Reference (677)

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December 3, 1984

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Dear Bill:

Enclosed are three copies of the draft report of the extended analysis related to Control Room Habitability. Several preliminary drafts of this analysis have been sent to Phil Matthews.

If you have any questions, please contact Wade Bickford (FTS: 444-4649) or myself.

Sincerely,

Tom Powers

T. B. Powers, Project Manager
Prioritization of Safety Issues Project
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TBP:th

cc: W. Minners, w/o

Enclosure

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A PROBABILISTIC EXAMINATION OF NUCLEAR POWER PLANT CONTROL ROOM HABITABILITY DURING VARIOUS ACCIDENT SCENARIOS

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SUMMARY

This report presents the results of an examination of control room habitability under a number of postulated threats. These include toxic gas clouds, smoke, fires in the control room, and radiation releases.

The Louisiana Power and Light Waterford plant was selected as the reference plant and site for this analysis primarily because of its location in a heavily industrialized area. It was thought that analyzing this type of site would yield a conservative estimate of the frequency and severity of toxic gas initiating events which were of primary concern.

The results of the research undertaken in this project are summarized in Table S.1. The total estimated frequency for loss of habitability from the mechanisms considered is 5.1E-06/reactor year. This frequency is thought to be a conservative overestimate, based on a number of simplifying assumptions used for each of the cases considered. The assumptions used in the frequency calculations are summarized below.

It should be noted that these results do not calculate core melt frequency following loss of control room habitability. Most of these type of events are of a relatively short duration and would be unlikely to have significant impact on plant operations. Operators could leave the plant running, thus opening a short time window when no operator would be available to respond to a transient condition. Or, an operator could simply scram the plant which could also be done from the remote panel in case of a fire in the control room. The plant scram itself could then initiate a transient to which the operators could no longer respond. In either scenario, existing operating experience indicates that the probability of an upset during a several hour period or after scram that requires operator action is most likely to have a value much less than 1.0.

TABLE S.1. Summary of Loss of Control Room Habitability

Source of Insult	Estimated Frequency, 1/ry
Toxic Gas (Chlorine)	1.6E-07
On and Offsite Smoke	1.0E-06
Gas Impacting Fire Systems	-0-
Control Room Fires	2.1E-07
Radiation Releases:	
Steam Tube Rupture	3.6E-6
Large Break LOCA	1.8E-07
TOTAL	5.1E-06/ry

A number of simplifying assumptions were required to evaluate the hazard to control room habitability from the specific threats of interest. In the absence of data or specific design information, an attempt was made to bound the problem by assuming highly conservative values for the parameters involved. The following specific steps were taken to establish boundary conditions:

- Determine concentration limits or exposure leading to operator incapacitation.
- Estimate event frequency, differentiating by severity of release if possible.
- Estimate resulting airborne concentrations at the control room air intake.
- Determine the reliability of sensors and isolation signals.
- Examine the buildup of control room concentrations with time for various modes of isolation and air leakage.
- Determine the ability of the operator to respond with and without alarms by utilizing air masks.
- Determine the ability of the operator to respond to a failure of the automatic isolation signal.
- Determine the reliability of the air supplies for the fresh air masks.

For several of the accidents of interest, the presumed frequency of occurence was below the threshold (1E-07/yr) for inclusion in the Waterford FSAR (Louisiana Power and Light Co.). In such cases, occurence frequencies of events severe enough to impact the plant were assumed to be several orders of magnitude more frequent than indicated by the absence of cited data in the FSAR. For example, the frequency of offsite fires was chosen to be 1E-02/yr. Likewise chlorine was selected as the representative toxic gas since its release frequency and toxicity were significantly larger than other chemicals identified in the Waterford FSAR as being near the site. It was also assumed that most toxic gas releases would be of sufficient magnitude and duration to preclude habitability if the isolation and masking functions failed.

The peak concentrations at the air intake to the plant were modeled with conservative transport equations used in NRC site evaluations. The plume was then assumed to remain at the intake for an unspecified period of time. The response time of the isolation system and air leakage for various states of operation (or failure to isolate) were taken from the FSAR.

Operator masking was assumed necessary for habitability in the absence of data on airborne concentrations. It was further assumed that if concentrations exceeded allowable levels in under two minutes, insufficient time would be available for the operator to mask and habitability would be precluded.

Appropriate event trees were then constructed for the isolation signal, CRACs response, emergency filtration, operator response, and air supply function. No credit was given for repair of mechanical failures; although the operator was assumed to be capable of attempting manual isolation given failure of the automatic signal. The event trees were supported by fault trees which were used to estimate the failure probabilities of the mechanical systems involved. The FSAR was used to determine valve and damper responses required for isolation and operation of the emergency filtration systems and the emergency air supply.

The fault trees were then modified as needed to consider accident specific failure modes such as particulate buildup and failure of filters in heavy smoke plumes. Operator action or failure to isolate air intakes under such conditions was also considered.

Modeling of the Waterford ventilation system resulted in an estimate that the detection and isolation hardware are quite reliable in their functions. The weak links in the responses required to maintain habitability were presumed to be the operator and the air supply. This was due in part to the assumption that the air supply would be required in most accidents even in the event of successful isolation and operation of the filtration system. Also a relatively high error probability was assumed for masking given the time (two minutes) and sensory feedback available to the operator from smoke or gases such as chlorine. In addition, a high failure probability was assumed for the compressed fresh air supply, and no credit was given for the use of portable air packs found in the control room.

Based on the assumptions described above, the data shown in the summary table is thought to represent a very conservative estimate of the frequency of loss of control room habitability for the accidents considered.

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

This issue for which this research was undertaken concerns the ability of the control room air conditioning system (CRACS) at nuclear power plants to maintain a habitable working environment during various accident scenarios. The issue has three basic components:

1) Initiating events which challenge the CRACS,
2) Automatic response of the CRACS, and
3) Actions of the operator to manually control the CRACS and utilize the fresh air supply.

The following approach was used:

1) Define the basic accident scenarios of interest.
2) Identify a reference plant and site.
3) Quantify the frequency of initiating events for the scenarios.
4) Develop appropriate event trees for response of the control room air conditioning system.
5) Develop a data base and quantify event trees for the reference site.
6) Calculate overall probabilities for scenarios leading to loss of control room habitability.

Note that in using this approach the probability of core damage or core melt was not directly estimated. In such cases, scenarios would have to be carried further to a plant upset with failure of automatic corrective systems, thus requiring action from the unavailable operator. The initiating failure could be coincident with the loss of the operator, or occur at some later time if the plant were assumed to simply continue operation. This period of time would most likely be several hours at best as emergency teams are likely to respond to accidents of sufficient magnitude to cause loss of the operators.

In any event, the bounding case is to simply assume a probability of 1.0 for such scenarios leading to core melt after loss of habitability. Thus, before investigating the core melt scenarios too rigorously, the probability of loss of habitability must be evaluated. If the probability of loss of habitability is sufficiently small (i.e., on the order of <1E-6/yr), the contribution to core melt frequency from these type of accidents would become relatively insignificant.

Specific accident scenarios for loss of habitability requested by the U.S. Nuclear Regulatory Commission (NRC) are discussed next.

2.0. BASE LINE ASSUMPTIONS

The types of accidents which could possibly result in loss of control room habitability and the reference plant to be used in this study were specified by the NRC. These specifications are discussed in this section.

2.1. ACCIDENT SCENARIOS

A broad range of accident scenarios was requested for inclusion in this study by the NRC. Because the response of plant systems during the accident is determined to some extent by the overall operating conditions of plant, the initiating events were classified into three broad categories which reflect the initial status of the plant: independent initiating events, common cause initiating events, and radiation release events.

Independent initiating events include independent events external to the plant which have no initial association with the overall operating condition at the plant. The scenarios specified include:

- Offsite release of toxic gas, with no impact on fire detector or deluge systems.
- Offsite release of toxic gas, which may trigger fire detectors and deluge system in safety areas.
- Offsite and onsite release of smoke.

Note that response to this type of event could include maintaining normal plant operation or initiating shutdown or SCRAM as the last action of the operator.

Common cause initiating events include events which can impact control room habitability as well as operations in the remainder of plant. The scenario that was specified for examination was fire in the control room leading to loss of habitability.

Note that two responses to this event can be assumed: 1) Immediate shutdown of the plant at the initiation of the event or 2) immediate evacuation of the control room followed by shutdown of the still-operating plant from the emergency shutdown control board.

Radiation release events include radiation release accidents that occur at a number of locations in the plant. The two accidents specified for study were a steam generator tube rupture and a LOCA initiated core damage event.

Steam generator tube rupture incidents occur when the plant is operating and represent a small loss of coolant accident. A large LOCA scenario where core damage had already occurred was also studied to establish any conditions about the effect of a radiation release on control room habitability.

2.2 REFERENCE DESIGN

The NRC requested that the Louisiana Power and Light's Waterford PWR (Combustion Engineering design) be used as the reference site for this analysis of control room habitability. This site represents a bounding case of toxic gas events because of the extensive industrial development surrounding the plant. This development includes major chemical and petroleum facilities, gas pipelines, and shipment routes of hazardous chemicals by rail, truck, and ship. In the Waterford FSAR, an analysis of the potential for serious accidents was made with the provision for including appropriate defenses in the plant design for accidents with a probability of greater than 1.0E-7 per year. Specific details of the Waterford plant are compiled in the Appendix and used as reference material in the following sections.

3.0 TOXIC GAS CLOUD, WITH NO RESPONSE OF FIRE SUPPRESSION SYSTEMS

The first accident sequence requested by the NRC and its impact on control room habitability are discussed in this section.

3.1 TOXIC GAS CLOUD EVENT TREE

The response to a toxic gas release, whether onsite or offsite, is the same. This response includes detection of the cloud, control room isolation, and recirculation of control room air. The event tree used to model the probability of such an event which would have an impact on the control room habitability is shown in Figure 3.1 and consists of the following steps:

- Determination of frequency of initiating event.
- Detection by sensors.
- Demand for automatic isolation.
- Functioning of isolation hardware (valves, dampers, etc.).
- Detection of gas and remote manual isolation of CRACS.
- Masking by operators in less than 2 minutes.
- Functioning of breathing apparatus.

The choice of actions listed above was made to reflect the fact that gas concentrations could build up fast enough to preclude successful donning of breathing masks by operators. Tracing the flow of events through this tree should indicate if habitability will be maintained on a short and long term basis. It should be noted that no credit was given for filtration by the plant's charcoal filter beds. This point will be discussed further with the final conclusions.

The first decision point in the event tree, shown at the left in Figure 3.1, is the sensor/alarm function. If the sensors/alarms fail to operate, the course of events follows the lower branches of the tree. To be successful in maintaining habitability, the toxic gas must be detected by the operator without benefit of an alarm. The air conditioning system must then be isolated by a remote manual signal.

If an isolation signal is sent, the logic for configuring the network must function. Failure of this logic then presents a similar case as above, but the operator now has benefit of the alarm signal. Operator detection and action is thus more likely.

If the logic functions but the isolation hardware itself fails (e.g., valves, dampers, etc.), operator detection with benefit of the alarm and use of the breathing apparatus is required. No credit was given for potential repairs to the malfuntioning isolation hardware. In addition, no credit was given for the use of back-up portable air masks due because of the short time available for masking in the event of a major toxic gas release. The NRC requires a maximum two minute period for masking.

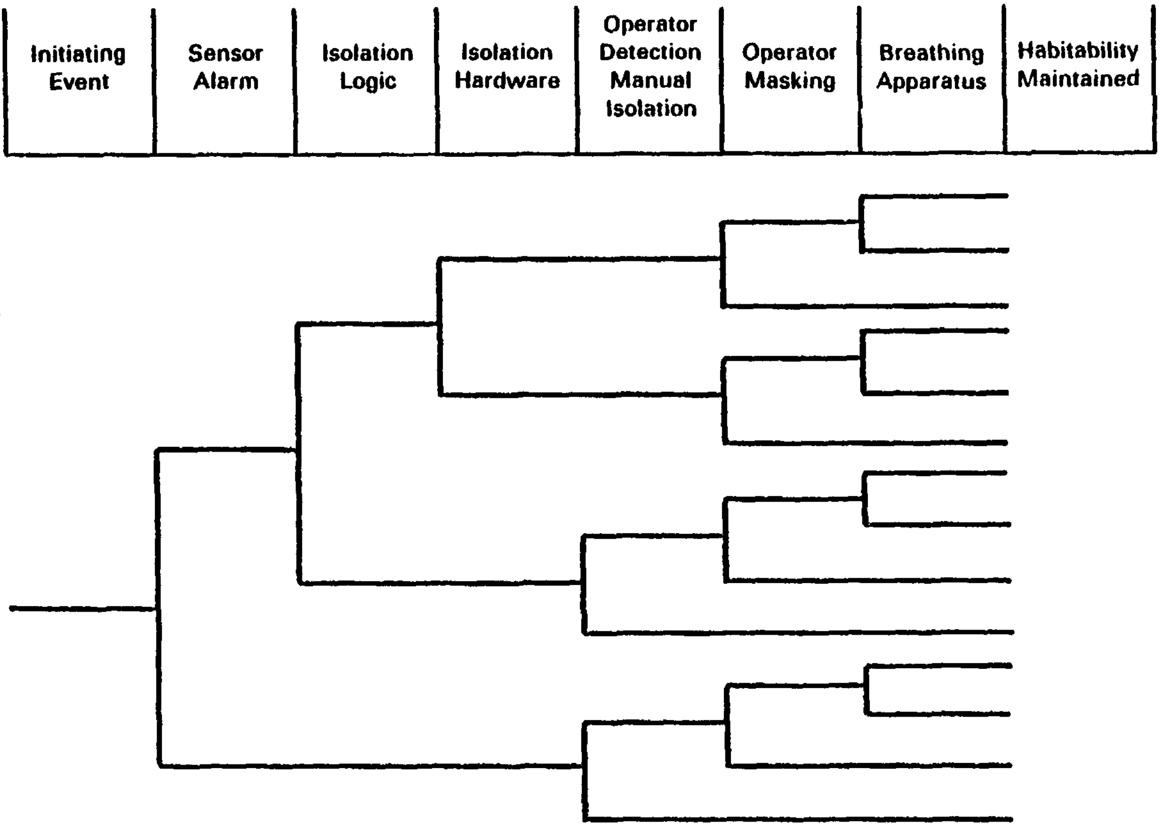


FIGURE 3.1. Toxic Gas Cloud Event Tree

3.2 TOXIC GAS CLOUD: FREQUENCY OF INITIATING EVENTS

The Waterford FSAR considered the release of a number of chemicals, including acrolein, chlorine, glycol, hydrofluosilicic acid, phosphoric acid, tetraethyl lead, toluene di-isocyanate, perchlorethylene, styrene monomer, and vinyl chloride. A relative measure of their toxicity and threat to the plant was made by comparing the quantity of each gas available for release, its vapor pressures, and the immediately-dangerous-to-life-or-health (IDLH) concentration. The IDLH is a measure of the concentration from which a person could escape after a 30 minute exposure with no irreversible health effects.

Of the toxic chemicals considered in the Waterford FSAR (Table 2.2A-2 in the FSAR), chlorine was identified as having the highest relative toxicity (as defined on FSAR page 2.2A-3). For the purpose of our analysis, chlorine leaks were used to determine plant response to a toxic chemical release.

Frequency of events and severity of accidents were examined in this study. The ability of the isolation system and operators to respond to chlorine releases will depend on the assumed magnitude of the chlorine concentrations in the inlet air and how fast chlorine concentrations build up in the control room under various scenarios. It was assumed that Waterford responds satisfactorily for the releases considered when its automatic isolation systems function. Of interest in this study were releases of chlorine which may preclude successful operator response if manual isolation is required.

Table 2.2-4 of the Waterford FSAR lists potential chlorine release quantities at various distances from the plant. Calculated maximum chlorine concentrations at the control room air intake are also given for some of these releases. The frequency of releases and the final control room air concentration were not presented because the chlorine concentrations were determined to be values covered under the exemptions of Regulatory Guide 1.95 (NRC 1977). For the purposes of this analysis, the frequency of release for the various source types (pipeline, etc.) were based on the accident frequencies cited in Chapter 2 of the FSAR, assuming when necessary a 10 mile exposure distance and 10 trips per year. A 0.005 factor for the most unfavorable meteorological conditions was also used in the Waterford numbers. Data resulting from our calculations are shown in Table 3.1.

TABLE 3.1. Assumed Chlorine Release Frequencies for Waterford

Source Type	Prob of Release(yr-1)	Quantity Released(g)	Peak Air Inlet Concentration	
			g/M03	PPM
S	1.6E-7	5.5E+8	5.2E+2	1.7E+5
P	2.8E-5	3.3E+8	<5.2E+2	<1.7E+5
P	2.8E-5	8.5E+7	<5.2E+2	<1.7E+5
R	4.0E-8	9.1E+7	6.1E+2	2.0E+5
P	2.8E-5	3.8E+5	<5.2E+2	<1.7E+5
S	1.6E-7	4.5E+8	1.7E+1	5.7E+3
R	4.0E-8	3.3E+8	5.4E+1	1.8E+4
S	1.6E-7	6.8E+4	3.4E-1	1.1E+2
T	1.4E-8	6.8E+4	3.4E-1	1.1E+2
S	1.6E-7	6.8E+4	7.5E-1	2.5E+2
T	1.4E-8	6.8E+4	6.1E+0	2.0E+3
P	2.8E-5	2.3E+8	<5.2E+2	<1.7E+5
TOTAL	1.53E-4/yr			

Source
S = stationary
P = pipeline
T = truck

A standard criterion for the plant is that, after receipt of the initial alarms, operators need at least 2 minutes to don air masks before toxic gas concentrations reach an uninhabitable level. The FSAR indicated that Waterford passed this test, but documentation of the test was not included. Estimates were required in this study to determine if sufficient time is available for manual isolation in the event of an automatic-system failure. The following assumptions were used for making these estimates:

- The evacuation limit of chlorine is 25 ppm, the ILDH limit. The NRC uses 15 ppm for conservative licensing calculations, however for this study 25 ppm was considered to be a more representative concentration of sufficient toxicity and irritability to induce evacuation.
- The human detection limit for chlorine is 3.5 ppm.
- The effective reduction in chlorine concentration by charcoal filters is 0.01 (i.e., 99% effective as with iodine).
- The response time of the chlorine detectors is 7 seconds.
- The gas transport is 4 seconds to the isolation valve, which has a closure time of 2 seconds. This gives an effective isolation time of 5 seconds (FSAR p.6.4-7b Amendment 12, 9/80).
- The normal air infiltration rate for Waterford is 0.6 air changes per hour. This rate decreases to 0.012 air changes per hour after isolation.

It was initially thought that the calculations for Waterford were performed with the equations given in the FSAR to model acrolein buildup in the control room as a function of time (p.2.2-29 Amendment 31, 3/83). Equation (1) was solved for X_o, the maximum allowable inlet concentration if control room concentrations are to be kept below 25 ppm during a 5 second isolation time. This solution resulted in a chlorine concentration of 2.0E+4 ppm.

$$X_1 = C_o + \left[1 - e^{-(R_1/3600)t}\right] X_o \tag{1}$$

where

t = time, seconds
X_1 = control room concentration, ppm
C_o = initial control room concentration at alarm, ppm
X_o = maximum intake concentration, ppm
$R_1/3600$ = air infiltration rate , volume changes per second.

As can be seen in Table 3.1, the chlorine concentrations corresponding to the assumed highest frequency release situations exceed 2.0E+4 ppm. This indicates that habitability could not be maintained unless some chlorine removal by charcoal filters is considered.

Based on this consideration, a decision was made to estimate control room chlorine concentrations using methods given in the NRC's unpublished Review of Methodology Used in Past NRC Toxic Gas Calculations. Following are equations used in that methodology:

$$X_1 = \frac{R_1 (t)^2}{4.7\sigma} X_o \qquad (2)$$

where

X_1 = control room concentration at isolation, mg/m^3
R_1 = normal air exchange rate, 1/hr
t = isolation time, sec
X_o = peak outside concentration, g/m^3
$\sigma = (\sigma_x^2 + \sigma_I^2)^{1/2}$

where

σ_x = standard horizontal plume deviation, m

$$\sigma_I = \left[\frac{Q_I}{(7.87)(3209 \text{ g chlorine/m}^3)}\right]^{1/3}, \text{m}$$

Q_I = release quantity, g.

Assuming that the Waterford numbers were correct, Equation 2) of the NRC Toxic Gas Methodology [Equation (3) below] was used to calculate the standard deviations used to determine the intake concentrations given in Table 3.1. Entries of "less than" were ignored for the moment. This was

$$X_o = Q_I \left[6.28 \, (\sigma_x^2 + \sigma_I)^2 \, H\right]^{-1}, \text{mg/m}^3 \qquad (3)$$

where H is the receptor height, established to be 17m in the Waterford FSAR.

The standard deviations are typically as given in Figure 1 of Regulatory Guide 1.78(NRC 1974). However, the standard deviations required to duplicate the inlet concentrations as given in the Waterford FSAR are not those given in Regulatory Guide 1.78 for a Pasquill Type G stability. Rather than change the intake concentrations given in the FSAR, the correlation between distance and deviation used for Waterford was plotted, and is shown in Figure 3.2. Estimated intake concentrations were then calculated for the "less than" entries in Table 3.1. These are presented in Table 3.2.

As a check, control-room chlorine concentrations after 2 minutes were calculated using another recommended equation from the NRC Methodology (and a modification of that equation). The highest chlorine concentration resulting from use of these equations was used [shown below as Equations (4) and (5)].

$$X_2 = \left[\frac{R_1 t^2}{432} + 17 \frac{R_2}{K}\right] X_o, \text{ mg/m}^3 \tag{4}$$

$$X_2 = X_1 + 17 \frac{R_2}{K} X_o \tag{5}$$

where

t = time to isolate (assumed to be 5 seconds)

X_2 = control room concentration after 2 minutes, ppm

R_2 = isolated air exchange rate, 1/hrs

K = buildup factor (assumed to be 8).

Equation (5) was used because Equation (4) sometimes predicted a decrease in concentration after isolation. This decrease was the result of assumptions used for calculating X_I.

As shown in Table 3.2, the control room concentrations after 2 minutes were calculated to be equal to or less than 15 ppm, with the exception of Release 4, which resulted in a concentration of 22 ppm when using Equation (5). With the 25 ppm criteria used in this analysis, it was assumed that the operator has sufficient time to don a mask when automatic isolation functions properly. This same assumption was made in the Waterford FSAR.

If automatic isolation fails, several release events may preclude manual isolation. In these events, concentrations may exceed 25 ppm before manual isolation or successful masking can be achieved. To develop estimates for these situations, it was assumed that 10 seconds would be required to manually initiate the isolation function following operator detection of chlorine concentrations at 3.5 ppm. Equations (2) and (4) or (5) were again used to determine if a concentration of 25 ppm was exceeded in the 2 minute period (the time needed to don a breathing mask) after isolation. This time period, plus the 10-second period needed to initiate the isolation signal, results in a total

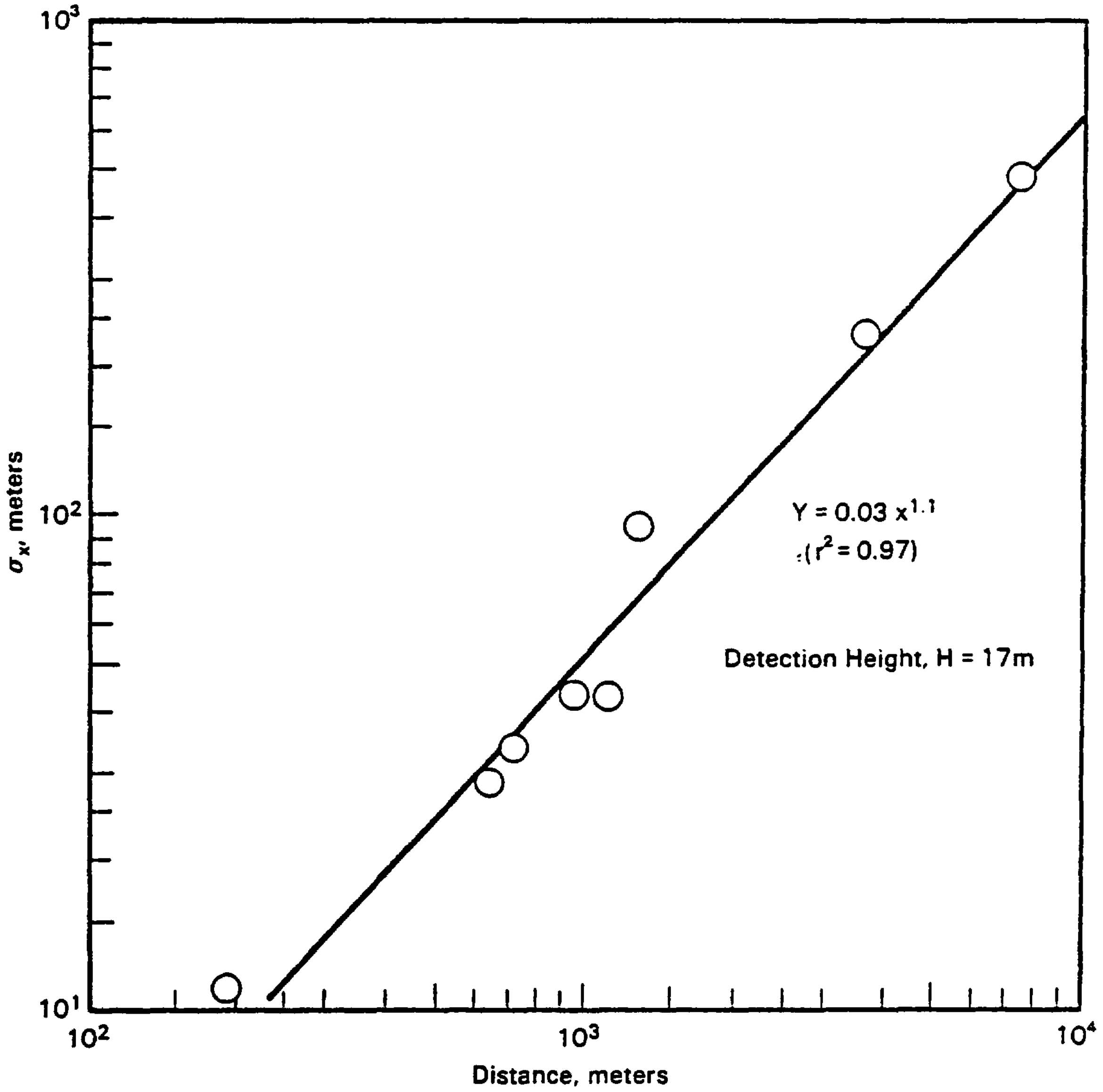


FIGURE 3.2 Assumed Standard Horizontal Deviations for Waterford

TABLE 3.2. Waterford Control Room Chlorine Concentrations

Release #	Frequency 1/yr	Distance M	Q_T Quantity Released g	α_I	α_X	Xo Peak Inlet Concentration g/m3	Control Room Concentration, ppm			Failure of Isolation Hardware t=120 sec
							Auto Isolation t=125 sec	Manual Isolation t=10 sec	Manual Isolation t=130 sec	
1	1.6E-7	1290	5.5E+8	27.92	95.54	5.2E+2	1.0E+1	25.7	30.1	3.5E+5
2	2.8E-5	1290	3.3E+8	23.55	95.54	3.2E+2	6.4E+0	17.3	20.1	2.1E+3
3	2.8E-5	1290	8.5E+7	14.98	95.54	8.5E+1	1.7E+0	7.3	8.0	5.7E+2
4	4.0E-8	724	9.1E+7	15.33	34.09	6.1E+2	2.2E+1	71.5	76.7	4.1E+3
5	2.8E-5	1770	3.8E+5	2.47	112.2	2.8E-1	1.0E-2		--	1.9E
6	1.6E-7	7560	4.5E+8	26.11	497.26	1.7E+1	3.4E-1		--	1.1E+2
7	4.0E-8	3620	3.3E+8	23.55	238.0	5.4E+1	1.1E+0		--	3.6E+2
8	1.6E-7	965	6.8E+4	1.39	43.3	3.4E-1	1.0E-2		--	2.3E
9	1.4E-8	1126	6.8E+4	1.39	43.3	3.4E-1	1.0E-2		--	2.3E
10	1.6E-7	644	6.8E+4	1.39	29.1	7.5E-1	3.0E-2		--	5.0E
11	1.4E-8	193	6.8E+4	1.39	10.2	6.1E+0	6.9E-1		--	4.1E+1
12	2.8E-5	3781	2.3E+8	20.88	258.5	3.2E+1	6.4E-1		--	2.1E+2
	1.53-4									

time limit of 2 minutes 10 seconds. The results shown in the last columns of Table 3.2 indicate that Releases 1 and 4 would exceed this time limit with a total frequency of 2.0E-7/yr. If Release 2 with a concentration of 20.1 ppm is also included to be conservative, the frequency would increase to 2.8E-5/yr. It is doubtful that other sequences would contribute even if the time required for manual isolation was increased beyond 10 seconds.

The failure probability of the operator to don a mask was set at 1.0 for sequences where automatic isolation failed, with an initiating frequency of 2.8E-5/yr. The operator failure rate for other releases with a total remaining frequency of 1.2E-4/yr will be discussed in Section 3.3.4.

For failure of the isolation hardware, a conservative estimate would indicate the control room chlorine concentration reaching equilibrium with the intake concentration, as predicted by Equation (1). Equations (2) through (4) are not applicable for long-term buildup, since their solutions indicate an ever increasing concentration buildup with time.

Equation (1) indicates that all release events shown in Table 3.2, except Releases 5, 8, 9, and 10, would result in control room concentrations of 25 ppm or more 2 minutes after the 3.5 ppm detection level. This results in an initiating frequency of 1.25E-4/yr where the probability of failure of an operator to don his mask will be equal to 1.0 in the event of an isolation hardware failure.

3.3 QUANTIFICATION OF EVENT TREE FOR TOXIC GAS

Quantitative estimates for the remaining steps for the toxic gas event tree in Figure 3.1 are developed in this section.

3.3.1 Sensor Alarm Signal

The function of the gas detectors is to send a signal to the control logic which initiates isolation and alarm. The values for gas detector failure presented in WASH-1400 (1975) were used. The hazard rate given is 1E-6/hr. Using an 18 month calibration schedule and averaging over the interval gives an assumed failure probability of:

p(single detector failure) = (1E-06.hr)(18 mo)(720 hr/mo)(0.5) = 6.5E-3

The probability of both detectors failing independently is then 4.2E-5.

A simple fault tree for events that could lead to failure of detectors A and B to send an isolation signal is shown in Figure 3.3. The probability of multiple detector failure will include an independent failure of two detectors and common mode failures. The latter will include causes such as calibration errors which conservatively estimated here to be 10% of a single independent failure or 6.5E-4. This value compares to values typically used in WASH-1400 and is the square root of the product of single and double independent failures, i.e., the square root of (6.5E-3)(4.2E-5), or 5.2E-4.

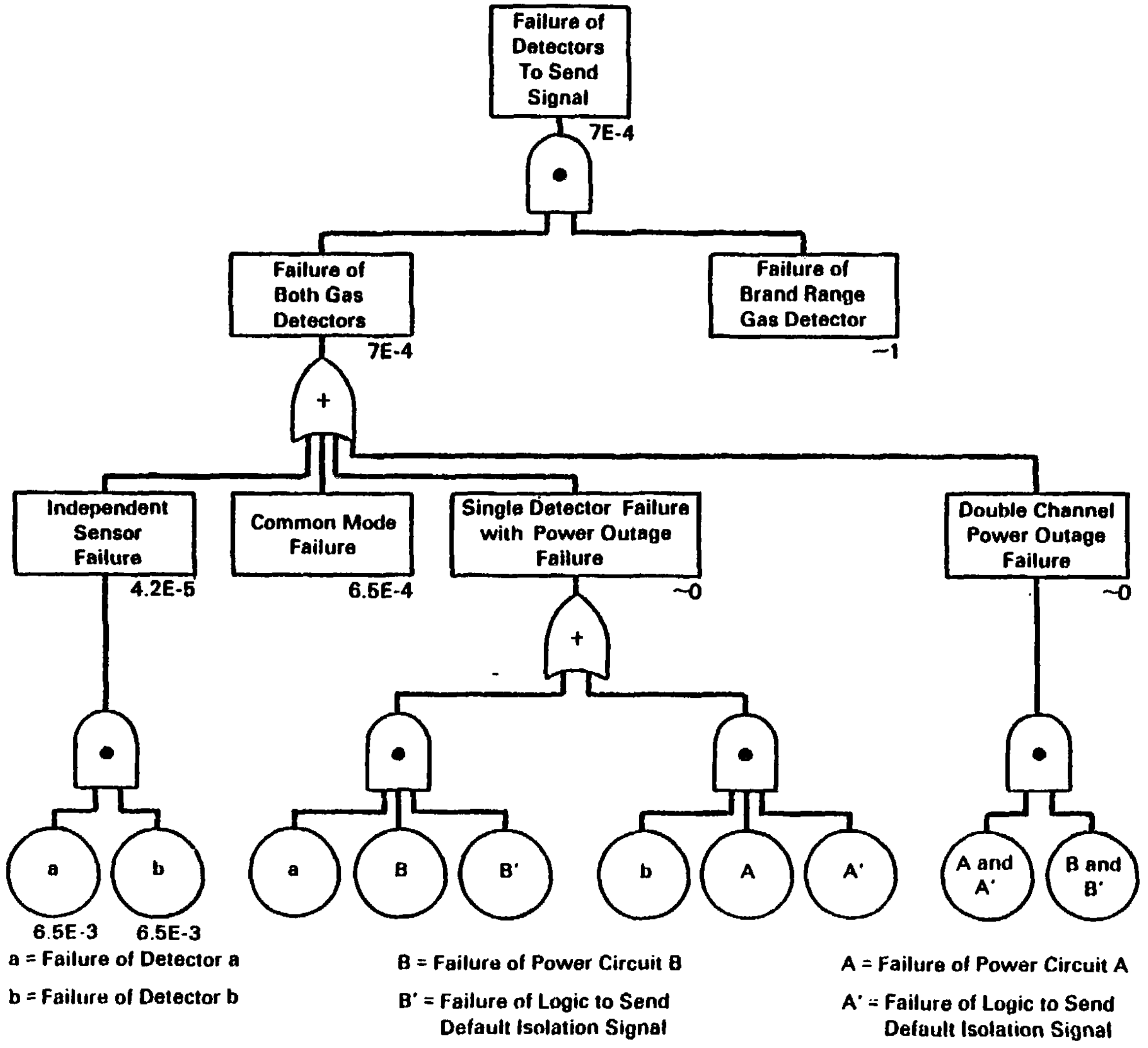


FIGURE 3.3. Total Detector Failure Fault Tree

Note that the system is designed so that loss of an electric circuit to either detector constitutes a fail-safe signal to isolate. This holds true for the isolation hardware also, with the normal air intake and emergency air valves being designed to fail closed and fail as-is, respectively. The probability of failure for this "null" signal is, thus, zero for power failure cases described in Figure 3.3. The system also includes a backup broad-band gas-detection system, but to be conservative it was assumed that this system will not detect chlorine.

The total probability of independent and common mode detector failures is then 6.5E-4 + 4.2E-5, or approximately 7E-4.

3.3.2 Control Isolation Demand (Logic)

Cases involving normal functioning of the detectors will require the operation of a logic function to initiate the isolation process. Solid state devices that may control relays typically have demand failure probabilities on the order of 1E-6. A demand failure probability of 1E-4 is typical for simple relays. A redundant system would be more reliable, but the 1E-4 probability value was used in this study as a conservative estimate.

Note that the "null" signal mentioned above for power failure constitutes a default fail-safe operation of the isolation signal logic. In addition, it was assumed that the same control logic is used to configure the air circulation system for isolation if the signal is sent automatically or manually.

3.3.3 Isolation Actuation (Hardware)

The fault tree for the assumed CRACS hardware configuration is shown in Figure 3.4. This fault tree shows the major assumed pathways for failure to isolate the control room: the intake and exhaust ducts and emergency filtration units (EFU). The most obvious path into the main system is through the main air intakes. This path would require the failure of two normally-open, fail-closed valves. The probability of this occurrence was assumed to be 1E-4 for one independent failure and 1E-8 for two failures resulting in failure to isolate. The Wash-1400 approach would give a failure estimate of 1E-6 for both valves failing due to a common cause.

These valves are also designed to fail closed upon loss of electric power. Failure to isolate in this manner would require the loss of electric power and failure to fail closed. This probability is estimated to be significantly less than simple failure to close on receipt of the signal.

The exhaust system could also fail to isolate if two normally open fail-closed valves fail to close. The probability of this occurrence was assumed to be 1E-8. Two exhausts are indicated for Waterford, giving a probability for failure of the valves to isolate totalling 2E-8. A common mode failure of 1E-6 for each of these valve sets is also assumed, resulting in an assumed total probability for common mode failure of the exhaust amounting to 2E-6.

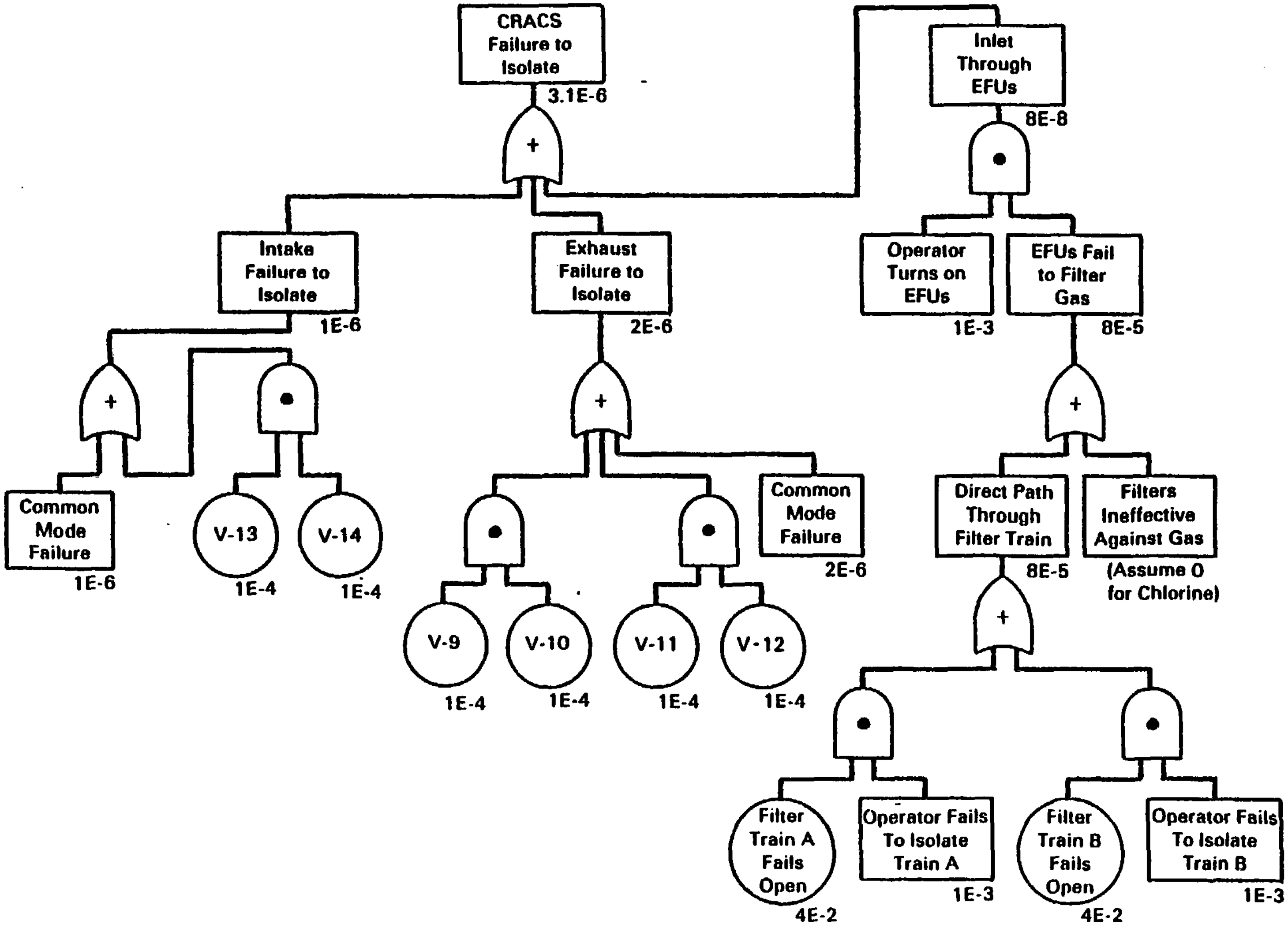


FIGURE 3.4. Isolation Hardware Fault Tree

The probability of mechanical failure to isolate is dominated by the assumed common mode failure of valve sets and is thus estimated to be 3E-6.

To be conservative, the role of operator error will also be considered here as a mechanism for failure to isolate the control room. Operation of the EFUs is not an automatic response to the toxic gas cloud, however they could be turned on in error by the operator (error probability = 1E-3). No credit is typically given in licensing calculations for removal of gas by the charcoal filter beds although they are considered to be highly effective for removing chlorine. In this study, credit was taken for the filters. (Note that credit for filtration was ignored in Section 3.2, where control room concentration buildups were examined for the purpose of establishing conservative assumptions for the initiating frequencies of releases. In that case releases which would preclude operator masking if automatic isolation failed were identified).

The EFU air intake rate is 200 cfm, resulting in 0.06 volume changes per hour, which is 5 times the 0.012 changes per hour for isolated air infiltration assumed for Waterford. However, the filtration efficiency of the charcoal filters more than makes up for this increased intake rate, effectively reducing infiltration to equal or better than that of simple isolation. The latter case is likely to be true because operation of the EFUs will result in control room pressurization.

For failure of isolation via the EFUs, a filter failure would have to be assumed. To be highly conservative, a failure probability of 0.04 will be used, based on the observed failure rate of respiratory filters during a TMI acceptance testing program. This information on the failure rate of respiratory filters during TMI acceptance testing was provided to PNL by the NRC. Failure of one filter train then requires filter failure and operator failure (1E-3) to transfer to the other train, resulting in a total failure probability of 4E-5. This probability is doubled to 8E-5 for both trains. The operator error in activating the EFUs for the toxic gas release (1E-3) further reduces the probability for loss of containment via the EFU system to 8E-8.

The total probability estimated for failure of the CRACS to isolate as shown in Figure 3.4 was calculated to be approximately 3.1E-6. (Note that the exact configuration of the valves and dampers for various emergencies considered by the Waterford plant are given in Table 9.4.2 of the Waterford FSAR. A brief description is given in the Appendix.

Note that filtration by the EFUs has been discussed; however, no credit was taken in this analysis for filtration of the chlorine by the main intake filters. This is because the main inlets provide for particulate filtration but do not contain charcoal beds which would provide removal of chlorine.

3.3.4 Operator Detection and Initiation of Manual Isolation

At this point, a number of operator actions are required: detection of the gas, configuring the valves for isolation, and masking. Because the ability to successfully don masks in 2 minutes depends on control-room isolation for some of the release events studied, descriptions of operator response were divided into two sections: this section which describes operator detection of the chlorine and initiation of manual isolation and the following section which describes operator masking.

The potential for operator detection of a gas depends greatly on the type of gas in question. For chlorine which is being considered here, operator detection at a concentration of 3.5 ppm is very likely. For this study, probabilities of failure to detect the gas with the alarm and without the alarm are assumed to be 1E-4 and 1E-3, respectively.

If the automatic isolation logic fails, manual isolation should still be possible. Manual operation requires that the operator put the CRACS in the proper configuration. The probability of human error in configuring the valves was assumed to be 1E-3. This valve-configuration error would dominate any mechanical failure to isolate as was shown in Figure 3.4.

These considerations yield total probabilities of failure to manually isolate the control room of 1.1E-3 with alarm and 2.0E-3 without alarm.

3.3.5 Operator Masking

As discussed above, several of the release sequences will preclude sufficient time to allow masking in the event of a failure to isolate. As a result, the event tree must have a decision point to reflect these sequences. For slower buildups of chlorine, the ability of the operators to don their masks is expected to be very high. This expectation is due to the most likely operator response in seeking a fresh air supply and the rapid feedback the operator will receive from purging and fitting the mask. The probability of failure is assumed to be 1E-4. This probability of failure is considered to be a conservative estimate since the operators have gas mask drills every six months and Waterford participates in the St. Charles Emergency Preparedness Hot Line System. In fact, the operators will most likely be able to successfully don their masks in less than two minutes, even in situations when chlorine concentrations are higher than 25 ppm. However, failure of the operator to mask in chlorine concentrations greater than 25 ppm is assumed here. This assumption is considered to be highly conservative.

3.3.6 Breathing Apparatus

The installed emergency air system consists of a compressor, four gas storage tanks, pressure regulators, and six delivery stations, each with multiple delivery ports. The capacity is sufficient to provide air for a minimum of six hours to the necessary staff (estimated at seven), assuming no further operation of the compressor. Most valves in the delivery path are locked open. It is assumed that these are not directly controllable by the operator.

Possible failure modes are indicated in the fault tree depicted in Figure 3.5. Failure due to under-pressure would require excessive consumption or leakage which would deplete the air before the six hour criteria, coupled with failure of the compressor or its pressure switch to make up the air supply. Failure of the switches on demand is assumed to be 1E-4. Failure of the compressor on demand is estimated to be 5E-3. Failure of the compressor would dominate any assumed common mode failure of the pressure switches.

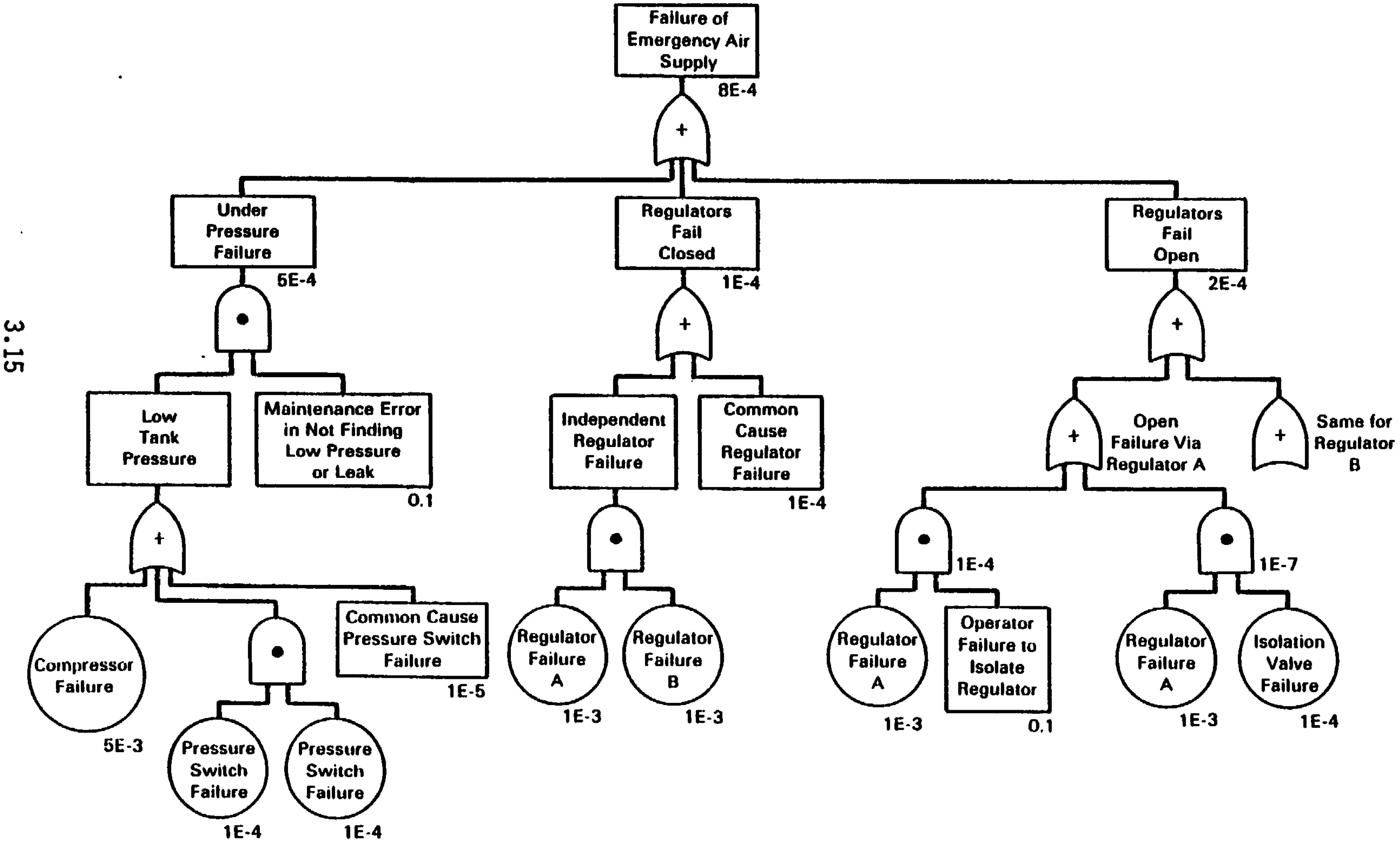


FIGURE 3.5. Breathing Apparatus Fault Tree

The potential for the presence of an excessive number of personnel in the control room causing a lowering of the effective emergency air supply is a possibility despite procedures to the contrary. This probability is estimated at 0.1, dealing as it does with human error under stress.

The other failure modes require failure of a pressure regulator. In the Waterford plant two parallel diaphragm valves are used for pressure regulation. The independent probability for the regulator to fail (open or closed) was estimated to be 1E-3 per demand. The probability of a common cause failure of both regulators was assumed to be 1E-4. Isolation of a failed open regulator would require detection of failure (obvious on attempted use of the air system), the proper selection of the correct isolation valve (maximum failure probability of 0.1 assuming no instrumentation), and proper functioning of a manual isolation valve (failure probability of 1E-4 assumed). The probability of mechanical failure of the breathing apparatus was estimated to be 8E-4.

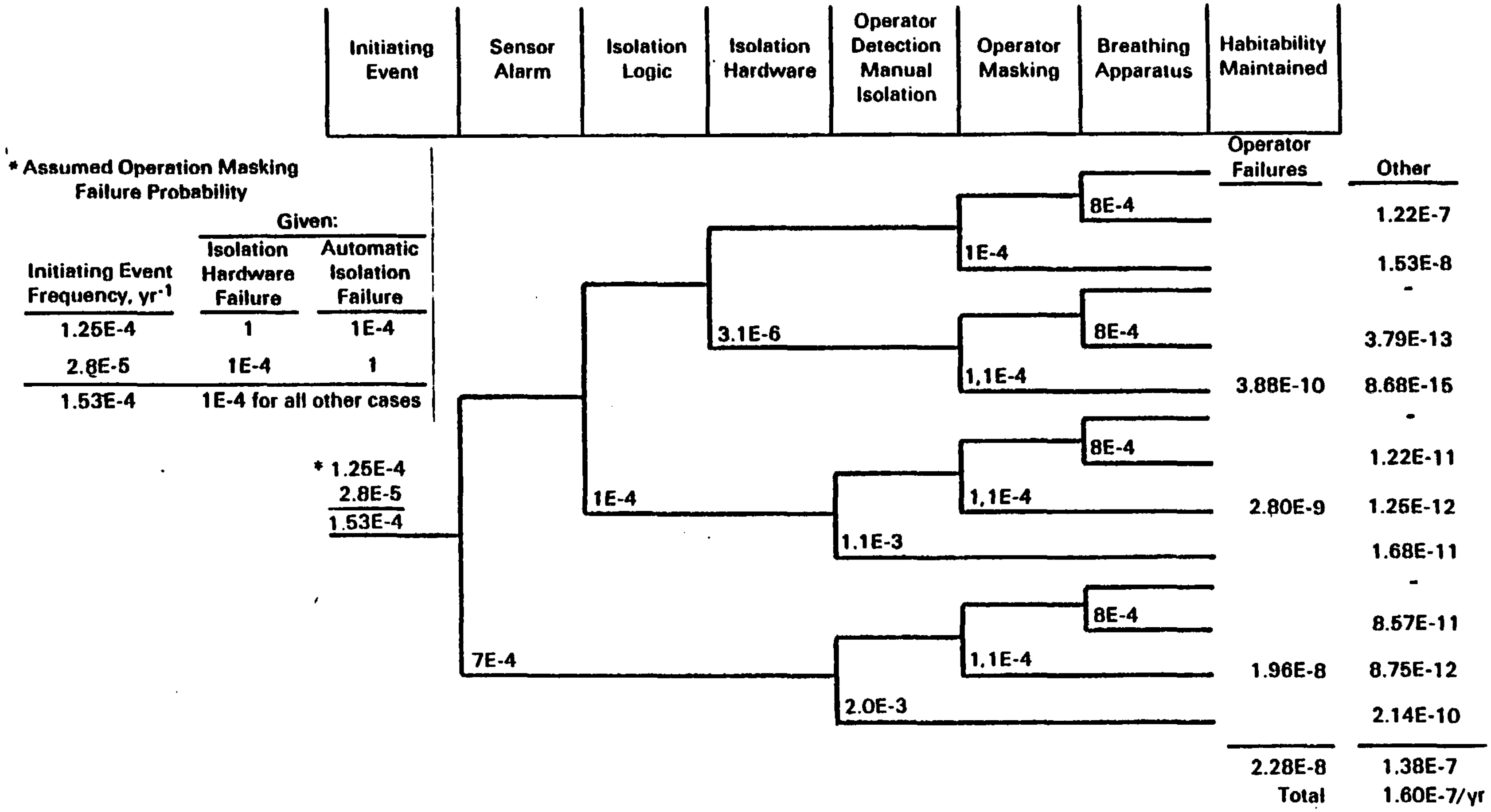
Note that the availability and use of portable air packs was not included in this analysis. This is considered consistent with the two minute time period allotted for attempting to use the installed air supply. If the installed air system failed, the time required to identify or diagnose the problem would most likely exceed the two minute criteria.

3.4 RESULTS OF TOXIC GAS CLOUD

The results for the toxic chlorine cloud with no impact on fire suppression systems are depicted in Figure 3.6. The total failure probability is divided into short term failures where operator masking was precluded by rapid buildup of chlorine and more mundane failures.

The total predicted failure frequency for loss of control room habitability from chlorine is estimated to be 1.6E-7/yr. As can be seen, the dominant sequence of 1.22E-7/yr is due to the assumed failure probability of the breathing apparatus (shown at the top of the event tree). Long term habitability could not be maintained with this failure.

As can be seen in Figure 3.4 failure of isolation hardware plays a less significant role in the total due to the low failure probability to isolate of 3.1E-6. Other sequences of failure of alarm signal and isolation logic do not contribute significantly to the total.



* Assumed Operation Masking Failure Probability

Initiating Event Frequency, yr^{-1}	Given: Isolation Hardware Failure	Given: Automatic Isolation Failure
1.25E-4	1	1E-4
2.8E-5	1E-4	1
1.53E-4	1E-4 for all other cases	

FIGURE 3.6. Results of Toxic Gas Event Tree

4.0 TOXIC GAS CLOUD WITH RESPONSE OF FIRE SUPPRESSION SYSTEMS

The question if whether toxic gas releases from offsite can activate fire suppression systems and result in inoperative CRACS has been asked by the NRC. This question was considered in terms of the Waterford plant. A scenario with the following conditions was used in our analysis:

- The gas or smoke penetrates a room with equipment vital to the operation of the CRACS.
- The gas or smoke activates a sensor.
- The sensor automatically actuates fire suppression systems or the operator initiates a manual response.
- The fire suppressant renders the equipment inoperable.
- The physical protection (spray shields, etc.) fail to perform.

Sensitive equipment located in the auxiliary building at Waterford and vital to the control room or the CRACS are identified in Table 4.1. The fire detection instrumentation is identified by detector function in terms of heat, flame, or smoke. (This information was condensed from Table 3.3-11, page 3/4 3-52 of the Waterford FSAR.) The actual types of detectors are discussed more fully below.

TABLE 4.1. Sensitive Control Room and CRACS Equipment in Waterford Reactor Auxiliary Building

	Detector Function		
Room Name/Number	Heat (x/y)	Flame (x/y)	Smoke (x/y)
Control Room Envelope/304	0	0	8/0
Control Room Proper/304	0	0	12/0
Emergency Equip. Ventilation Room/314	0	0	10/0
Ventilation Equipment Room/299	0	0	36/0
HVAC Switchgear Equipment Room/323	0	0	8/0
High Voltage Switchgear Room A/212A	0/1	0	15/0
High Voltage Switchgear Room B/212	0/1	0	15/0
High Voltage Switchgear Room A/B/212B	0/1	0	5/0
Control Room HVAC Equipment Room/124	0/1	0	6/0

Notes:
x is the number of sensors giving detection only.
y is the number of sensors giving detection and actuation of a fire suppression system.

4.1 GAS ACTIVATION OF DETECTORS

The instrumentation listed in Table 4.1 consists of heat, flame, and smoke detectors. These three types of detectors are discussed further below.

4.1.1 Heat Detectors

Detectors in this category can include those which react to a fixed temperature (e.g., bimetallic strips, eutectic fuses, thermistors) or those which react to a rate of change in temperature (e.g., air filled chambers, etc.). It is doubtful that such detectors would be affected by gas or smoke.

4.1.2 Flame Detectors

These detectors can include infrared or ultraviolet detectors which react to a specific band of electromagnetic radiation. Each radiation band (infrared and ultraviolet) can respond to signals other than an open flame. However, gas or smoke would not be considered a sufficient source of such radiation to give false signals. Smoke would most likely obscure the optical window of such devices.

4.1.3 Smoke Detectors

Smoke detectors include photoelectric types, in which smoke obscures a light beam directed at a photocell, and the ionization type, in which combustion products change the ionization potential between a small air gap. In both types, the detection device triggers an alarm. Both of these types are obviously affected by smoke. However it is uncertain what concentration, if any, of a toxic gas would be sufficient to trigger the ionization detectors. The photoelectric detectors would most likely be activated if concentrations are sufficient to block the light beam. Such concentrations for the gases of interest, such as chlorine, are most likely to be far in excess of toxic limits, and it is uncertain if any credible scenario could transport such concentrations to an isolated room in the reactor auxiliary building. However, to be conservative in our analysis it was assumed that gas clouds are capable of triggering smoke detectors.

4.2 DAMAGE OF EQUIPMENT BY ACTUATION OF FIRE SUPPRESSION

As can be seen from Table 4.1, the only locations for automatically actuated fire suppression systems are the high voltage switchgear rooms and the HVAC equipment room. These rooms have gas suppression automatic systems. However, these all utilize heat type detectors for the auto-actuation function. As discussed above, these types of detectors would most likely not be affected by gas clouds or smoke.

Smoke detectors are present in the locations of interest which could be activated by gas. These detectors are instrumented to sound an alarm only; no direct automatic actuation of the fire suppression systems occurs with these detectors. As a result, an automatic actuation of the fire suppression system by a toxic gas or smoke cloud is considered to be a potentially credible event at this time. If the smoke detectors did respond, manual activation of the suppression system by plant operators would be required.

5.0 OFFSITE AND ONSITE SMOKE

The impact of offsite and onsite smoke on control room habitability is considered in this section.

5.1 DEFINITION OF SMOKE HAZARD

The combustion products emitted during a fire depend on the type of material involved and the conditions under which combustion takes place. These combustion products can range from volatile gases to condensable gases and particulates. Some of the gases will undoubtedly be toxic. However, for this analysis it was assumed that the most likely primary sources of toxic gases around the Waterford site were those identified and examined in Section 3.

Smoke generated at a source outside the plant is assumed to be of a general nature and is associated with the burning of petroleum products, wood, trees, brush, etc. rather than from the combustion of a specific toxic chemical that would have been identified previously. The smoke produced from such a fire was assumed to have a varied composition, containing oxides of carbon, nitrogen, unburned hydrocarbons, and suspended particulates. It was also assumed that the particulates were of greatest concern since the gases and other volatiles will be dispersed more rapidly by the fire's plume.

The assumptions described above would not be true for fires in the control room where smoke from cable insulation, building materials, etc. would be the primary source and would contain toxic gases as well as general particulate irritants.

The toxicity of smoke from a general-type fire is not specified explicitly in handbooks such as Dangerous Properties of Industrial Materials (Sax 1979). The toxicity of the smoke is typically described by the toxicity of its constituents. For non-toxic particulates where the hazard is primarily one of eye and lung irritability, an occupational limit of 5 mg/m^3 was specified. For uncertain mixtures of dust and fumes, the limit is lowered to 0.5 mg/m^3. The latter value was used in this study to be conservative. Smoke from fuel oil fires is also typically considered to be a simple asphyxiant.

For emergency or short term exposure to airborne particulates, Dangerous Properties of Industrial Wastes indicates that no filter is needed for airborne concentrations of 2 to 5 times the 0.5 mg/m^3 established above. A filter is needed for 5 to 20 times this concentration, and a respirator is needed for concentrations above 20 times this level (i.e., 10 mg/m^3.) For this analysis it was assumed that concentrations reaching this latter level within 2 minutes of the alarm will preclude operators from successfully donning their masks.

5.2 FREQUENCY OF INITIATING EVENTS

Efforts were undertaken to determine the frequency of offsite fires producing sufficient smoke at the air intakes to challenge control room habitability. The Waterford FSAR does not consider such an event. FSARs for other plants, such as Midland, indicate that such events are generally not considered to be credible because of the following reasons:

- the large distance to flammable material (i.e. greater than 0.5 miles)
- the limited areas of brush and trees close to the plant
- the high dispersion due to the buoyant plume from the postulated fire
- the particulate removal capability of the air filters
- the smoke detectors and isolation capability of the control room.

Because the occurrence of fires that produce enough smoke to impact control room habitability is considered unlikely, no estimates of their frequency are available. Based on this lack of information, the frequency of such fires was assumed to be less than 1E-7/yr, which is the probabilistic threshold for offsite design basis events set forth in SRP2.2.3. An examination of the Waterford FSAR for petroleum product fires indicates a calculated frequency of 5.7E-8/yr for fires or explosions within one mile of the plant.

For the conservative nature of these calculations, it was be assumed that such offsite smoke sources occur with a frequency of 1E-2/yr. This assumption includes a conservative probability of a fire of sufficient magnitude to be a problem at the plant. In addition, a 0.01 factor that the meteorological conditions lead to transport of the plume to the control room air intakes yields an effective frequency of 1E-4/yr. Assuming that the plume is blowing towards the plant rather than originating at the plant, it was further asssumed that the plume was of sufficient size to cover all intakes including the emergency intakes.

For onsite fires, discussions with the NRC resulted in a suggested frequency of 1E-2/yr for smoke from sources such as diesel oil, turbine lube oil, yard transformer oil etc. Applying a 0.1 factor for wind direction towards the intakes from an onsite source gave an estimated initiation frequency of 1E-3/yr. Again for simplicity it was assumed that the plume would cover both intakes. For other onsite accident scenarios, occurrence of this type event is unlikely; however, the multiple source points for fires make it difficult to totally eliminate as a possible occurrence. Based on these assumptions and conditions, the total for occurrence frequency on and offsite sources was estimated to be 1.1E-3/yr.

Event Severity

The frequency of events which are severe enough to preclude operator masking are also of interest. The main air intakes at the Waterford plant include medium efficiency particulate air filters which are designed to remove an assumed 85% of the types of suspended particulates that could be expected with smoke.

Rather than undertake detailed hypothetical calculations of the buildup of smoke in the control room (as was done for chlorine), it was simply assumed that operator masking and operation of the air supply is required to maintain habitability. This assumption is highly conservative, because simple filtration will most likely be sufficient for most of the smoke plumes that do reach the air intake.

The following assumptions were used:

- All releases with a frequency of 1.1E-3/ry were transported in the proper direction to encounter the main and emergency intakes.
- All releases were of sufficient magnitude to require use of breathing air. Breathing air is most likely only to be required in two events: upon failure of filters or in less frequent but sufficiently severe fires with large smoke outputs and long durations.
- The EFUs would not be run unless the main filters failed.

5.3 OFFSITE AND ONSITE SMOKE EVENT TREE

The assumed event tree for offsite smoke is given in Figure 5.1. Note that it is similar to the one assumed for toxic gas, expect for inclusion of the role of the filters. For long-term habitability, smoke could continue to infiltrate and build up in the control room even if successful isolation were accomplished. Operating the CRACS in their recirculation mode, however, will continue to pass recycled air through the filters. The probability of filter failure is developed more fully below.

The final line of defense is the breathing apparatus which was assumed to be necessary.

5.4 QUANTIFICATION OF SMOKE EVENT TREE

Probability assumptions for the event tree branches portrayed in Figure 5.1 are developed in this section.

5.4.1 Sensor Alarm

The air intakes and control room are equipped with smoke detectors. To be conservative, only two sensors were assumed to be present. The failure probability for these detectors was assumed to be 7E-4.

5.4.2 Isolation Logic

A failure probability of 1E-4 was assumed for the isolation logic. This is the same assumption made for the toxic gas release event.

5.4.3 Isolation Hardware

A failure probability of 3.1E-6 was assumed for the isolation hardware. This is the same assumption made for the toxic gas release event.

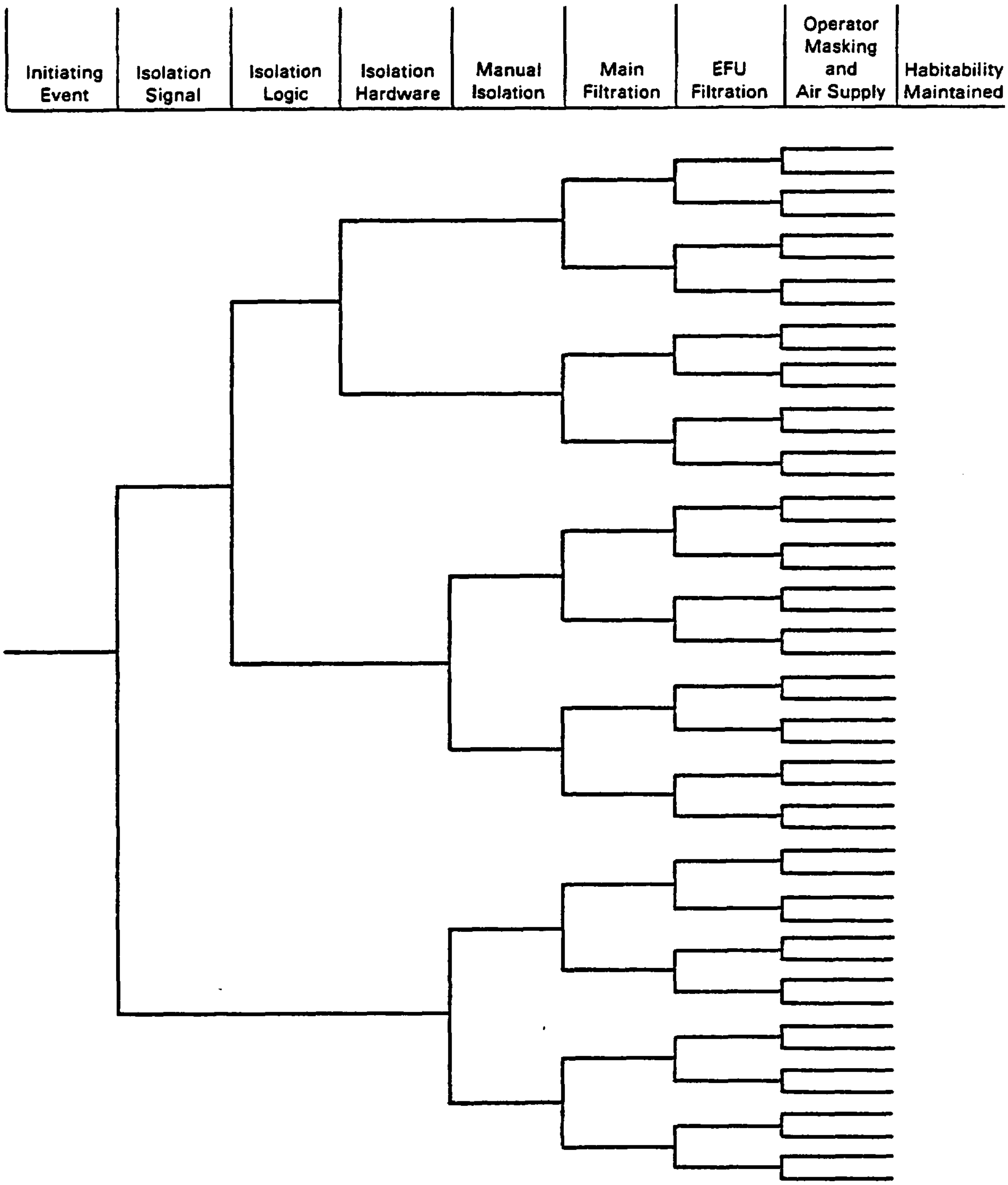


FIGURE 5.1. Offsite Smoke Event Tree

5.4.4 Operator Detection and Manual Isolation

The failure probability for operator detection of smoke and manual isolation of the control room was assumed to be 1.1E-3 for events when an alarm sounds and 2.0E-3 for events when there is no alarm.

5.4.5 Filter Failure

The main air inlet filters are only of medium efficiency, and thus failure could result from the passage of fine particulates. Filter loading could also occur. A frequency of one fire in ten with sufficient plume density and duration could be assumed for this failure mode. If control room isolation occurs, the EFUs in recirculation mode could handle the smoke.

The other failure mode would be rupture of the filter due to particulate buildup and excessive pressure drop. To be conservative, the more severe case of filter rupture was modeled in this study, again assuming that one fire in ten is of sufficient severity to cause this event.

The fault tree developed to predict the main filter train failure is depicted in Figure 5.2. Again, the system consists of one operating and one standby redundant filter train handling 2200 cfm of air intake and 37,000 cfm of recirculation air for the control room complex.

The three failure paths consitered are 1) both filter trains fail initially; 2) one filter train fails during the course of the accident due to particulate buildup, pressure drop, subsequent rupture, and the operator fails to detect this failure and transfer operation to the standby train; and 3) both filter trains eventually rupture due to particulate buildup. As in the toxic gas analysis, a highly conservative initial failure probability of 0.04 for the filters was assumed based on the observed failure rates of small respirator filters.

The potential for filter failure due to particulate buildup, pressure drop and subsequent rupture depends on the design of the filters. The filters could simply clog and restrict flow. For the purposes of this analysis however, it was assumed that if isolation fails, the probability of filter failure is 0.1. This value was obtained by simply assuming that one in ten fires will be of sufficient magnitude to cause excessive particulate buildup in the event of a failure to isolate. This probability value is given in parenthesis in Figure 5.2.

If isolation succeeds, the effective outside air flow through the filter train drops by a factor of 0.6/0.012, or a factor of 50. It was therefore assumed that if isolation succeeds, the probability of failure due to excessive particulate buildup is 0.002.

For the redundant filter train, it was assumed that the probability of failure without and with isolation is 1/2 of that for the first train. This is because the probability of the plume density remaining at its initial intensity for a duration long enough to cause failure of both filters is assumed to be less.

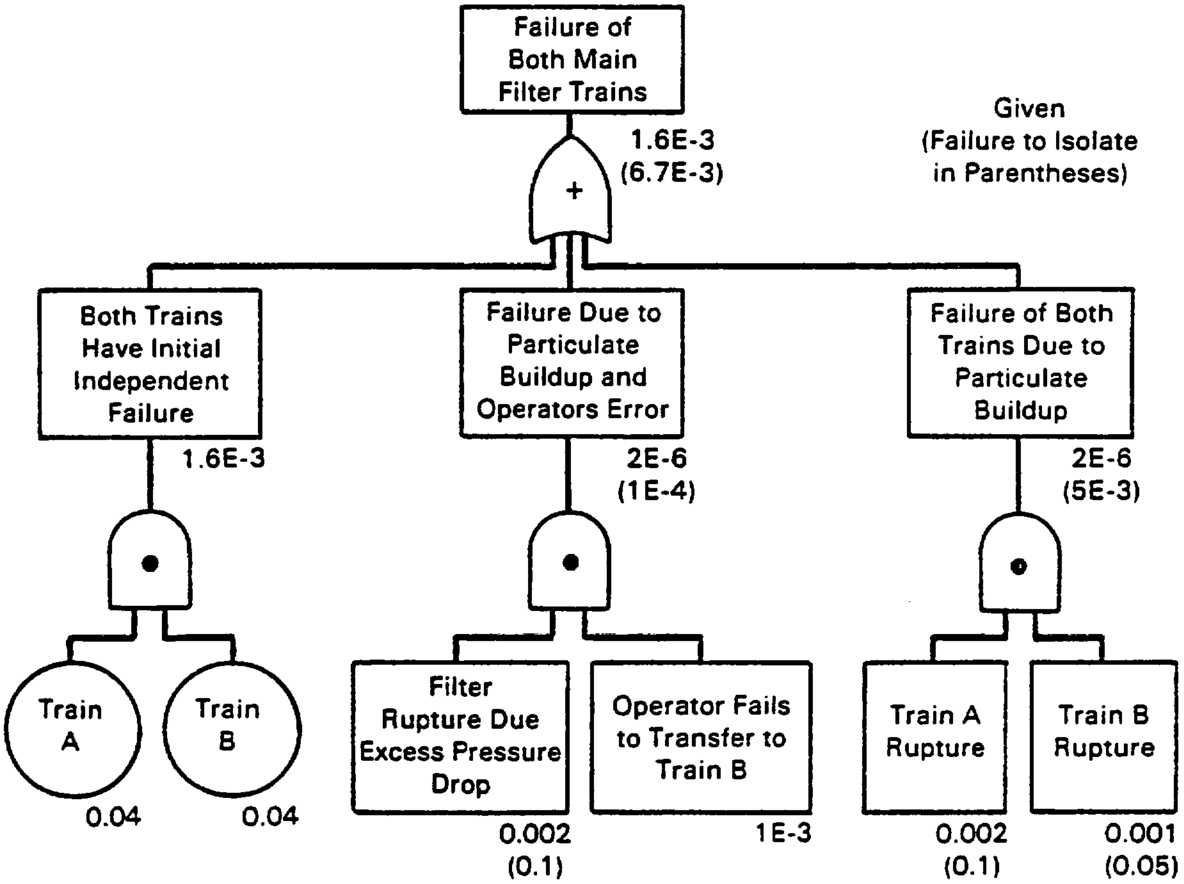


FIGURE 5.2. Main Filter Fault Tree

Based on the assumptions and conditions discussed above, the total failure probability for the filter trains was assumed to be 1.6E-3 in the event of isolation and 6.7E-3 when isolation fails.

5.4.6 EFU Filtration

If the main filter units fail, the operator can still attempt to utilize the emergency filtration units. The failure probability for the EFUs is developed in Figure 5.3. These units can either be in the recirculation mode with the emergency air inlets closed, or in a mode in which they draw in outside air. To be conservative, the latter case will be modeled with the chance for filter rupture again.

With a flow of 200 CFM compared to 2200 CFM for the main intake, the failure probability due to excessive particle loading was assumed to be 0.01 for Train A of the EFUs. As with the backup filter train for the main filters, it will be assumed that the Train B failure probability is one half of 0.01 or 0.005. The probability for failure of both trains is still dominated by the high assumed initial failure probability of 0.04. The total failure probability is assumed to be of 1.65E-3.

In an event when the EFU is operated after main filter failure and when isolation also failed, it was assumed that any EFU filtration will be ineffective because of the 200/2200 flow ratio. In this case the failure probability was assumed to be 1.0.

5.4.7 Operator Masking and Breathing Apparatus

It was assumed that the probability of operator failure to don masks and failure of the air supply would be (1E-4 + 8E-4), or 9E-4. However, to reflect the loss of visibility that would accompany this situation, it was assumed that the probability of loss of habitability due to failure of these two items would be 0.5 in the event of filter failure, and 1.0 in the event of filter failure and failure to isolate.

5.5 RESULTS OF OFFSITE AND ONSITE SMOKE

The results of the event tree for offsite smoke are given in Figure 5.4 The most conservative sequence is shown at the top where it was assumed that masking had to be maintained for all fires. This assumption yields an estimated frequency for loss of control room habitability from offsite fires of 9E-8/yr and 9E-7/yr for onsite fires. Based on this analysis, the total frequency assumed was 9.9E-7/yr. The top sequence shown in Figure 5.4 is dominant and again assumes loss of habitability upon failure of the breathing apparatus for all fires. A more realistic estimate would reduce the frequency of fires that have sufficient smoke density and duration to require operators to don their masks. Operation of the EFUs in recirculation mode would most likely eliminate the long term need for masks for many of the smoke sources considered. The frequencies for all other sequences considered are several orders of magnitude lower than the estimate developed here.

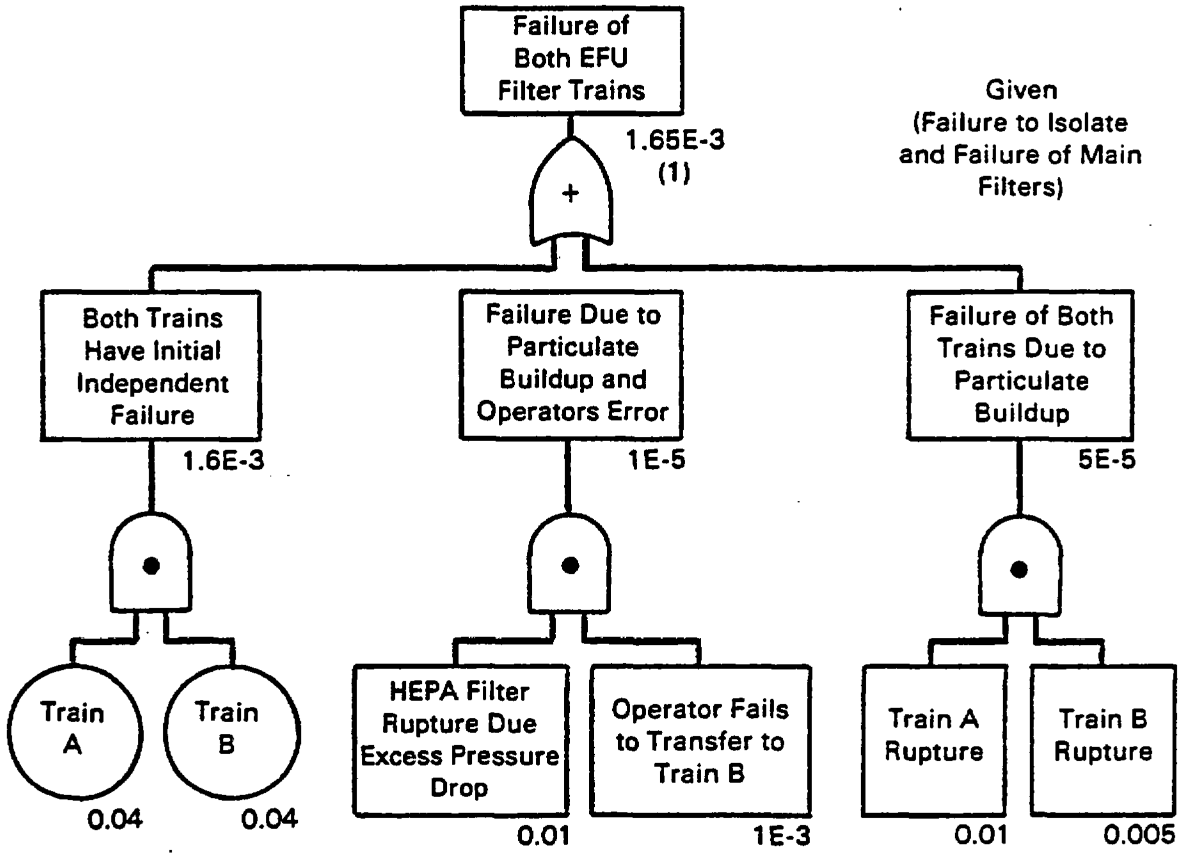


FIGURE 5.3. EFU Filter Fault Tree

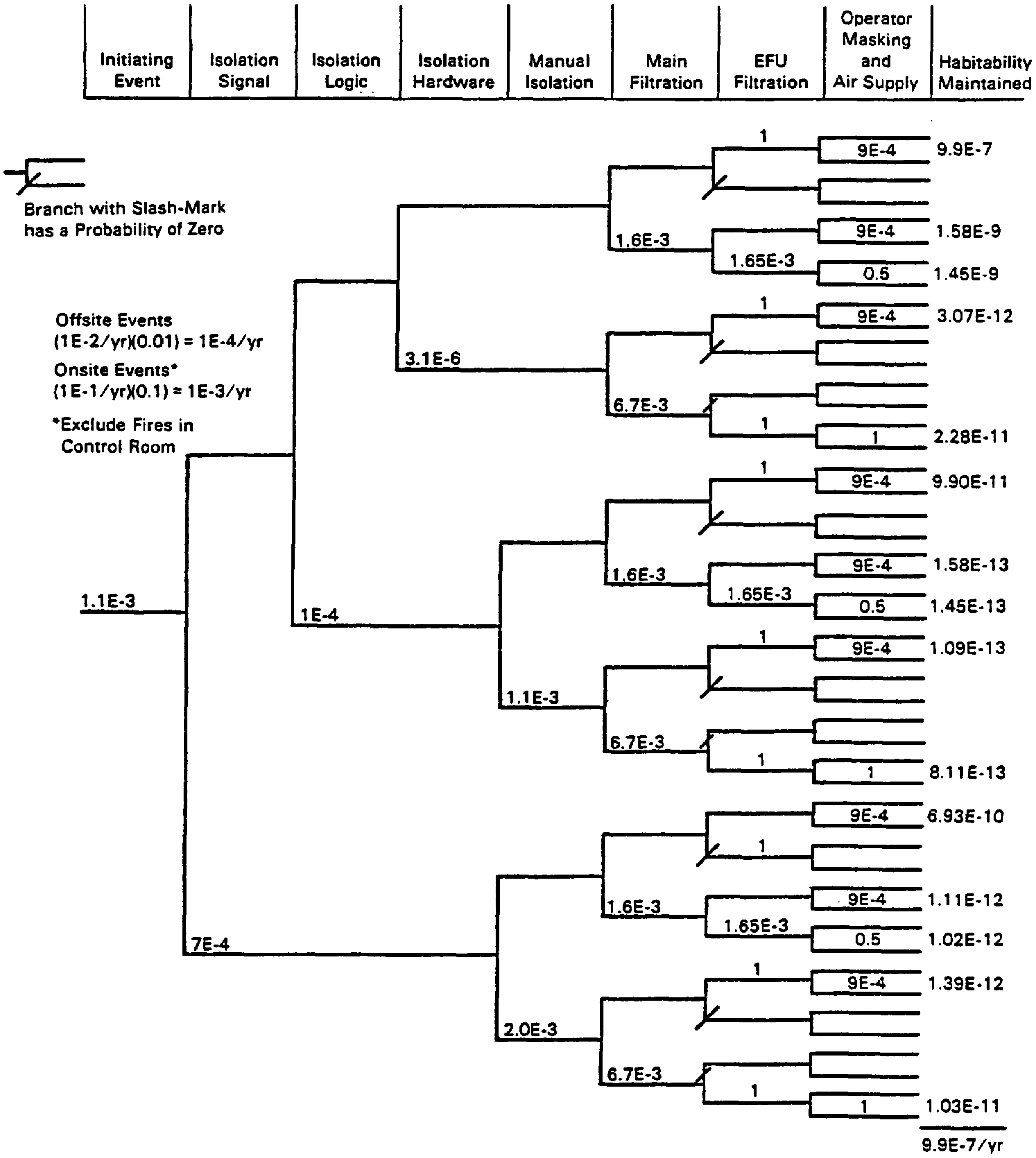


FIGURE 5.4. On and Offsite Smoke Event Tree

The conservative nature of these calculations can be questioned when the uncertain definition of smoke being primarily a simple eye and lung irritant of suspended particulates is considered. However, any significant offsite sources of toxic chemicals that could be transported to the site were assumed to have been considered previously as toxic gases. Assuming combustion and plume transport as a toxic smoke would in fact further aid dispersion, and thus lower the estimated concentrations assumed to reach the air intake. The plume rise expected with petroleum fires is an example.

It is thus believed that classification of offsite smoke as a general irritant is correct given the separate consideration of toxic gas clouds which preceded this analysis of smoke. This assumption would have to be modified of course for fires in the control room.

6.0 FIRE IN THE CONTROL ROOM

The probability of a fire of sufficient magnitude to preclude control room habitability is considered in this section.

6.1 CONTROL ROOM FIRE EVENT TREE

Fire initiation, detection, and suppression were the primary actions considered in developing the control room fire event tree. The severity of the fire would determine the ability of the CRAC system and breathing apparatus to successfully provide ventilation and visability. The severity of the fire may also lead to the loss of vital plant equipment or controls. However, in this study, only the extent to which the ventilation system itself may be impacted was considered.

The event tree developed for control room fires is shown in Figure 6.1. The first branch, as expected, shows the frequency of fires in the control room. The next branch shows the probability of detection, which is expected to be approximately 1.0 in the control room where both operators and sensors provide detection.

Another branch models the probability of a fire propagating to the point where it is a threat to control room habitability. However, subsequent impacts on habitability were difficult to quantify because of a lack of historical data on fire growth and smoke generation. Rather than develop a detailed model for fire growth, a simple relationship between fire severity and resulting impact on habitability with respect to its likelihood was developed. More severe fires would be less probable. A probability was developed relating fire severity after initiation to impacts on the ability of the CRACS and operator to respond.

Following this rationale, a branch for mechanical failure of the CRACS purge function was developed. Branches reflecting operator masking and operation of the breathing apparatus were also developed.

This event tree is useful for depicting the logic flow and in estimating probabilities associated with loss of habitability from control room fires. However, the use of the fire suppression term to signify fire size after initiation and impact on the CRACS and operator introduces a multiple branch at the "Suppression" junction which is difficult to model using the standard event tree form. As a result, the event tree itself is not used directly in the final presentation of the results. Rather, a tabular form is used.

6.2 FIRE INITIATION FREQUENCY

The actions of fire detection and suppression and the severity of the fire are all highly interrelated. However, for the purposes of this analysis, they were treated distinctly. The issue of concern here is the frequency of fires, particularly those of sufficient magnitude to exceed the ventilation system capacity to remove smoke and maintain control room habitability or cause the direct failure of the HVAC controls.

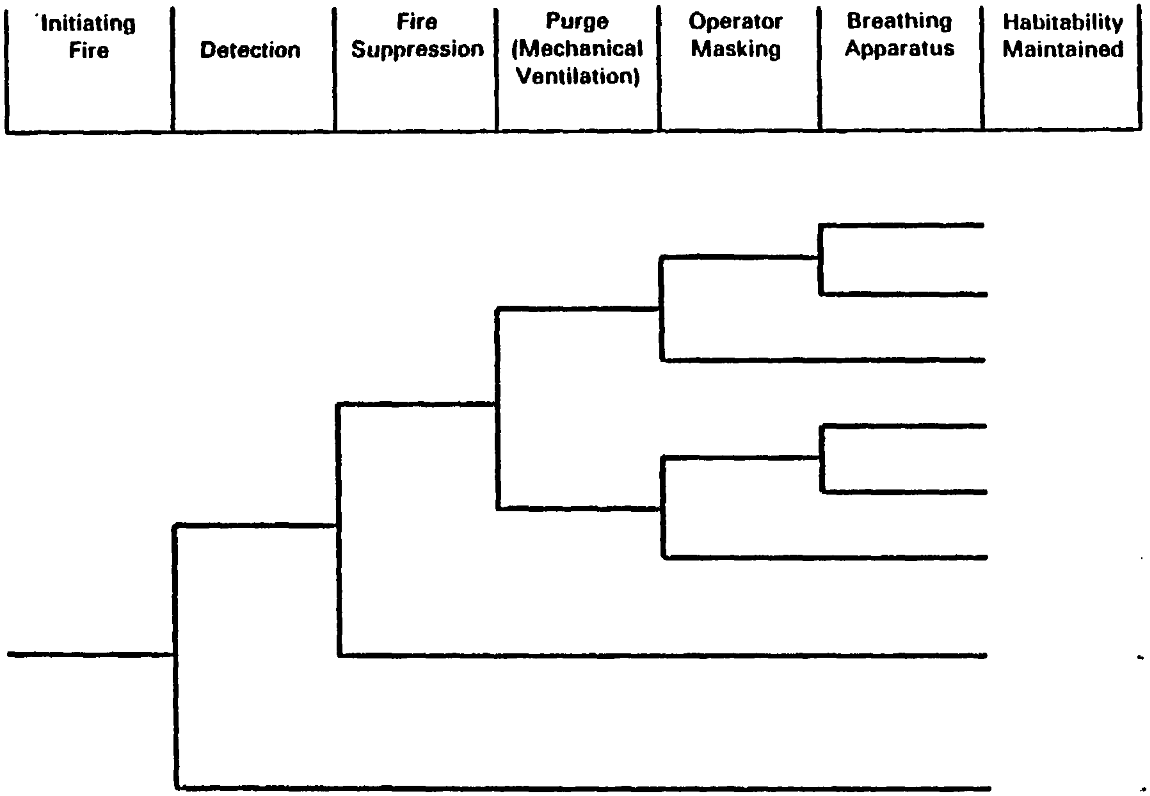


FIGURE 6.1. Control Room Fire Event Tree

The major problem in performing this analysis is the lack of data on fires in control rooms. A literature review indicated that there have been few recorded incidents. One report (Dugan 1983) lists two fires in a control room, one resulting from ignition of plastic airhoses by a welding spark and the other resulting from a failed zener diode where an operator noticed smoke coming from a panel.

A second report published as NUREG/CR-2258 lists only one fire (no details provided) with a resulting frequency of 1 per 288.5 control room years (3.5E-3/cry) (Kazarians and Apostolakis 1981). The number of reactor years was 337 (2.3E-3/ry) with the difference resulting from shared control rooms at some plants with 2 units. With various statistical analyses, the authors of NUREG/CR-2258 estimated a frequency range of 3E-4/cry to 1.2E-2/cry with 90 percent confidence limits. In terms of reactor years this frequency would be 2.6E-4/ry to 1.0E-2/ry.

The severity of the fire was not indicated in NUREG/CR-2258. Although the NRC requires the reporting of all fires that affect plant safety, most of the data came from insurance-inspectors' reports. It would be expected that the severity of fires vary inversely with frequency with less severe fires occurring most frequently.

For the purposes of this study, the conservative initiating frequency of 1E-2/ry was assumed for all fires. Because the ventilation equipment is used in purging smoke during a fire, loss of this equipment will impact habitability. Therefore, it was also assumed that fires initiated in the CRACS equipment room account for 10 percent of the total, or 1E-03/ry. These frequencies are shown in Table 6.1.

TABLE 6.1. Assumed Fire Frequency by Location

Fire Type	Frequency
CRACS equipment room	1E-3/ry
Other (control room, computer room, etc)	9E-3/ry
Total	1E-2/ry

Fires that may knock out the ventilation equipment directly are called out seperately in Table 6.2. Note that a factor to compensate for the range in expected severity and the ability to extinguish these fires without loosing habitability or loss of the CRACS equipment are developed in Section 6.3.2.

6.3 EVENT TREE QUANTIFICATION

Values and assumptions necessary to quantify the event tree given in Figure 6.1 are developed in this section.

6.3.1 Detection

Detection of a fire in the control room can be by one of the control room personnel or by a smoke detector. The Waterford control room has five ionization type smoke detectors: one each in the main control room, HVAC equipment room, and emergency living quarters. The computer room has two detectors: one above the floor and one below in the cable runs.

It is highly probable that a fire will be detected at some point in its progression even if it is self-extinguishing. The question is when detection will occur. Reviews of detector response time (Hill 1983) indicate that ionization detectors typicaly respond in less than one minute. Human detection is the recorded mode of detection in most reported fires at nuclear plants (Dugan 1983). In a closed space, the response time of human detection could be expected to be the same order of magnitude or better than ionization type smoke detectors.

Using the probability value for single detector failure of 6.5E-3 adopted in Chapter 3 and 1E-3 for human failure yields a total probability value of 6.5E-6 for failure to detect a fire. Loss of control room habitability is assumed to occur if early detection fails. In this event the fire would progress to a point where it could not be extinguished.

The question of fire duration and ability of the HVAC to function will be addressed in the following sections.

6.3.2 Fire Suppression and CRACS Purge Function

Given the frequency of initiating events, the probability of a fire progressing to the point where toxic or irritating smoke is produced in sufficient quantity to challenge or defeat the ventilation system and masks remains to be determined. A simplified approach similar to that used by Kazarians and Apostolakis (NUREG/CR-2258, p.103) to relate fire duration and probability was used. In this analysis, the probability of a compartment fire exceeding various times was given (i.e., 5, 10, 15 minutes, etc.) with the short duration fires being the most probable. The cumulative probability totalled 1.0

The approach described above was modified to relate the less probable (i.e., longer duration) fires directly to the potential impact on habitability. This approach assumes that longer burning fires present a greater potential source of smoke and subsequent threat to habitability. The conditions necessary to maintain habitability escalate along with the severity of the fire. First, purging becomes necessary but sufficient; then, purging and masks are required; and finally, smoke generation exceeds visibility requirements purging capacity.

The assumed probabilities and control room requirements are shown in Table 6.2. The assumed frequency of fire initiation was multiplied by these numbers, effectively reducing the expected frequency of fires with specific impacts on the ventilation system and ability of the operator to remain in the control room.

TABLE 6.2. Probability of Fire Severity and Impact on CRACS

Severity of Fire and CRACS Response	Probability
Low smoke output, no mask or purging required	0.99
Medium smoke output, purging sufficient	0.01
High smoke output, mask and purge used but mask alone sufficient	0.001
Higher smoke output, mask and purge must be used	0.0001
Smoke output exceeds capacity of system (i.e. visability lost)	0.00001
Fire in CRAC Equipment Room leading to loss of function, but mask still sufficient	0.001
Fire in CRAC Equipment Room leading to loss of function, and mask not sufficient	0.0001

Note that all reported fires mentioned in this report have fallen in the top category where no masking was required to maintain habitability. From a historical standpoint, the probability of this situation occurring is 1.0; however, for this study it is considered to be 0.99. Purging or masks would likely be used in such small fires as a routine procedure or a convenience to remove irritants. However, the purpose of this analysis was to estimate the minimum requirements necessary to avoid incapacitating the operator during an emergency. Because of low smoke output and rapid suppression, habitability would not be lost even if masks or purging failed with the small fires that have been reported.

For slightly more severe fires, purging of smoke will likely be sufficient to maintain habitability. Masks may be used as standard procedure to mitigate the irritating effects of any smoke, but would not be required from the view of toxicity.

The severity of the fire is then increased and probability decreased progressively until the assumed smoke output exceeds all habitability standards even with purging and the use of mask.

For fires in the CRACS equipment room (frequency of 1E-3/ry), there is a 0.001 assumed probability that fire will inactivate the equipment. In this situation, masks would still be considered sufficient for operators. Slightly less probable (0.0001) would be the loss of CRACS equipment in a fire that generated enough smoke to exceed any habitability standard even if masks were worn.

The net result of this approach is to change the frequency of initiating events that are severe enough to result in loss of habitability if the CRACS and air masks fail.

6.3.3 CRACS Mechanical Failure

In addition to failure of the purge function due to excessive smoke, the possibility of mechanical failure must be considered. Referring to the figure of the Waterford CRACS given in the FSAR Section 9.4.1.2.2, the main control room can be purged of smoke or fumes by fan E-42 after damper D-43 is opened. The FSAR states that dampers D-44, D-64, and D-67 from the conference room, computer room, and kitchen, respectively, should also be closed. Failure of the latter dampers would not eliminate purge flow from the control room but would reduce it.

Failure of only one damper from a side room to close is not considered sufficient to cause failure of the purge function, but failure of two or three are. However, it was assumed that the additional flow provided by fan E-34 would be sufficient to maintain adequate purge air flow in the event 2 out of 3 dampers from other rooms (D-44, D-64, and D-67) were not closed.

Successful operation of backup fan E-34 requires the closing of dampers D-46 and D-68 and opening of damper D-45.

Mechanical failure of the purge function was assumed to be caused by the loss of fan E-42, the loss of the flow path by failure of damper D-43 to open, or insufficient flow. The CRACS mechanical failure fault tree with assumed failure probabilities is shown in Figure 6.2. Dampers were assumed to be the fail closed type. A failure-to-open probability of 1E-3 and a failure-to-close probability of 1E-4 were assumed.

As can be seen from the fault tree, the failure of D-43 to open is the assumed weak link. The probability of a total failure was assumed to be 1.5E-3. The probability of any assumed common mode failure of D-44, D-64, and D-67 occurring would most likely be 1.5E-3 so that branch was not developed in Figure 6.2.

6.3.4 Operator Masking

The same probability for operator masking that was developed for the response to toxic gas releases was used in this analysis. This probability was assumed to be 1E-4 for an event when an alarm is received. Successful detection and proper operator response are considered quite probable in the confined space of a control room. A normally expected fire progression rate will most likely allow considerable time for donning the mask.

6.3.5 Breathing Apparatus

A probability of breathing apparatus failure of 8E-4 was developed in the toxic gas analysis. The same probability was used for this analysis.

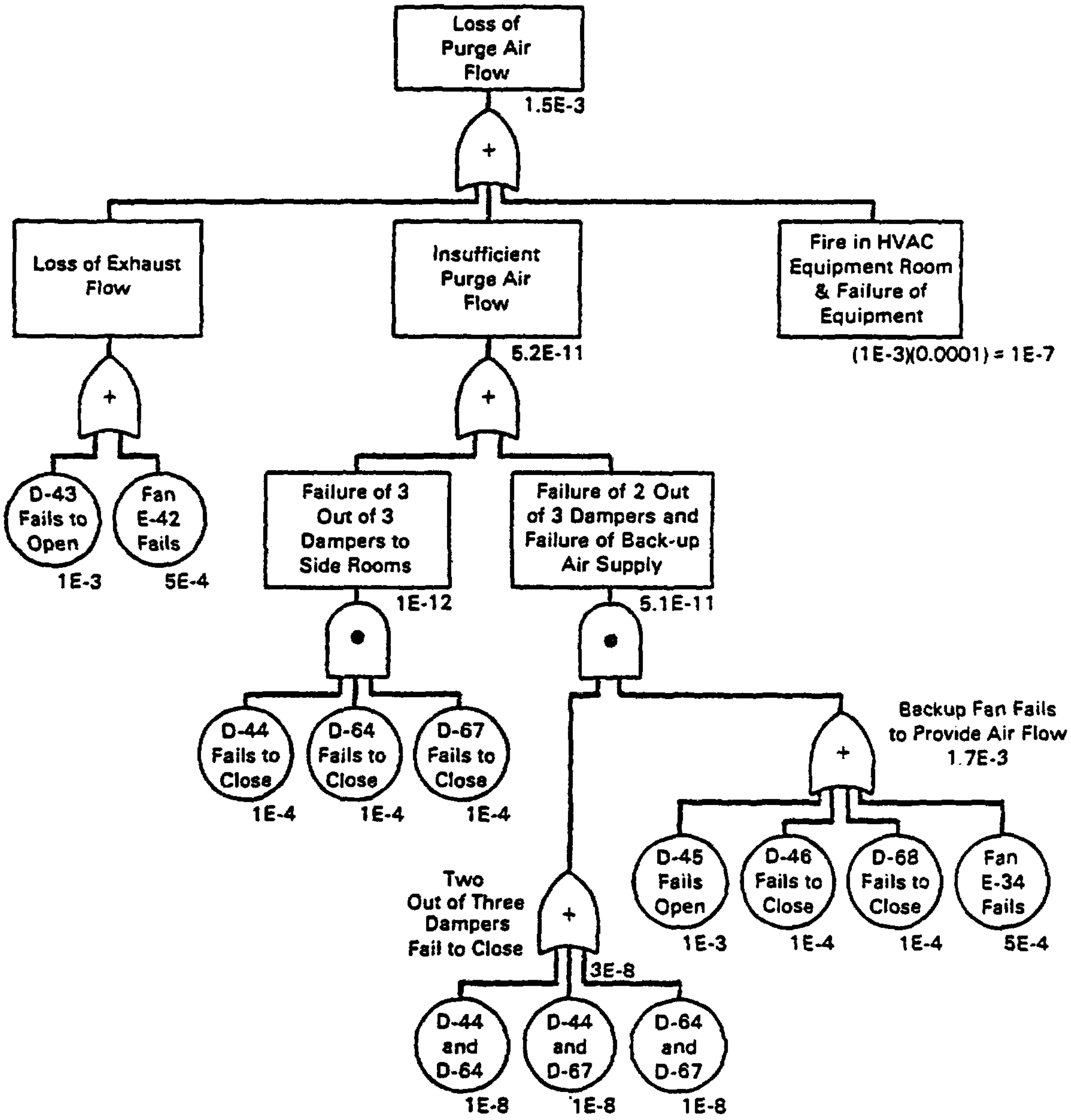


FIGURE 6.2. Loss of Purge Flow Fault Tree

The failure probability of an operator failing to receive breathing air is the total of failure to mask (1E-4) plus failure of the breathing apparatus (8E-4), or 9E-4.

6.4. RESULTS OF FIRE IN THE CONTROL ROOM

The estimated frequencies for loss of control room habitability due to fire are given in Table 6.3. The predicted frequencies were obtained by multiplying the fire initiation frequency by the probability factor used to estimate fire severity (derived in Section 6.3.2) and then multiplying by the probability of any subsequent mechanical failure of the CRACS or breathing mask functions. The fire suppression probability used to determine if purging and/or masking are required to retain control-room habitability was obtained from Table 6.2.

As can be seen, the dominant sequences are the result of an assumption that all fires (frequency of 1E-2/ry) will progress to a level that will produce conditions that exceed any habitability criteria with a probability of 0.00001. Also, there is a probability of 0.0001 that fires in the ventilation equipment room (frequency of 1E-3/ry) will progress to a point that produces uninhabitable conditions. This is again regardless of purging or use of masks. They represent a frequency of 2E-7/ry out of a total predicted 2.1E-7/ry.

Other sequences represent mechanical failure to purge or provide breathing air and contribute a total frequency of 1.2E-8/ry.

It should be noted that the analysis of impacts of control room fires is based on qualitative assumptions about fire progression since no data about the frequency and probable severity of control room fires is available. In the absence of data, the inclusion of fires whose severity is beyond the level of ventilation systems to respond (2E-7/ry) represents a conservative estimate of the overall frequency of loss of habitability from control room fires.

It also should be noted that the above analysis did not consider the role of the remote shutdown panel in stabilizing plant conditions. If the remote shutdown capability is considered, operators could evacuate the control room, provide safe shutdown, and terminate any possible progression of the accident sequence. With remote shutdown considered, the frequency of a control room fire leading to loss of safe shutdown capability is estimated to be less than 2E-7/ry.

TABLE 6.3. Results of Control Room Fire

Initiating Event Frequency (ry^{-1})		Failure of fire suppression (assumed probability)	Failure of CRACS Purge Function	Failure of Breathing Air	Habitability Maintained ?	Frequency (ry^{-1})
			(1.5E-3)	(9E-4)		
CRACS fires	1E-3	0.01	Y	N	Y	-
OTHER Control Room Fires	9E-3		N	Y	Y	-
			Y	Y	N	1.35E-10
			N	N	Y	-
Total	1E-2					
		0.001	Y	N	Y	-
			N	Y	N	9.00E-9
			Y	Y	N	1.35E-11
			N	N	Y	-
		0.0001	Y	N	N	1.50E-9
			N	Y	N	9.00E-10
			Y	Y	N	1.35E-12
			N	N	Y	-
		0.00001	(assumed severity of fire exceeds capacity of CRACS, masks)		N	1.00E-7
CRACS FIRE with fire induced failure of equipment	1E-3	0.001	Y (fire)	N	Y	-
			Y (fire)	Y	N	9.00E-10
		0.0001	(CRACS failure due to fire, smoke exceeds mask capacity)		N	1.00E-7

Frequency of assumed failures due to assumed fire severity	2.00E-7
Other failures	1.20E-8
Total	2.10E-7/ry

7.0 RADIATION RELEASES

In this section, the impact of significant radiation releases on control room habitability will be examined. The scenarios requested by the NRC included steam tube rupture and a LOCA core damage scenario. The radiation releases that would result from these two scenarios are considered typical of the range of radiation releases that a control room must withstand. The FSAR calculations are reviewed first to examine the likely range of radiation releases.

7.1 SUMMARY OF FSAR RADIATION RELEASES

Chapter 15 of the Waterford FSAR presents analyses of a number of radiation releases including Design Basis Accidents (DBAs) and more realistic calculations concerning available inventories and release pathways. Because this study is a probabilistic examination of the impact of releases on control room habitability and not a licensing worst case type of analysis, the more realistic calculations are more suitable for our use. These are summarized in Table 7.1.

TABLE 7.1. Summary of Waterford FSAR Realistic Radiation Releases

	Dose for a Given Location (REM)					
	Exclusion Area Boundary		Low Population Zone		Control Room	
	Thyroid	Whole Body	Thyroid	Whole Body	Thyroid	Whole Body
Large LOCA	2.9E+2	1.2E+1	9.8E+1	2.7E+0	24	0.5
Letdown Line (Aux. Bldg.)	4.6E-1	1.5E-3	3.5E-2	1.2E-4	-	-
Rad Waste Tank	2.8E-4	4.6E-4	2.1E-5	3.5E-5	-	-
Rad Waste Valve	2.5E-4	2.7E-5	1.9E-5	2.1E-5	-	-
Fuel Handling (16 rods)	2.0E-3	4.7E-4	1.6E-4	3.9E-5	-	-
Steam Tube (with spike)	2.5E-3	2.7E-4	2.4E-4	2.1E-5	-	-

The radionuclide inventories assumed for the various releases differ depending on the holdup and decay of shorter lived nuclides but in general vary in proportion with the resulting doses. The large break LOCA results in the highest calculated doses, followed by the letdown line rupture. The LOCA was also the only accident where calculated control room doses were given, essentially defining the design basis accident for control room isolation.

Of the remaining release scenarios listed in Table 7.1, the steam tube rupture is of the same order of magnitude or larger than the other releases shown in Table 7.1. The other accidents involve releases from the reactor auxiliary building which would result in further isolation and holdup of the release. The steam tube rupture modeled in the FSAR would also result in some holdup in the secondary side coolant. However, this accident will be modified here to include a stuck-open PORV with a resulting direct radiation release to the atmosphere. The basis for this modification is an incident at Ginna plant which occurred subsequent to the publication of Waterford FSAR. Inclusion of the stuck-open PORV provides a better boundary range of accidents by including the direct atmospheric release.

The modified steam tube rupture and the LOCA will then be used in our analysis to represent radiation releases.

The thyroid dose was assumed to bound the dose to the operator in our analyses. This was the case for all scenarios whose data are summarized in Table 7.1 with the exception of the radiation waste tank release where the thyroid and whole body doses were comparable. This exception was most likely due to the holdup in the tank and decay of iodine nuclides. For the LOCA and steam tube rupture cases, the thyroid dose was assumed to dominate.

7.2 RADIATION RELEASE FROM STEAM GENERATOR TUBE RUPTURE

A maximum credible release resulting from a steam generator tube rupture and subsequent venting of primary coolant via the steam generator relief valve directly to the atmosphere was be postulated here. Iodine was considered to be the radionuclide of interest, with a conservative estimate made of the thyroid dose in the control room. The beta and gamma whole body dose was assumed to contribute little radiation in the confined control room since the effective cloud size would be quite small. A thyroid dose of 30 rads (as per NUREG-0800 SRP 6.4) was assumed to preclude habitability (NRC 1981).

7.2.1 Initiating Events for Steam Generator Tube Rupture

The information on frequency and severity of steam generator tube rupture contained in NUREG-0844 (NRC 1983) will be utilized in this analysis.

Release frequencies and severities shown in Table 7.2 were assumed. These represent an industry-wide average for all PWR types and include the Ginna event of January 1982.

TABLE 7.2. Assumed Tube Failure Frequency

Leak Rate, gpm	Frequency, 1/ry
Observed	
< 0.1	0.279
0.1 < R < 0.3	0.134
0.3 < R < Rupture	0.107
Rupture	0.015
Total	0.535
Assumed	
Single Rupture	0.02
Multiple Rupture	0.002
> 10 Ruptures	0.0002

Source: SAI 1983 (Table 2-6 of Enclosure E)

The current NRC Standard Technical Specification require a forced shutdown when leakage through one steam generator exceeds 0.3 gpm. This condition is reflected by the entry in Table 7.2 where leakage is greater than 0.3 gpm but less than a rupture. Shutdown then occurs in an otherwise routine fashion. Actual practice at many plants is to shut down, inspect and repair the leaking generator at lower leak rates.

The rupture category represents essentially a small break LOCA into the secondary side. Because of the Ginna incident, it was assumed that a single tube rupture with a most likely frequency of 0.02/ry will result in over-pressurization of the steam generator shell with subsequent lifting of a SS relief valve external to containment.

This direct-release-to-the-atmosphere scenario is a better representation of a worst case release via a tube rupture than other scenarios that would require transport past isolation valves and release through the condenser and gas treatment systems. In the other scenarios the resulting holdup, decontamination and filtration, and additional component failures required would all reduce the significance of other release pathways for steam tube rupture.

Release Magnitude

Concentrations of radionuclides were estimated on the basis of actual operating experience. From PNL Analysis of Safety Issue 74, Reactor Coolant Activity Levels for Operating Reactors(a) it was seen that the proposed limiting condition for operation of PWRs is set at 1E-6 Ci I-131 equivalent per gram of primary coolant and 0.1E-6 Ci/g on the secondary side. Actual observed PWR primary concentrations typically range from 0.01 to 0.1E-6 Ci/g, with the value of 0.1E-6 Ci/g used as a best estimate. The exception has been the Ginna plant, where levels of 0.5E-6 Ci/g have been observed.(b) Iodine spiking incidents which increase the release rate of iodine into the primary coolant have been observed with coolant concentrations as much as 500 times above equilibrium levels. Plants with the lowest routine levels typically show the highest spikes in concentration.

Safety Issue 74 indicates that an average increase in coolant activity of 20 times equilibrium is typical for iodine spiking incidents. When coupled with the worst case Ginna coolant concentrations, an assumed peak concentration of 10E-6 Ci/g of equivalent I-131 activity results. Further NRC analysis on this issue uses an equilibrium coolant concentration of 0.1E-6 Ci/g as a best estimate, and assumes a 20% likelihood of the maximum 500 peaking factor (a 100-fold increase in the release of activity). These assumptions result in a radiation value of 10E-6/Ci/g which will be used in this analysis.

(a) W. B. Andrews, Letter transmitting draft analysis of Safety Issue 74, to W. Milstead. September 9, 1983. Pacific Northwest Laboratory, Richland, Washington.

(b) L.G. Hulman, "Generic Issue on Iodine Coolant Activity Limiting Conditions for Operation." June 6, 1983, Memorandum to Warren Minners, U.S. Nuclear Regulatory Commission, Washington, D.C.

Note that after a transient such as a steam tube rupture, the iodine concentrations in the coolant do not increase instantaneously. Rather the release rate of iodine to the coolant is increased temporarily. This in turn causes the observed activity concentrations to rise, peak, and gradually decline over a period of time ranging from several minutes to hours after the transient. Thus a conservative assumption can be made that these inventories are available for release from a relief valve which opens for, at most, several minutes after the transient.

The Ginna tube rupture incident (NRC 1983) was used to define boundary for the release of primary coolant. Ginna is an early 2 loop Westinghouse/Babcock and Wilcox design of 1520 MWt as compared to the 3410 MWt 2 loop Waterford (CE) plant used as the reference design in this study. However, the Ginna plant (2 pumps at 14,400 lbs/hr) operates at a system pressure of 2232 psig and the Waterford plant (4 pumps at 16,700 lbs/hr) operates at 2235 psig. With essentially identical operating pressures and mass flow rates sized to system surface areas, tube ruptures in the two plants would most likely respond in a similar fashion. A PORV response to a pressure transient would also likely be similar.

Investigators of the Ginna incident reported that mass balance calculations on the primary coolant after the accident indicated that an estimated 18,300 gallons of primary coolant was expelled. Approximately 7,000 gallons were thought to have been the result of the relief valve failing to reseat properly. The larger value will be used in our analysis to represent a large primary coolant loss due to tube rupture. After conversion to grams, this total loss of primary coolant equates to approximately 7E+07 grams.

The total assumed release is the product of (7E+7 g)(10E-6 Ci/g), or 700 Ci of I-131 equivalent activity. The NRC best estimate is 106 Ci, assuming a slighty smaller release of coolant and modeling the activity spike buildup during the transient. In both cases, no credit has been given for partitioning of primary/secondary coolant or plateout in the SG shell. Also, no credit has been given for partitioning after leaving the SG shell. Assigning reasonable values to these factors and the range of coolant activities that could be expected, the NRC estimates the range of releases from 2 to 4445 Ci, again with 106 Ci as the best estimate. As a result, it is felt that the 700 Ci value derived above is representative of and slightly conservative to the NRC best estimate value and is, thus, suitable for use in this analysis. A dose factor for I-131 is also established as 1.48E+6 Rad/Ci.

Estimated Dose at Control Room Intake

To estimate the resulting possible dose at the control room air intake, the conservative equation presented in Regulatory Guide 1.25 to approximate thyroid dose from inhalation of radioiodine was used. This equation assumes exposure to the entire time integrated release.

$$D = \frac{CB(X/Q)}{F} \qquad (6)$$

where

D = thyroid dose, rads,

C = curies released, Ci

B = breathing rate, assumed to be 3.47E-4 cubic meters per second

(X/Q) = atmospheric diffusion factor

F = effective iodine filtration factor.

The whole body and thyroid dose at the air intake was be estimated with the conservative approach given in Regulatory Guide 1.25. Referring to Equation 6 it was assumed that there is no credit for decontamination during release via the relief valve. The dose factor for I-131 is 1.48E+6 Rad/Ci.

For atmospheric dispersion over the distance from the release point at the PORV to the control room air intake, credit can be taken for the distance and mixing in the containment building wake. The value proposed in NUREG-0909 (NRC 1982) of (X/Q) was 1.7E-3 sec/cubic meter. This same value will be used in this analysis.

Solving Equation 6 using these assumed values results in a predicted thyroid dose of 611 Rads for a person standing outside at the main air intake.

Control Room Dose

To estimate the potential thyroid dose in the control room, it was assumed that dose is proportional to airborne concentration. The equations used in Section 3 of this report to predict toxic gas concentrations in the control room could then be used to predict radiation doses.

Using the equation for concentration buildup in the control room presented in Section 3 results in the following expression:

$$\frac{D_1}{D_0} \propto \frac{1}{C_0} = \left[1 - e^{-(R_1/3600)t}\right] \qquad (7)$$

where

D_1 = dose in control room, rads

D_o = dose at air intake, rads.

This approximation assumes constant exposure, when in fact the gradual buildup of iodine would give a smaller integrated dose over time. This assumption is again considered to be conservative in that the above expression assumes exposure in an infinite cloud, a condition that would not exist in the contol room.

To be more exact, the time integrated average concentration was used to estimate dose. The time integrated average is given below in Equation 8, where D_1 represents the average dose inside the control room, and D_o is the estimated exterior dose at the air intake.

$$\frac{D_1}{D_o} = \frac{1}{C_o} \int_0^t \frac{C_1(t)dt}{t} = \frac{1}{C_o}\left[\frac{t - \left(\frac{3600}{R}\right)\left(1 - e^{-(R/3600)t}\right)}{t}\right] \qquad (8)$$

Table 7.3 presents the results of solving this expression for the various configurations and associated air exchange rates. In each case, the time required to reach a concentration equal to a thyroid dose of 30 Rads was calculated.

TABLE 7.3. Predicted Control Room Doses

Configuration	Air Changes/hr	Seconds to 30 Rad
Normal Operation, no filtration	0.6	6E+2
Isolation, leakage through cracks	0.012	3E+4
EFU Operation on Recirculation	0.011	2.8E+4
EFU Operation, no filtration	0.055	6.5E+3
EFU Operation, with credit for EFU filtration	0.00055	6.5E+5

The only failure identified above that would result in exposures over 30 Rads is the failure to isolate the control room. Even this event takes 600 seconds to reach, which is on the same order of magnitude as the valve release time. All other failure modes would require times longer than the valve release time to reach 30 Rads and are, therefore, considered credible.

Also, it was assumed that the dose would result primarily from iodine inhalation and successful masking would prevent loss of habitability.

7.2.2 Steam Generator Tube Rupture Event Tree

The event tree used for this analysis was the same as was shown in Figure 5.1. Again, it was assumed that habitability could be maintained using either isolation or the air supply. The EFU operation is not really required and would be ineffective in the event of a failure to isolate. Again, the relief value is assumed to exhaust directly to the atmosphere.

If the radiation detectors failed, no operator response would be expected and excessive radiation exposure and loss of habitability would be assumed. The radiation levels would be too low to cause incapacitation, so an exact mechanism for loss of habitability is not known.

The only credible failure scenario for this event requires failure to isolate and failure of operator masking or the air supply. The effective filtration provided by normal isolation is such that the operation of the EFUs would not even come into play in a release of such low magnitude and duration. The use of the EFUs however would further assure success in maintaining habitability.

7.2.3 Steam Generator Tube Rupture Event Tree Quantification

Because of the low release levels, a number of highly conservative assumptions were made to demonstate that the frequency of loss of habitability due to releases associated with tube ruptures could be expected to be very low.

A frequency of 0.02/ry was selected for the initiating event: a conservative, single tube rupture. An additional probability factor of 0.1 to account for wind blowing towards the control room was added. The sum of these two frequencies yielded effective initiating frequency of 2E-3/ry.

For radiation detection there are two redundant pairs of detectors in Waterford, one pair each in the two redundant outside air intake plenums. Referring to Figure 3.3 for detector failure, it can be seen that the additional two detectors would not decrease the failure probability substantially if a common cause failure mode of 10 percent of single failure is assumed. Assuming a single detector failure probability of 6.5E-3, as was used for toxic gas release, yields a dominant common cause failure mode of 6.5E-4 for the four detectors.

In addition to radiation detectors, the Waterford plant includes provisions to isolate the control room in the event a safety injection signal is received. The presence of this additional signal significantly reduces the failure probability which is now assumed for automatic isolation relying on the radiation detectors alone.

In actual plant operating experience, the safety injection signal has been actuated in the majority of steam tube ruptures. Although the presence of the additional isolation signal is highly likely, particularly for larger multiple tube ruptures, its presence is not certain. To be extremely conservative in this analysis, it was assumed that no safety injection signal was received and the isolation signal relied only on the radiation detectors.

Isolation Logic - The probability value of 1E-4 as developed for the toxic gas analysis was used.

Isolation Hardware - The probability value of 3.1E-6 as developed for the toxic gas analysis was used.

Operator Manual Isolation - In the event of automatic isolation function failure, the probability of an operator detecting and taking corrective action and for the hardware to function properly in isolating the control room as derived in the toxic gas analysis were 1E-4, 1E-3, and 3.1E-6, respectively with alarm for a total of 1.1E-3. However in this case, the operator will not be able to detect the radioactive plume. The same error probability with alarm will be used, but will be put at 1.0 given failure of the alarm.

The Waterford plant also has provisions for area radiation monitors in the control room. These would not provide an automatic isolation signal, however they could alert the operator to the need to isolate the control room. Assuming that these detectors are independent of the main air intake monitors, a similar failure probability for two of 6.5E-4 could again be assumed for providing an additional radiation signal to the operators. Adding this to the 1.1E-3 gives a total failure probability of 1.75E-3.

Main Intake Filtration - The main intakes are ineffective against iodine; therefore, the probability of failure is 1.0

EFU Operation - The fault tree developed for failure of the EFUs is shown in Figure 7.1. The original release frequency incorporated a 0.1 factor for wind blowing in the direction of the air intakes, so the probability of the air intakes being in the plume must be increased by a factor of 10. This results in a failure probability of 2.6E-5.

Operator Masking and Air Supply - The previous probability estimates for these failures were 1E-4 and 8E-4. The total probability for failure of the air supply and operator masking is, therefore, 9E-4. Since a radioactive gas cannot be detected by humans, the probability that the operator will fail to mask properly will presumably be higher. The probability that operators will fail to mask was assumed to be 1E-3 with operation of the EFUs and 1E-2 without the EFUs. The total failure probability is 1.8E-3 with EFUs and 1.08E-2 without EFUs. The inclusion of the EFU function is considered to provide a better reflection of the most likely iodine concentrations in the contol room, and the subsequent impact of failure to mask upon loss of habitability. Note that if the EFUs fail, credit is still given for masking and loss of habitability is not assumed. (This will be assumed, however, for the larger LOCA event in the following section).

Without receipt of an alarm, it was assumed that no attempt to mask will be made and the failure probability will be 1.0.

7.2.4 Steam Tube Rupture Event Tree Results

The steam tube rupture event tree is shown in Figure 7.2. The dominant sequence is the initiating event times the assumed failure of masking and the breathing apparatus, resulting in a frequency of 3.6E-6/ry. The frequencies for other sequences are several orders of magnitude lower than this.

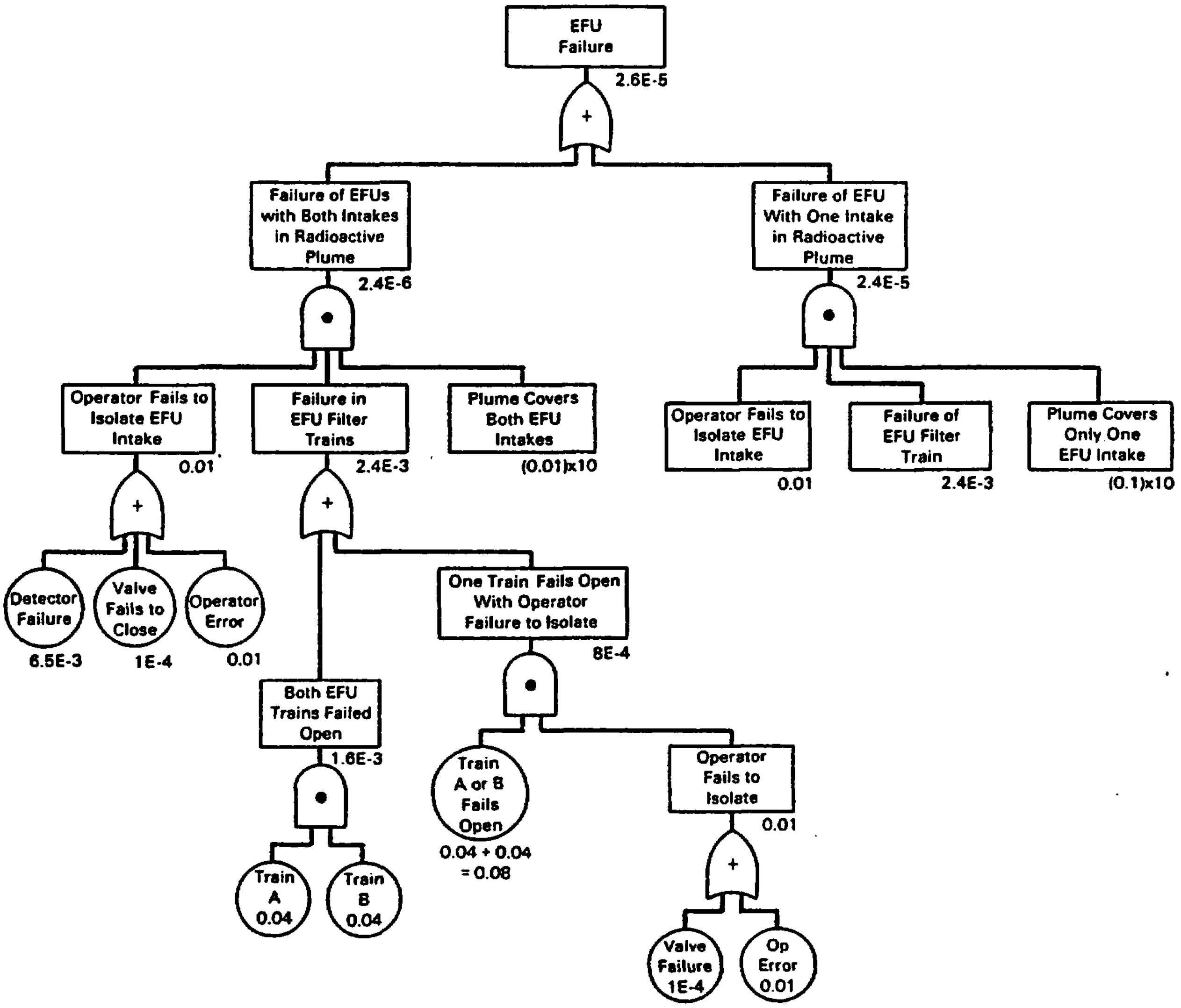


FIGURE 7.1. EFU Failure Fault Tree

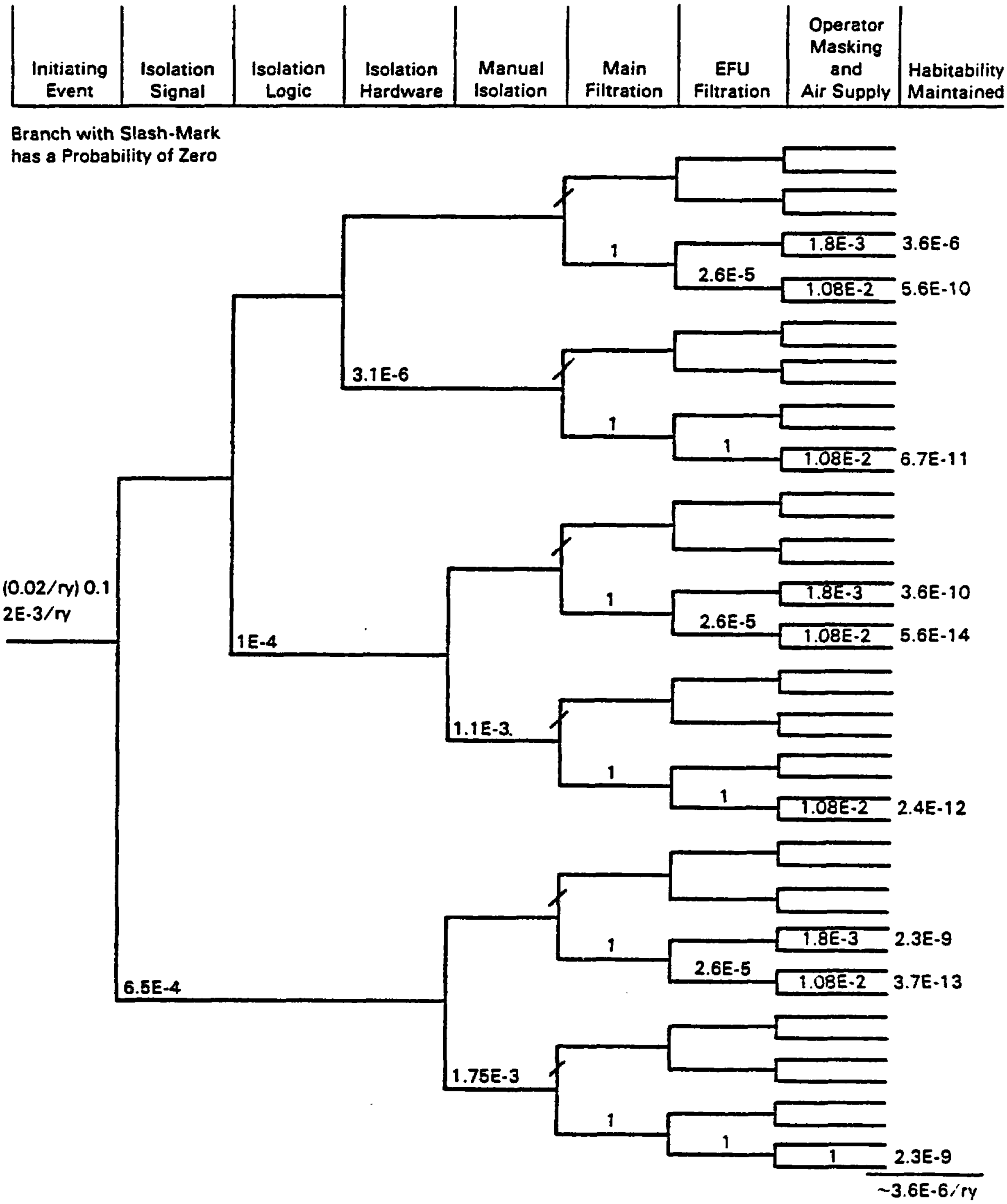


FIGURE 7.2. Steam Generator Tube Rupture Event Tree Results

This assumed frequency is considered to be very conservative. The following assumptions were made:

- high initiating event frequency which lifts the relief valve
- iodine spiking and unrealistic step increase of coolant activity
- no partioning of primary coolant in the SG shell or plate-out
- high common mode failure probability for radiation detectors.

Credit is taken for portable detectors in the control room, but not for a safety injection signal to isolate. The primary failure mechanism is assumed to be failure to properly mask, but the radiation levels estimated are such that the actual impact on the operators in terms of incapacitation would most likely be slight.

In all likelihood, the probability for loss of habitability due to steam tube rupture would be several orders of magnitude less than the 3.6E-6/ry frequency predicted here.

7.3 RADIATION RELEASE FROM LARGE LOCA

The final radiation release to be examined was a large LOCA with significant fuel damage. The specific accident scenario involved the large break LOCA design basis accident considered in Chapter 15 of the Waterford FSAR. Habitability of the control room over a 30-day time period is required for this event.

7.3.1 Initiating Event for Large LOCA

The design basis accident scenario presented in the Waterford FSAR was used in this analysis. Although site meteorology may differ, the habitability requirement is similar in all plants. Site specific modifications may be introduced so limiting doses are not exceeded. The net results should thus be applicable to other sites. No detailed analysis of the accident progression, release, and transport calculations are given in this report. Rather, the results of the Waterford analysis are utilized to estimate any additional dose in the control room as the result of postulated failures.

The large LOCA event assumes a 50 percent release of iodine and a 100 percent release of noble gases from the available core inventory. The actual activities assumed in curies are given in Table 15.6-18 in the Waterford FSAR. The containment leak rate of 0.5 percent was chosen for the first 24 hours, and 0.25 percent for the remainder of the 30-day period. The leakage pathway is assumed to be 52 percent via the filtered Reactor Auxiliary Building, 6 percent via unfiltered bypass lines, and the remaining 40 percent via direct containment leakage. Filtration efficiencies are estimated to be 99 percent for iodine.

LOCA Dose Results

The resulting doses for the design basis accident at Waterford were assumed to be 24 rem thyroid, 9.7 rem skin, and 0.5 rem whole body. This compares to the SRP-6.4 limits of 30, 30, and 5 rem respectively. Control room habitability is assumed to be maintained.

The ratio of thyroid to other doses confirms the assumption used in the previous sections that the thyriod dose is the dominant contributor to control room dose. If the thyroid dose limit is not reached, none of the others will be.

The predicted doses from the Waterford analysis were used to estimate doses in the control room in the event of ventilation system failure. To accomplish this, it was assumed that the doses were proportional to the effective air exchange rate in the control room in its various configurations as was presented previously for the steam tube rupture analysis. This assumption gives credit for 99 percent filtration of iodine when the filters are functional. It was also assumed that the 24 rem thyroid dose assigned in the Waterford FSAR corresponds to full isolation and operation of the EFUs. The resulting predicted doses are shown in Table 7.4.

TABLE 7.4. Predicted LOCA Control Room Doses

Configuration	Air Changes/hr	Predicted Dose, rem Thyroid	 Skin	 Body
Normal Operation, no filtration	0.6	2.6E+4	1.1E+4	5.5E+2
Isolation, leakage through cracks	0.012	5.2E+2	2.1E+2	1.1E+1
EFU Operation in Recirculation	0.011	4.8E+2	1.9E+2	1.0E+1
EFU Operation, no filtration	0.055	2.4E+3	9.7E+2	5.0E+1
EFU with credit for EFU filtration	0.00055	24	9.7	0.5
NRC Regulations		30	30	5

As can be seen in Table 7.4, the assumed accident is of sufficient severity that thyroid exposures are near the 30 rem limit at the end of 30 days. Additional exposure would cause operator exposure to exceed that limit. It could thus be postulated that any additional failure in the ventilation system would result in loss of habitability.

The 24 rem thyroid dose shown in Table 7.4 corresponds to a best case ventilation system configuration with no margin for failure, rather than a worst case situation as was used in the previous less severe SGTR accident scenario.

Note that no mention of credit was given in the Waterford analysis for use of breathing masks. It was assumed in this analysis that the 24 rem thyroid dose resulted from non-use of the mask, but successful isolation and operation of the EFUs were assumed. A second number will be carried through the event tree however, assuming that the mask must function.

If isolation or the EFUs fail in this case, the mask presumably would be unable to block the skin doses and whole body doses given above. Failure of these components would then result in loss of habitability regardless of the use of the mask.

Accident Duration

Exactly what loss of habitability would mean in terms of actual impact to the plant operators and plant in terms of core melt probabilities is highly speculative in this case because of the long duration of the accident. In 30 days there would be a number of shift changes, and repairs made. The probability of an original operating shift still being at its post 30 days after an accident is essentially zero; therefore, no one crew will receive the entire dose.

However, the CRACS failures postulated above increase the estimated dose by factors ranging from 20 to 1E+3. It could likewise be assumed that the time required to reach the original thyroid dose of 24 rem in 30 days is decreased by the same factors, or from 1.5 days to less than one hour. Large doses in a short time period then become a factor for the worst failures. It was therefore assumed that any of the failures described above would in fact lead to loss of habitability of the control room.

Initiating Event Frequency

The frequency of occurance for LOCAs is typically estimated at 1E-4/ry for a large break and 1E-3 for a small break. The radiation release calculations are for the large break, so the 1E-4/ry initiating frequency was used. The Waterford FSAR calculations do consider changes in atmospheric diffusion over the 30-day period, so no factor for wind blowing towards the inlets was included.

7.3.2 LOCA Event Tree

The event tree used to depict loss of habitability for the LOCA will again be that as shown in Figure 7.2. It is the same event tree used for the steam tube rupture release. Slashed lines across particular branches depict forced failures with a probability of 1.0. Examples of these failures are loss of control room isolation causing failure of EFU function.

7.3.3 LOCA Event Tree Quantification

The values used in the event tree are developed in this section. Note that in a long term LOCA, if wind direction or other weather conditions change during the course of the accident, the operator is always able to isolate individual inlets or even both inlets for short periods of time and run the system in the recirculation mode. It was assumed in this analysis that the FSAR calculations did consider the changing wind direction along with the meteorology and operator response to select the best air intake has been included.

Initiation Signal

It was assumed that the LOCA will actuate the safety injection signal, which also sends a signal to isolate. The probability of failure of this signal will be assumed to be 1E-3. Failure of the isolation signal then requires failure of the radiation detectors (6.5E-4) and failure of the injection signal (1E-3). The total failure probability of these events occurring is 6.5E-7.

Isolation Logic

A probability value of 1E-4 for isolation logic failure was assumed. This is the same probability used in the toxic gas analysis.

Isolation Hardware

A probability value of 3.1E-6 for isolation hardware failure was assumed. This is the same probability used in the toxic gas analysis.

Operator Isolation

The probability of operator failure to manually isolate the control room was assumed to be 1.1E-3 upon receipt of an isolation signal and 1.75 upon receipt of a signal from the area radiation detectors.

Main Filtration

The main filters are ineffective against iodine; therefore, their probability of failure is 1.0.

EFU Filtration

The EFU failure probability of 2.6E-5 developed for the steam tube rupture analysis was used. Wind direction factors are considered in this assumption.

Operator Masking and Air Supply

In the steam tube rupture analysis, the probability that an operator will fail to mask properly was assumed to be 1E-3 given operation of the EFUs and 1E-2 given failure of the EFUs. Including the factor of 8E-4 for failure of the breathing apparatus results in a total failure probability of 1.8E-3 with EFUs and 1.08E-2 without EFUs. Inclusion of the EFU function reflects the actual need for masking in the control room.

Without receipt of an alarm, it was assumed that no operator attempt to mask would be made. In the event of control room isolation or EFU failures, it was assumed that masks would be ineffective against skin and whole body dose, so the failure probability is 1.0.

In the steam tube rupture analysis, credit was given to the mask for protection if the EFUs failed.

7.3.4 LOCA Results

The results of the LOCA event tree are depicted in Figure 7.3. If it is assumed that masks are still required given control room isolation and proper EFU function, addition of mask failure term would result in a 1.8E-07/ry sequence. Otherwise, the dominant sequence is the assumed high failure probability of the EFU filter beds, leading to failure of the EFU filtration function and loss of control room habitability. Again, this is considered to be highly conservative. However, the estimated frequency of occurence of this sequence of 2.6E-9/ry is very small, and no further quantification of the failure mechanisms should be required.

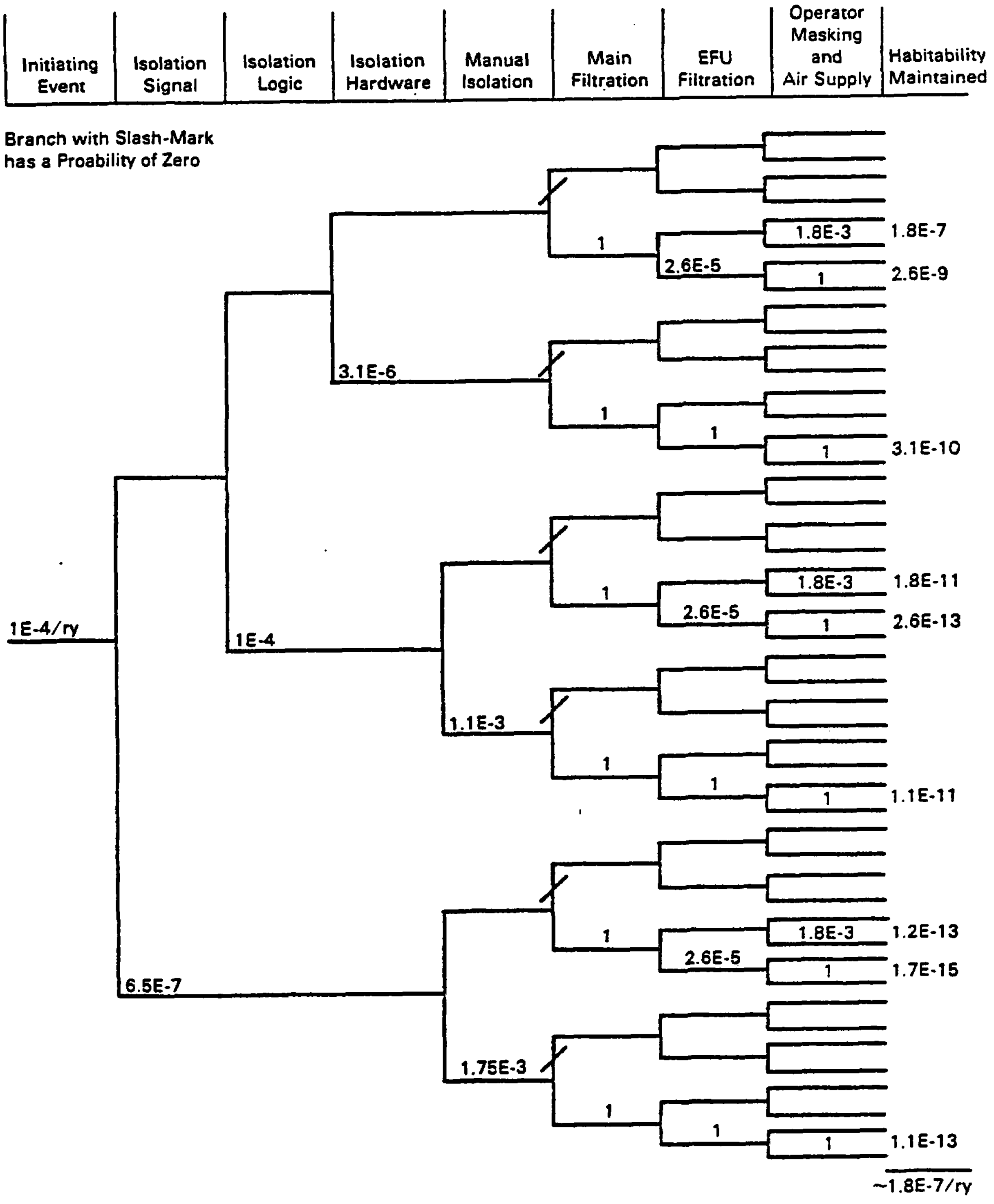


FIGURE 7.3. LOCA Event Tree Results

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APPENDIX

A.1 WATERFORD PLANT REFERENCE DESIGN

The NRC requested Louisiana Power and Light's Waterford PWR (CE design) be used as the reference site for this analysis of control room habitability. This site represents somewhat of a bounding case because of the extensive industrial buildup surrounding the plant. This development includes major chemical and petroleum facilities, gas pipelines, and shipment routes of hazardous chemicals by rail, truck, and ship. In the FSAR for the Waterford plant, an analysis of the potential for serious accidents was made and included a provision for appropriate defenses in the plant design for accidents with a probability of greater than 1.0E-7 per year.

The various systems needed for the fault tree examination in the report are presented here as background information.

A.2. CONTROL ROOM AIR CONDITIONING SYSTEM (CRACS)

The Control Room Air Conditioning System (CRACS) for the Waterford plant is diagrammed in Figure 6.4.1 of the FSAR. This system provides for filtered recirculated air, widely separated dual emergency air inlets, and positive pressure. The normal air inlet is equipped with redundant, normally-open, air-operated butterfly valves that fail in the closed position. The normal exaust has redundant isolation butterfly valves arranged on two electric channels to preclude failure to isolate given an electric fault.

Emergency outside air is provided to the control room envelope by the redundant Emergency Filtration Units (EFUs). The widely separated emergency outside air intakes each contain one normally open and one normally closed fail-as-is butterfly valve in series. Two emergency power channels are used for the valves. These power channels are arranged so that loss of one channel does not preclude the ability to open an emergency intake for control room pressurization or close the emergency intake for isolation. In normal operation, the emergency intakes are closed. In this configuration, isolation is maintained in the event of a power failure. The fail-as-is provision would prevent automatic isolation of the EFUs given a total power failure.

During a toxic gas and radiological emergency, the modes of operation of the CRACS are, respectively:

1) Automatic isolation with automatic recirculation.
2) Automatic isolation with provisions for manual initiation of filtered pressurization, recirculation and partial filtration.

Automatic isolation consists of the three following steps (referring again to Figure 6.4.1 of the FSAR):

1) Close normal outside air isolation valves V-13 and V-14, close exaust isolation valves V-9, V-10, V-11 and V-12 to isolate the air flow paths into and out of the control room.

2) Stop operating exaust fans E-42 and E-43.
3) Open recirculation dampers D-18 and D-19 associated with blower AH-12 to recirculate air to the control room.

No outside air is drawn into the control room in this configuration, which would be used in response to toxic gases. To provide pressurization and filtration, the identical steps as above are required, with the additional step:

4) Start both Emergency Filtration Units S-8 to provide filtration and adsorption of 200 cfm of outside air for pressurization. The blowers are designed to recirculate an additional 3800 cfm for a total recirculation of 4000 cfm.

The positioning of valves and dampers in response to various accidents is given in Table 9.4.2 of the Waterford FSAR.

A.3. DETECTION EQUIPMENT

Detection equipment for toxic gas protection in the Waterford CRACS is discussed in this section. The exact configuration of the valves, dampers, and air blowers when an isolation signal is sent to the CRACS are discussed below.

A.3.1 Chlorine

Redundant chlorine detectors using solid state non-wet chemistry type activation are used. Upon detection of chlorine, a signal is sent to initiate isolation of the control room. In addition, an alarm is sounded in the control room, and a chlorine concentration readout is available from the plant computer. The chlorine detectors are powered from independent non-safety related buses which in turn draw power from safety related buses. In case of loss of power, the detectors assume a fail-safe position and initiate an isolation signal.

A.3.2 Anhydrous Ammonia

Redundant ammonia detectors are also provided near the CRACS normal outside air intake. These detectors use derivative gas phase spectroscopy activation. As with chlorine, upon detection of ammonia, an isolation signal is sent, along with an alarm and concentration information to the plant computer. On loss of power, the detectors also assume the fail-safe position and initiate isolation.

A.3.3 Broad Range Gas Detector System

Redundant systems are provided for detection of a broad range of toxic gases (see Table 6.4-5, Waterford FSAR, Docket 50-382). This system consists of a control panel, a microprocessor, and an analyzer oven panel that includes three photoionization detectors, one flame ionization detector, and a gas chromatograph. If toxic gas concentrations detected reach a pre-set level, the isolation signal is sent, and an alarm is actuated. An alarm is also sent for loss of power, low battery voltage, or loss of carrier gas through the system.

In addition to the above gas detection system on the air intakes, five ionization type smoke detector zones are located within the control room.

A.4. EMERGENCY AIR SUPPLY FOR WATERFORD

The Waterford FSAR indicates that the plant has an installed emergency air supply, as shown in Figure 6.4.4 of the FSAR. A central compressor fills a number of storage tanks. Air is then regulated and distributed to 6 stations throughout the control room.

Portable air packs are also thought to be used at the Waterford plant, but no credit has been given for their use in this report.