of vessel failure by about a factor 2 at 32 EFPY. The reduction factor was limited by the fact that the very shallow flaws which would not be detected or repaired actually make a significant contribution to the total probability of vessel failure.

Since the Oconee analysis was performed, many questions have been raised concerning the efficiency of flaw detection methodologies* used and the practicality of repairing flaws. As a result, this explicit analysis was not performed for Calvert Cliffs Unit 1. However, a review of the dominant sequences reveals a distribution of failures with respect to flaw depth which is similar to that observed for Oconee. Thus under the same assumptions as used in the Oconee analysis, a factor of 2 reduction in vessel failure probability due to identification and repair of flaws would not appear to be unreasonable.

6.3.5. Annealing of the Vessel

Annealing of the vessel will restore the fracture toughness of the vessel material, effectively cancelling the effects of neutron fluence. The extent of recovery will depend on the chemistry of the vessel material, the time-temperature characteristics of the annealing procedure, and the number of times the vessel is annealed. If it is assumed that full recovery of the vessel is achieved, a reduction of 1 to 2 orders of magnitude of the risk relative to that at 41 EFPY may be possible.+ However, further annealing would be required on some periodic basis if this measure is to prevent regrowth of the risk. It should be noted that the feasibility of in-place vessel annealing was not addressed in sufficient detail by this study to assure the effectiveness and practicality of this measure.

6.3.6. Improvement in Operator Training

Operator training was not directly addressed as a variable in this study,

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*There is at least some indication that some flaws less than 6 mm depth can be detected with reasonable accuracy.

+The actual risk reduction factor is dependent upon the nature of the dominant sequences and the age of the vessel when annealing is performed. For this analysis, annealing was assumed to occur at 9 years. This gave a risk reduction factor of 0.57. Annealing at a later time in life could have produced a larger reduction in risk, but the minimum reduction obtainable with one annealing appears to be about a factor of 5 for this plant.

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but it was indirectly examined as part of the human factors evaluation of operator actions. In situations requiring relatively rapid response (<10 min), training would be considered to be a dominant influence on the success or failure of the action. However, since the large steam generators and low head HPI system at Calvert Cliffs Unit 1 appear to spread out the time available for the operator to perform the important actions with respect to PTS, it does not appear that increased training would greatly affect the integrated risk due to PTS at Calvert Cliffs Unit 1.

However, two items should be pointed out which do not greatly impact the risk at 32 or 41 EFPY but which are associated with training and could have some impact under different conditions (at much higher values of $\underline{RT}_{NDT}$ or much higher frequencies of low decay heat, etc.):

(1) A good portion of the probability associated with the failure of the operator to control pressure with respect temperature during an overcooling event was attributed to the written procedures. Very little guidance other than a simple caution was provided to the operators. This does not mean that a series of procedure steps are necessary to address the issue. One or possibly two well worded procedure steps could reduce potential confusion.

(2) A review of the dominant sequences reveals that almost all of the risk is associated with events occurring at low decay heat. In our review of the training program it did not appear that the special significance of low decay heat was emphasized. This does not mean that training should ignore the potential for a PTS

event in any operational mode. But the special potential of a PTS consequence should be recognized for any event which occurs at a low decay heat condition.

6.3.7. Maintaining RCP Operation During Secondary Side Overcooling Transient

It has been mentioned at several times in this report that the staff of Baltimore Gas and Electric is considering a change in criteria for tripping the reactor coolant pumps. The present procedures require tripping the pumps whenever safety injection is actuated. The new procedures would require tripping only two of four pumps upon safety injection actuation, with the tripping of the remaining two pumps in the case of a LOCA or loss-of-power event.

The principal effect of this procedure will be to ensure forced circulation during all steam-line break and overfeed events. Based on a LANL TRAC analysis, this could lead to a downcomer temperature that is higher by as much as 100°F for excess steam-line flow events occurring at low decay heat.

When the value of $\underline{RT}_{NDT} + 2\sigma$ is less than 270°F, the risk reduction due to this procedure change would be negligible since the secondary side events contribute little to the overall risk. However, when $\underline{RT}_{NDT} + 2\sigma$ increases beyond 270°F the small steam-line break at hot 0% power becomes a larger and larger contribution to the total risk. By leaving two pumps in operation, this contribution to the risk is reduced by 1 or 2 orders of magnitude.

6.3.8. Summary of the Effects of Potential Risk Reduction Measures

Of the seven potential risk reduction measures discussed in the previous sections, only four were found to actually have a significant potential for actual risk reduction. These four actions were:

(1) fluence reduction,

(2) heating of HPI water,

(3) vessel annealing,

(4) change of pump trip philosophy.

The effects of these measures are graphically presented in Figure 6.3.

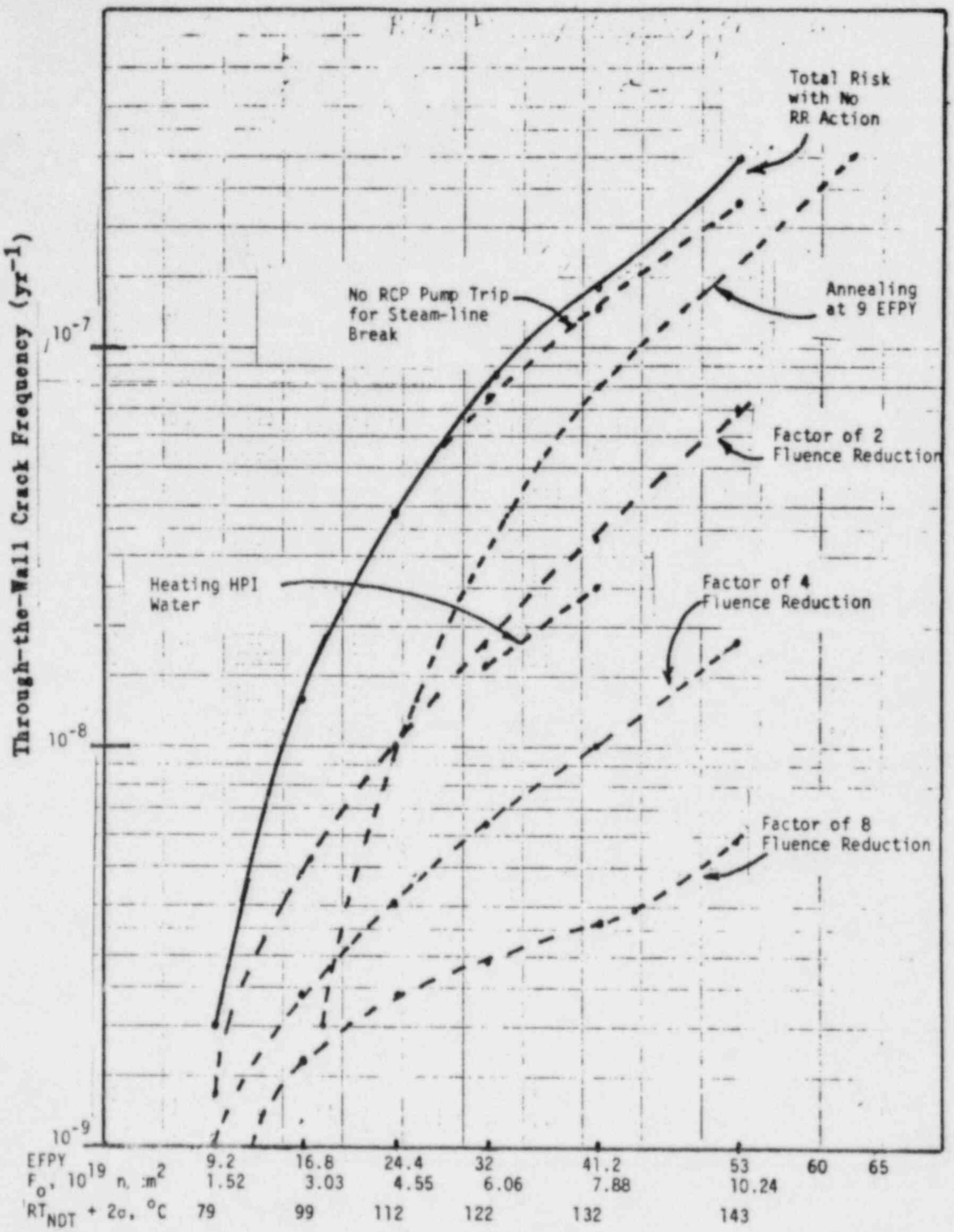

Figure 6.3. Effects of potential risk reduction actions. (Note: The top (solid) curve gives the total risk if no risk reduction (RR) actions are taken. The remaining curves show the total risk when specific risk reduction actions are taken.)

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REFERENCES

1. Oconee PTS report.

PDR

August 28, 1984

Roy Woods

Here is the review draft of Chapter 6, "Risk Integration", for ORNL's draft PTS report based on the Calvert Cliffs design.

Please call me if you have any comments.

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