DRAFT REPORT

HAZARDOUS WASTE TANK FAILURE MODEL: DESCRIPTION OF METHODOLOGY

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1.0 INTRODUCTION

1.1 Overview

Risks to human health and the environment from the operation of hazardous waste tank facilities may result from air emissions, leaks from tanks and piping, or large spills or overflows. Some losses are relatively constant baseline releases resulting from the facility's design or normal operating practices. Other losses are more sudden and result in short-term high-volume releases of concentrated material. Such releases may result from natural catastrophes or from bursting pipes or ruptured tank seams. High-volume releases are also possible from long-term undiscovered leaks. Such leaks may linger for years at levels just below the detection threshold, releasing thousands of gallons of hazardous waste into the environment.

The cause of release varies from incident to incident, but may include one or more of the following:

- normal operating discharges or air emissions from the facility;
- equipment aging or deterioration from environmental exposure;
- human error in design, construction, installation, or operation;
- system-generated stresses due to incompatibilities between waste constituents and equipment; or
- severe environmental stresses such as fires, floods, storms, or earthquakes.

The purpose of this study is to evaluate the frequency and severity of various failure mechanisms for a variety of hazardous waste treatment and storage tank systems. To accomplish this objective, we used published sources and our own engineering analyses to develop failure scenarios (combinations of events leading to system failure) for each tank system. We evaluated these scenarios using fault tree techniques and a Monte Carlo simulation model to predict the probabilities, magnitudes, and concentrations of releases over a 20-year operating life.

By modelling the reliability of various tank designs, the present study will provide information to help the Agency develop regulations for the management of hazardous waste tanks. The Agency can also apply our predicted release volumes to contaminant transport models and dose-response models in order to estimate human health risks from various tank designs. In addition, the Agency may combine these risk estimates with design and operating cost data to evaluate the cost-effectiveness of various regulatory approaches.

1.2 Methodology

This study involved two basic techniques: fault tree analysis and Monte Carlo simulation.

Fault tree analysis is a common engineering method for evaluating the reliability of complex systems. The first step in such an analysis is to select a "top" or "ultimate" failure event. In the case of hazardous waste tanks, such an ultimate failure involves the release of hazardous waste from the tank system. This top event is then traced backward to identify all relevant intermediate failure events which might lead to it. These events are in turn traced back to their antecedents, and the analysis is continued until no further reduction is possible or no data are available. The resulting chains of causation are the fault trees.

After the fault trees have been designed, the next step in fault tree analysis is to estimate the frequency and timing of each of the basic failure events. To do this, we used a combination of engineering analysis and published tables of average service lives or annual failure rates for various components of a tank system. Such data, however, did not enable us to predict with certainty the date of failure for any particular piece of equipment. There are two reasons for this: (1) many types of failure are intrinsically probabilistic in nature; and (2) many others are not well understood. Therefore, it was necessary for us to assign failure probabilities to most of the events, rather than deterministic dates of failure. Consequently, the frequency and timing of the top event is also stochastic in nature, and its probability distribution is a mathematical function of the initiating event probabilities.

Many of the probabilities used in the model involve external events, such as hurricanes or floods and are time-invariant. Other probabilities, such as operator errors or electronic equipment failures, are also assumed to be time-independent, either because their time variations occur over too short a cycle to be of interest to the model, or because the nature of their time-dependencies is unknown. In some cases, however, the probability of component failure may increase with time due to such factors as material aging or accumulated environmental stresses. These failure event probabilities may show complex time-dependencies.

The fault trees developed for this study will be described in detail in Chapter 3. These fault trees model a number of mechanisms by which tank releases can occur. These mechanisms include:

- Overflow
- Leaks and ruptures
- Natural catastrophes
- Releases from secondary containment
- Human error

We evaluated these fault trees by using a computerized Monte Carlo simulation model. During each of the modeled time periods this computer model determines the occurrence of each of the basic failure events by drawing a random number. Using the fault trees, the computer then determines whether the combination of basic failure events which has occurred is sufficient to cause a release. If a release results, the computer calculates the volume of hazardous material that escapes to the environment by first determining the size of the hole (often this involves the selection of one or more additional random numbers), and then calculating the leak rate appropriate for the hole's size and location. The model then determines the time lag until the leak is detected, either by visual inspection, inventory shortfall, or other more sophisticated techniques. Multiplying this time lag by the leak rate gives the total loss volume. Under no circumstances, however, is the leak volume allowed to exceed the sum of the tank's initial contents plus additional deliveries during the detection period.

The model then replaces any tank components whose failure is detected, increments the ages of all surviving components by one time period, and repeats the simulation process. As a result, it generates a time series of releases from the modeled tank. This entire process is repeated hundreds of times, producing a new time profile for each iteration in order to estimate expected failures. The result is as though several hundred tank facilities of similar design were being evaluated for their performance. The resulting distribution of release profiles can be used to determine average, median, and extreme cases. In addition, types, dates, and frequencies of failure can be compiled, as well as expected release volumes and their standard deviations.

1.3 Report Outline

The remainder of this report will discuss in detail the methodology of the hazardous waste tank failure model. The results will be presented in a separate report.

Chapter 2 of this report gives background information about existing hazardous waste tanks. We used this information to determine what types of facilities to model and what types of failure scenarios to include in the fault trees. Chapters 3 and 4 describe the fault trees and the Monte Carlo simulation model, respectively. Chapter 5 concludes the main body of the report by discussing the model's limitations and proposing modifications that might increase its range of applicability.

In addition, this report contains five appendices. Appendix A details the derivation of the probabilities and release volumes used for the fault tree events. Appendix B contains a statistical analysis of a survey of 300 service station tanks, while Appendix C presents case study data on 57 hazardous waste tank failures. Appendix D gives technical specifications for the modeled components and tank systems, and Appendix E lists the computer code for the Monte Carlo model. These appendices will be more thoroughly described in subsequent sections of this report.

2.0 PRELIMINARY ANALYSES

2.1 Introduction

Before designing the fault trees, we conducted several preliminary studies to determine what elements should be built into our fault trees and our Monte Carlo model. These studies included:

- A determination of the design characteristics of existing hazardous waste tanks;
- An analysis of the processes for which these tanks are used;
- A review of the relevant regulations to determine what leak prevention and detection techniques are of the greatest interest to EPA; and
- A review of the relevant technical literature to determine the types of failures to be incorporated into the fault trees.

2.2 Design Characteristics of Existing Hazardous Waste Tanks

Hazardous waste tanks fall into four basic categories: storage tanks, treatment tanks, accumulation tanks, and small quantity generator tanks. Based on the Office of Solid Waste's RIA Tank Survey and the Small Quantity Generator Survey, we subdivided each of these categories according to tank construction material, whether the tanks are above-, below-, or in-ground, and whether the tanks have open or closed tops. As a result, we identified 21 basic types of tank systems. These systems are listed in Table 1, along with their median ages and median capacities. Within each of these categories, however, system age and tank capacities showed considerable variation. Tank ages and capacities are treated as variables in the model. However, for the sake of simplicity, we have assigned fixed values for these parameters in this study.

Not all of the tank systems characterized in Table 1 were specifically identified by the two surveys. Waste accumulation tanks, for example, were not distinguished from storage tanks. Since the only technical difference between storage and accumulation tanks is the length of time between pump-

TABLE 1: CLASSIFICATION AND CHARACTERIZATION OF EXISTING HAZARDOUS WASTE TANKS

Tank Function	Design Configuration	Construction Material	Median Age (yrs)	Median Capacity (gallons)
Treatment	Closed top, above-ground, cradled	Carbon steel	5	2,300
	Open top, above-ground, cradled	Carbon steel	5	2,300
	Open top, above-ground, on-grade	Carbon steel	9	60,000
	Open top, in-ground	Concrete	10	3,700
	Open top, in-ground	Stainless steel	10	3,700
Storage	Closed, above-ground, cradled	Carbon steel	6	5,500
	Closed, above-ground, on-grade	Carbon steel	7	210,000
	Below-ground	Carbon steel	7	4,000
	Below-ground	Fiberglass	7	4,000
	Below-ground	Stainless steel	7	4,000
	In-ground, open	Concrete	8	2,100
	In-ground, open	Carbon steel	8	2,100
Small Quantity Generators	Above-ground, closed	Carbon steel	6	200
	Below-ground	Carbon steel	7	200

TABLE 1. CLASSIFICATION AND CHARACTERIZATION OF EXISTING HAZARDOUS WASTE TANKS (Cont.)

Tank Function	Design Configuration	Material of Construction	Median age(yrs)	Median size (gallon)
Accumulation	Above-ground, cradled, closed	Carbon steel	6	5,500
	Above-ground, on-grade, closed	Carbon steel	21	210,000
	Below-ground	Carbon steel	7	4,000
	Below-ground	Fiberglass	7	4,000
	Below-ground	Stainless steel	7	4,000
	In-ground	Concrete	8	2,100
	In-ground	Carbon steel	8	2,100

outs, we assumed that the storage tank data could also be applied to accumulation tanks. Similarly, since the Small Quantity Generator Survey provides no information on tank construction materials or design capacity, we made the following simplifying assumptions. Since carbon steel is the most common construction material revealed by the RIA survey, we assumed that this material is also used for Small Quantity Generator tanks. We estimated the design capacities of these tanks from through-put information provided by the Small Quantity Generator survey.

The tank systems identified in Table 1 as "Treatment Tanks" are actually used for a wide range of treatment processes. The most common of these processes are listed in Tables 2 and 3 by design capacity and by number of tanks, respectively. We selected six of these processes to model, including distillation, neutralization, cyanide oxidation, chrome reduction, evaporation, and precipitation. In general, we selected the most common processes, but we changed some of the categories used in Tables 2 and 3. Thus, we have combined precipitation, clarification, and sedimentation into a single process which we will label as "precipitation." In addition, because they are similar to short-term storage, we have eliminated blending and decanting from further consideration. (Blending is merely a method of combining wastes for later treatment or storage; decanting is merely a method for separating unlike wastes.)

2.3 Storage and Treatment Processes

In order to provide a visual representation of the processes for which hazardous waste tanks are used, we have developed flow diagrams for storage tanks and for each of the six selected treatment processes. These flow diagrams are presented in Figures 1 through 7. The symbols used in these diagrams are explained in Figure 8. The flow diagrams are somewhat simplified, but they help to illustrate the major components involved in the modeled tank systems. We used these diagrams to develop the framework for our computer model and to identify the effects of specific equipment failures for each of the modeled tank systems. Based on these diagrams, the computer model tracks the hazardous wastes as they pass through different stages of the tank system, checking for component failures at each location where a release might occur.

TABLE 2. 15 MOST COMMON TREATMENT PROCESSES BY TOTAL CAPACITY

Treatment Process or Combination of Processes	Sum of Design Capacities (Gallons)	% of Total Capacity	Number of Tanks
* Decanting	9,930,478	16.6	57
Clarification, Flocculation, Flotation	7,020,000	11.7	3
Clarification, Flotation	5,901,500	9.9	3
* Chemical Precipitation, Neutralization	4,940,320	8.3	26
Activated Sludge	3,138,000	5.2	5
* Clarification	2,843,927	4.8	22
* Neutralization	2,742,940	4.6	124
Clarification, Flocculation	2,450,000	4.1	3
Chlorination, Neutralization	1,501,200	2.5	4
* Sedimentation	1,562,154	2.6	16
Flotation, Sedimentation	1,347,228	2.3	10
Thickening	1,161,674	1.9	10
* Decanting, Filtration, Sedimentation	1,100,490	1.8	15
Flotation, Sedimentation, Evaporation, Aerobic Tank	880,000	1.5	2
Chemical, Reduction, Flocculation, Flotation	750,000	1.3	3
All other technologies	12,523,459	20.9	571
Total	59,793,370	100%	874

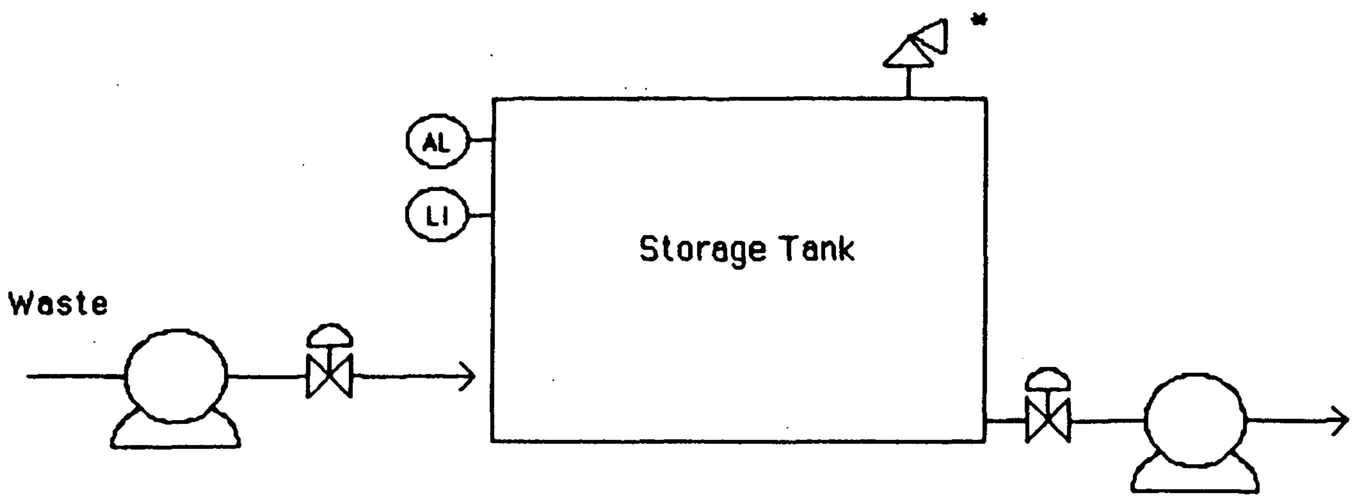
* This process is also included in Table 3 (most common treatment processes by number of tanks).

TABLE 3. 15 MOST COMMON TREATMENT PROCESSES BY NUMBER OF TANKS

Treatment Processes or Combination of Process	Number of Tanks	% of Total Number of Tanks	Sum of Designs Capacities (Gallons
* Neutralization	124	14.2	2,742,840
* Decanting	57	6.5	9,930,478
Chemical Reduction	48	5.5	113,549
Chemical Oxidation	44	5.0	204,409
Blending	31	3.5	512,375
* Chemical Precipitation, Neutralization	26	3.0	4,940,320
Chemical Reduction, Degradation	24	2.7	20,640
Chemical Precipitation	23	2.6	226,001
Cyanide Destruction	23	2.6	92,016
* Clarification	22	2.5	2,843,927
Sedimentation, Blending	18	2.1	385,425
* Sedimentation	16	1.8	1,562,154
Evaporation	16	1.8	21,115
* Decanting, Filtration, Sedimentation	15	1.7	1,100,490
Chemical Reduction, Neutralization	11	1.3	87,700
All other technologies	376	43.0	35,009,931
Total	874	100%	59,793,370

* This process is also included in Table 2 (most common treatment processes by total capacity).

FIGURE 1. STORAGE

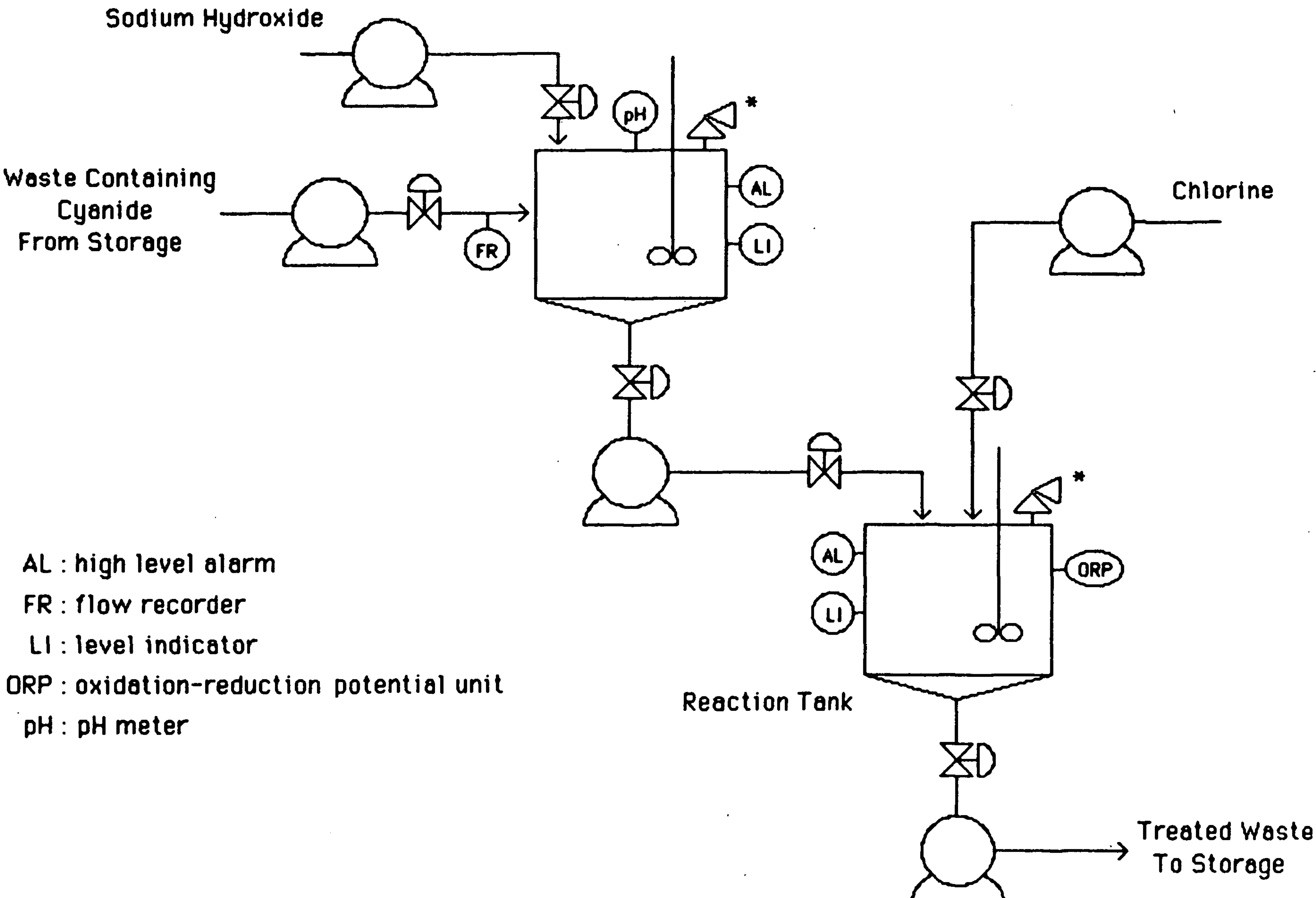


AL: high level alarm

LI: liquid level indicator

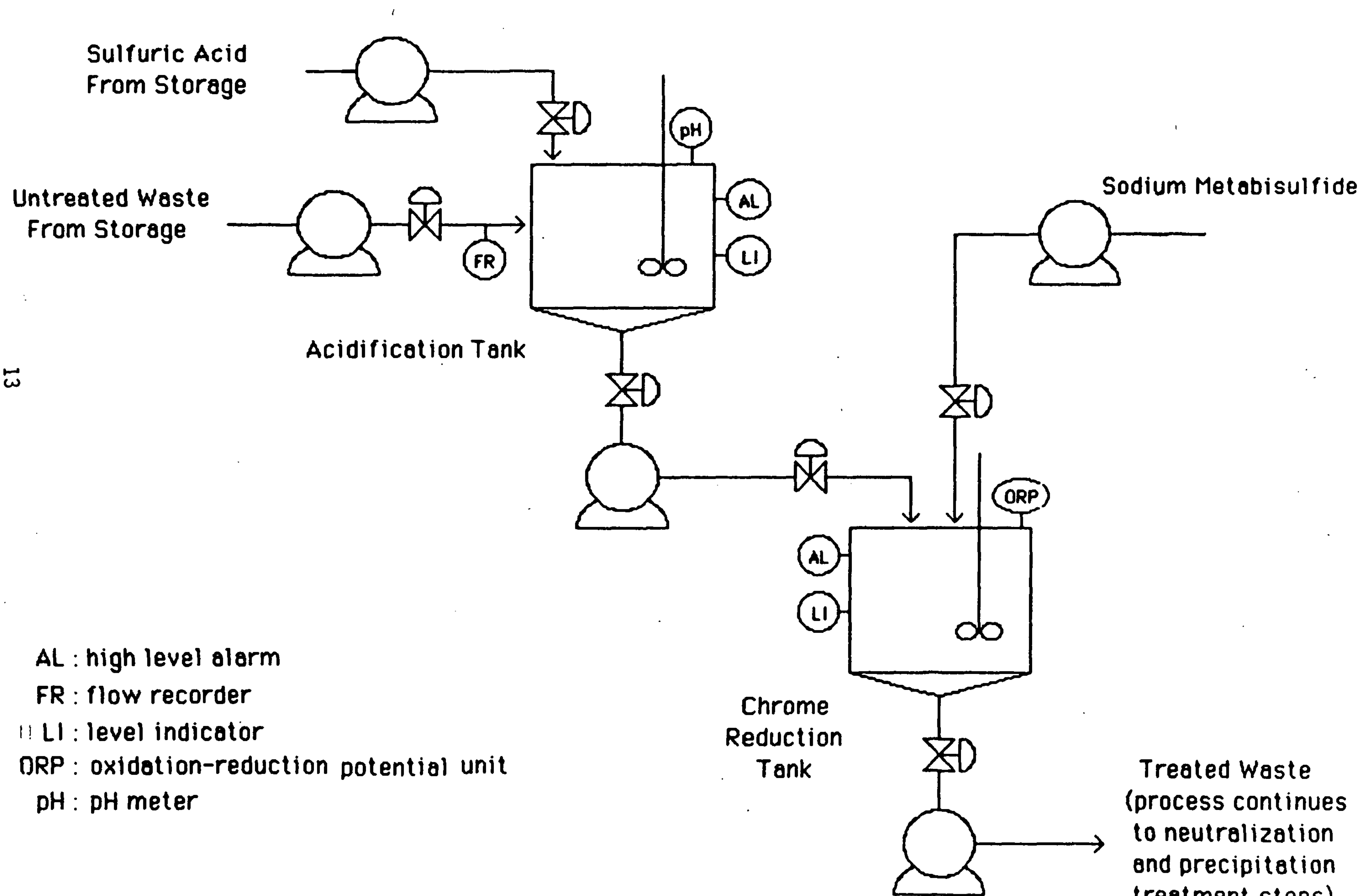
* Closed tank is also equipped with an overflow valve.

FIGURE 2. CYANIDE OXIDATION



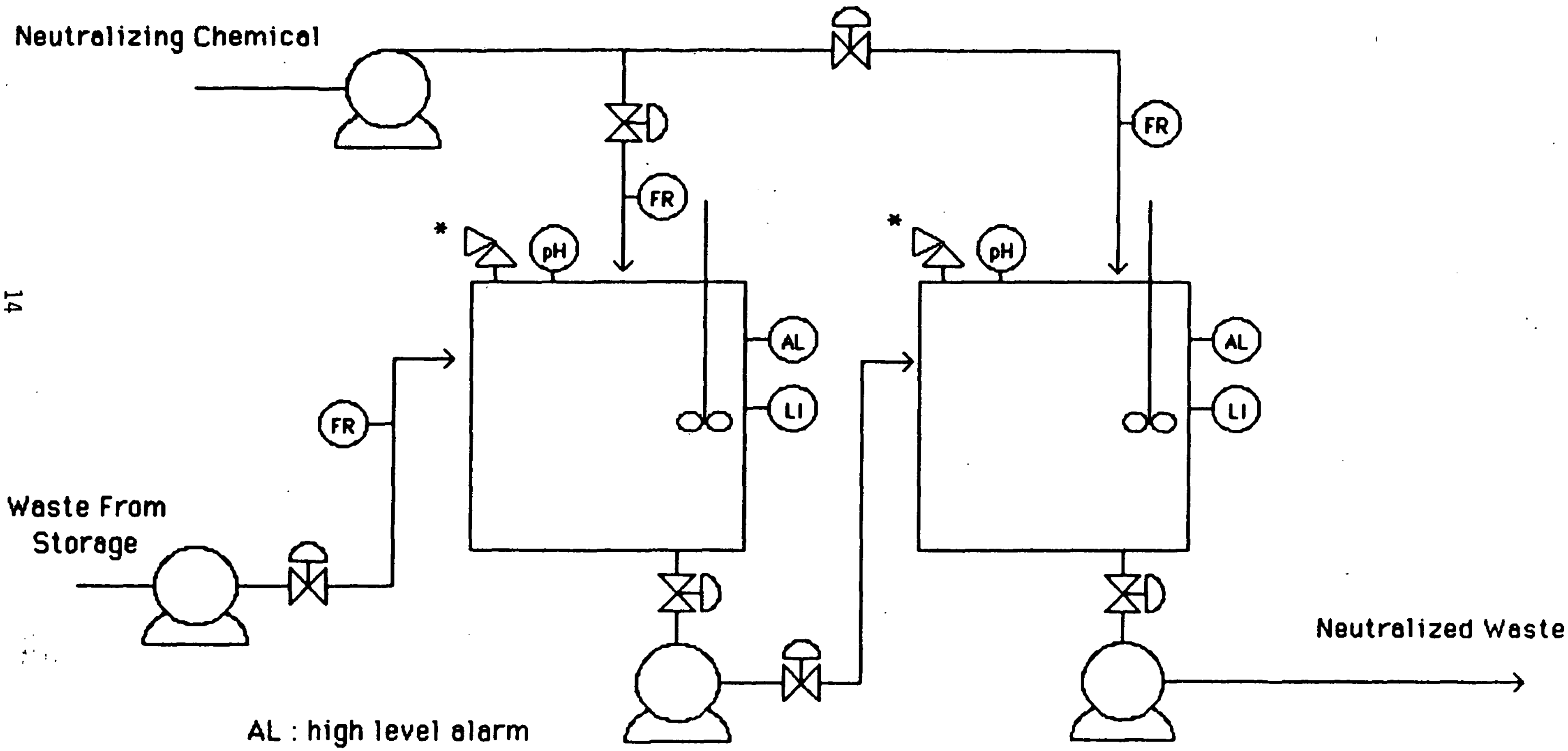
* Closed tanks are also equipped with overflow valves.

FIGURE 3. CHROME REDUCTION



AL : high level alarm
FR : flow recorder
LI : level indicator
ORP : oxidation-reduction potential unit
pH : pH meter

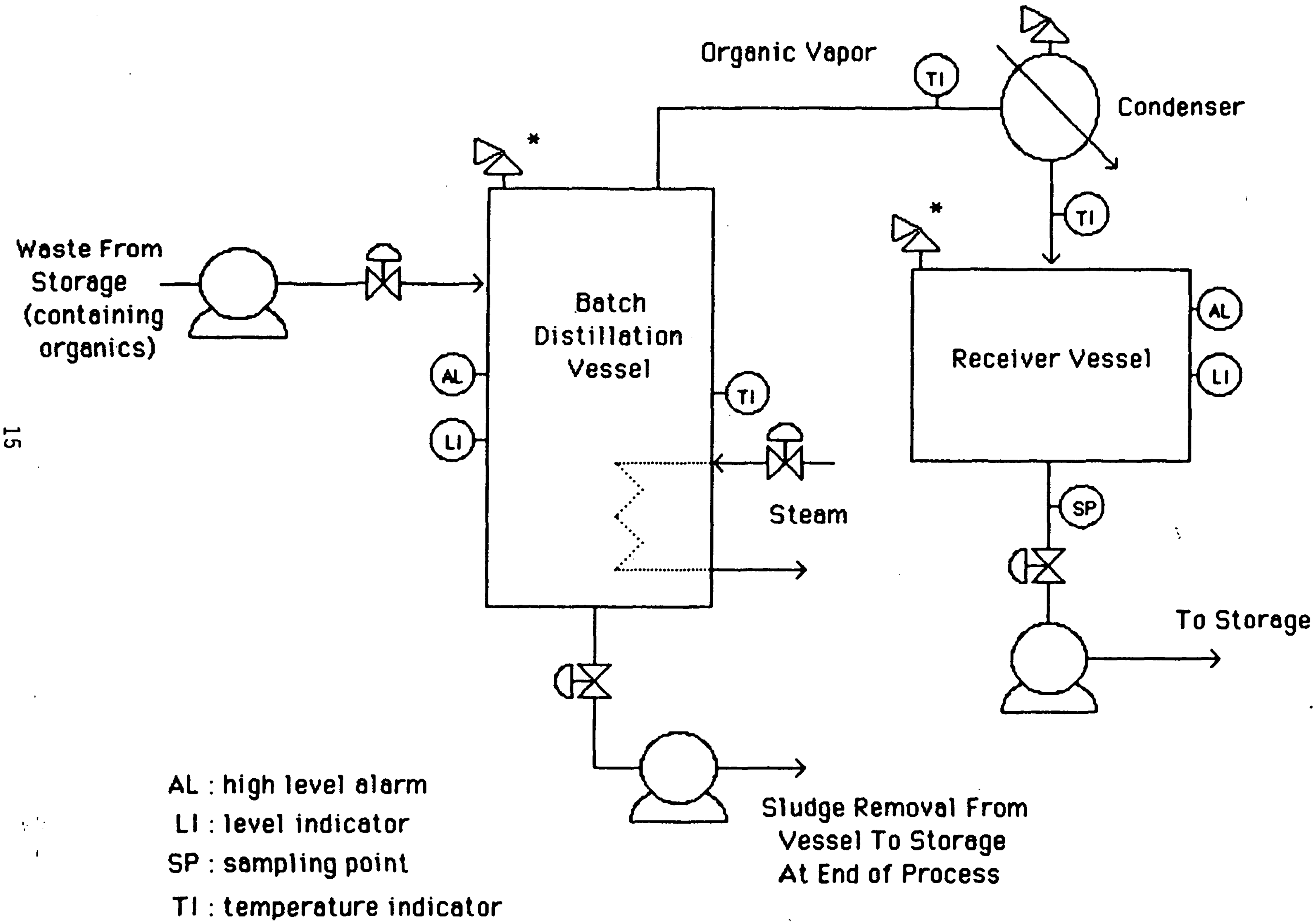
FIGURE 4. NEUTRALIZATION



AL : high level alarm
FR : flow recorder
LI : level indicator
pH : pH meter

* Closed tanks are also equipped with overflow valves.

FIGURE 5. DISTILLATION



* Closed tank is also equipped with an overflow valve.

FIGURE 6. EVAPORATION

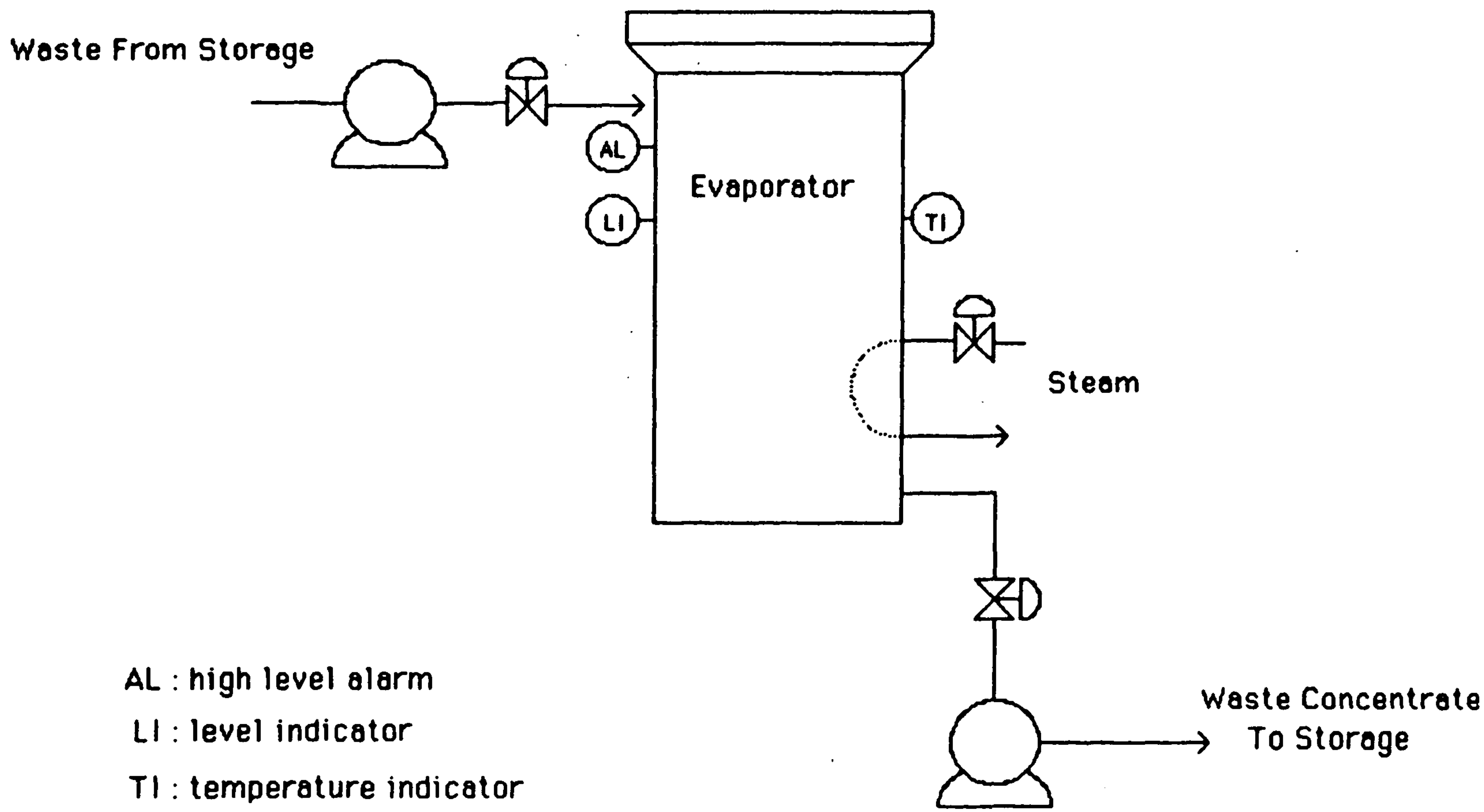


FIGURE 7. PRECIPITATION

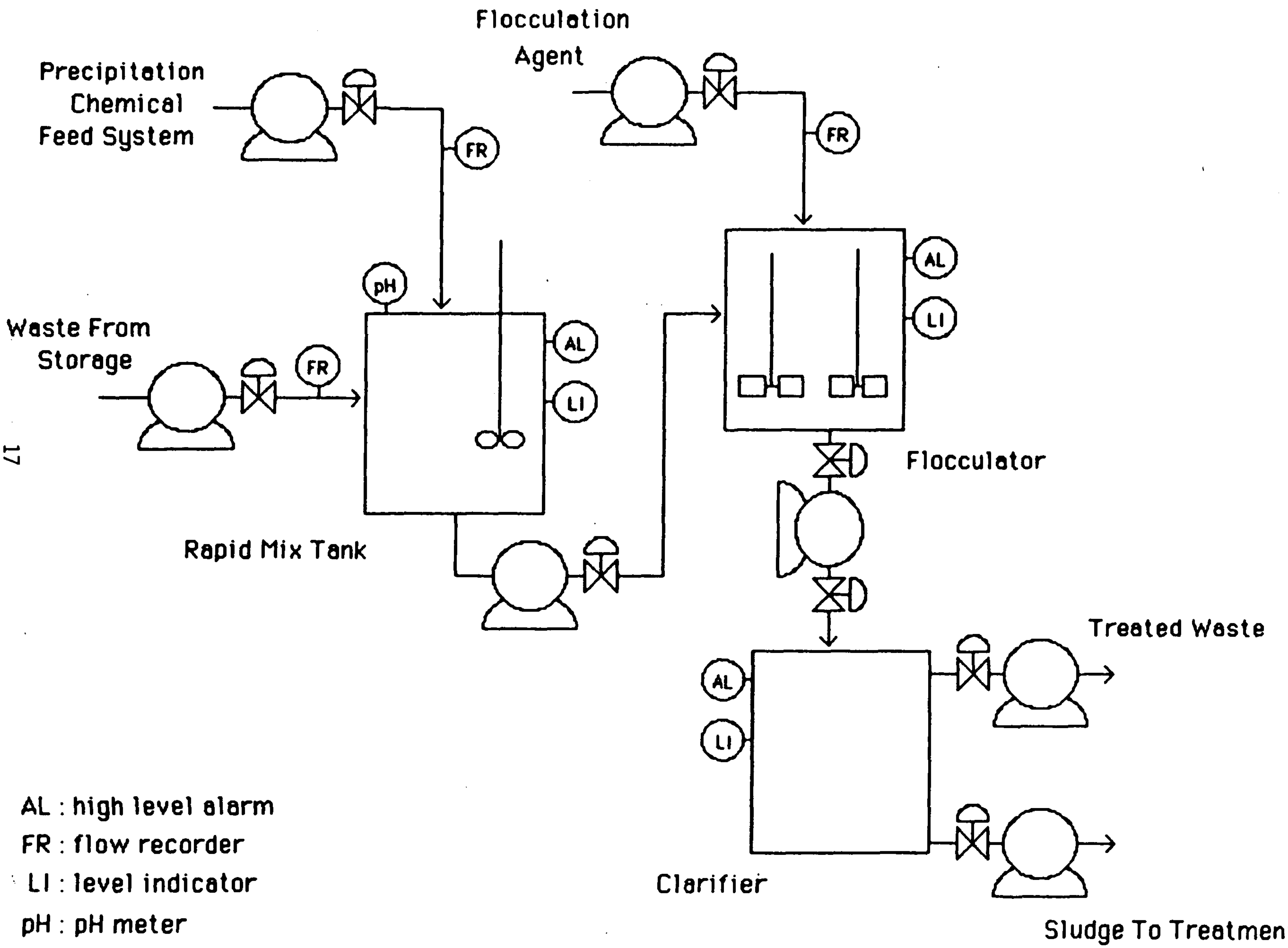
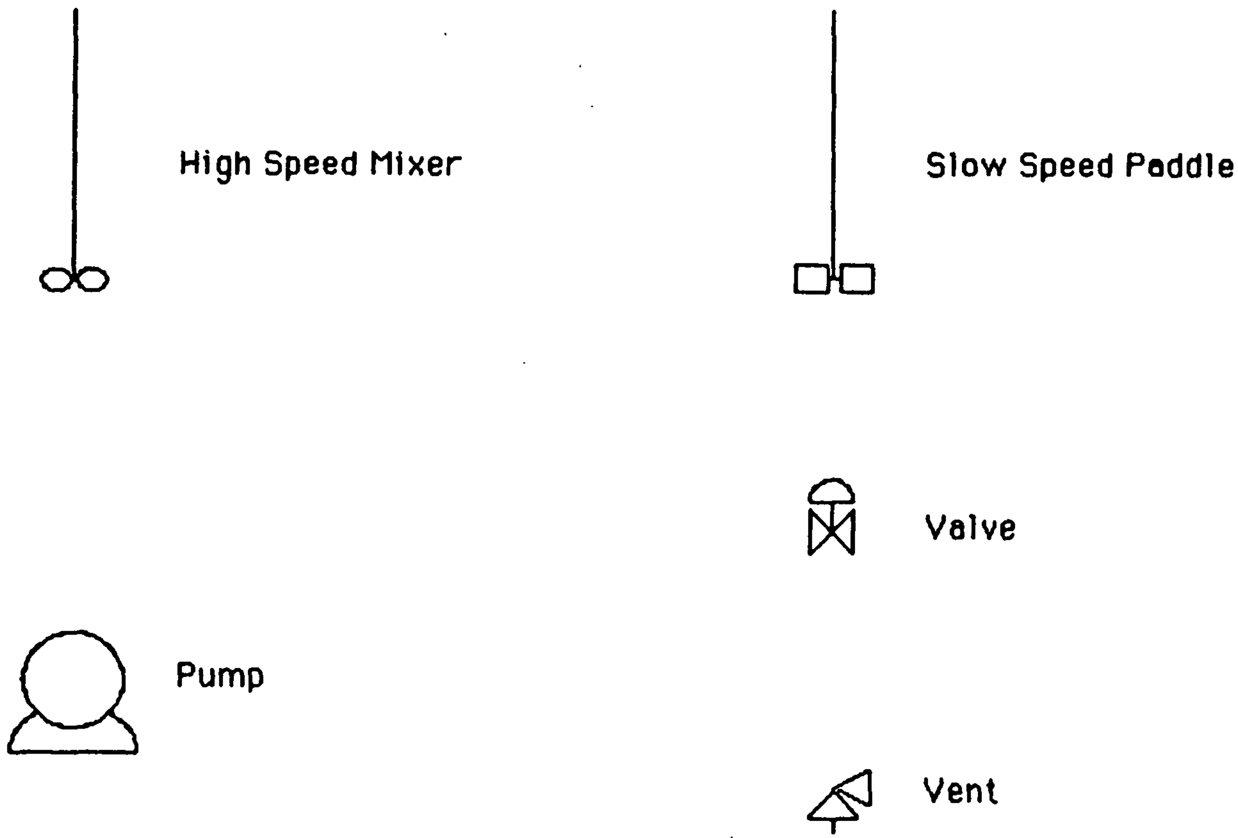


FIGURE 8. SYMBOL LEGEND



Storage and Accumulation Tanks

These tanks (Figure 1) are the simplest tank systems. EPA defines storage tanks as tanks that store wastes for greater than 90 days, while accumulation tanks are those that store wastes for less than 90 days. A storage tank may continuously contain some waste, but an accumulation tank must be completely emptied at least every 90 days.

Storage and accumulation tanks consist of three basic elements: a fill and discharge system (either using pumps or gravity-feed), piping, and the tank itself. The tank may be above-ground, in-ground, or below-ground and may vary in size and material of construction, (see Table 1). The pipes may be above-ground or below-ground, and the fill/discharge system may include such features as liquid-level indicators, high-level alarms, or automatic shut-off controls.

Treatment Tanks

Treatment tanks differ from storage and accumulation tanks by having additional equipment and by requiring more attention during process operations when chemicals are mixed or added. The six selected treatment processes are diagramed in Figures 2 through 7. The following discussions present brief explanations of each of these diagrams.

Cyanide Oxidation, Chrome Reduction, and Neutralization. These processes are diagramed in Figures 2 through 4, respectively. These treatment technologies can be discussed together because all three involve chemical processes designed to render the waste less hazardous. The flow diagrams are therefore similar, with each treatment process involving a two-stage tank system as well as the storage tanks generally used for both untreated and treated wastes.

The first of these processes, cyanide oxidation, involves the oxidation of free cyanide to carbon and nitrogen. (Destruction of free cyanide to cyanates is also possible; we did not model this process, however, because cyanates are still somewhat toxic and may in some cases require further treatment). Several oxidizing agents are possible, but in this model we assume chlorine is used. For this process, an alkaline environment (pH of at least 8.5) is required to prevent the formation of an extremely toxic gas, cyanogen chloride.

As is shown in Figure 2, the pH adjustment and the addition of chlorine occur as two distinct phases of treatment. In the first phase, the pH is adjusted to the desired level; in the second phase chlorine is added to the waste and allowed to react for 90 minutes. The treatment efficiency approaches 100 percent, but rather than specifying any given percentage, we have left this variable as an input parameter for the model.

In a cyanide oxidation facility, the first tank can be open or closed, but a vent and an overflow valve must be added if the tank is closed. A mixer blends the pH-adjusting chemical (generally sodium hydroxide) with the hazardous waste, and a pH meter monitors the results. Other tank accessories include a level indicator and a high-level alarm. The second tank is always closed because of the possibility of cyanogen chloride formation if the pH has been improperly controlled. Like the first tank, this tank has a vent, an overflow valve, a mixer, a level indicator, and a high-level alarm. An ORP (oxidation-reduction potential) meter is also used to determine when the chlorine has fully reacted with the cyanide.

Chrome reduction (Figure 5) is similar to cyanide oxidation. As with cyanide oxidation, the pH must first be adjusted, this time by adding sulfuric acid until the pH is between 2 and 3. The reduction of chromium (VI) to the less toxic chromium (III) is then carried out in the second tank by the addition of sodium metabisulfite. The resulting chromium (III) can later be precipitated out of the waste stream.

Both the pH adjustment tank and the reaction tank can be open or closed, and each has the same features as the equivalent cyanide oxidation tank, including mixers, level indicators, high-level alarms, a pH meter on tank 1, and an ORP meter on tank 2.

Neutralization alone is not regulated as a hazardous waste treatment technology. It is modeled in this study, however, because neutralization must be used to treat the highly acidic products of the chrome reduction process. Neutralization is therefore a necessary adjunct to this treatment process.

A neutralization process is a two-stage procedure for adding a dilute solution of an acid or a base to move the waste's acidity into the range of pH 6 to 8. Half of the necessary neutralizing agent is added in each stage of the process, and the mixture is allowed to react for thirty minutes. Both tanks in the neutralization process are equipped with mixers, pH meters, high-level alarms, level indicators, and overflow valves (if the tanks are closed).

Evaporation, Distillation, and Precipitation. We can also discuss distillation, evaporation, and precipitation together because these three treatment technologies all involve the concentration of the hazardous constituents for recovery or further treatment. The flow diagrams for these processes are presented in Figures 5 through 7.

Evaporation and distillation are very similar treatment methods. Both use a heat source to volatilize and separate a portion of the waste. In evaporation, the solvent (usually water) is evaporated, leaving the concentrated hazardous waste in the evaporator. In some cases the evaporator is an open, outdoor tank using solar energy to evaporate the solvent.

Distillation also involves volatilization, but in this process the volatilized fractions are the hazardous materials, which must therefore be collected for subsequent treatment or disposal. Sometimes, multiple distillations may be used to separate and recover the various hazardous constituents.

Precipitation is the most complex of the three "concentration" processes. In the first step of this process, sodium hydroxide is added to the waste to alter the pH to the level appropriate for the particular waste being treated. The waste is then vigorously agitated and passed to a flocculating tank, where a flocculating agent is added to agglomerate the solids. Slow mixing is used at this stage to assure adequate contacting without breaking up the flocs that have developed. From the flocculating tanks the waste flows into a clarifier. Here, the solids settle to the bottom and are removed as a sludge. The clarified liquid is the treated waste. Thus, precipitation involves three tanks, all of which are equipped with level indicators and high level alarms; the first two tanks also have mixers.

2.4 EPA's Proposed Hazardous Waste Tank Regulations

EPA has recently proposed revised regulations for hazardous waste tanks. These regulations would apply to existing tank facilities seeking permits, new tank facilities, and existing tanks operating under interim status. Slightly different requirements would apply to each of these types of facilities.

The proposed permitting standards for existing tanks include the following features:

- The tank system's structural integrity would have to be assessed by a qualified engineer.

- For metal tanks, this assessment would have to include a determination of the type and degree of corrosion protection needed to ensure the integrity of the system for its intended life. (This requirement would replace the minimum shell thickness requirements currently in force).

- The facility would be required to either install full secondary containment or implement a groundwater monitoring program.

- Facilities that elect to use a groundwater monitoring program instead of full secondary containment would still be required to install partial secondary containment for any above-ground portions of their systems. In addition, such facilities would also need to test the integrity of their underground components every six months.

- Facilities that have secondary containment would be required to maintain leak detection systems capable of detecting leaks within 24 hours.

- All tanks subject to the 90-day accumulation provisions of 40 C.F.R. §262.34 would be required to have full secondary containment.

The proposed permitting requirements for new tank systems address similar concerns, as do the proposed regulations applying to tanks under interim status. The primary differences between the regulations for new tanks and those for existing tanks are that new tank systems would have no alternative to the installation of secondary containment, would be required to install corrosion protection, and would be required to obtain expert certification of proper installation. Facilities with interim status would be required to meet requirements similar to those applicable to existing facilities seeking permits, except that interim status facilities would be given six months to implement the necessary changes.

In order to assure the effectiveness of these permitting standards, EPA proposes to revise the inspection regulations to require that structures or devices required under the new regulations, such as corrosion protection devices and leak detection systems, be periodically inspected. In addition, these revisions would require owners and operators to establish schedules for assessing the integrity of above-ground and in-ground tanks and to establish procedures for responding to leaks once they are detected.

As the preceding discussion indicates, the proposed regulations incorporate a number of technological features. These features include:

- partial secondary containment,
- full secondary containment,
- groundwater monitoring,
- corrosion protection,
- periodic visual inspections,
- leak testing, and
- leak detection.

The purpose of our Tank Failure Model is to evaluate the effectiveness of these options, either alone or in combination. Although it is possible to include all of these features in a single simulation model, the groundwater monitoring options have not been directly included in our model. Because groundwater monitoring does not affect tank failure probabilities or frequencies the Hazardous Waste Tank Failure Model does not simulate these scenarios. Instead, the Agency will examine how these regularory options influence riask using the Hazardous Waste Tank Risk Model.

2.5 Tank Failure Mechanisms

In addition to reviewing EPA's proposed tank regulations, we also reviewed the relevant technical literature for information on system and component reliabilities and failure modes. This review focused on the causes, consequences, and probabilities of failure, as well as on the magnitude of release once failure occurs.

Our literature search used the following sources and data bases:

- o PRA's in-house library;
- o University of Minnesota libraries;
- o COMPENDEX (computer search);
- o National Technical Information Service (computer search); and
- o Pollution Abstracts (computer search).

Based on both a manual search of more recent periodicals and the computer searches, we obtained, reviewed, and abstracted those articles that we deemed pertinent to this study. The Bibliography to this report lists these sources. The PRA report titled "The Analysis of Component Failures of Hazardous Waste Storage and Treatment Systems: Annotated Bibliography," (Draft, July 1984), contains the abstracts.

We also reviewed and abstracted case studies of particular failure incidents. In reviewing these case studies, we were primarily interested in determining the following:

- o a description of the incident;
- o the cause of the release;
- o the identity of the released materials;
- o the duration of the incident;
- o tank design and operating characteristics;
- o environmental conditions; and
- o the geologic characteristics of the subgrade materials.

Appendix C summarizes these case studies.

Using these case studies and our general literature review, we developed a classification of the various mechanisms that could cause tank system failures. We identified five general categories of failure mechanisms:

- o stresses due to the tank's external environment;
- o stresses arising from the tank's internal environment;
- o design flaws;
- o construction and installation errors; and
- o operation or maintenance errors.

Once we had identified these mechanisms, we used vendor information and engineering handbooks to determine the specific ways in which each mechanism could contribute to the failure of various tank components. The results of this analysis are presented in matrix form in Tables 4 through 6.

Table 4 tabulates the possible effects of external environmental stresses. The vertical axis lists the types of stresses which may occur, while the horizontal axis indicates which components are vulnerable to each type of stress. The table also identifies the process by which each of these external stresses may lead to component failure.

This table indicates that external environmental factors contributing to failure include temperature extremes, high winds, excessive rainfall, adverse soil conditions, earthquakes, poor air quality, power failures, and vandalism. These stresses may result in corrosion, rupture, spills, or overflows. The affected components may include tanks, pipes, pumps, valves, level indicators, or process control equipment such as automatic level controllers, overflow alarms, or emergency shut-off systems. Each type of external stress, however, does not affect all components. Thus, adverse soil characteristics only affect below-ground pipes or in- or below-ground tanks, and power failures only affect pumps, valves, level indicators and process control equipment. Some events, such as earthquakes, could affect any component. Since these events would affect the entire tank system simultaneously, however, the damage to the pipes and ancillary equipment would be unimportant compared to the damage to the tank itself. Therefore, for such catastrophic events, Table 4 only lists damage to the tank and ignores the incidental effects on other components.

Table 4. TANK SYSTEM FAILURE MATRIX: EXTERNAL ENVIRONMENTAL STRESSES

		AFFECTED COMPONENTS										
FACTORS CONTRIBUTING TO FAILURE	TYPE OF FAILURE	Above-ground tanks	In-ground tanks	Below-ground tanks	Pumps	Valves	Above-ground piping	Below-ground Piping	Welded Flanges	Gaskets	Level indicators	Process control equipment
power failure	overflow				*	*					*	*
temperature extremes	explosion; cracking	*	*	*								
high winds/storms	rupture; spills; over-turning	*	*									
humidity extremes	corrosion	*	*		*		*					
floods	overflow; overturning	*	*	*								
adverse soil characteristics	corrosion		*	*				*	*			
earthquakes	rupture; overturning; spills	*	*	*								
adverse air quality	corrosion	*	*		*		*					
vandalism/unauthorized entry	rupture; overflow; fire	*	*	*								
other catastrophic event	rupture	*	*	*								

* Signifies an effect upon the particular component or upon its operation.

Table 5. TANK SYSTEM FAILURE MATRIX: INTERNAL ENVIRONMENTAL STRESSES

		AFFECTED COMPONENTS										
FACTORS CONTRIBUTING TO FAILURE	TYPE OF FAILURE	Above-ground tanks	In-ground tanks	Below-ground tanks	Pumps	Valves	Above-ground piping	Below-ground Piping	Welded Flanges	Gaskets	Level indicators	Process Control Equipment
equipment aging	equipment failure or malfunction: corrosion; rupture	*	*	*	*	*	*	*	*	*	*	*
pH extremes	corrosion	*	*	*	*	*	*	*	*	*	*	
excess amounts of suspended solids	abrasion;				*	*	*	*	*	*		
ignition of waste	explosion, rupture, loss of system contents	*	*	*	*	*	*	*				
temperature extremes	corrosion	*	*	*	*	*	*	*	*	*		
pressure extremes	rupture or collapse	*	*	*	*	*	*	*				

* Signifies an effect upon the particular component or upon its operation.

Table 6. TANK SYSTEM FAILURE MATRIX: DESIGN, CONSTRUCTION, AND OPERATION ERRORS

FACTORS CONTRIBUTING TO FAILURE	TYPE OF FAILURE	AFFECTED COMPONENTS: Above-ground tanks	In-ground tanks	Below-ground tanks	Pumps	Valves	Above-ground piping	Below-ground Piping	Welded Flanges	Gaskets	Level indicators	Process Control Equipment
DESIGN												
poor material selection	collapse or rupture; corrosion	*	*	*	*		*	*	*	*		
poor component selection	accelerated component aging				*	*			*	*	*	*
inadequate structural support	overturning; collapse; rupture	*	*	*	*		*	*	*			
CONSTRUCTION/INSTALLATION												
damage during installation	cracks; scrapes; dents	*	*	*	*	*	*	*	*	*	*	*
improper materials used	corrosion; rupture or collapse	*	*	*	*	*	*	*		*		
improper component installed	accelerated component aging due to excessive stress				*	*					*	*
poor subgrade preparation	settling; cracking; rupture; corrosion	*	*	*			*	*	*			
OPERATION/MAINTENANCE												
operator fails to control process	overflow; internal environmental extremes; failure to detect on-going release	*	*	*								
operator deliberately ignores safety or control measures	overflow; internal environmental extremes; failure to detect on-going release	*	*	*								
improper cleaning, inspection, observation, record-keeping, or replacement	equipment malfunction/failure; failure to detect on-going release	*	*	*	*	*	*	*	*	*	*	*

* Signifies an effect upon the particular component or upon its operation.

Table 5 itemizes internal environmental stresses, including extremes of temperature, pressure, and pH, and variations in the amount of suspended solids. We have also included equipment aging in this category. These internal factors may result in accelerated corrosion, equipment overload, overflows, or equipment malfunctions. The specific components affected by each factor are identified in the table.

Two of these factors, temperature extremes and pressure extremes, are important stresses for many classes of industrial tanks, but are not particularly important for hazardous waste tanks because these tanks are seldom operated at high temperatures or pressures. For completeness, we have included these factors in Table 5, but we will not give them special status in our model.

Table 6 examines design, construction, and operation errors. Such errors include poor material selection, use of improper components, inadequate structural support, improper process design, installation damage, use of improper materials or components, operator error, or improper maintenance. These errors may cause structural collapse, rupture, accelerated corrosion, equipment malfunction, inadequate capacity, improper process control, or failure to detect on-going releases. The specific components vulnerable to each of these failures are identified in the table.

3.0 FAULT TREES

3.1 Introduction to Fault Tree Analysis

Fault tree analysis is a common engineering tool for evaluating the reliability of complex systems. The first step in such an analysis is to identify the "top" or "ultimate" failure event to be modeled. In the present study, the ultimate failure event is the release of hazardous materials from the tank system. To construct our fault trees, we then identified all of the relevant intermediate failure events which might lead to such a failure. We then traced these events back to their antecedents, continuing the analysis until no further reduction was possible or no data were available. The resulting chains of causation are the heart of our fault trees.

In many cases, we found it useful to simplify the fault trees by combining similar events and by eliminating very low-probability events or events whose occurrence may always be assumed. Examples of these last two types of events are the probability of a meteor strike or the presence of oxygen to support an outdoor fire, respectively. In general, we have pruned events with probabilities less than 10^{-5}, though in a few cases we have retained them in order to show that they were indeed considered.

Fault trees are generally depicted by a standardized set of schematic symbols which represent the linkages between the basic, intermediate, and top events. There are two principal types of fault tree symbols: event symbols and logic gates. Event symbols are used to distinguish various types of events, as well as to illustrate the connections among the different portions of a large fault tree. The event symbols which will be used in this report are illustrated in Figure 9.

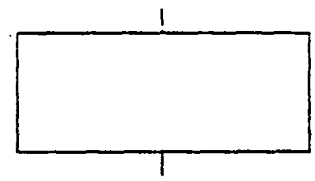
Logic gates are used to link higher fault tree events to their precursors, and ultimately to basic events for which probability data are available. A fault tree may have many levels, but consecutive levels must be linked through one of two basic types of gates: .AND. gates and.OR. gates. Symbols for these gates are illustrated in Figure 10.

.AND and .OR. gates may have several inputs, but can only have one output. The output event will occur only if the appropriate combination of input

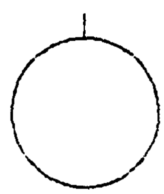
FIGURE 9. FAULT TREE EVENT SYMBOLS

Event representations:

The rectangle identifies an event that results from the combination of events through the input of a logic gate.

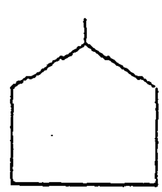


The circle represents a basic event that requires no further development.



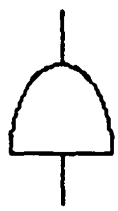
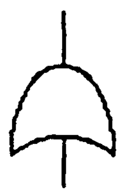
Triangles are used as transfer symbols. A line from the top of the triangle indicates a transfer in, and a line from the side a transfer out.

The house is used as a switch to include or eliminate parts of the fault tree that may or may not apply to certain situations.



(Henley and Kumamoto, 1981)

FIGURE 10. FAULT TREE LOGIC GATES

Gate Symbol	Gate Name	Causal Relation
	AND gate	Output event occurs if all input events occur simultaneously.
	OR gate	Output event occurs if any one of the input events occur.

(Henley and Kumamoto, 1981)

events occurs. Thus, the output event from an .AND. gate only occurs when all of the input events occur simultaneously, while the output event from an .OR. gate occurs whenever any of the input events takes place.

3.2 Selection of Fault Tree Events

We derived the basic fault tree events by reorganizing the failure mechanisms identified in Section 2.5. Some of these basic events represent combinations of the failure mechanisms listed in Tables 4-6; others are elaborations of events that those tables include as single entries. For example, the fault trees combine all causes of corrosion into two events (internal corrosion and external corrosion) but they delineate several distinct forms of operator error in addition to the broad categories listed in Table 6. In all cases, we have included as much detail in the model as is warranted by the available data. A listing of the changes that we have made is presented in Table 7.

3.3 Hazardous Waste Tank Fault Trees

The hazardous waste tank fault trees are presented in Figures 11 through 16, using the standard symbols discussed in Section 3.1 of this report. In these figures, we have assigned all of the basic events coded names, such as "MOPMOE" or "B13." Because we used some of the same labels in the computer programs, we were required to restrict their lengths to a limited number of characters. Since these labels are sometimes cryptic, the fault trees also include brief translations. Further explanation of these basic events (including derivations of their probability distributions) are presented in Appendix A; the more important events (such as tank corrosion and pipe corrosion) will be discussed more thoroughly in Chapter 4.

We have designed the fault trees to be as general as possible, so that a single set of trees can be used for all possible tank configurations. This means that the trees contain component systems that are not present in all configurations. Our computer model is designed so that these optional branches can be switched on or off depending on the requirements of the tank system being modeled. For optional branches connected to .AND. gates, this is done by treating the absent component as though it is in a

TABLE 7. REORGANIZATION OF FAILURE MECHANISMS FOR USE IN FAULT TREES

We included the following failures in our baseline probabilities for tank or pipe ruptures or flange leaks.

- Poor material selection
- Poor component selection
- Inadequate structural support
- Poor subgrade preparation
- Improper materials installed
- Miscellaneous external catastrophes (vehicle collision, airplane crash, etc.)

We included variations in the following factors in our baseline corrosion model:

- Internal temperature
- External temperature
- Humidity
- Air quality

We included the following factors in our baseline estimates of ancillary equipment failure rates:

- Power failure
- Equipment aging
- Poor component selection
- Damage during installation
- Improper component installed
- Poor maintenance

We pruned the following factor as extremely low-probability:

- Pump Rupture

We have made the following elaborations on the failure mechanisms listed in Tables 4-6.

- We have divided operator errors into errors of commission and errors of omission.
- We have divided process control equipment into several categories, including automatic shut-down systems, level controllers, and high level alarms.

FIGURE 11. HAZARDOUS WASTE TANKS: BASIC FAULT TREE

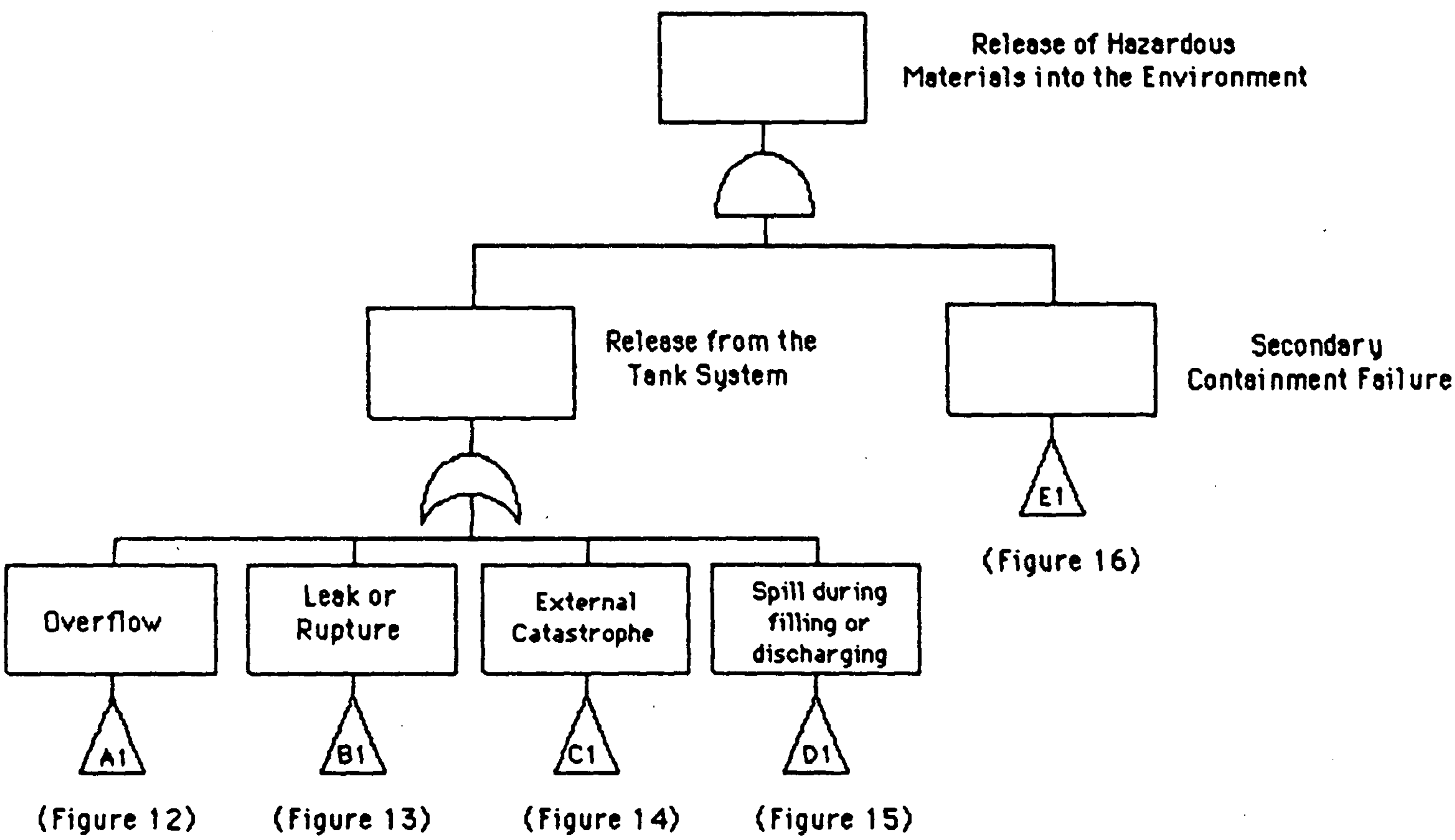


FIGURE 12A. OVERFLOWS

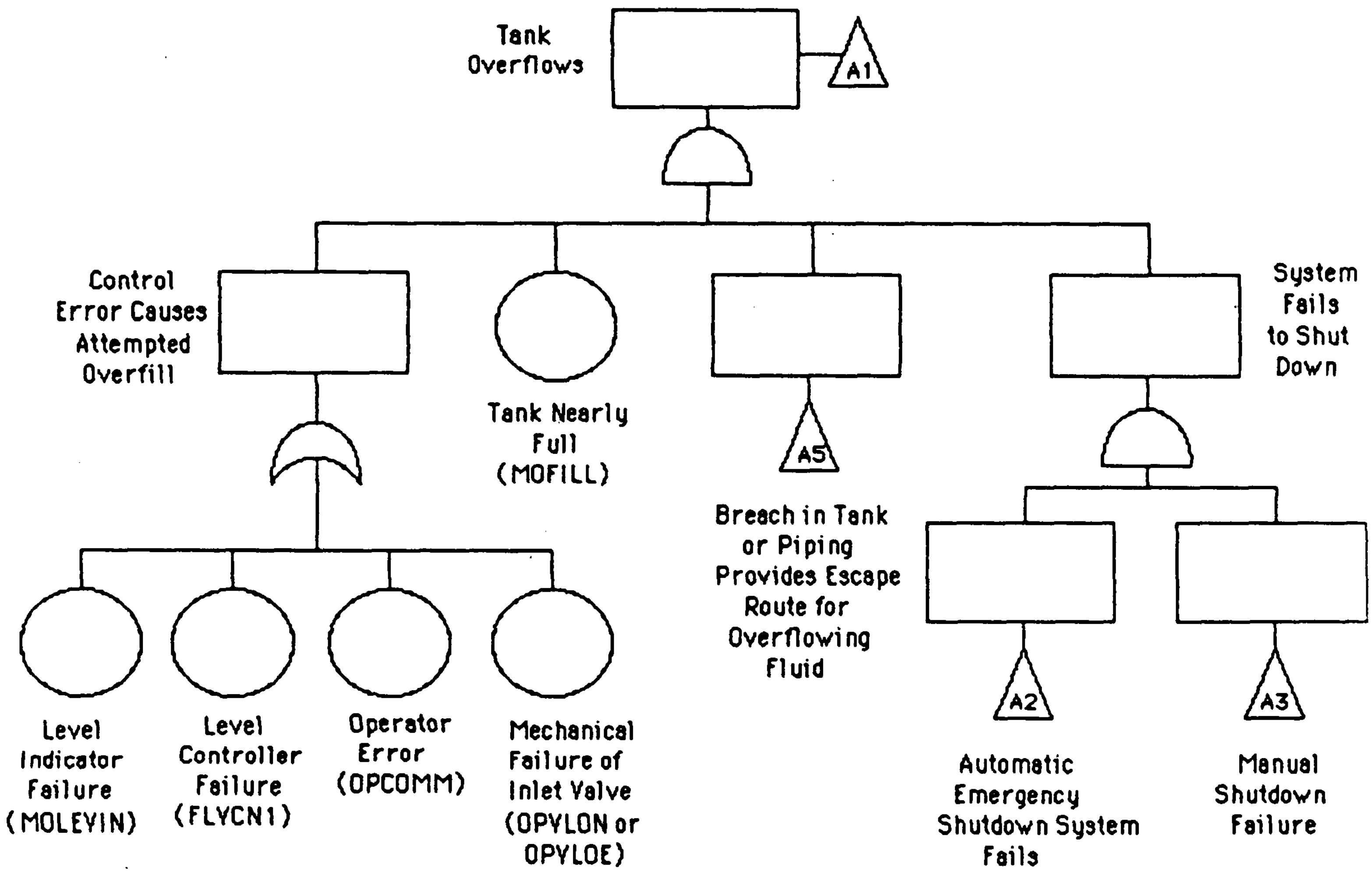


FIGURE 12B. OVERFLOWS (cont.)

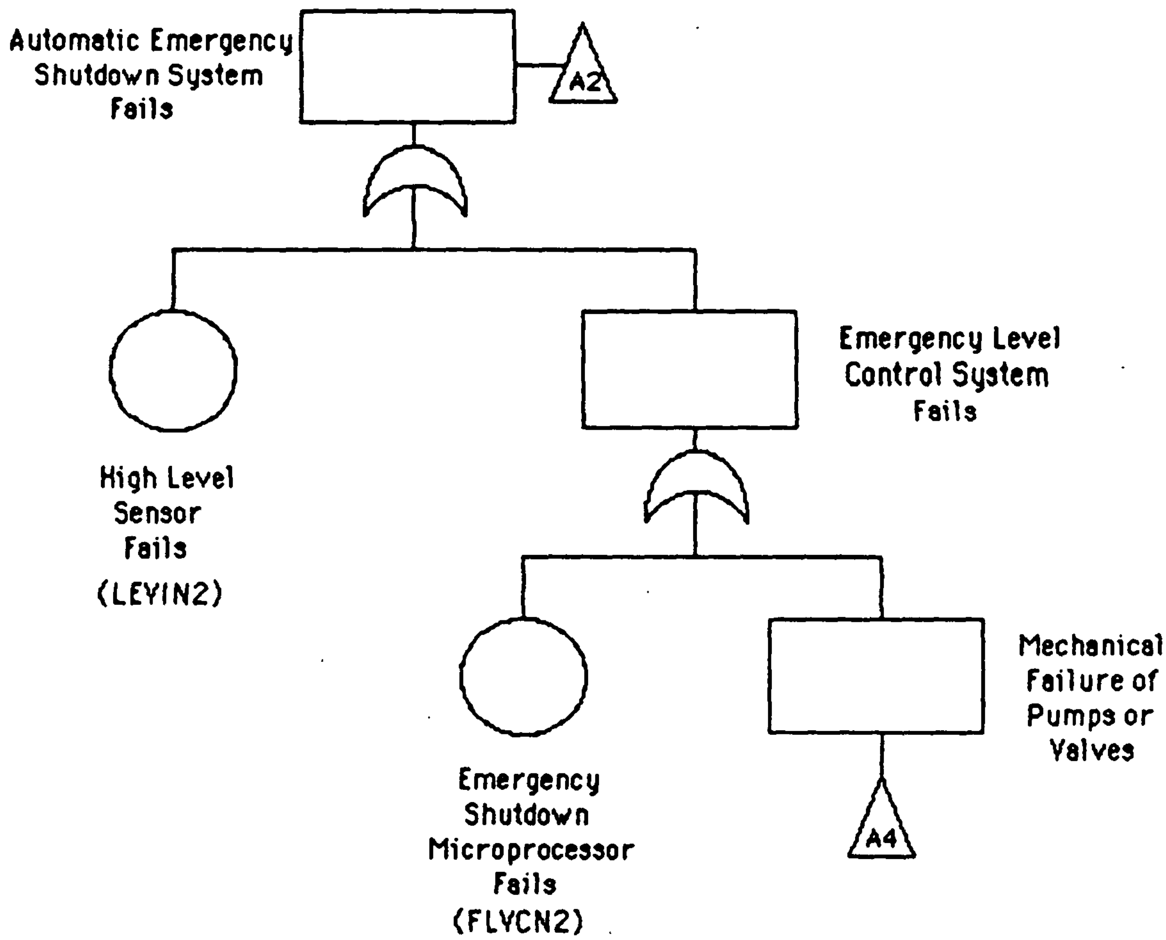


FIGURE 12C. OVERFLOWS (cont.)

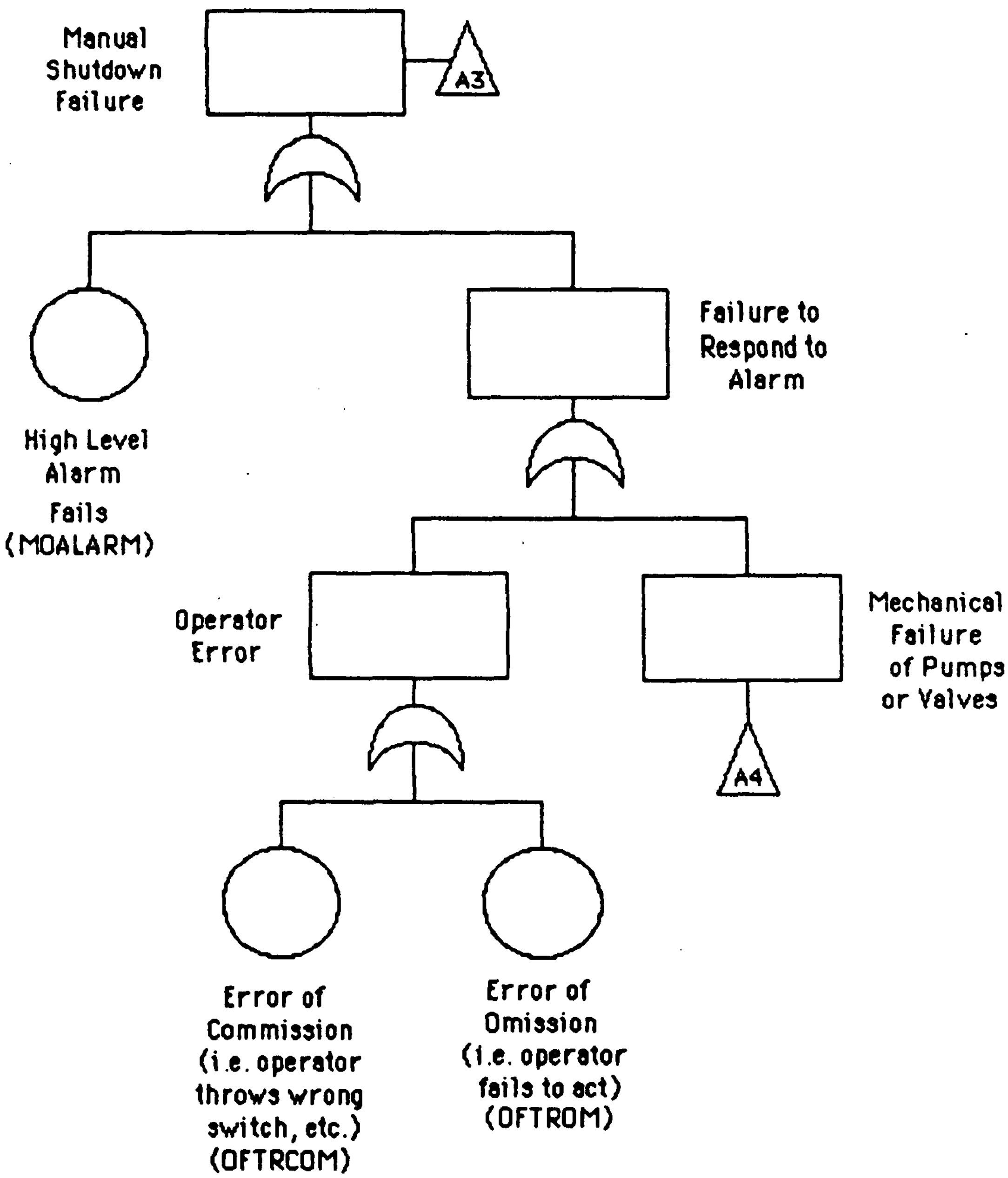


FIGURE 12D. OVERFLOWS (cont.)

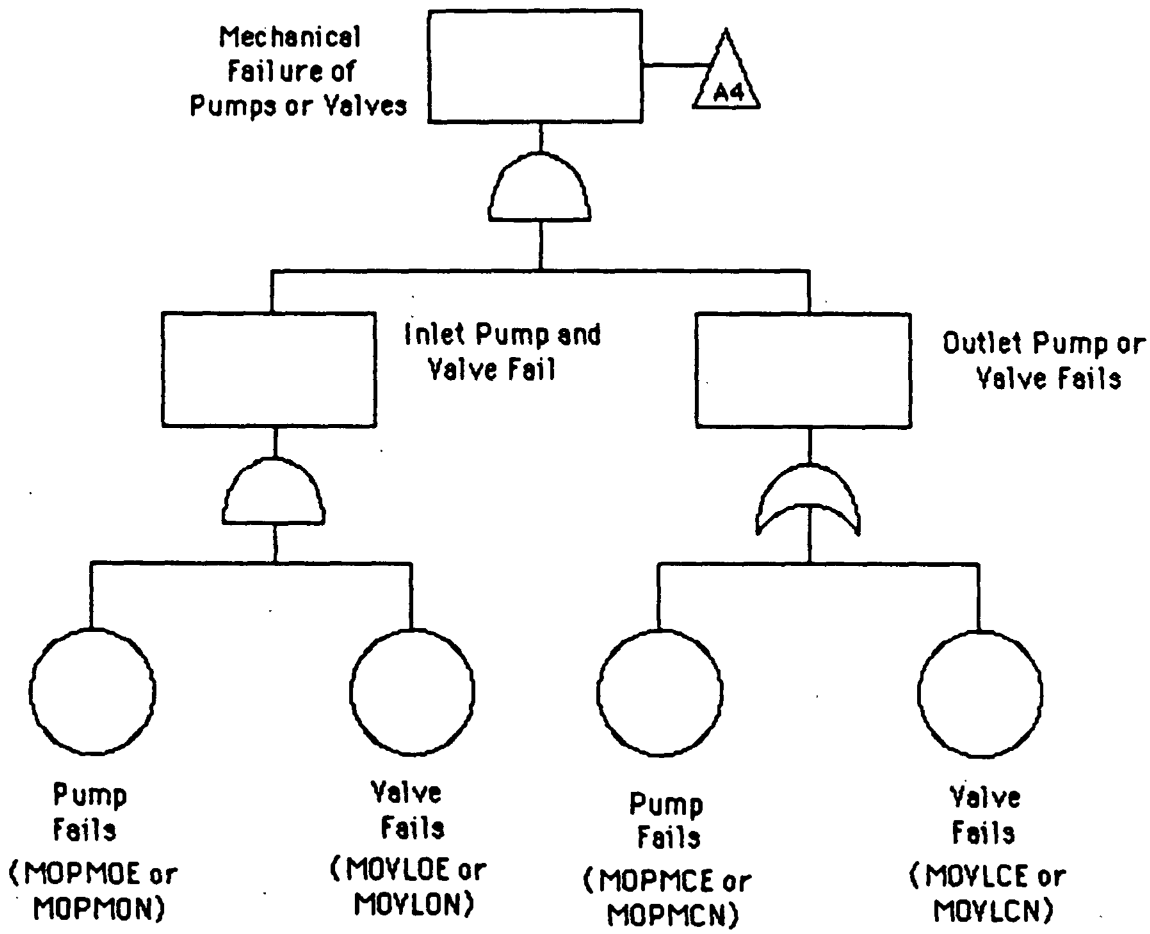


FIGURE 12E. OVERFLOWS (cont.)

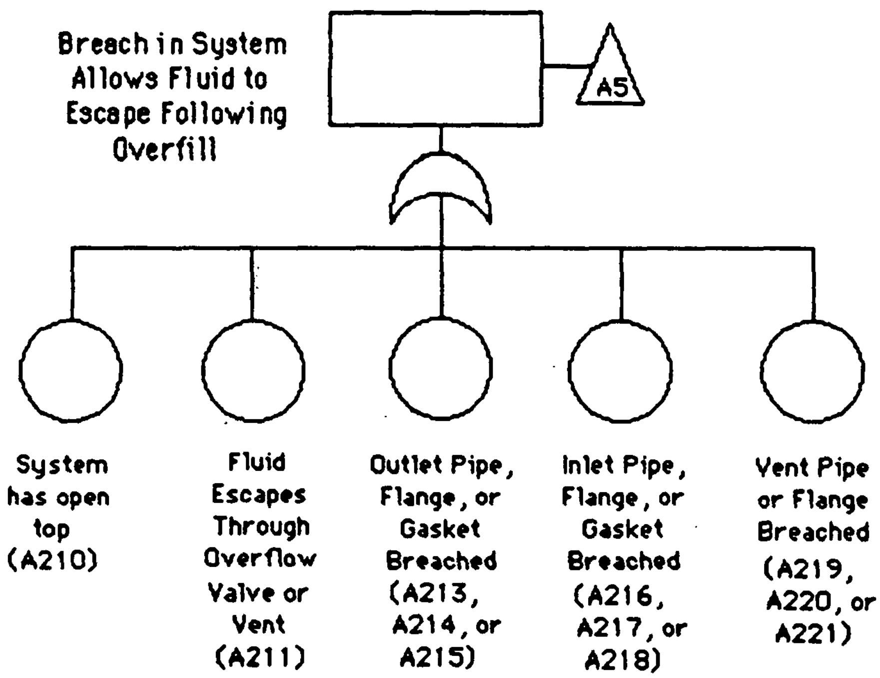


FIGURE 13A. LEAKS AND RUPTURES

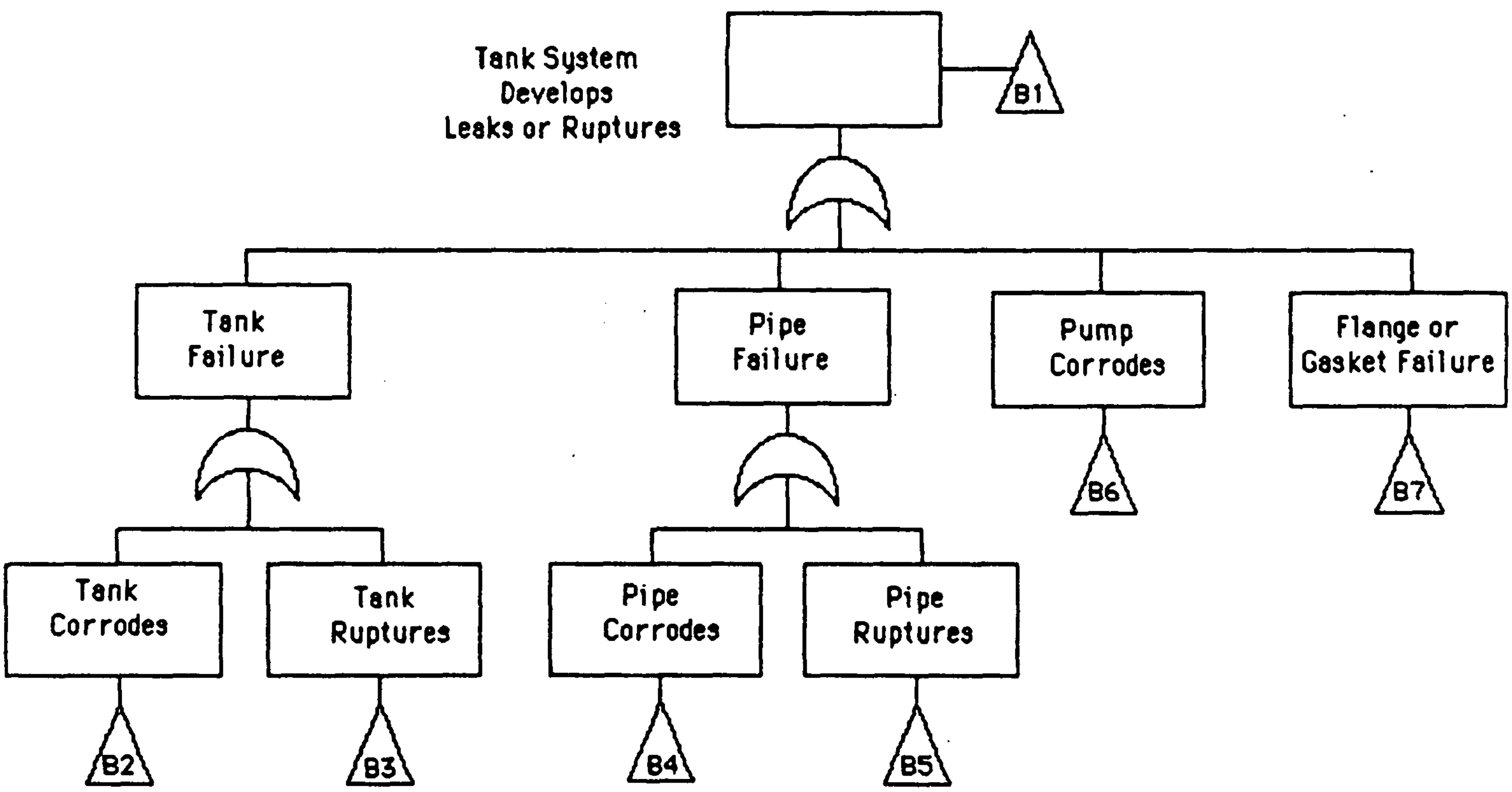
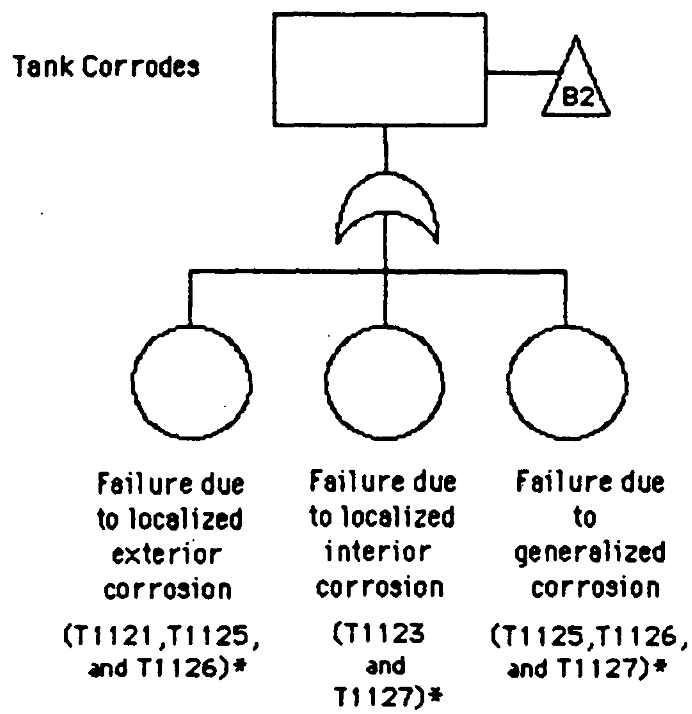


FIGURE 13B. LEAKS AND RUPTURES (cont.)



*These event labels describe different aspects of the tank corrosion model. They are explained in Appendix A.

FIGURE 13C. LEAKS AND RUPTURES (cont.)

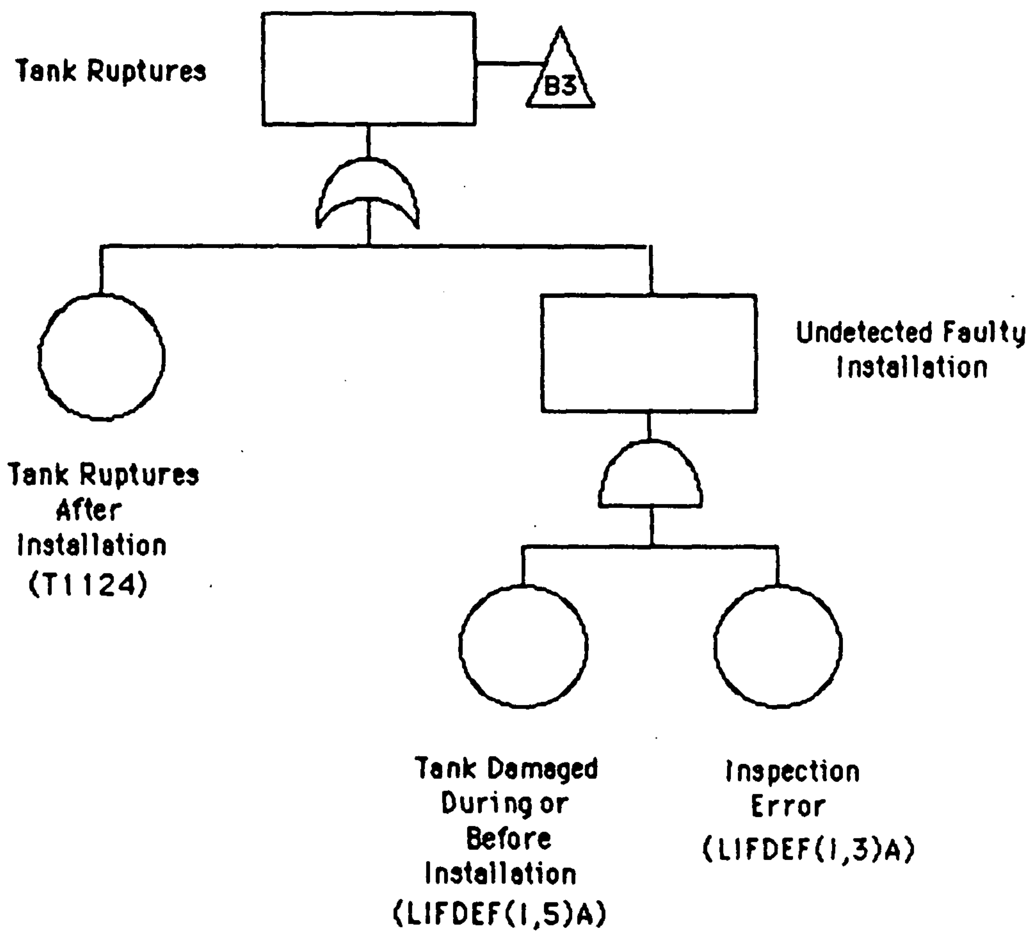
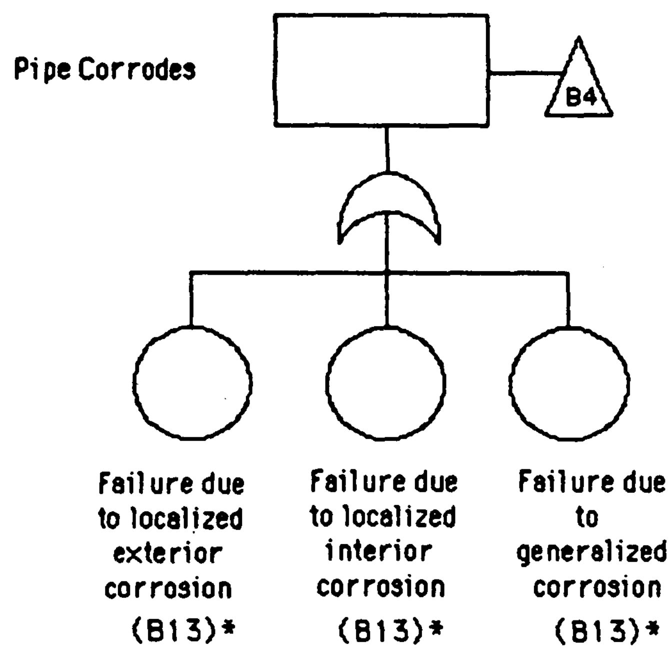


FIGURE 13D. LEAKS AND RUPTURES (cont.)



* All forms of pipe corrosion are included in Appendix A under this one label.

FIGURE 13E. LEAKS AND RUPTURES (cont.)

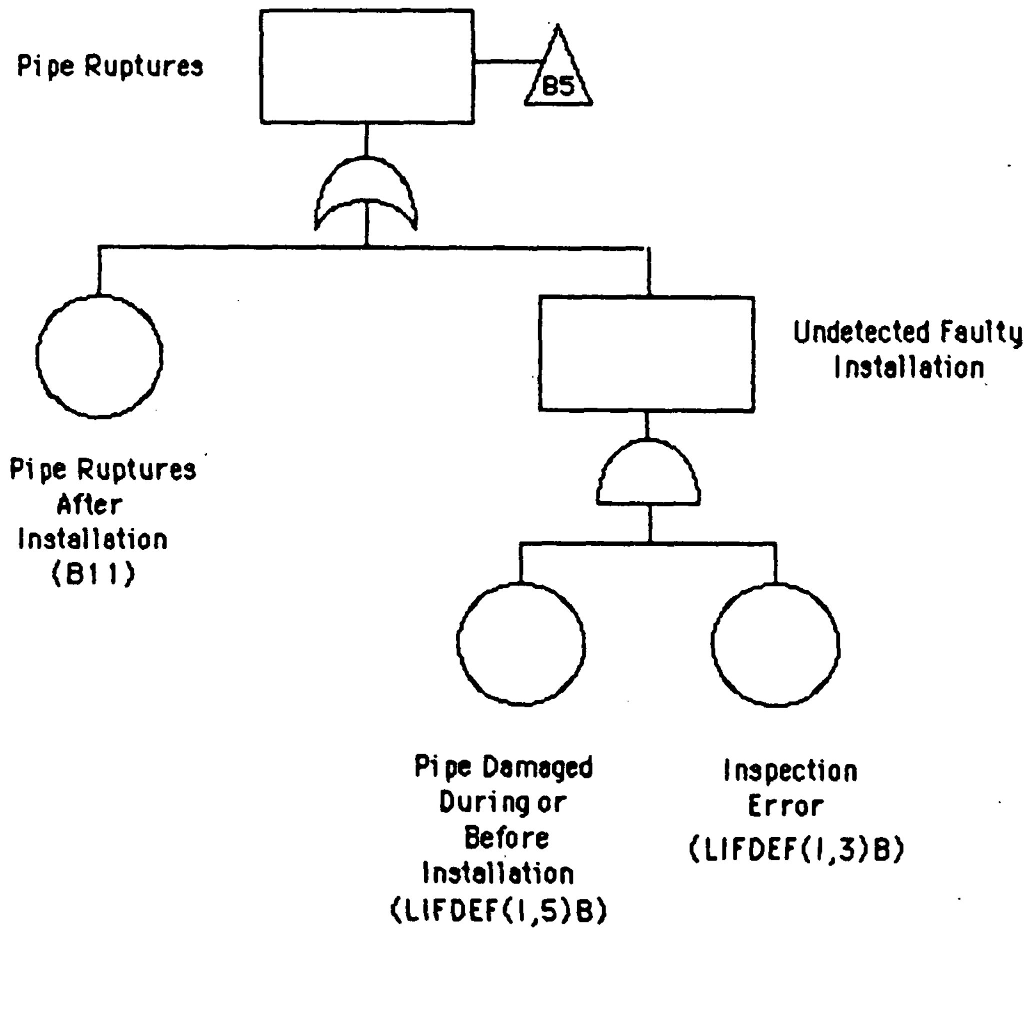
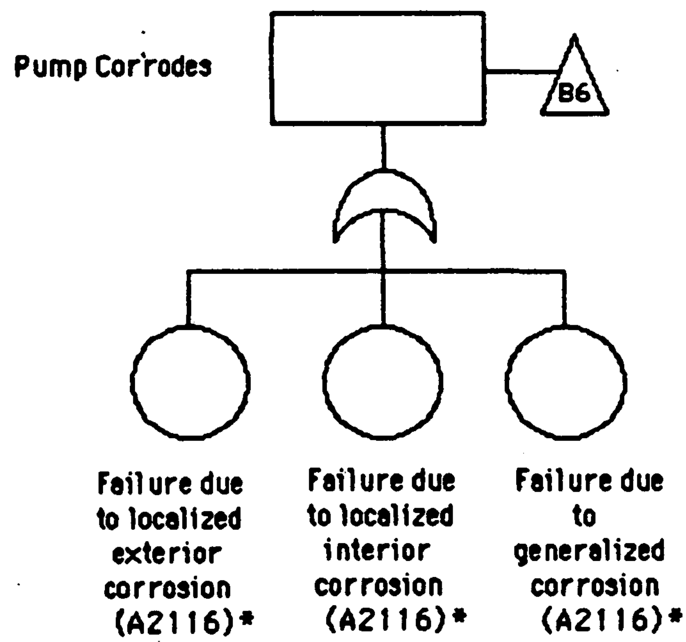


FIGURE 13F. LEAKS AND RUPTURES (cont.)



* All forms of pump corrosion are included in Appendix A under this one label.

FIGURE 13G. LEAKS AND RUPTURES (cont.)

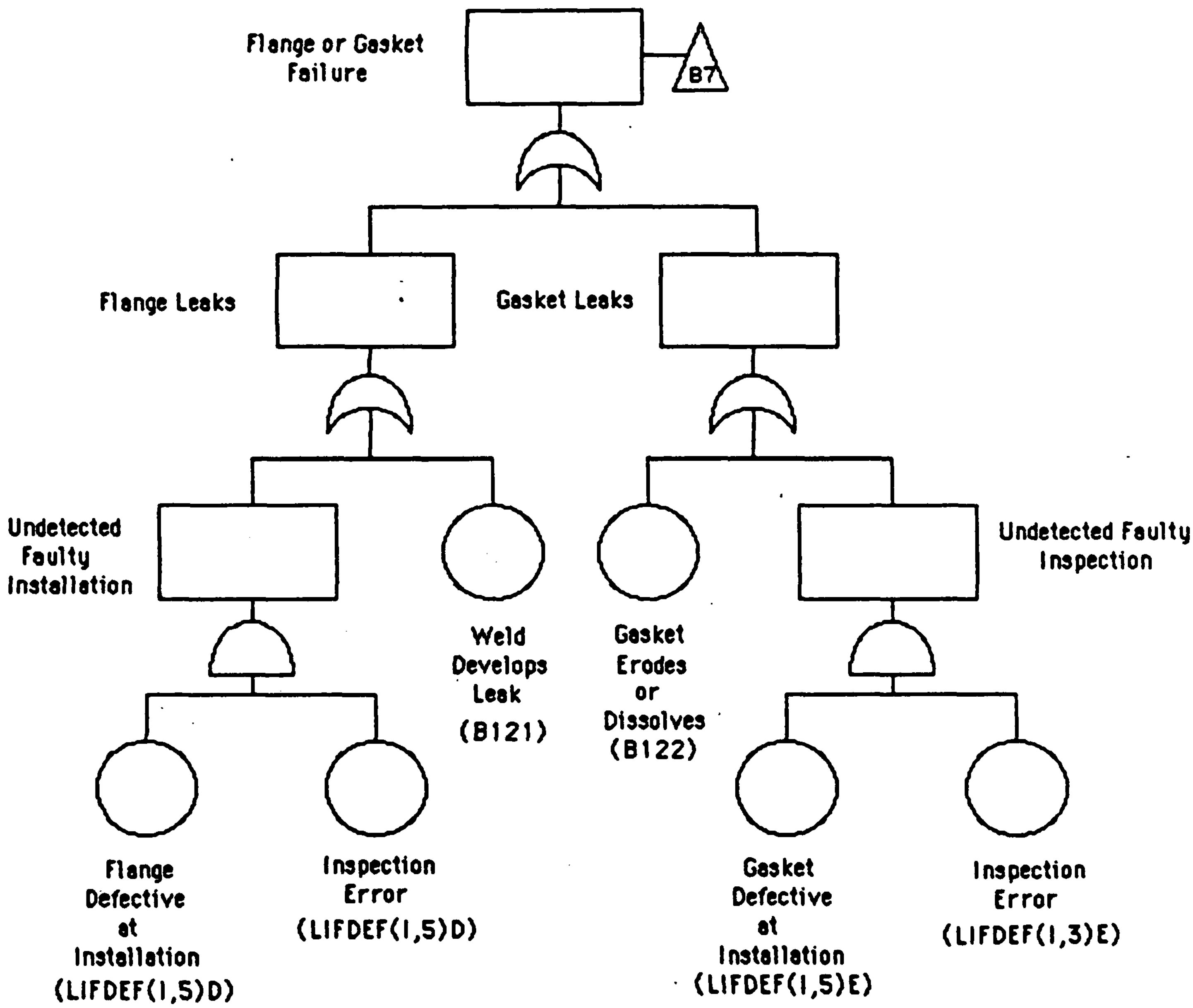


FIGURE 14. LOSS OF SYSTEM CONTENTS DUE TO EXTERNAL CATASTROPHE

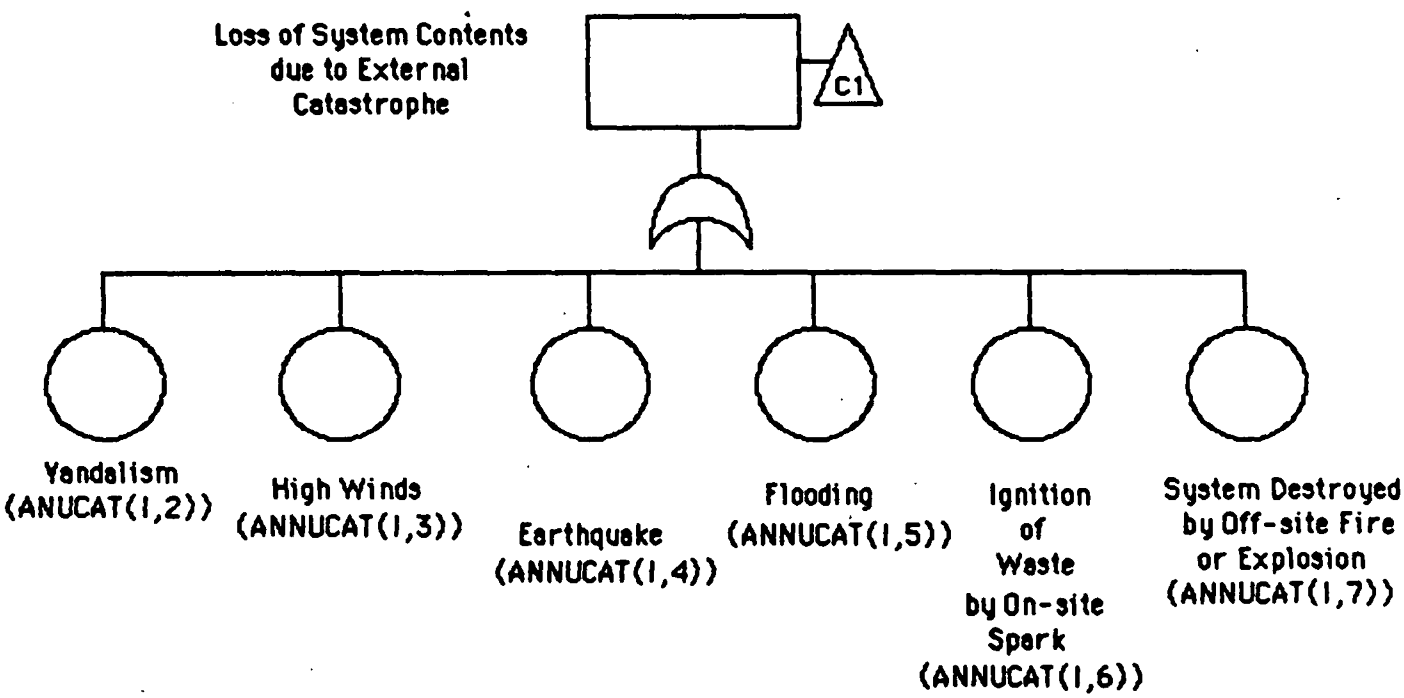


FIGURE 15. SPILL DURING FILLING OR DISCHARGING

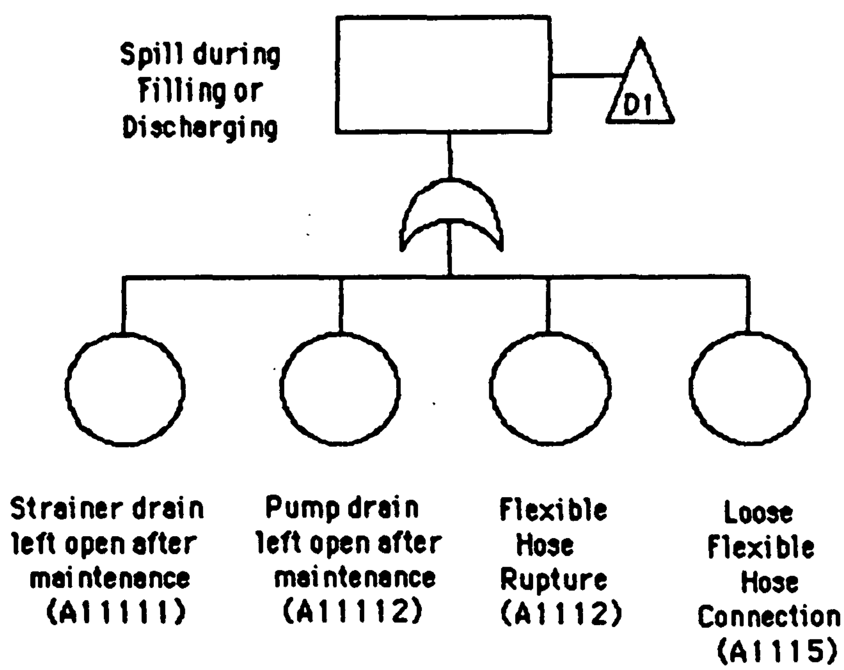
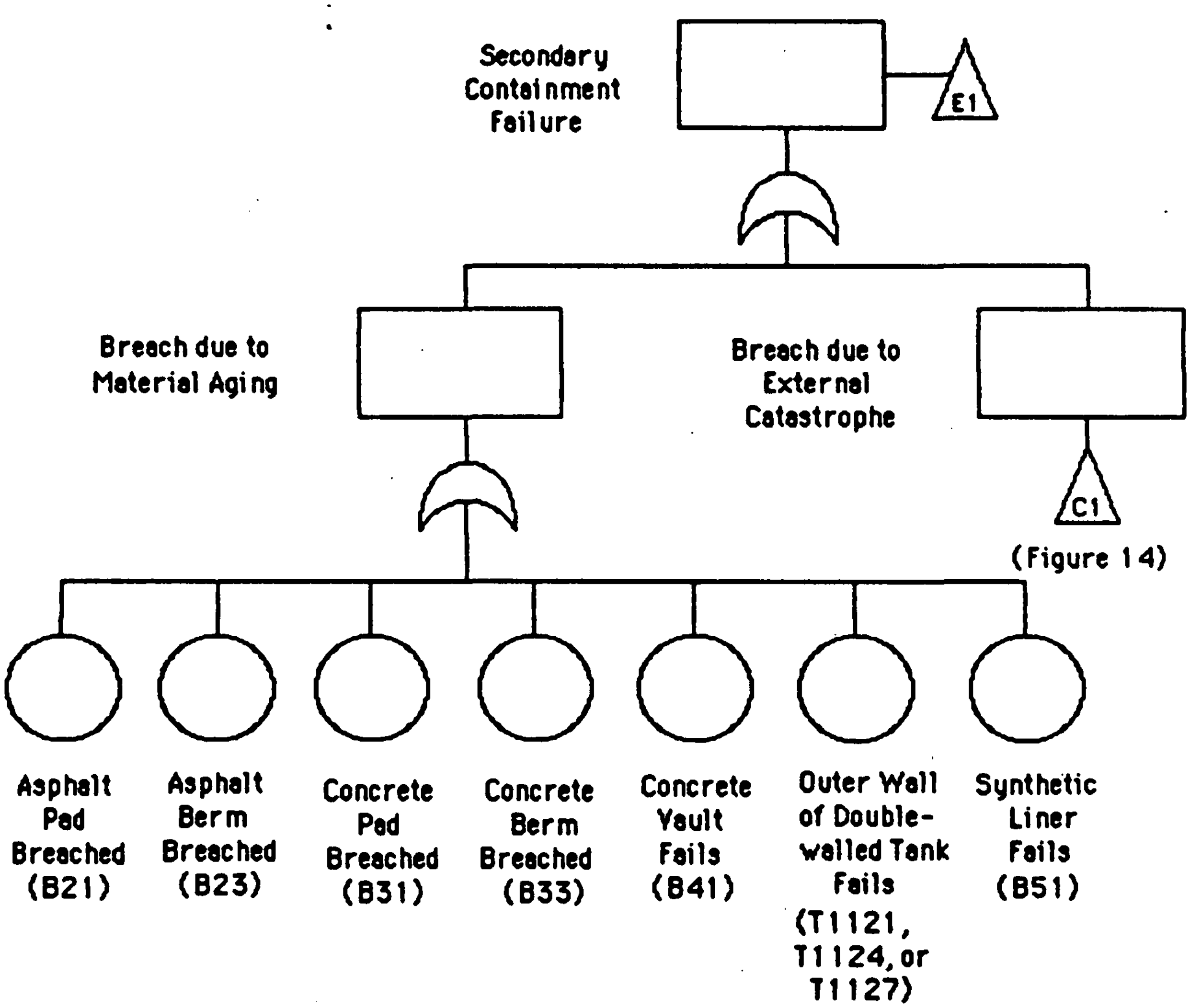


FIGURE 16. SECONDARY CONTAINMENT FAILURE



failed state. Since the .AND. gate will not allow failure unless all of its branches occur simultaneously, there is no difference between eliminating an absent event or treating it as though it has occurred; in either case the .AND. gate will register failure if and only if all of the remaining events occur simultaneously. On the other hand, absent fault tree branches connected to .OR. gates must be treated as though they have not occurred, for otherwise their absence would inevitably cause the .OR. gate to register failure, a result which would not occur unless the component system under consideration were not truly optional.

A couple of simple examples may help to clarify this process. In order to prevent overflows, tank systems generally have emergency shut-down systems. These may be manual or automatic, or both systems might be present at once. Obviously, there will be no emergency shut-down failures unless all existing shut-down systems fail. Thus, the fault tree connects the manual and automatic systems by an .AND. gate. If the automatic system is absent, however, failure will occur whenever the manual system fails. Treating the absent automatic system as though it has already failed will ensure this result. Similarly, if the facility were to rely solely on an automated system, emergency shut-down failure would occur whenever the automatic system failed. This would be the case if the missing manual back-up system were treated as though it were always in a failed state.

As an example of the opposite case, consider the possibility of natural catastrophe. Such catastrophes could result from floods, earthquakes, hurricanes, or tornadoes, so these events are all connected by an .OR. gate. All of these catastrophes, however, are not possible in every geographic location. Thus, if the tank system is not located in a flood-prone region, the flooding event should be deemed not to have occurred, and a natural catastrophe will only result if one of the other events takes place. A similar analysis applies to other failure events connected by .OR. gates.

With this background, it is now possible to turn to a more detailed analysis of the individual fault trees.

The basic tank failure fault tree is presented in Figure 11. This fault tree contains the overall top event (release of hazardous wastes to the environment) and identifies the general mechanism by which it might occur. As is indicated by this figure, uncontained releases may only occur if two intermediate events occur simultaneously: a failure of the tank system itself, and the failure (or absence) of secondary containment. Tank releases are described in Figures 12 through 15; secondary containment failures are described in Figure 16.

Tank System Failures

Tank system failures may be grouped into four categories: overflows, leaks and ruptures, external catastrophies, and spills during filling or discharge operations.

Overflows. The overflow fault trees are presented in Figures 12A through 12E. As the tank overflow fault tree (Figure 12A) shows, four events must occur before an overflow can result: the tank must be close enough to full that an overflow is possible; there must be a control error resulting in an attempt to add too much fluid to the tank; there must be a failure of the emergency shut-down system; and there must be a route by which overflowing fluid may escape from the tank.

All four of these events must occur before any tank system can overflow, but the manner in which they may arise varies with the sophistication of the tank's control system, the sophistication of its emergency shut-off system, and the manner in which it is filled and discharged. We have therefore modeled two types of control systems (automatic and manual), three types of emergency shut-off systems (automatic, manual, and automatic with manual back-up), and two general types of fill/discharge processes (discrete batches and continuous throughput). The fault trees, which apply equally well to storage or treatment tanks, allow us to model any combination of these designs, but in practice only certain designs are likely. Table 8 presents a complete list of the level control, emergency shut-off, and fill/discharge systems which we consider to be likely. As this table indicates, we have assumed that tanks with automatic level controls also have automatic emergency shut-off controls, and that facilities with automatic emergency shut-off generally maintain manual shut-off controls as back-ups. In addition, we have assumed that continuous treatment tanks use automatic controls, while batch treatment tanks use manual controls. We

TABLE 8. FILL/DISCHARGE, LEVEL CONTROL, AND EMERGENCY SHUT-OFF SYSTEMS

Type of Tank	Fill/Discharge Process	Level Control System	Emergency Shut-Off System
STORAGE			
	Batch	Manual	Manual
	Continuous	Manual	Manual
	Continuous	Automatic	Automatic (manual back up)
TREATMENT			
	Batch	Manual	Manual
	Automatic	Automatic	Automatic (manual back-up)

have generally assumed that storage tanks are batch systems with manual controls, but we have also modeled continuous storage tanks. We have assumed that such facilities are used as settling tanks and only rely on manual controls if they maintain such a large freeboard that careful level monitoring is unnecessary.

The first requirement for any of these tank systems to overflow is that the tank be close enough to being full that an overflow is even possible; a half-empty 10,000 gallon tank, for example, cannot be overflowed by the addition of a 1,000-gallon batch. How often a potential overflow situation arises is therefore a function of the system design and operating policy. Our assumptions for the various types of tanks are listed in Table 9. In general, we have assumed that potential overflow situations occur constantly for continuous treatment processes (because fluid is regularly added when the tank is already filled to its normal operating depth), once per batch for batch treatment processes (because the operator is adding fluid from a storage tank which we assume to have larger capacity than the treatment tank itself), and infrequently (once per year) for storage tanks (because storage tanks are generally filled in comparatively small batches and pumped-out before they get dangerously full; we make the conservative assumption that once per year there is a fluctuation in waste-generation rates or a failure to follow the pump-out schedule, thereby allowing the tank to become full). Continuous storage tanks (settling tanks) are modeled on a case-by-case basis by comparing their daily throughputs to their normal reserve capacities.

Even if the tank is full, there must also be a control error before an overflow can result. Such an error would occur if a malfunction in a level indicator causes too much fluid to be added to the tank (either in automatic or manual systems), if an automatic level controller fails, if the operator of a continuous system makes an error in the morning start-up routine, if the operator of a manual system ignores the liquid level indicator and adds too much fluid, or if an automatic inlet valve sticks in the open position.

These control errors, however, will not result in an overfill unless the emergency shut-down system fails. The most sophisticated emergency shut-

TABLE 9. FREQUENCY OF FILLING A NEARLY-FULL TANK FOR VARIOUS TANK SYSTEMS

Type of Tank System	Frequency of Filling a Nearly Full Tank
TREATMENT TANKS	
Continuous	100% of operating day
Batch	Once per batch
STORAGE TANKS AND ACCUMULATION TANKS	Once per year

down systems (depicted in Figure 12B and 12D), consist of a high level sensor connected to a microprocessor which automatically shuts down the inlet pump and valve. If the inlet system fails to shut down, the microprocessor instead adjusts the outlet pump and valve to increase the rate of out-flow.

All of these components are subject to failure. Mechanical failure of the pumps and valves, however, will only be critical if both the inlet and outlet pump systems fail; proper operation of either of these systems will prevent the accumulation of excess fluid in the tank. In addition, emergency shut-off will still occur unless both the inlet pump and the inlet valve fail to shut down. If either of these components functions properly, it will cut off the flow of fluid, thereby preventing the overflow. For the outlet pump system, however, the pump is more important than the valve; in continuous processes the valve is always at least partially open, so we have assumed that a change in pumping rate will be effective even if the valve sticks.

Automatic emergency shut-off controls are most likely to be found on continuous treatment tanks (see Table 8), but in order to make the fault trees as general as possible, we have also modeled automatic shut-off systems for batch processes. The only difference between automatic shut-off systems for batch and continuous tanks lies in the outlet pump system. In batch systems, the outlet valve will always be closed while the tank is being filled, so it must be opened before the outlet system can be used to pump out excess fluid. The outlet system will therefore fail if either the pump fails to start or the valve fails to open.

Storage and accumulation tanks are also unlikely to have automatic emergency shut-off systems, but for completeness, we have also included such systems in the model. Since these systems are generally emptied by a pump-out truck, there is no on-site outlet pump, and the emergency shut-off system would only be connected to the inlet pump and valve. A failure of either of these components would therefore result in an emergency shut-off failure.

Emergency shut-off systems for manual treatment and storage tanks are depicted in Figure 12C. In these systems, an overfill will trigger a high-level alarm, thereby summoning the operator, who will then manually shut off the appropriate pumps and valves. Such a manual shut-off system is vulnerable to three types of failure: mechanical failure of the high-level alarm, operator error, or mechanical failure of the pumps or valves. Operator error may result from either a failure to act, or from such improper actions as turning off the wrong pump or opening or closing the wrong valve. Pump and valve failures will have the same effects as they do in the corresponding automatic systems.

The final requirement for an overflow to occur is that there be a route by which the excess fluid may escape (see Figure 12E). For some tank designs, such routes always exist. Open-topped tanks, for example, need no other overflow route, and pump-fed tanks can overflow through their vents. Closed, gravity-fed tanks, however, are less subject to overflow, for the model assumes that their vent pipes open at a level above the highest possible fluid level in their fill tanks. For such tanks, an overfill can only result in leakage if there are corrosion holes or ruptures (cracks) in the fill pipe, the vent pipe, or the outlet pipe or valve, or if there are faulty flanges or gaskets.

Leaks and Ruptures. Leaks and ruptures are the second major category of system failures. Their fault trees are presented in Figures 13A through 13G. Leaks are losses due to corrosion; ruptures include both large cracks and small weld failures. As is shown by Figure 13A, such failures may develop in the tank, pipes, pumps, flanges, or gaskets. For all of these components, the basic failure routes are the same: they may crack because of component defects or due to strains caused by settling, vibration, temperature changes, faulty installation, or vehicle crashes; or they may corrode due to the combination of internal and external attack.

Some of these failure routes have been pruned from Figure 13. Pump ruptures, for example, have been omitted because they are extremely unlikely ($p < 10^{-7}$), and flange corrosion has been combined with the corrosion of the tank and pipes. Similarly, although they are subject to both rupture and corrosion, valves are not separately listed in Figure 13, but are instead included as parts of the attached pipe segments.

Corrosion is modeled in Figures 13B (for tanks), 13D (for pipes), and 13F (for pumps). For each of these components, these figures identify three basic types of failure: localized external pitting, localized internal pitting, and the generalized corrosion of large segments of the component wall. In many cases, several of these mechanisms may occur simultaneously, producing more rapid failure than would result from any mechanism acting alone. In such situations, we combine the corrosion rates, computing the remaining wall-thicknesses for the deepest exterior pits, the deepest interior pits, and the rest of the component's surface. When one of these wall-thicknesses reaches zero, we assume that a leak develops. Continued corrosion will enlarge the holes, increasing the leak rates until the loss is detected and the component is replaced. See Chapter 4 of this report for a more detailed discussion of the corrosion model, the hole growth model, and the calculation of leak rates.

Ruptures are modeled in Figure 13C and 13E for tanks and pipes, respectively. These fault trees are very similar. For either type of component, ruptures may result from one of two sources: undetected installation damage or normal operating hazards. Normal operating hazards may produce ruptures at any time during the facility's life; installation defects will result in immediate failures. We assume that the probability of detecting installation defects depends on the quality of the inspection. The model allows for four types of inspection. The most effective of these is the combination of visual inspection, weld testing, and tightness testing. We assume that this will catch 95% of installation errors. Visual inspection alone we assume to be 50% reliable, and visual inspection with weld testing we assume to be 75% effective. The fourth option is no inspection at all, in which case no defects will be detected. Since inspection requirements are one of the regulatory options being modeled, the choice of inspection levels is made by parameter selection at the beginning of each simulation.

The final category of leaks and ruptures are flange and gasket failures. These are depicted together in Figure 13G. Flange leaks are similar to tank or pipe ruptures, resulting from improper installation or normal operating hazards. Gaskets, however, have different failure mechanisms. They may leak due to improper installation, but if they are properly installed, they are subject to gradual attack by the fluid, rather than to sudden cracking. This gradual attack is a corrosion-like process (although the mechanism is quite different), and we have modeled it by computing an annual gasket-disintegration rate. This process will be discussed in greater detail in Chapter 4, below.

External Catastrophies. External catastrophies are depicted in Figure 14. They are all assumed to cause the sudden loss of the system's entire contents, and may result from vandalism, high winds (tornadoes or hurricanes), earthquakes, floods, on-site fires, or damage from nearby fires or explosions. Not all of these events will occur for any given system design; non-flammable wastes cannot burn, and not all geographic regions are vulnerable to all of the other hazards. Thus, these events are controlled by the choice of waste streams and a set of geographic variables. External catastrophies could have been included with leaks and ruptures, but because they are exogenous events uninfluenced by system design (except that below-ground tanks are safe from wind-storms and relatively safe from nearby fires or explosions), we have modeled them separately.

The final type of tank failures are spills other than overflows during filling and discharging. These releases, depicted in Figure 15, result when the operator fails to close a pump or strainer drain after maintenance, or when a portable flexible hose ruptures or is improperly connected. Which of these spill mechanisms is possible depends on the details of the system design. Treatment systems, for example, do not use portable hoses for fluid transfer, nor do they use strainers. Their fill and discharge pumps, however, are maintained annually, and there is a chance that the operator will forget to close a pump drain afterward. This will produce a spill the next time the pump is used. Storage and accumulation tanks, on the other hand, are pumped out by flexible hose. Spills are possible if this hose ruptures or is improperly attached. In addition, the pump-out truck carries a portable pump and strainer, which can produce a spill if the tank being pumped out is the first one to be visited after faulty pump or stainer maintenance. We have not modeled fill pumps and strainers for such tanks, however, for these pieces of equipment, if they even exist, are generally located at the upstream end of the tank's fill pipe, and are more closely associated with the operator's process equipment than they are with the storage or accumulation tank.

Secondary Containment

Secondary-containment systems generally consist of berms, pads, or underground vaults designed to retain fluid following a breach in the tank system itself. In addition, some tanks have two closely-spaced walls, with a liquid sensor in the middle. Thus, a breach in either wall will trigger the liquid sensor, (either due to leaking waste or to infiltrating soil moisture), allowing the owner to repair the tank before a release can occur. A variety of secondary-containment systems are possible, but in general, above-ground tanks employ berms and concrete or asphalt pads, while underground systems use concrete vaults (with or without a liner) or double-walled tanks.

Secondary-containment systems may be complete or partial. Complete systems encompass the entire tank system and all of its ancillary equipment. Partial systems only contain releases from certain components. In-ground or on-grade tank systems, for example, often have only partial secondary-containment systems. These systems will contain above-ground releases, but will not contain releases from the on- or below-grade portions of the tank. We account for partial secondary-containment systems by first determining the location of the particular primary-containment leak. Then, based on the design of the modeled system, we determine which, if any, secondary-containment devices are involved, and then determine whether the appropriate component has failed. This process also allows us to specify separate secondary-containment systems for different portions of the hazardous waste facility. Thus, tanks may be placed in one secondary-containment system, while pipes are placed in another. A pipe leak will therefore only produce a release if the piping secondary-containment system is breached, while a tank leak will only produce a release if the tank secondary-containment system has failed. If pipes and tanks use separate secondary-containment systems, the secondary-containment fault tree must be evaluated independently for each system.

Secondary-containment failures are depicted in Figure 16. As Figure 16 indicates, there are two basic causes of secondary-containment failure: breaches due to external catastrophe, and breaches due to internal events such as settling, freeze/thaw action or normal material aging. External catastrophes which may breach secondary containment are the same as those which may breach the tank system itself. Because these events usually involve serious structural damage to the entire tank facility, we have assumed that whenever such catastrophes breach one containment system, they also breach the other. Thus, this type of secondary-containment failure always occurs in concert with the failures listed in Figure 14.

Failures due to internal events, on the other hand, are independent processes for the tank system and the secondary-containment system. Thus, these types of failures may occur at different times for each system. A release to the environment will only occur if both systems are in failed states at the same time.

Conclusion

As the preceding discussions reveal, the fault trees present a flexible general framework allowing a number of system design options. In addition, the preceding discussions should also have revealed that evaluation of the fault trees is not a one-time procedure. Instead, the fault trees represent a dynamic system, with various events occurring at different times and with events being switched on and off as failures occur and are detected and repaired. Thus, since the probability of many failure events (most notably corrosion) depends on the age of the component under consideration, the fault trees and leak detection systems must be continuously monitored to determine the timing and duration of any failures that develop. It is for this purpose that we developed the Monte Carlo Simulation Model, the details of which will be discussed in the next chapter.

4.0 MONTE CARLO SIMULATION MODEL

4.1 Introduction

The fault trees developed in Chapter 2 form the basis for the computerized Monte Carlo simulation model. This model simulates each of the fault tree events by drawing a random number to determine if that event occurs. The computer then evaluates the fault tree logic gates to determine whether the events that occur in month one are sufficient to cause a release. If no release occurs, the computer determines whether inspection or scheduled maintenance will cause any components to be replaced, advances the facility age by one month, and draws another series of random numbers to determine if any additional components fail during month 2. To save computer time, however, some fault tree branches are only evaluated once per model year. These branches represent events whose probabilities are low enough that the possibility of multiple occurrences in any given year can be safely ignored. In general, we have assumed that events with annual probabilities of less than 3% need only be evaluated annually (such events have less than one chance in a thousand of occurring twice in any given year), while those with higher probabilities need to be evaluated monthly. When one of the annually-evaluated events occurs, the computer determines the exact month of failure by the simple expedient of drawing a random number between 0 and 12. This process of repeated fault tree evaluation continues until a failure occurs or until the entire time period to be modeled has elapsed.

When a release occurs, the computer interrupts this process to determine the leak rate and whether or not the leak is detected in the month in which it began. If the leak is detected, the computer determines the exact detection period, calculates the total loss volume, and replaces the failed components. If the leak is not detected, the computer carries it into the next month, evaluates the fault trees for new leaks, increments the sizes of existing corrosion holes (but not of ruptures), and determines which leaks can now be detected.

The output from this procedure is a time series of releases, identified by component, starting date, ending date, total volume of loss, and method of detection. This time series we call the "release profile" from the modeled tank. Once the release profile is completed, the simulation is rerun through hundreds of iterations, generating a new release profile for each iteration. If enough iterations are run, these release profiles represent the spectrum of possible behavior for the modeled system, and can be used to generate average, median, and extreme values for releases from various components. These values can be compared for various system designs in order to determine their relative performances.

A simplified flow chart for this entire process is presented in Figure 17. A more complete flow chart, identifying individual computer subroutines, is contained in Appendix E. Appendix E also contains the computer code for the simulation model.

The flow chart in Figure 17 identifies five basic components of the simulation model. In order of occurrence, these are:

- The choice of system design and the calculation of the related system parameters;
- The evaluation of the fault trees to determine the occurrence of stochastic events;
- The calculation of leak rates;
- The determination of detection lags; and
- The presentation of results.

The following sections will discuss the details of the first four of these steps. Section 4.2 will list the user-chosen parameters employed by the model and will explain the impact of these parameters on system behavior. Section 4.3 will give a general explanation of the basic techniques used for modeling the occurrence of stochastic events, while Section 4.4 will list the probabilities used for each of the basic fault tree events. Sections 4.5, 4.6, 4.7, 4.8, and 4.9 will explain in more detail the manner in which we calculate leak rates for tank corrosion, pipe corrosion, pump and valve corrosion, erosion, and gasket deterioration, respectively. Section 4.10 will explain how the model determines hole sizes, and Section 4.11 will explain the calculation of leak rates. Section 4.12 will

FIGURE 17. FLOW CHART FOR SIMULATION MODEL

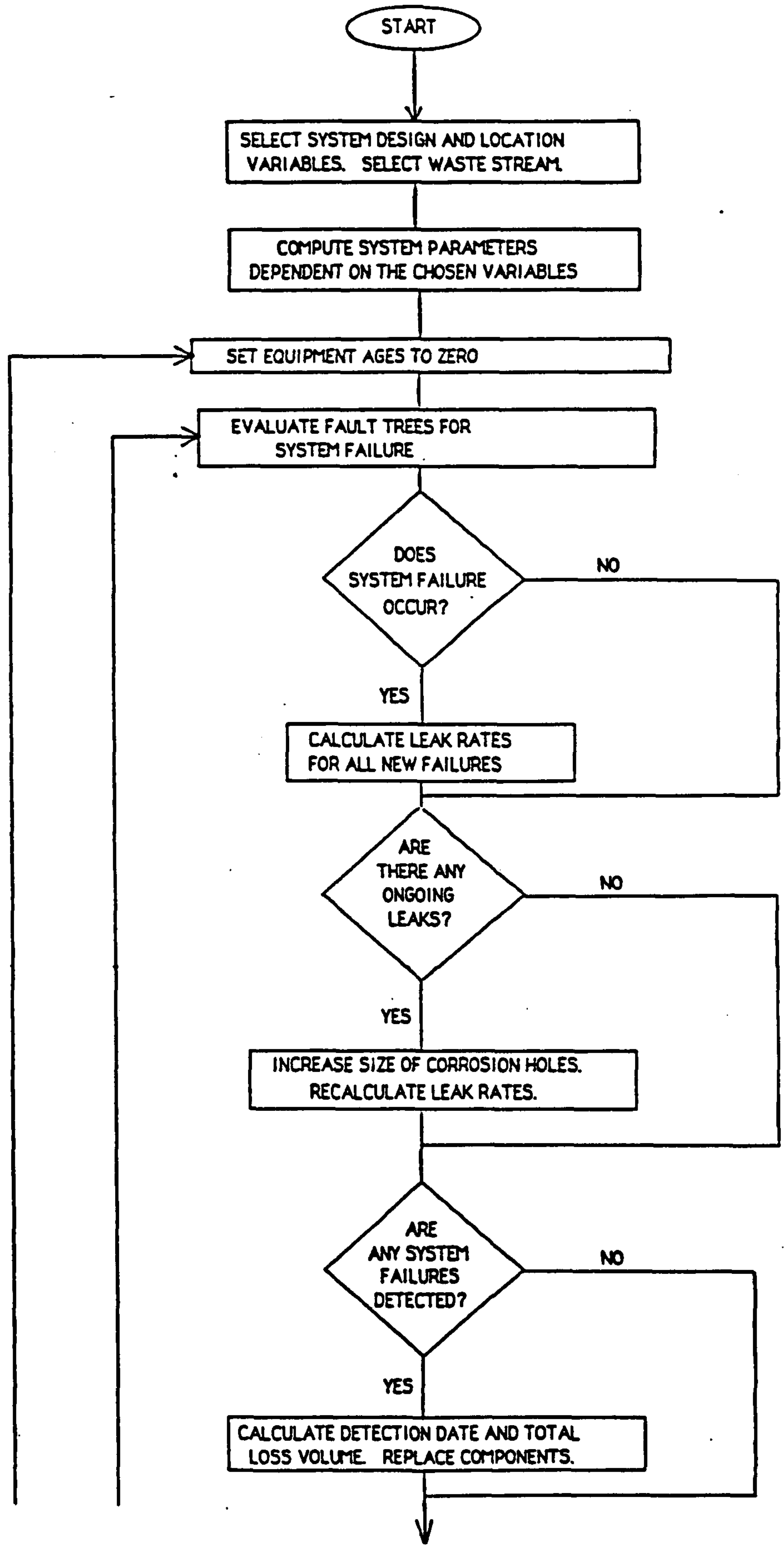
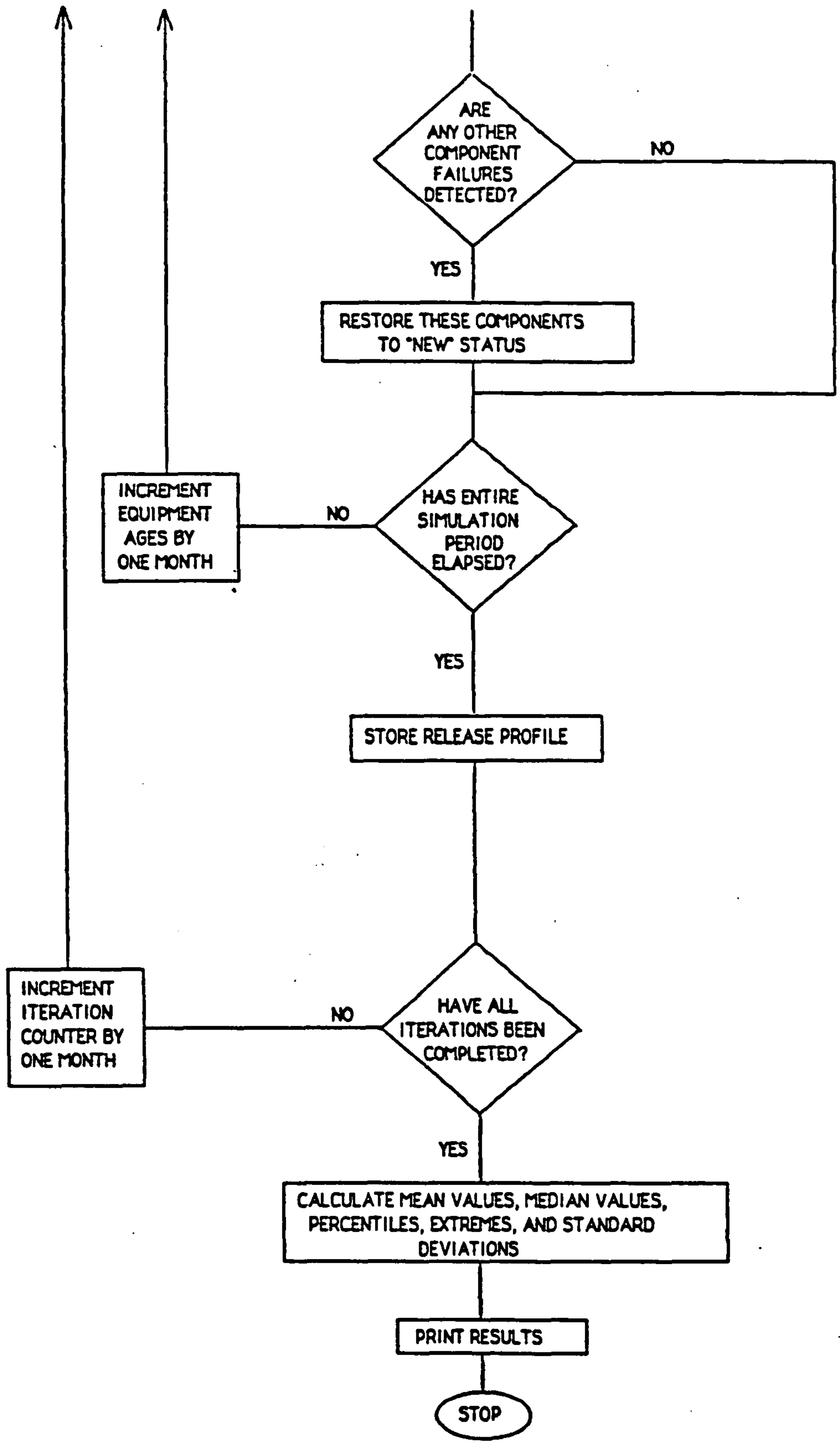


FIGURE 17. FLOW CHART FOR SIMULATION MODEL (Continued)



conclude the chapter with an analysis of the various leak detection methods examined by this model.

4.2 User Inputs

The Hazardous Waste Tank Failure Model is general enough to allow us to simulate a wide range of tank systems. As a result, the model has a large number of user-selected parameters. These parameters are listed in Table 10. That table also gives a brief description of the effect of these parameters and lists cross references to the sections of this report explaining these effects.

As this table indicates, there are six general categories of user input variables. These variables include:

- System design parameters,
- Environmental characteristics,
- Waste characteristics,
- Secondary containment characteristics,
- Leak detection system parameters, and
- Simulation control variables.

System Design Parameters.

The system design variables are used to select the storage or treatment process to be modeled, determine construction materials and system capacity, select the corrosion protection features to be built into the tank, and determine what components are above-, below-, or in-ground. These parameters also determine whether the process is continuous or batch, whether the control system and emergency shut-off systems are manual or automatic, and whether the tank is open- or closed-topped. A variety of miscellaneous variables are also included in this group, including the choice of welded flanges or gaskets, the choice of pump location, the interval between pump-outs for storage or accumulation tanks, and the

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL

Variable Description	Possible Choices	Effect	Cross References
SYSTEM DESIGN			
Process for which tank is used	Storage or accumulation Chrome reduction Cyanide oxidation Distillation Evaporation Neutralization Precipitation	Determines number of tanks, pH of contents, number and location of pumps.	Section 2.3
Tank construction material	Carbon steel Stainless steel Fiberglass Concrete	Determines corrosion rate and rupture probability.	Section 4.5
Pipe construction material	Carbon steel Stainless steel Fiberglass	Determines corrosion rate and rupture probability.	Section 4.6
Tank capacity	200-50,000 gallons (underground tanks) 200-unlimited (above- or in-ground tanks)	Influences tank surface area, tank wall thickness, maximum loss volume from major ruptures, hydraulic head for smaller leaks.	Section 4.2
Yearly throughput	Any	Determines inventory monitoring detection threshold, maximum yearly loss volume, total fill/discharge time.	Section 4.2
Number of operating days per year	100-365	Influences failure probabilities for pumps, valves, and system control equipment. Influences annual loss volumes from leaking ancillary equipment.	Section 4.4

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
SYSTEM DESIGN (Continued)			
Number of operating hours per day	1-24	Influences failure probabilities for pumps, valves, and system control equipment. Influences daily loss volumes from leaking ancillary equipment.	Section 4.4
Location of tank	Above-ground (on-grade) Above-ground (on cradles) In-ground Below-ground	Influences corrosion rate, vulnerability to external catastrophes, and leak rate.	Section 4.2
Tank top	Open Closed	Open tanks overflow more easily.	Section 3.3
Fraction of in-ground tank that is underground	0-100%	Influences corrosion rate and leak rate.	Section 4.5
Location of pipes	Above-ground Below-ground	Influences corrosion rate, vulnerability to external catastrophes, and leak rate.	Section 4.6
Treatment efficiency	0-100%	Determines concentration of hazardous constituent in downstream piping.	Section 2.2, Appendix D
Fraction of main constituent	Any	Determines concentration of hazardous constituent at various stages of the treatment or storage process.	Section 2.2, Appendix D
Fraction of suspended solids	Any	Determines erosion rate when fluid is in motion.	Section 4.8

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
SYSTEM DESIGN (Continued)			
Tank orientation	Horizontal Vertical	Determines operating pressure at various locations.	Section 4.2
Pump location	Above-ground Submersible	Submersible pump failures cannot cause releases.	Section 4.7
Tank/pipe joint construction	Welded flanges Gaskets	Determines failure rate and mechanism.	Sections 4.4, 4.9
Emergency shut-off controls	Manual Automatic (manual back-up) Automatic only	Affects overflow probability.	Sections 3.3, 4.4
Operating procedures	Continuous Batch	Affects overflow probability, fill/discharge rates, and total daily fill/discharge time.	Sections 3.3, 4.4
Level Control system	Manual Automatic	Affects overflow probability.	Sections 3.3, 4.4
Number of batches per day (batch systems only)	Any	Determine the number of opportunities for tunities for start-up errors or overflows.	Section 4.4
Number of days before tank is emptied	1-365	Affects inventory detection threshold.	Section 4.12
Corrosion protection for tanks (carbon steel only)	Interior coating Exterior coating Interior and exterior coatings Cathodic protection with interior and/or exterior coatings No protection	Retards onset of corrosion.	Section 4.5

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
SYSTEM DESIGN (Continued)			
Corrosion protection for piping (carbon steel only)	Interior coating Exterior coating Interior and exterior coating Cathodic protection Cathodic protection with interior and/or exterior coatings No protection	Regards onset of corrosion.	Section 4.6
ENVIRONMENTAL CHARACTERISTICS			
Geologic or weather-related hazards	Each of these variables may be set to true of false. They may be used in any combination.	Determines system vulnerability to external catastrophes.	Section 4.4
• Earthquake zone			
• Flood plain			
• Hurricane region			
• Tornado region			
Soil characteristics			
• pH	5.0 - 9.0	These variables all influence leak rates from underground leaks.	Section 4.5, 4.6
• Resistivity	50-50,000 ohm-cm		
• Presence of sulfides	Yes or No		
• Moisture content	Dry Damp Saturated		

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
ENVIRONMENTAL CHARACTERISTICS (Continued)			
Backfill material	Clay Silt Sand Gravel	Influences leak rate from underground leaks.	Section 4.11
WASTE CHARACTERISTICS			
pH	2 to 9	Determines if environment is extreme or normal (cut-off is pH=3.5).	Section 4.4
Density	No limitations	Influences leak rate.	Section 4.11
Viscosity	No limitations	Influences leak rate.	Section 4.11
Ignitability	True or false	Determines if on-site fires or explosions are possible.	Section 4.4
Diffusivity in air	No limitations	Influences time lag for detection by vapor wells.	Section 4.12
Vapor pressure	No limitations	Influences time lag for detection by vapor wells.	Section 4.12

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
SECONDARY CONTAINMENT			
Tank system	Concrete pad and curb Asphalt pad and curb Concrete vault Synthetic liner Concrete vault with synthetic liner Double-walled tank (with or without other secondary containment features) No secondary containment	As long as they are functioning, secondary containment systems prevent tank releases from reaching the environment.	Section 4.4
Pipe system	Asphalt pad (with earthen dikes or asphalt or concrete curbs) Concrete pad (with earthen dikes or asphalt or concrete curbs) Liner (with or without other forms of secondary containment) Double-walled piping (with or without other forms of secondary containment) No secondary containment	As long as they are functioning, secondary containment systems prevent pipe releases from reaching the environment.	Section 4.4
Maintenance level for pad and vault	Good Poor	Determines failure date of secondary containment component.	Section 4.4
Thickness of asphalt pad	2 to 6 inches	Determines failure date of asphalt pad	Section 4.4

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
LEAK DETECTION SYSTEM			
Possible detection methods (may be used in any combination)	Visual inspection Inventory monitoring Tank integrity testing Pipe integrity testing Ultrasonic testing (tanks only) Interstitial monitoring for tanks and/or pipes (double-walled or lined tanks and pipes only). U-tubes Pollulert system Pipe monitoring Vapor wells Liquid sensor in vault No leak detection	Determines leak duration.	Section 4.12
Inspection frequency	Casual only Weekly Monthly	Determines leak duration.	Section 4.12
Inventory monitoring frequency	Weekly After any specified number of months	Determines leak duration.	Section 4.12
Inventory monitoring detection limit	Any specified % of throughput	Determines minimum leak rate which may be detected.	Section 4.12
Tank integrity testing frequency	Semi-annual Annual Every five years In any specified set of years (up to 10 years may be specified)	Determines leak duration.	Section 4.12

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
LEAK DETECTION SYSTEM (Continued)			
Pipe integrity testing frequency	Semi-annual Annual Every five years In any specified set of years (up to 10 years may be specified)	Determines leak duration.	Section 4.12
Tank integrity testing limit	Any	Determines minimum leak rate which may be detected.	Section 4.12
Pipe integrity testing limit	Any	Determines minimum leak rate which may be detected.	Section 4.12
Pipe monitoring detection limit	Any	Determines minimum leak rate which may be detected.	Section 4.12
Ultrasonic testing frequency	In any specified set of years (up to 5 years may be specified)	Determines leak duration.	Section 4.12
Vapor well distance from pipes, pumps, and tank	Any non-zero distance	Determines lag until detection.	Section 4.12
Vapor well detection threshold	Any	Determines minimum leak rate which may be detected.	Section 4.12
Frequency of U-tube monitoring	Weekly Monthly Quarterly Annually	Determines leak duration.	Section 4.12

TABLE 10. USER INPUTS FOR HAZARDOUS WASTE TANK FAILURE MODEL (Continued)

Variable Description	Possible Choices	Effect	Cross References
SIMULATION CONTROL VARIABLES			
Number of iterations	Any	Larger numbers of iterations produce more accurate release profiles.	Section 4.2
Length of simulation period	1-40 years	Determines duration of simulation period.	Section 4.2
Initial age of tank population to be modeled	0-39 years	Determines stochastic characteristics of existing tank systems.	Section 4.2
Types of failures to be culled from existing tank population	Detected tank failures only Detected tank failures plus undetected tank failures All tank leaks and ruptures	Determines stochastic characteristics of existing tank systems.	Section 4.2

number of operating hours per day and operating days per week for treatment tanks.

Tank Dimensions. Tank dimensions are calculated according to the formulas presented in Table 11. These formulas are derived from the standard geometric formulas for the column of a cylinder. In deriving these formulas, we have assumed that each tank is 1.005 times larger than its rated capacity. In addition, we have used a fixed height-to-diameter ratio for each category of tanks. These height-to-diameter ratios are presented in the last column of the table, and are derived from tank dimension data obtained from Kirby (1979), Holzauer (1980), personal communications with an oil refining manager, and personal observations.

Steel and stainless steel tanks of less than 50,000-gallons capacity are horizontal or vertical cylinders with flat or ellipsoidal ends. These tanks have lengths (or heights) that are twice as large as their diameters. A 10,000-gallon tank is therefore 9.5 feet in diameter and 19 feet long. A 50,000-gallon tank is 16 feet in diameter and 32 feet long. Because the difference between flat and ellipsoidal ends is not significant, we have used a single formula for both shapes.

Steel and stainless steel tanks with capacities in excess of 50,000 gallons are always vertical and are not so elongated, having length-to-diameter ratios of 1. Thus, a 60,000-gallon tank is 22 feet in diameter and 22 feet high, while a 375,000-gallon tank is 40 feet in diameter and 40 feet high. For strength reasons, steel tanks are seldom more than 40 feet in height. Therefore, for tanks larger than 375,000 gallons, we have fixed the height at 40 feet and enlarged the diameter to include the the necessary volume.

Fiberglass tanks, on the other hand, are more elongated than even the smallest steel tanks, having lengths that are three times greater than their diameters. Because fiberglass is not as structurally strong as steel, these tanks are not extremely large. Based on Kirby (1978) and Holzauer (1980), we have chosen 30,000 gallons as a practical limit to the size of fiberglass tanks.

TABLE 11. DIMENSIONS FOR TANKS OF VARIOUS CAPACITIES AND CONSTRUCTION MATERIALS

Tank Material	Tank Capacity (gallons)	Tank Shape	Tank Diameter (feet)	Tank Length or Height (depending on orientation) (feet)
Steel or Stainless Steel[1,4]	≤50,000	horizontal cylinder	$.440(1.005 \times \text{volume})^{1/3}$	2 x Diameter
	≤50,000	vertical cylinder	$.440(1.005 \times \text{volume})^{1/3}$	2 x Diameter
	50,001 to 375,000	vertical cylinder	$.554(1.005 \times \text{volume})^{1/3}$	1 x Diameter
	>375,000	vertical cylinder	$.0652(1.005 \times \text{volume})^{1/2}$	40 feet
Fiberglass Reinforced Plastic (FRP)	≤ 30,000	horizontal cylinder	$.385(1.005 \times \text{volume})^{1/3}$	3 x Diameter
	≤ 30,000	vertical cylinder	$.385(1.005 \times \text{volume})^{1/3}$	3 x Diameter
Concrete[2,4]	any	vertical cylinder	$.698(1.005 \times \text{volume})^{1/3}$	1/2 x Diameter
		rectangular	$.406(1.005 \times \text{volume})^{1/3}$ (gives both length and height)	2 x Width (gives tank length)

Sources: [1] Holzauer (1980).
[2] SCS Engineers (Estimated Cost of Compliance (1984)).
[3] Kirby (1978).
[4] PRA estimates based on personal observations and conversations with oil refinery managers.

Concrete tanks may be any size and may be either cylindrical or rectangular. Cylindrical tanks are always vertical, with heights that are only 50% of their diameters. Rectangular tanks are always horizontal, with length, width, and height having ratios of 2:1:1, respectively. Unlike steel tanks, concrete tanks may exceed 40 feet in height.

Tank Thickness. Tank wall-thicknesses are selected to give the tank the necessary structural strength. For steel and stainless steel tanks, these thicknesses also include a standardized corrosion allowance. Table 12 presents the standard tank wall-thicknesses for steel, stainless steel, and concrete tanks of various capacities. For steel and stainless steel tanks, these thicknesses range from .25" to .625". For concrete, they range from 6" to 15". We use these wall-thicknesses to calculate dates of corrosion failure (for steel tanks) and rates of fluid seepage through the pores of concrete tanks. These calculations will be described in Section 4.5 below. Tank wall-thickness does not influence our estimated probability of rupture, however. Instead, we assume that the tank is designed to have a sufficient safety margin against normal operating stresses. Larger tanks have stronger walls, but they also experience greater stresses. We assume that these two factors cancel out and that tank rupture probabilities are therefore independent of tank size.

Component Specifications and System Layout. The choices of tank capacity, tank orientation, throughput, tank location, and the process for which the tank is being used serve to specify a number of other design parameters. These parameters include the average depth of the fluid in the tank, the identity of the fluid contained in each tank or pipe, the number and operating pressures of the pumps, the diameter of the pipes, and the relative elevations of pipes, fill tanks, and process or storage tanks.

These parameters influence two important aspects of the model: they determine the operating pressure in each component, and they determine the fraction of the time when each of the pipes and ancillary components are in use. The operating pressures determine leak rates (see Section 4.11 below) while the periods of operation determine the fraction of the

TABLE 12. TANK WALL THICKNESSES

Tank Material	Tank Capacity (gallons)	Tank Wall Thickness (inches)
Steel and Stainless Steel[1]	<10,000	0.25
	10,001 - 20,000	0.31
	20,001 - 30,000	0.38
	30,001 - 100,000	0.50
	>100,000	0.625
Concrete[2]	<3,000	6
	3,001 - 20,000	8
	20,001 - 50,000	12
	>50,000	15

Sources:

[1] Holzauer (1980).

[2] SCS Engineers, Estimated Cost of Compliance 1984).

operating day during which leakage can occur, and determine the amount of wear and tear on pumps, valves, and other ancillary equipment.

It is impractical for the main body of this report to present the details of the calculation of operating pressures and periods of ancillary equipment operation. Because the model includes so many design options, it allows hundreds of different combinations of operating pressures and operating periods. The effect of each design option on these parameters is explained in Appendix D.

Environmental characteristics.

The model allows us to vary environmental parameters. Some of these parameters identify which geologic or weather-related hazards may threaten a particular locale. Other environmental variables allow us to specify the soil pH, resistivity, and moisture content at a particular site and to determine whether or not the soil contains sulfides. These soil characteristics determine the corrositivity of the soil; their effects will be described in Section 4.5, below.

Waste Characteristics

The model also allows us to vary the physical and chemical characteristics of the waste stream. These characteristics determine leak rates from above- and below-ground holes, influence the detection lags for various leak detection methods, and determine whether or not the waste is flammable. The effects of these variables are listed in Table 10; more detailed information may be obtained from the sections of this report listed there as cross references.

Secondary Containment and Leak Detection.

Two other classes of variables allow us to specify the design of the facility's secondary-containment and leak-detection systems. Table 10 lists the options for each of these systems, as well as the parameters affecting their performances. These systems and the effects of the listed parameters will be described in detail later in this report.

Simulation Control Variables

The final category of user inputs for the Monte Carlo model are the simulation control variables. These four variables allow us to control the number of iterations, set the length of the simulation period, set the initial facility age when existing tanks are being modeled, and determine the rules for culling existing tanks that have already failed before the start of the simulation period.

Number of Iterations. The number of iterations determines the accuracy of the release profiles produced by the model. A large number of iterations provides a more representative sample, and smooths out the effects of any particularly unusual results. In addition, a large number of iterations allows rare events to occur, so that the composite release profile more closely represents the entire range of possible performances.

Generally, 500 to 1000 iterations are recommended for simple Monte Carlo models (EPA, Liner Location Report, Appendix A, 1984). Because of budget constraints, however, complex models such as ours are often run with 200 or fewer iterations (EPA, Liner Location Report, Appendix A, 1984). For such models, their lengthy time horizons effectively increase the number of iterations by repeating major portions of the model once each simulation period. Thus, 200 iterations of a 30-year model serve to simulate 6000 operating years, or 72,000 operating months, thus providing opportunities for many different events to occur.

Length of Simulation period. Our model allows us to specify any simulation period between 1 and 40 years. In principal, the model could accomodate longer simulations, but few tank systems last that long, and there is almost no data on the performance of those that do.

Initial Age of Tank Facility and Culling Rules. The Monte Carlo model is capable of simulating either new or existing facilities. To simulate new facilities, we specify an initial age of zero. To simulate existing facilities we begin by specifying the age of the facilities to be modeled and the rule to be used to cull leaking tanks from the year-zero population. A simple example best illustrates how these two parameters work. Suppose that we wish to model 5-year-old storage tanks over a 20-year simulation period. For each iteration, the model first runs a 5-year simulation in order to determine the random processes that have already occurred before the start of the simulation period. If the tank fails within that period, the model uses the culling rule to determine whether the iteration should be continued. The purpose of the culling rule is to determine which types of presently leaking tanks we wish to include in the simulation. Tanks with detected leaks, for example, will have been replaced at least once, and we should no longer classify them as 5-year-old tanks. Similarly, if tightness testing is to be required as a condition for the granting of permits, we may wish to also cull tanks with previously undetected tank leaks, for they will be replaced at the time of testing. Using the options listed in Table 10, we can cull only iterations which have had detected tank failures, those which have had either detected or undetected tank failures, or those which have had leaks or ruptures in any system component. Iterations that are not culled before year 5 then continue through an additional 20-year simulation in order to predict their future performances. Thus, for those iterations which are not culled, the simulation process covers a total time period of 25 years.

We can use this technique to simulate existing tanks of any desired age, but because of the limitations on our failure data, the total modeled time period cannot exceed 40 years.

4.3 Probability Sampling

Once the system parameters have been chosen, the Monte Carlo simulation model begins to evaluate the fault trees. The basic element of this process is the simulation of individual stochastic events by a procedure referred to as "event sampling." Event sampling consists of the use of computer-generated random numbers to determine whether any of the stochastic events have occurred. There are two approaches to event sampling: binomial sampling and time-to-failure sampling. In binomial sampling, the computer selects a random number between 0 and 1 and compares that number to the event's probability. If the random number is less than or equal to the probability, then the event is declared to have occurred. Otherwise, it does not occur. In this way, the Monte Carlo model ensures that each binomial event occurs with the probability assigned to it.

In our model, binomial sampling may occur monthly, annually, or on a per demand basis. Monthly sampling is capable of detecting up to 12 occurrences per year (one per month). Annual sampling, however, can detect no more than one occurrence per year; the month of occurrence can be determined by drawing an additional random number between 0 and 12. Annual sampling requires less computer time because it uses at most two random numbers per year (monthly sampling uses 12), but is less accurate because it fails to detect repetitions of the same event during a single year. In order to compromise between computer costs and model accuracy, we have generally used annual sampling only when the annual probability is less than 3%. Under these circumstances, the probability of multiple occurrences is less than .09% (3% x 3%), which is insignificant compared to the uncertainty likely to be inherent in the original estimate.

In addition to being annual or monthly, binomial probabilities can also be specified on a per-demand basis. Per-demand probabilities give the likelihood of failure on each occasion that a component is needed. Thus, we often use per-demand probabilities when the component is part of an emergency back-up system. For such systems, it is much more useful to know the probability that a component fails when it is needed than it is to know the probability that it fails during any given month or year. Furthermore, by using per-demand probabilities for such components, we save considerable computer time, for then these events need only be sampled when the back-up systems are required.

It is possible to model any stochastic event using only binomial sampling, but time-to-failure sampling is more convenient for events for which cumulative time-to-failure probabilities are easily computed.

A cumulative time-to-failure probability is simply the probability that the failure event in question has occurred at or before a given time. A set of such cumulative probabilities is a cumulative time-to-failure distribution. An example is given in the following table:

Year	Cumulative Probability
1	.05
2	.10
3	.20
4	.60
5	1.00

This distribution means that there is a 5% probability that the event has occurred by the end of year 1, a 10% probability that it has occurred by the end of year 2, a 20% probability that it has occurred by the end of year 3, etc. This is equivalent to saying that there is a 5% probability the event occurs <u>in</u> year 1, a 5% probability that it occurs <u>in</u> year 2, and a 10% probability that it occurs <u>in</u> year 3. In this example, the event will occur with certainty by the end of year 5.

In time-to-failure sampling, the computer selects a random number between 0 and 1 and determines the date of failure by comparing that number to the cumulative probability distribution. In the above example, a random number of .4 would mean that the event occurs during year 3.

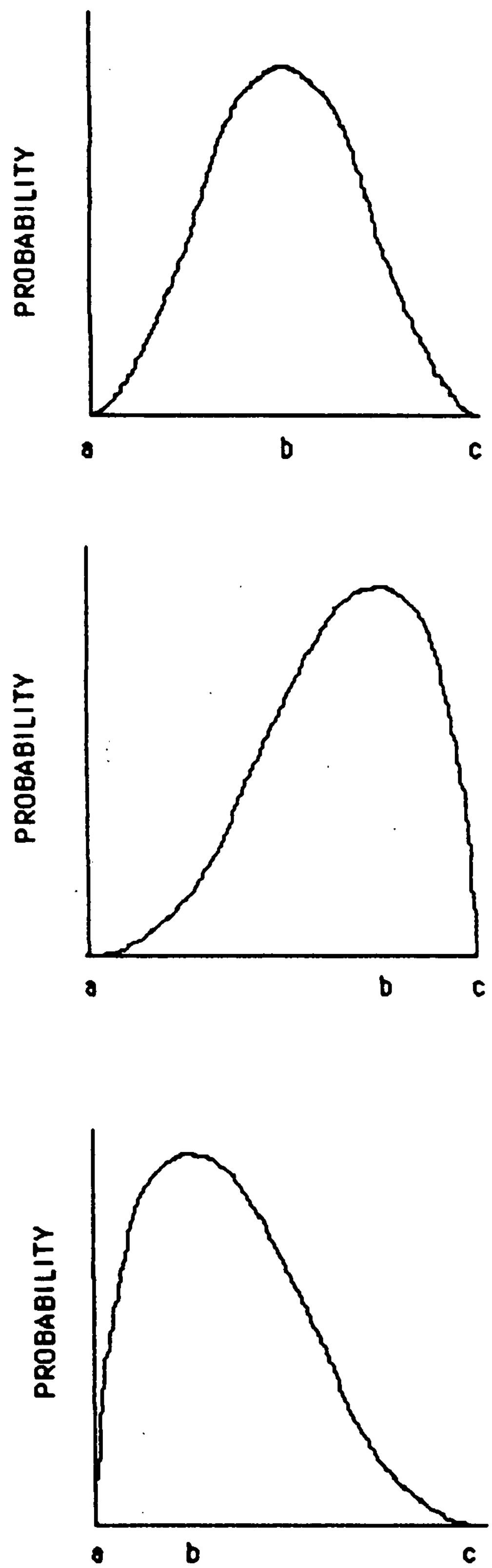
Binomial and time-to-failure sampling provide comparable but slightly different information. Binomial sampling reveals whether or not the sampled event occurs during any given time period; the sampling process must therefore be repeated regularly until the event occurrs. Time-to-failure sampling, on the other hand, need only be done once per component. The computer then remembers the date of failure, periodically compares the component age to its failure date, and determines whether or not the component has failed yet. Under either sampling technique, once the component fails it remains in its failed state until the failure is detected and repaired. At that time, the model assumes that the component is restored to an as-new condition, and the computer resumes the sampling process with the repaired component's age re-set to zero.

Our computer model uses time-to-failure sampling whenever a cumulative probability distribution is assigned to an event. These probability distributions fall into five basic categories:

- o Normal distributions,
- o Uniform distributions,
- o Empirical distributions,
- o Beta distributions, and
- o Conditional normal distributions.

The first four of these distributions are easy to describe. The normal distribution is usually represented by the familiar bell-shaped curve; its cumulative distribution is mathematically specified by its mean and standard deviation. A uniform distribution occurs when there is an equal chance of failure for any of a range of dates; its time-to-failure distribution is mathematically specified by the end points of that range. An empirical distribution is a distribution similar to the hypothetical distribution used above; its cumulative distribution is given as a series of dates and cumulative probabilities. A beta distribution looks somewhat like a skewed, truncated normal, with its peak shifted either to the right or the left. Examples are depicted in Figure 18. The beta distribution is completely specified by three values, the minimum, maximum, and mode (peak). Its cumulative distribution can also be obtained from these values.

FIGURE 18. BETA DISTRIBUTIONS



The final distribution used by our model is the conditional normal. This distribution is a combination of a binomial and a normal distribution. The binomial distribution is sampled once (in year 1) to determine whether failure occurs. If the response is positive, the normal distribution is then sampled to determine when the failure takes place. A conditional normal distribution therefore combines two random processes into a single probability distribution. One process is the binomial occurrence of the initiating event, the other is the (normal) determination of the date of failure.

In order to refer to these distributions conveniently, we have developed a shorthand notation for each of the five parametric distributions. These notations, which will be used throughout the remainder of this report, are:

- p = a (binomial distribution with probability a);
- N(x,y) (normal distribution with a mean of x and a standard deviation of y);
- FNU(a,b) (uniform distribution between values a and b);
- B(a,b,c) (beta distributions with minimum a, mode b, and maximum c); and
- pN(X,y) (conditional normal with binomial probability p and normal time-to-failure N(x,y)).

Empirical distributions will be described by a table of their cumulative probabilities.

4.4 Fault Tree Event Probabilities

We used a combination of engineering judgment, published failure data, and conversations with equipment vendors to assign probability distributions to each of the basic events in the fault trees in Chapter 2. Where possible, we drew our probability values directly from the most reliable published sources. In many cases, however, the available data were not directly applicable, and had to be modified to fit the events being modeled. Sometimes such modifications were required because failure data were not available for the proper component; on other occasions modifications were required in order to adjust the published failure rates to apply to the appropriate operating conditions.

Because of the number of events and the complexity of some of the derivations, it is impractical to discuss all of them in the main body of this report. Instead we have listed the probabilities in Table 13, and have presented the details of the derivations in Appendix A.

Many of the probabilities presented in Table 13 are dependent on system design characteristics. These probabilities have therefore been included in Table 13 as general formulas. These formulas use the following variables as inputs:

A = the surface area of the component.

H_d = the number of operating hours in a day. For storage tanks, H_d is the number of hours required to transfer a batch of waste from the collection tank to the storage tank. I.e., for the purposes of formulas using H_d, we only consider a storage tank to be "operating" when it is being filled.

H_m = the number of operating days per month. For storage tanks, H_m is the number of transfers per month. Thus, for storage tanks, $H_m = 30n_b$.

j = the number of pump-outs per year. (This parameter only applies to storage or accumulation tanks).

n_b = the number of batches per day. For storage tanks, n_b may be less than 1.

T_b = the time it takes to transfer one batch into the tank (in hours). For continuous sytems, $T_b = H_d$.

T_p = the time it takes to pump-out the tank (in hours). (This parameter only applies to storage or accumulation tanks).

The events in Table 13 are grouped into 9 categories:

- Corrosion,
- Ruptures,
- Installation damage,
- Control equipment failures,

TABLE 13. BASIC EVENT PROBABILITIES

Type of Failure and Event Label[1]	Probability[2]
CORROSION	
Tanks (T1121, T1123, T1125, T1127, T1128)	See Section 4.5
Pipes (B13)	See Section 4.6
Pumps (A2116)	See Section 4.7
Gaskets (B122)	See Section 4.9
Erosion (B13, A2116)	See Section 4.10
RUPTURES	
Tanks (above-, below-, or in-ground)	
• Steel (T1124)	5.3×10^{-3}/yr
• Stainless steel (T1124)	5.3×10^{-3}/yr
• Fiberglass (T1124)	1.06×10^{-2}/yr
• Concrete (B41)	N (35,10)
• Double-walled tanks (T1124)	
- inner wall	2.6×10^{-3}/yr
- outer wall	5.3×10^{-3}/yr
- conditional probability that outer wall breach also breaches inner wall	50%
Pipes (above- or below-ground)	
• Steel (B11)	3×10^{-3}/yr
• Stainless steel (B11)	3×10^{-3} /yr
• Fiberglass (B11)	6×10^{-3}/yr
• Double-walled pipes (B13)	
- inner wall	1.5×10^{-3}/yr
- outer wall	3×10^{-3}/yr
- conditional probability that outer wall breach also breaches inner wall	50%
Flange leaks (B121)	5×10^{-3}/yr

TABLE 13. BASIC EVENT PROBABILITIES (Continued)

Type of Failure and Event Label[1]	Probability[2]
INSTALLATION DAMAGE (or damage during shipping)	
Tank (below-, above-, or in-ground) (LIFDEF (I,5)A)	
• Steel	.03/tank
• Stainless steel	.03/tank
• Fiberglass	.04/tank
• Concrete	.03/tank
Pipe (below- or above-ground) (LIFDEF (I,5)B or LIFDEF (I,5)C)	
• Steel	.01/pipe
• Stainless steel	.01/pipe
• Fiberglass	.02/pipe
Welded flange (LIFDEF (I,5)D)	.02/flange
Gasket (LIFDEF (I,5)E)	.015/gasket
CONTROL EQUIPMENT	
Automatic level controller fails (FLVCN1)	.094/mo
Level indicator fails (MOLEVIN)	.16/mo
Mechanical failure of automatic inlet valve	
• normal environment (pH > 4.5)[3] (OPVLON)	$1-(1 - 3.4 \times 10^{-5})H_dH_m$
• extreme environment (pH $\leq$ 4.5)[3] (OPVLOE)	$1-(1 - 3.4 \times 10^{-4})H_dH_m$
Tank is being filled when nearly full (MOFILL)	
• Storage or accumulation tanks	.079/mo
• Treatment tanks	1.00/batch

TABLE 13. BASIC EVENT PROBABILITIES (Continued)

Type of Failure and Event Label[1]	Probability[2]
EMERGENCY SHUT-OFF-EQUIPMENT	
High level alarm fails (MOALARM)	.1/demand
High level sensor fails (LEVIN2)	.008/demand
Microprocessor fails (FLVCN2)	.05/demand
Inlet pump fails to shut off	
• Normal environment (pH > 4.5)[3] (MOPMON)	$7.5(T_b) \times 10^{-7}$/demand
• Extreme environment (pH $\leq$ 4.5)[3] (MOPMDE)	$7.5(T_b) \times 10^{-5}$/demand
Inlet valve sticks in open position	
• Normal environment (pH > 4.5)[3] (MOVLOE)	$3.4(T_b) \times 10^{-5}$/demand
• Extreme environment (pH $\leq$ 4.5)[3] (MOVLON)	$3.4(T_b) \times 10^{-4}$/demand
Outlet pump fails to open	
• Normal environment (pH > 4.5)[3] (MOPMCN)	$2(T_b) \times 10^{-6}$/demand
• Extreme environment (pH $\leq$ 4.5)[3] (MOPMCE)	$2(T_b) \times 10^{-4}$/demand
Outlet valve fails to open	
• Normal environment (pH > 4.5)[3] (MOVLCN)	$3.4(T_b) \times 10^{-5}$/demand
• Extreme environment (pH $\leq$ 4.5)[3] (MOVLLE)	$3.4(T_b) \times 10^{-4}$/demand
HUMAN ERRORS	
Failure to detect improper installation or shipping damage (LIFDEF(I,3))	
• No inspection	1.00/demand
• Visual inspection	.50/demand
• Visual inspection and weld testing	.25/demand
• Visual inspection, weld testing, and tightness testing	.05/demand
Operator throws wrong switch, etc. in response to an alarm (OFTRCOM)	3×10^{-3}/demand

TABLE 13. BASIC EVENT PROBABILITIES (Continued)

Type of Failure and Event Label[1]	Probability[2]
HUMAN ERRORS (Continued)	
Operator fails to act in response to an alarm (OFTROM)	3×10^{-2}/demand
Operator control error causes attempted overfill (OPCOMM)	
• Batch systems	$1-(.914)^{n_b}$/month
• Continuous systems	.086/mo
SECONDARY CONTAINMENT FAILURES	
Asphalt pad cracks (B21)	
≤2.5" pad, no maintenance	B(2.5,8,12)
≤2.5" pad, with maintenance	B(4,12,15)
>2.5" pad, no maintenance	B(4,12,15)
>2.5" pad, with maintenance	B(5,15,18)
Asphalt-covered berm (B21)	
≤2.5" thickness of asphalt, no maintenance	B(2.5,8,12)
≤2.5" thickness of asphalt, with maintenance	B(4,12,15)
>2.5" thickness of asphalt, no maintenance	B(4,12,15)
>2.5" thickness of asphalt, with maintenance	B(5,15,18)
Concrete pad develops cracks (B31)	N(30,5)
Concrete curb develops cracks (B33)	N(30,5)
Concrete vault develops cracks (B41)	N(35,10)
Synthetic liner fails (B51)	N(35,10)

TABLE 13. BASIC EVENT PROBABILITIES (Continued)

Type of Failure and Event Label[1]	Probability[2]
EXTERNAL CATASTROPHES	
Vandalism (ANUCAT (I,2))	1×10^{-6}/yr
Damage due to earthquake (ANUCAT (I,4))	8×10^{-4}/yr
Tornado damage (ANUCAT(I,3))	1.5×10^{-4}/yr
Hurricane damage (ANUCAT (I,3))	1.4×10^{-2}/yr
Damaging flood (ANUCAT (I,5))	5×10^{-3}/yr
Ignitable waste catches fire	1×10^{-6}/yr
Nearby fire or explosion (ANUCAT (I,7))	
• above- or in-ground system	3×10^{-3}/yr
• below-ground system	1×10^{-3}/yr
ACCIDENTAL SPILLS	
Strainer Drain Left Open After Maintenance	
• On-site strainer (A11111)	.01/mo
• Strainer on pump-out truck (A11111)	$6(j) \times 10^{-5}$/yr
Pump Drain Left Open After Maintenance	
• On-site pump (A11112)	.01/yr
• Pump on pump-out truck (A11112)	$5(j) \times 10^{-6}$/yr
Flexible hose ruptures (A1112)	$5(j)(Tp) \times 10^{-3}$/yr
Loose flexible hose connection (A1115)	$j \times 10^{-2}$/yr

1 These labels correspond to the labels in the fault trees. They are also used in Appendix A. That Appendix explains the derivation of each of these probabilities. It also lists the sources used in these derivations.

2 The notation used for these probability distributions is explained in Section 4.3 of this report. The variables used in these formulas are defined in Section 4.4.

3 We have chosen a pH of 4.5 as the cut-off between normal and extreme environments (Perry and Chilton, 1973, p. 23-4). Highly alkaline environments will also be extreme, but the present version of our model does not include caustic wastes.

- Emergency shut-off failures,
- Human errors,
- Secondary containment failures,
- External catastrophes, and
- Accidental spills.

These events correspond to the basic events in the fault trees in Chapter 2. To allow easy reference to the fault trees, Table 13 includes the label for each of the events. These labels are also useful in locating the derivations of these probabilities in Appendix A.

In addition to listing the event probabilities in Table 13, we have constructed Figures 19 through 23 to illustrate how these probabilities may be integrated into the fault trees. Because it is impractical to incorporate all of the design-dependent probabilities into a single fault tree, Figures 19 through 23 are merely an example based on a specific system design. Furthermore, since some probabilities (particularly those influencing corrosion) vary with component age, these sample fault trees represent only one model year; in this example, we assume that the facility is 10 years old.

The facility modeled in Figures 19 through 23 has the following design characteristics:

- It is used for 180-day storage.
- The tank and piping are below-ground and are constructed of unprotected carbon steel, without secondary containment.
- Filling is done in once-a-day batches by gravity feed from an off-site collection tank. The gravity-feed system has manual level controls and manual emergency shut-off.
- The tank is emptied using a flexible hose and a pump on the pump-out truck. Pump-out takes 2 hours.
- The tank has a capacity of 5,000 gallons.
- There are two pipes: a 100-foot, 2"-diameter, fill pipe, and a 10-foot, 4"-diameter, pump-out pipe.

FIGURE 19. BASIC FAULT TREE FOR A 5000-GALLON UNDERGROUND STORAGE TANK

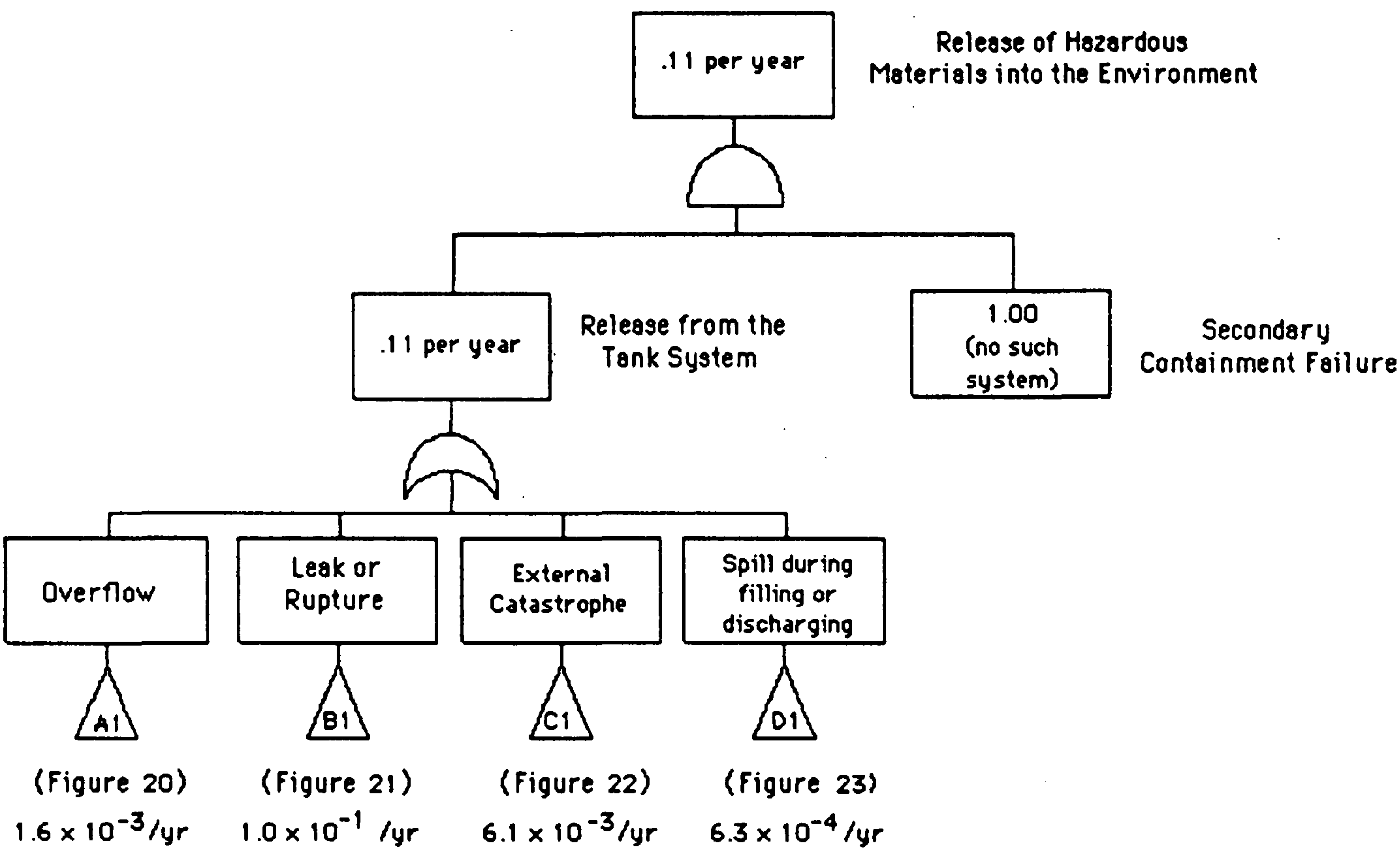


FIGURE 20A. OVERFLOWS FOR A 5000-GALLON UNDERGROUND STORAGE TANK

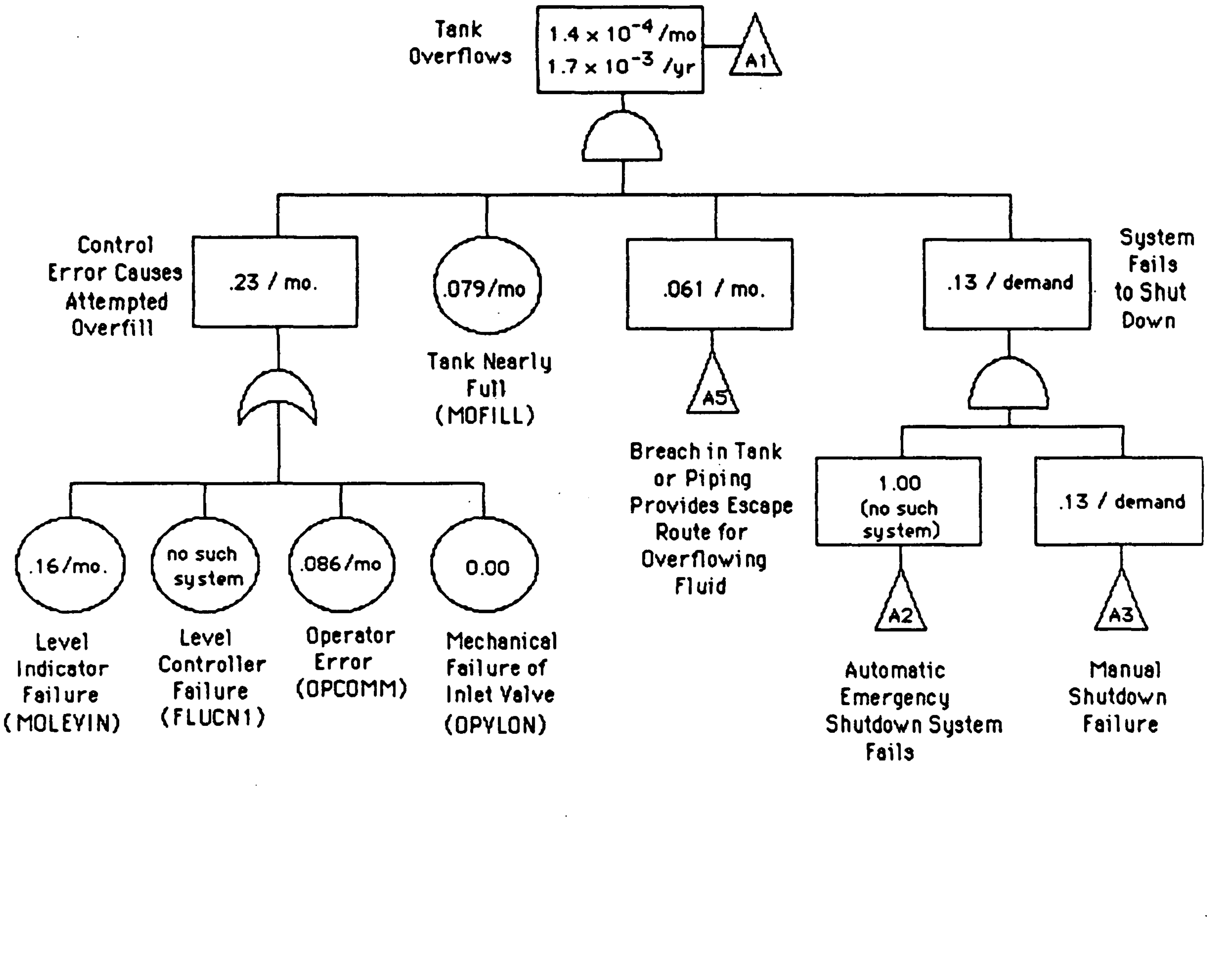


FIGURE 20B. OVERFLOWS FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

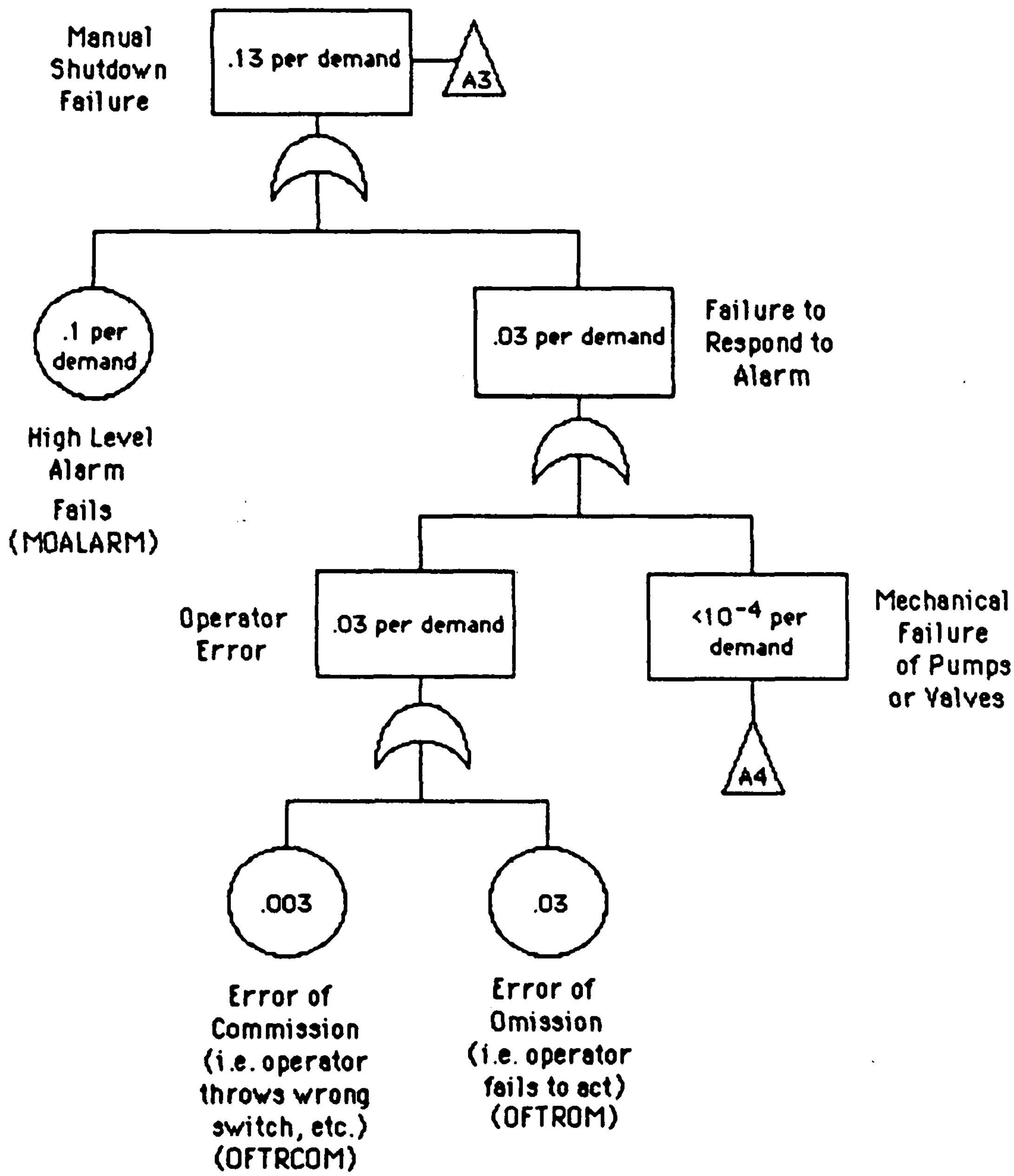


FIGURE 20C. OVERFLOWS FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

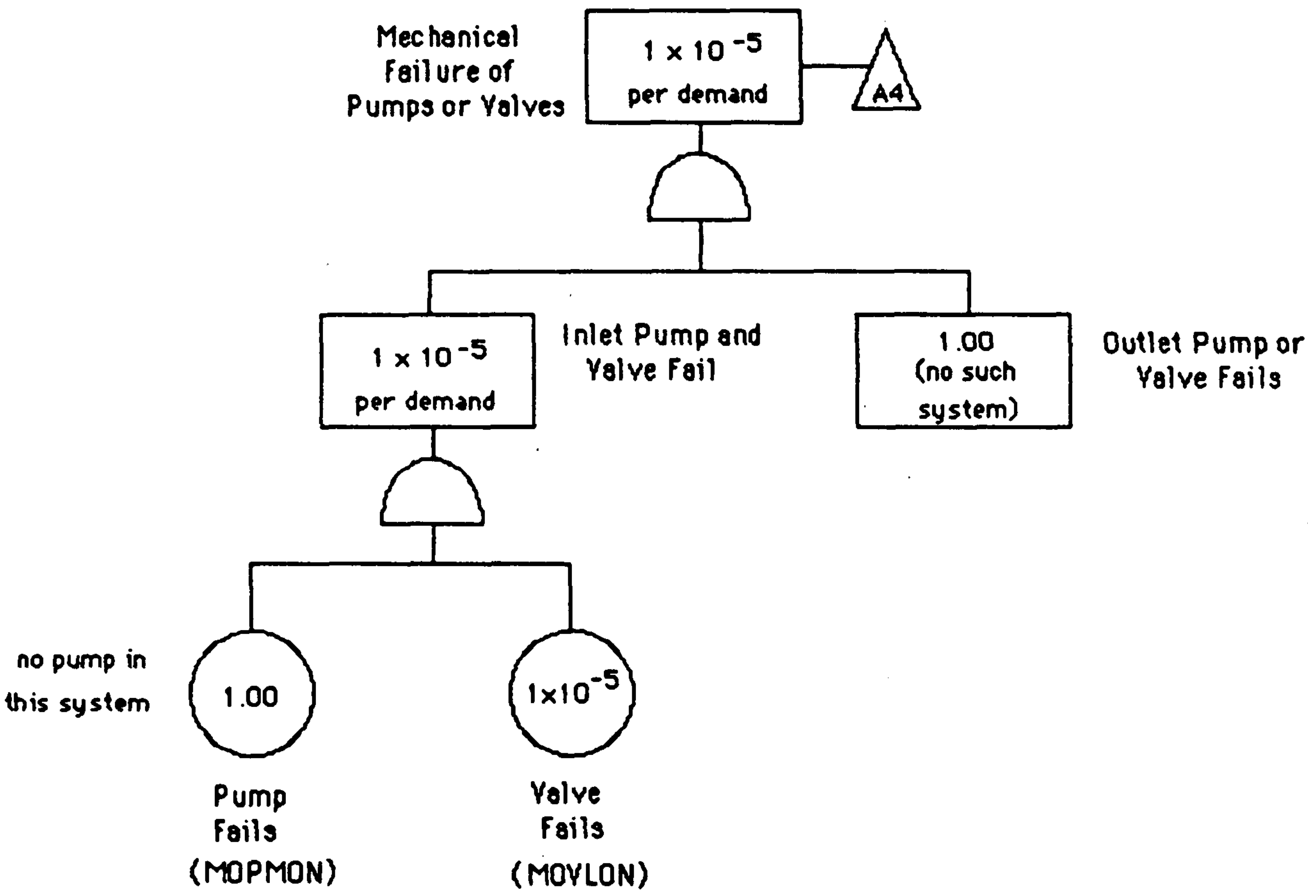


FIGURE 20D. OVERFLOWS FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

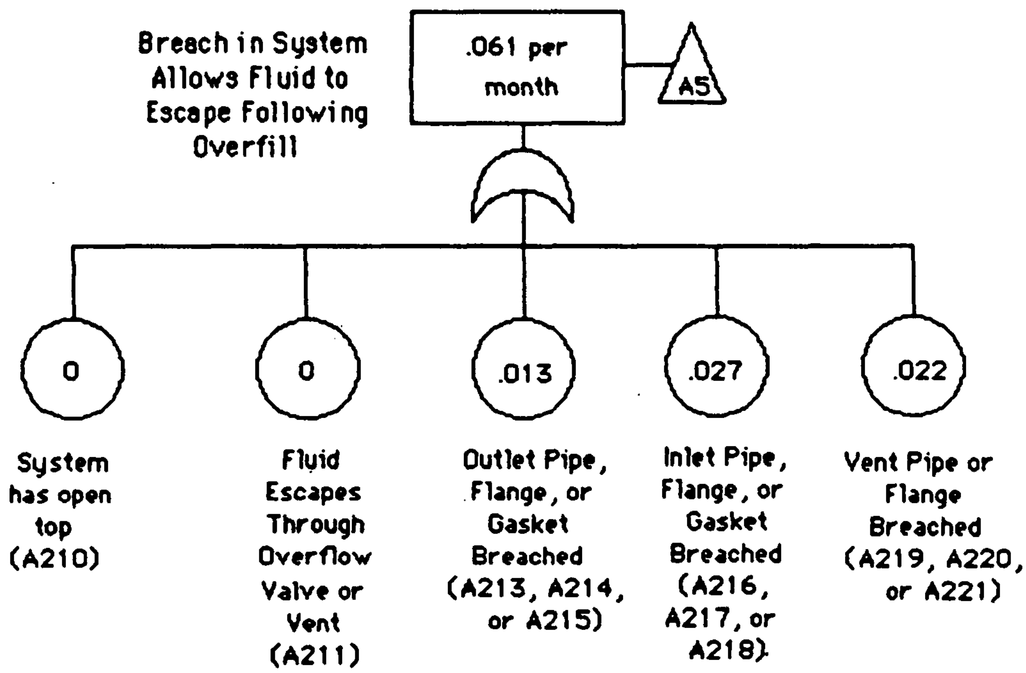


FIGURE 21A. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK

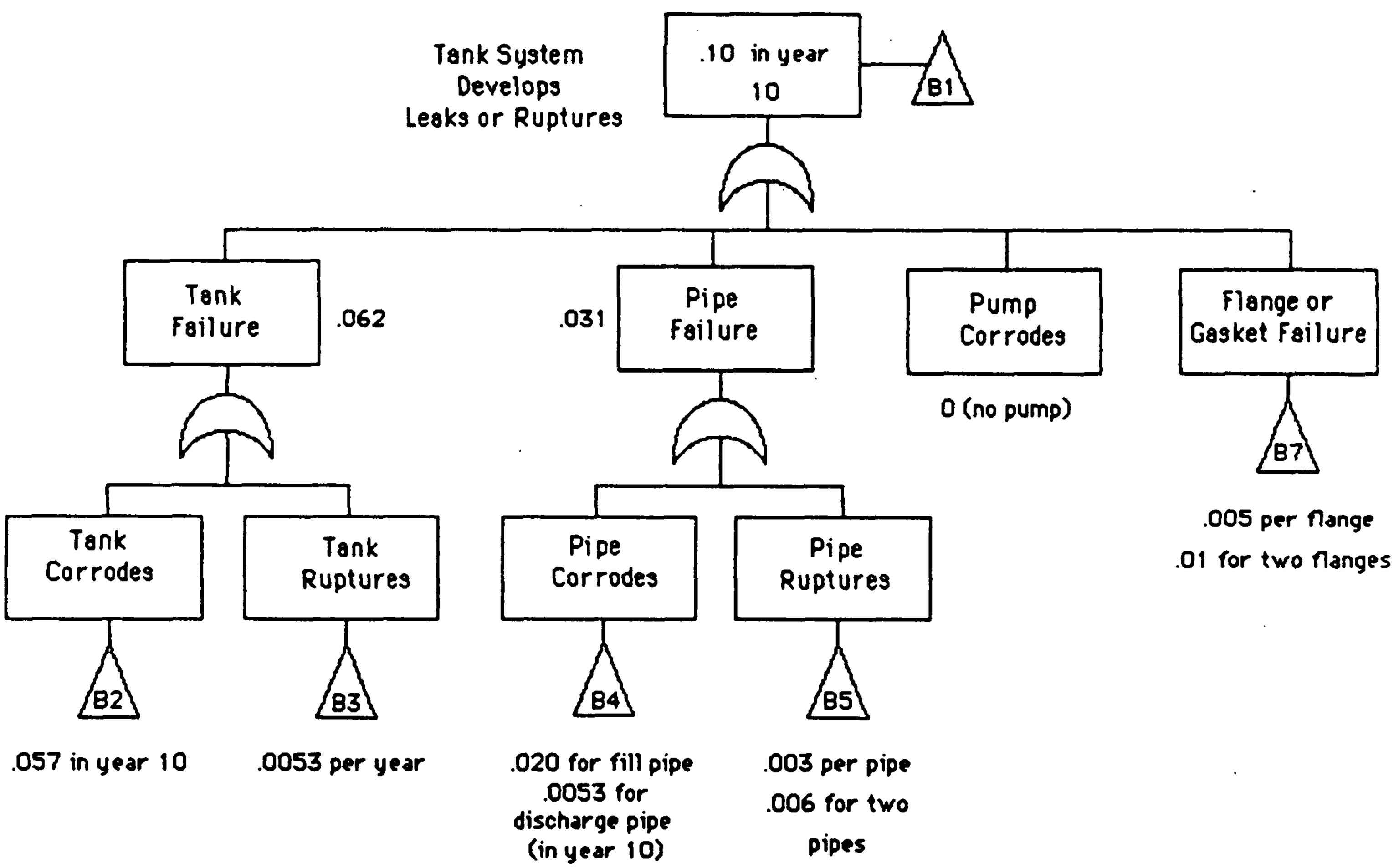


FIGURE 21B. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

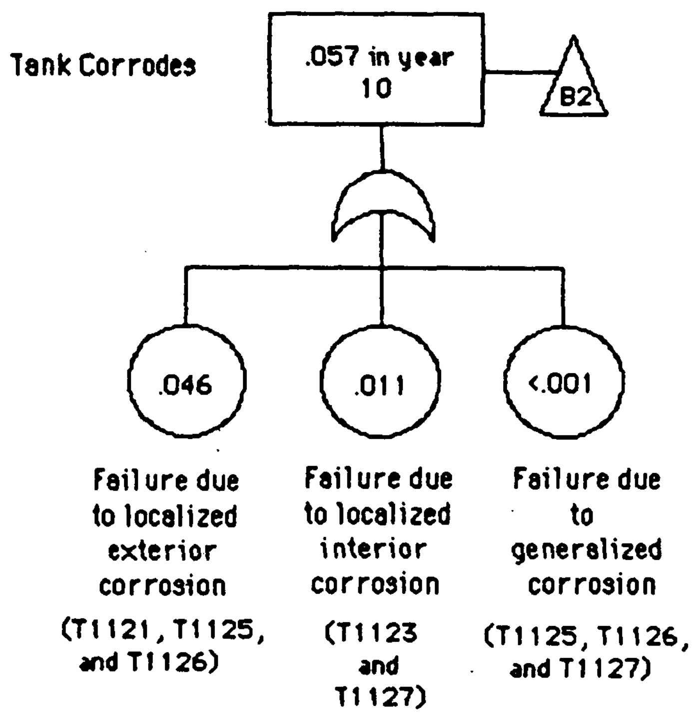


FIGURE 21C. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

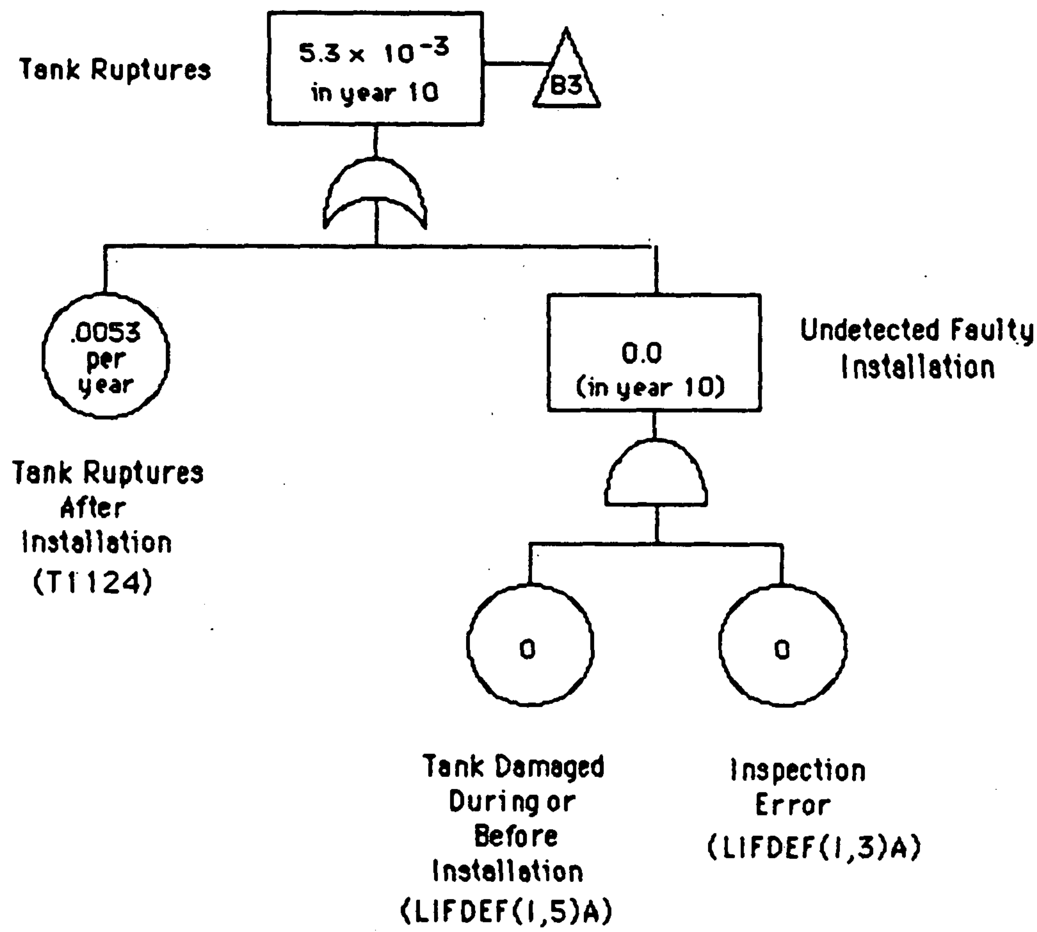


FIGURE 21D. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

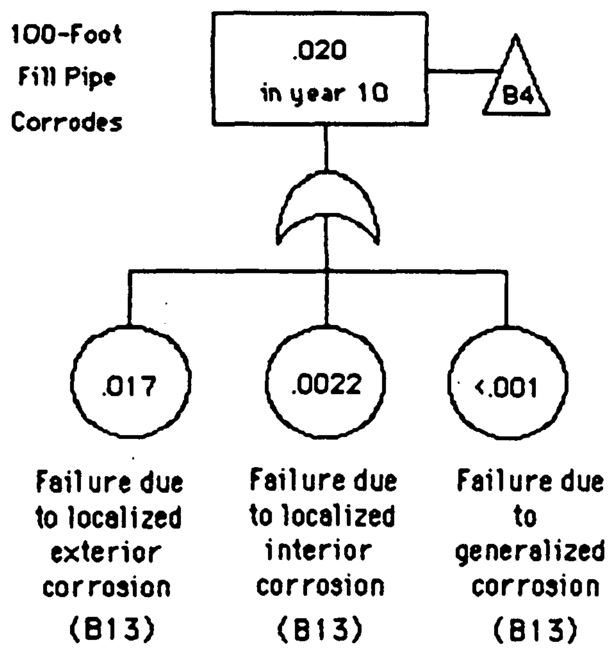


FIGURE 21E. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

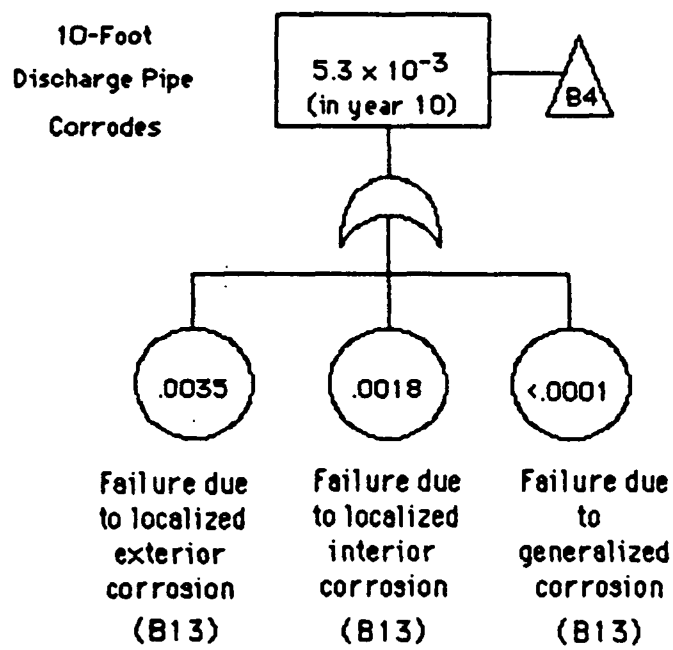


FIGURE 21F. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

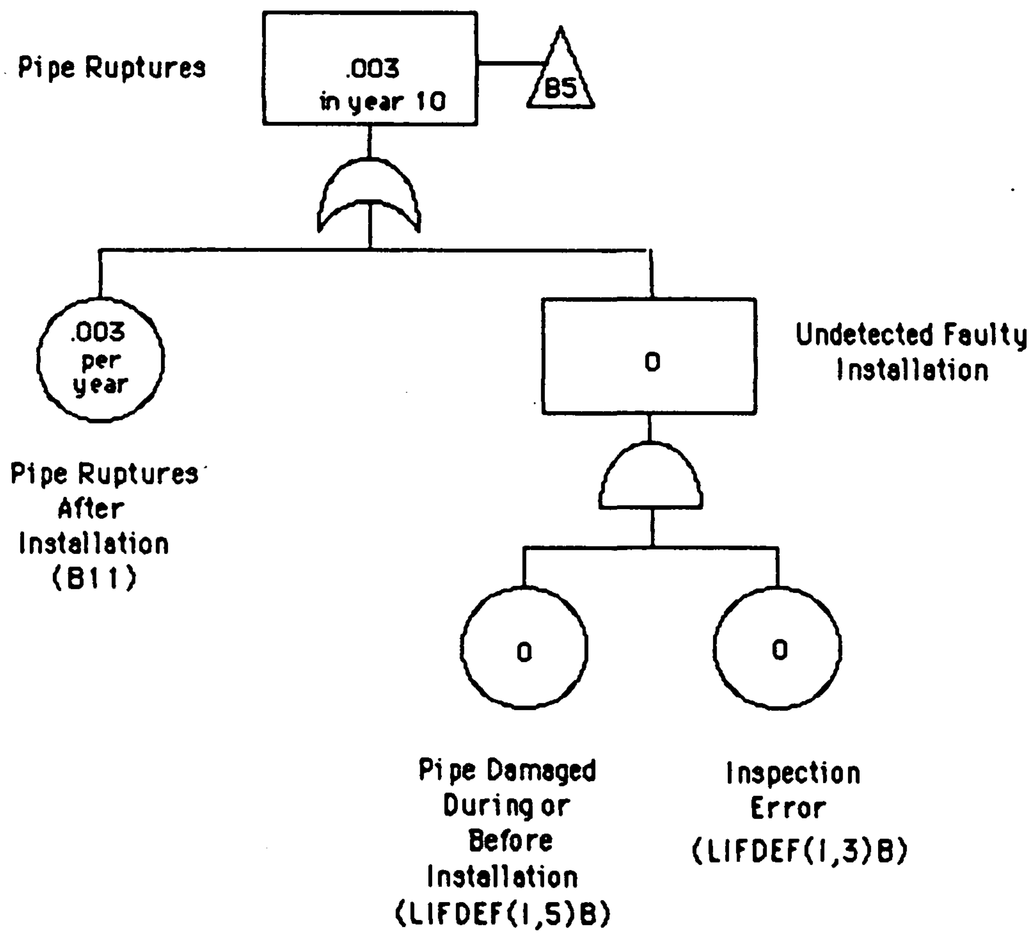


FIGURE 21G. LEAKS AND RUPTURES FOR A 5000-GALLON UNDERGROUND STORAGE TANK (cont.)

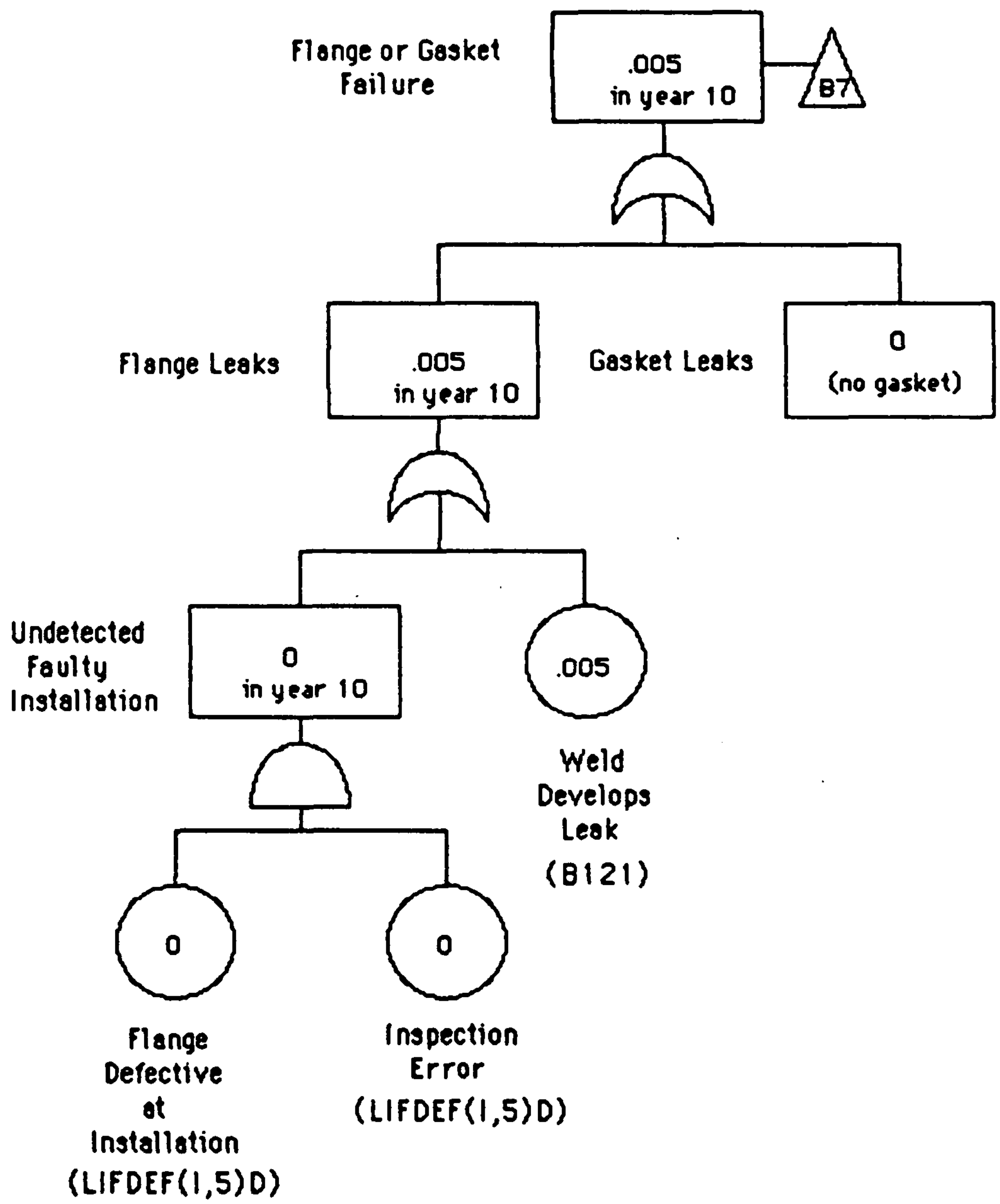


FIGURE 22. EXTERNAL CATASTROPHES FOR A 5000-GALLON UNDERGROUND STORAGE TANK

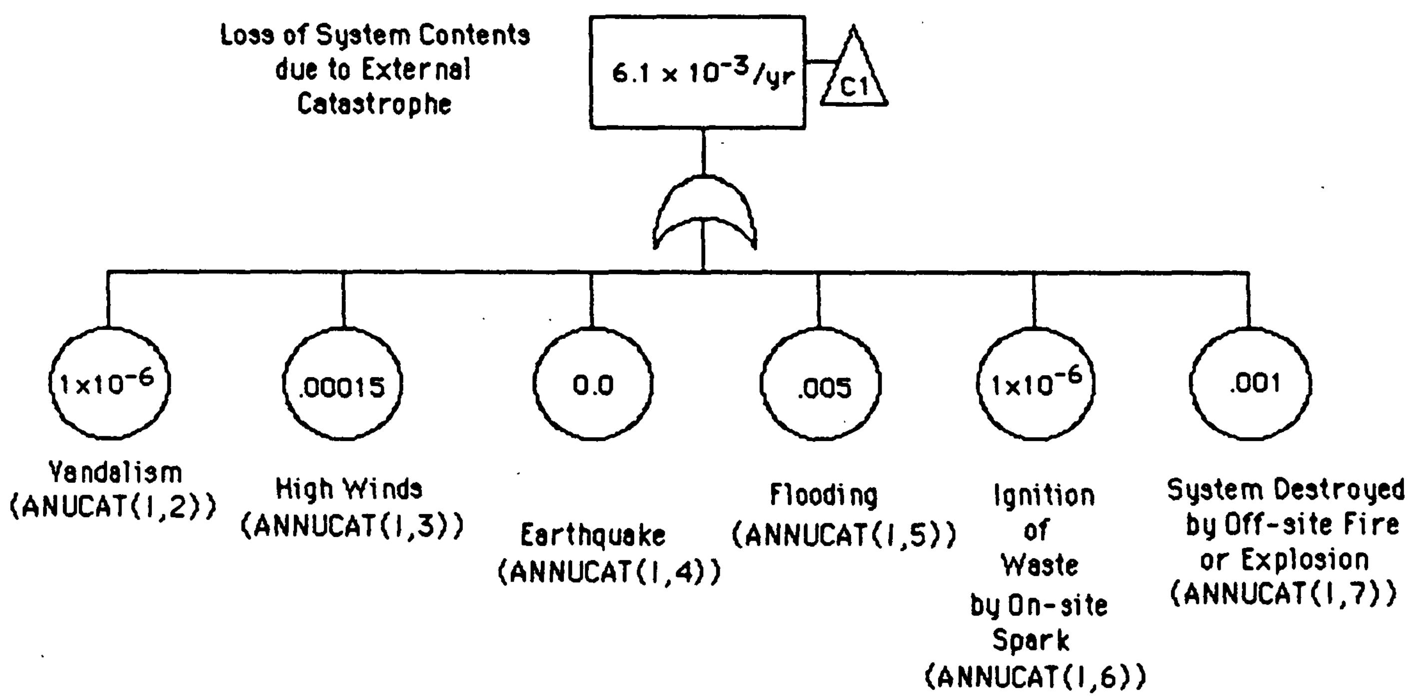
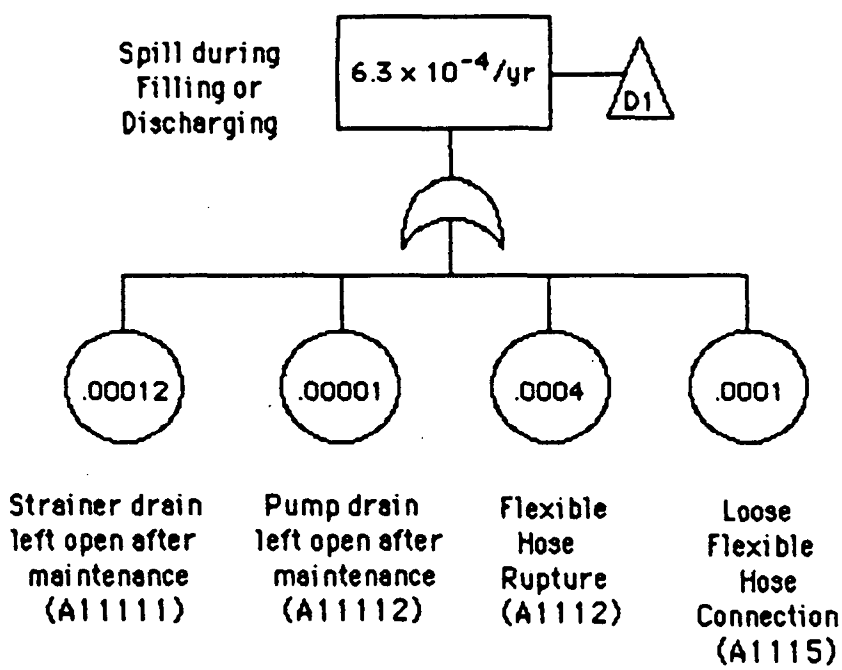


FIGURE 23. ACCIDENTAL SPILLS FOR A 5000-GALLON UNDERGROUND STORAGE TANK



- The soil around the pipes has a resistivity of 2000 ohm-cm and a pH of 5.
- The waste is flammable.
- The facility is located on a flood plain in a tornado region.

Based on these characteristics, we have computed the year-10 probabilities for each basic event and combined these probabilities to show the probabilities for intermediate and top events. In order to do this, we have replaced all time-to-failure distributions with these year-10 failure probabilities and have converted all monthly probabilities into annual probabilities.

To calculate the probabilities for the upper events on these fault trees, we had to take account of the presence of .AND. and .OR. gates. For events that are connected by .AND. gates, we calculated the upper-event probabilities by multiplying the initiating-event probabilities.

In the case of .OR. gates, the computation was more complex, requiring first the calculation of the probability that none of the events occurs, and then the subtraction of that probability from 1 in order to obtain the probability that one or more of the events occurred in some combination. Thus, for two events with probabilities p_1 and p_2, this probability is given by $[1-(1-p_1)x(1-p_2)]$. If p_1 and p_2, are small, this value can be approximated by $p_1 + p_2$. This simplification is generally sufficient whenever the algebraic sum is less than 0.1.

Figures 19-23 present a useful graphic depiction of the way that the probabilities and the fault trees relate. It must be realized, however, that such figures necessarily simplify the Monte Carlo model's approach to fault tree evaluation. These figures, for example, cannot allow for multiple occurrences of those events which the Monte Carlo model samples on a monthly basis. In addition, unlike the Monte Carlo model, such figures cannot account for the effects of prior failures on the year-10 failure probabilities, for these effects will vary from iteration to iteration. Instead, these figures are based simply on the failure distributions listed in Table 13, with no consideration of the possibility that a component might fail and be replaced prior to year 10.

With these caveats, however, Figures 19 through 23 still provide useful insights into the Hazardous Waste Tank Failure Model. They show, for example, that for underground storage tanks, leaks and ruptures are by far the most likely failure mechanisms. This does not mean, though, that all of the other failure mechanisms are unimportant; external catastrophes, for example, may be relatively unlikely, but when they occur, they produce large releases. Some release mechanisms, however, are comparatively unimportant. Accidental spills, for example are not only the least likely release mechanism, but they are also unlikely to involve large volumes (see Section 4.10 below). Similarly, overfills are unimportant loss mechanisms for underground storage tanks, for such tanks are infrequently filled to near capacity, and only have overflow routes if they are already leaking for other reasons. Thus, even though Figure 20B indicates that manual emergency shut-off systems have a 13% failure rate, these systems appear to be satisfactory for underground storage tanks.

Above-ground tanks, however, are much more likely to overflow, for their vents provide ready overflow routes. In addition, treatment tanks are also much more vulnerable to overflow, for not only are they generally above-ground, but they are also repeatedly filled nearly to capacity. Figure 24 therefore depicts the overflow fault tree for a batch treatment tank with manual controls. We assume that this tank operates 8 hours per day and processes 4 batches per day. Figure 25 depicts the overflow probabilities for a similar tank using a continuous process and automatic controls. These fault trees indicate that overflows are very probable for treatment tanks with manual shut-off systems, but less frequent for systems with automatic shut-off.

Probability calculations such as those illustrated in Figures 19 through 25 were very important to the development of our Monte Carlo model. Such calculations gave us benchmark failure rates against which to compare the results of the computer simulation. In addition they allowed us to determine visually which stochastic events deserved the most study.

These sensitivity analyses indicated that three failure mechanisms are particularly important: overflows, ruptures, and corrosion holes. We have

FIGURE 24A. OVERFLOWS FOR A 5000-GALLON TREATMENT TANK WITH 4 BATCHES PER DAY AND MANUAL SHUT-OFF

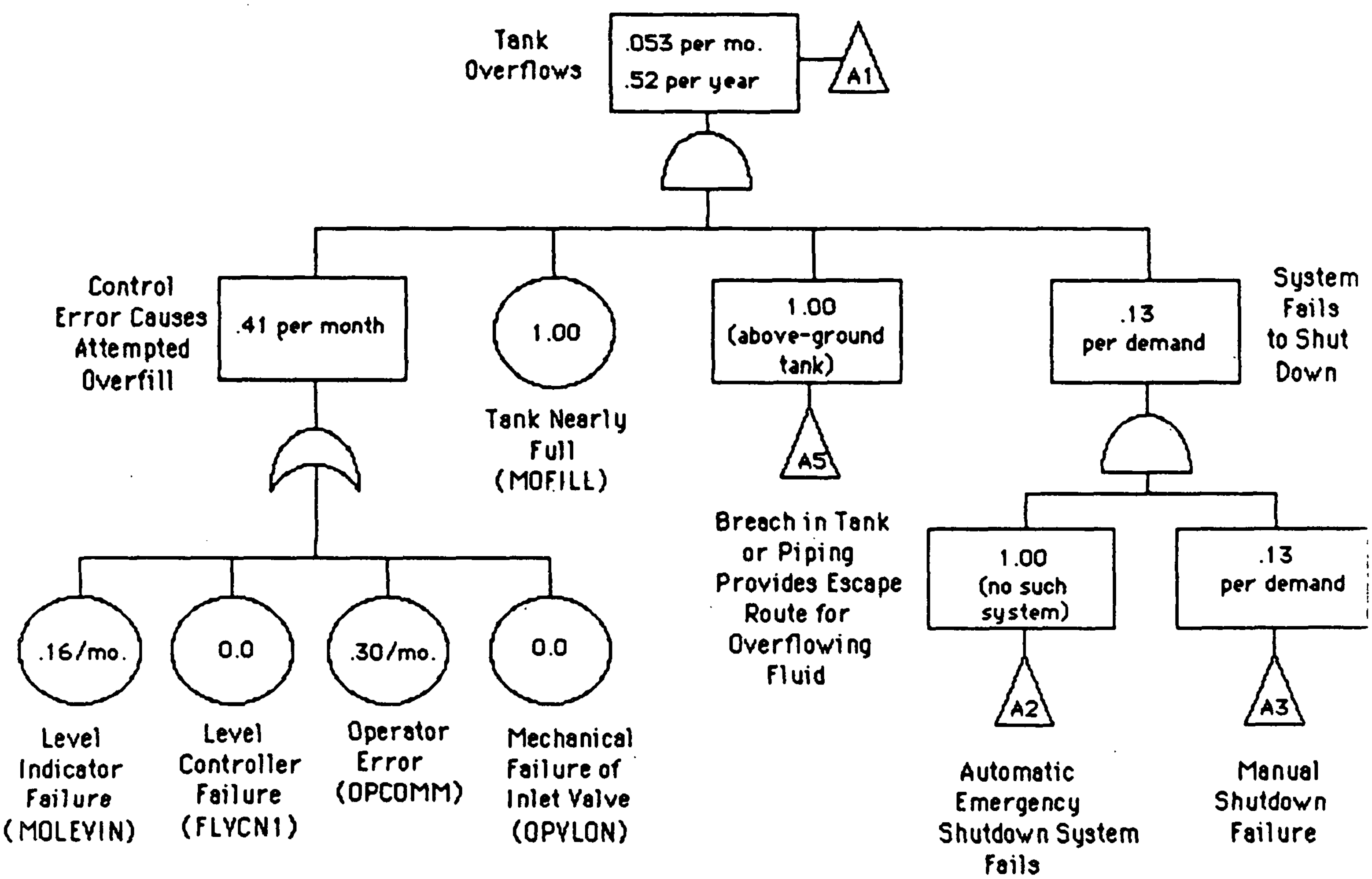


FIGURE 24B. OVERFLOWS FOR A 5000-GALLON TREATMENT TANK WITH 4 BATCHES PER DAY AND MANUAL SHUT-OFF

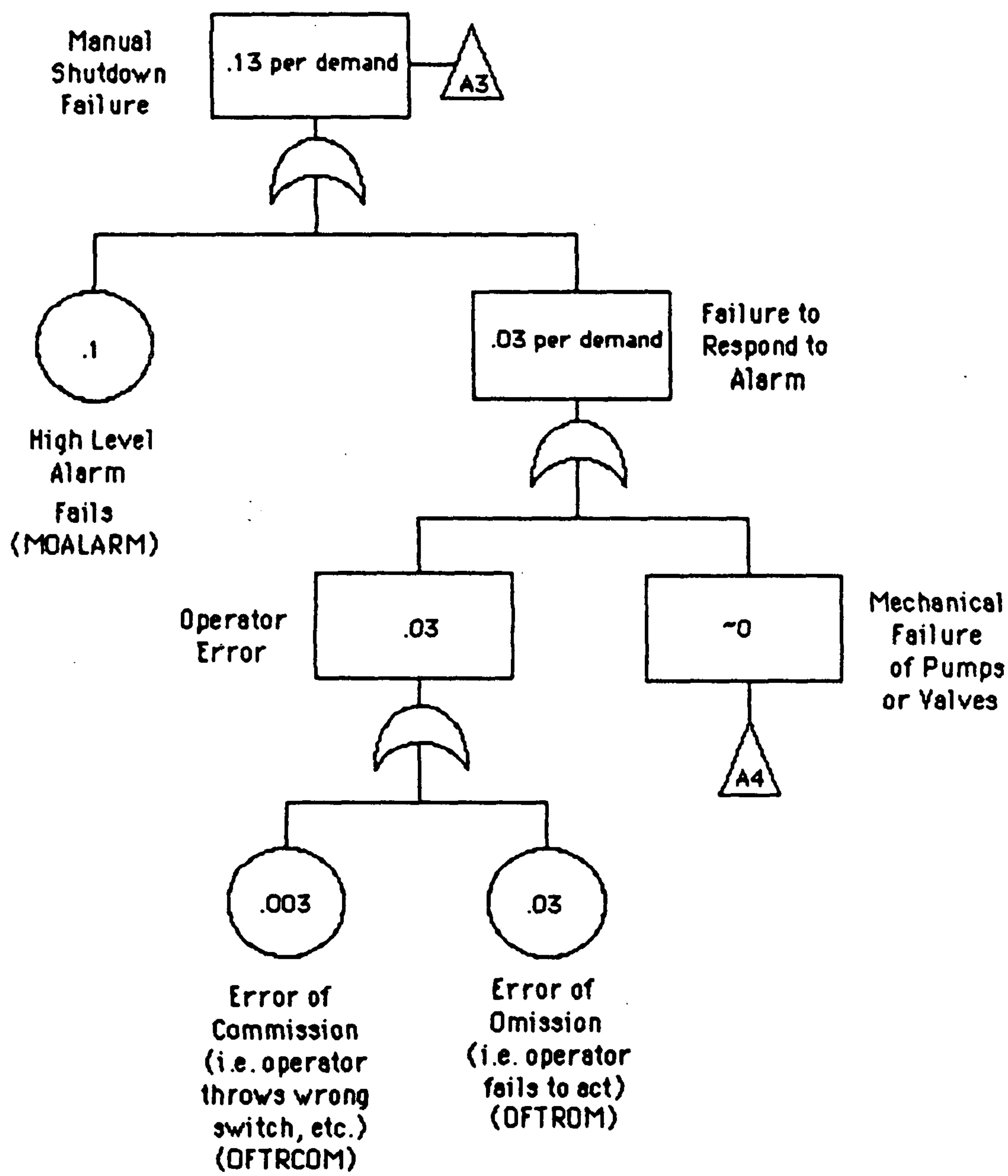


FIGURE 24C. OVERFLOWS FOR A 5000-GALLON TREATMENT TANK WITH 4 BATCHES PER DAY AND MANUAL SHUT-OFF

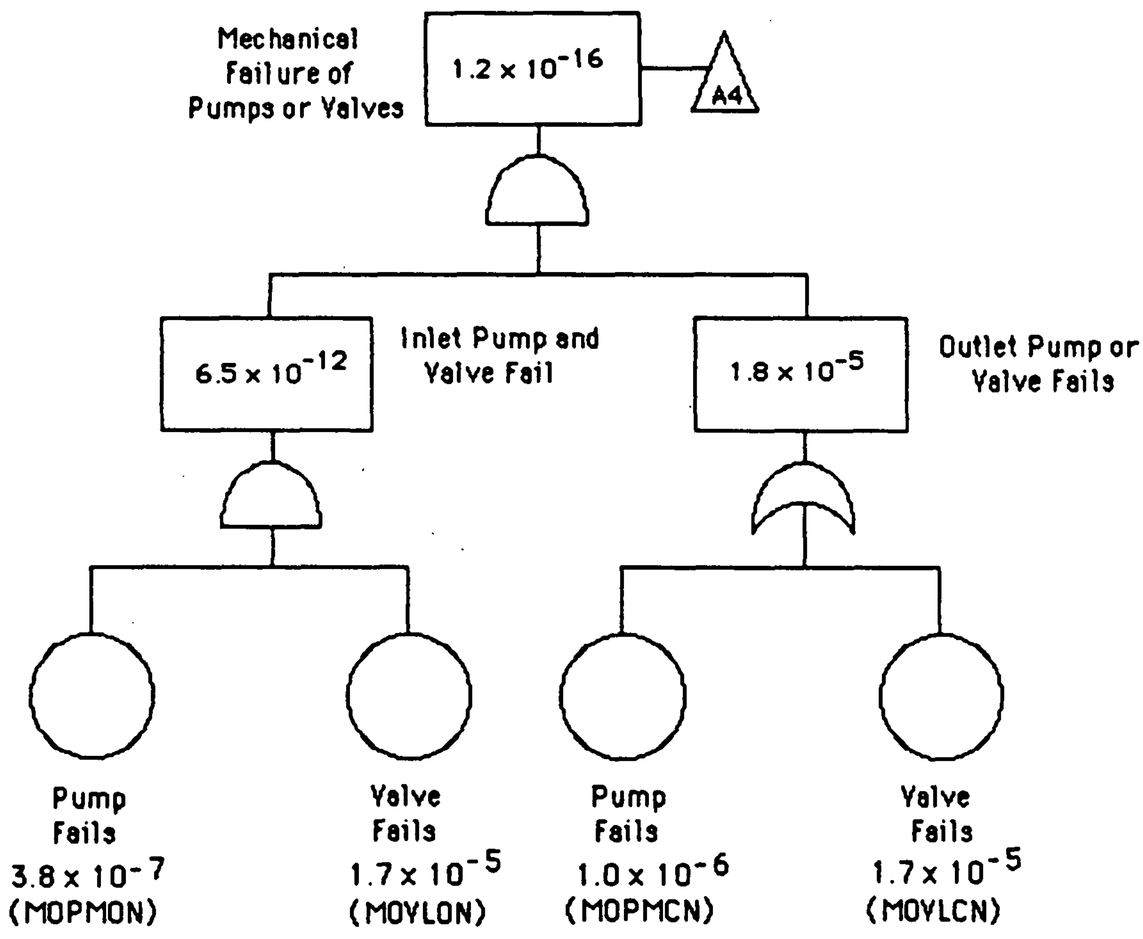


FIGURE 25A. OVERFLOWS FOR A 5000-GALLON TREATMENT TANK CONTINUOUS OPERATION WITH AUTOMATIC SHUT-OFF

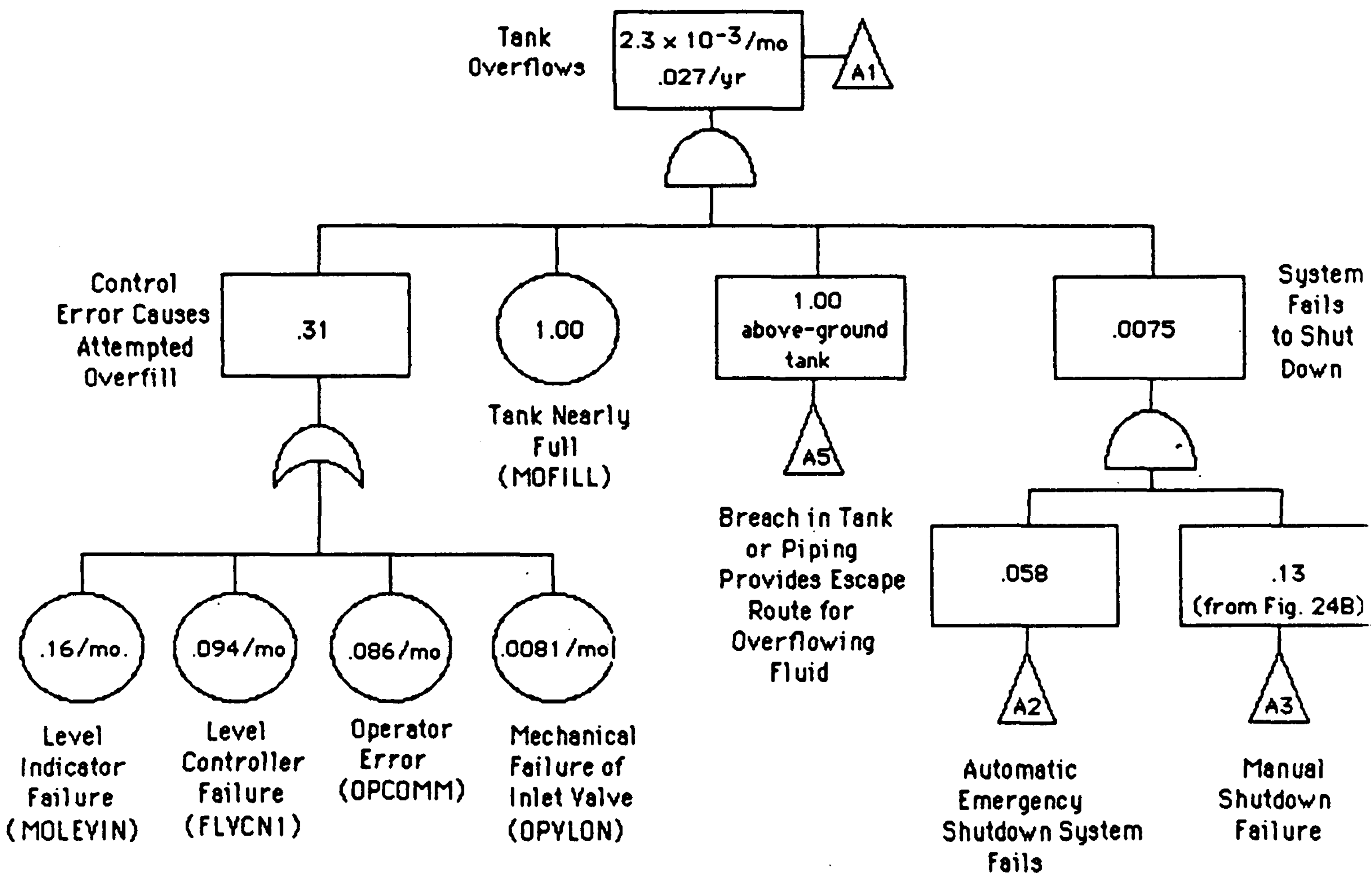
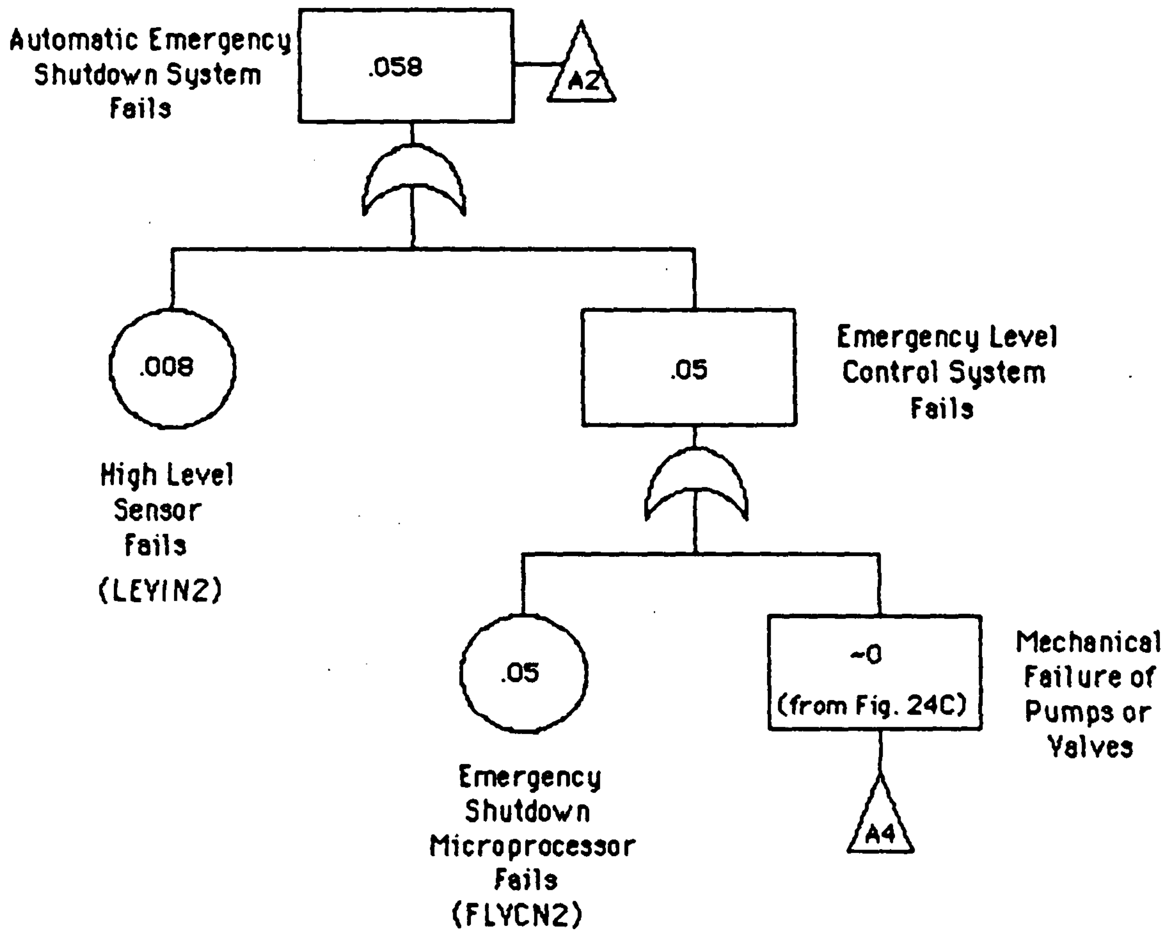


FIGURE 25B. OVERFLOWS FOR A 5000-GALLON TREATMENT TANK CONTINUOUS OPERATION WITH AUTOMATIC SHUT-OFF



already described overflows in this section and in Chapter 3; we will describe corrosion in Sections 4.5 through 4.9. We will discuss ruptures in the remaining portions of this section.

Rupture probabilities are listed in Table 13 for tanks and pipes. Welded flange leaks are also a form of rupture. In deriving our rupture probabilities we have assumed that ruptures may result from a large variety of causes, such as settling, freeze/thaw action, vehicle collision, or faulty construction materials. Some of these factors, such as the cumulative effects of freeze/thaw action, become increasingly important as equipment ages; others, such as settling, become increasingly unlikely. We assume, therefore, that these conflicting aging effects cancel out, and that rupture probabilities are dominated by external events that are uncorrelated to the age of the component. For this reason, we have treated installation damage separately from ordinary ruptures, even though the physical damage from the two types of failures is likely to be similar. By modeling these two events separately, we in essence use installation damage to increase the probability of rupture in year 1 while still assuming that ordinary ruptures are equally likely in any year.

Table 13 lists separate rupture probabilities for pipes and tanks constructed of steel, stainless steel, and fiberglass. As that table shows, we have assumed that steel and stainless steel are equally likely to rupture; stainless steel may be resistant to corrosion, but it is not significantly stronger than ordinary carbon steel. Based on discussions with contractors, however, we have concluded that fiberglass is approximately twice as likely to rupture as is steel. We have therefore applied this ratio to our rupture and installation damage probabilities for both tanks and pipes.

Rupture mechanisms are different for above- and below-ground systems. Above-ground ruptures are most likely to occur due to vehicle collisions, collisions with fork lifts, freeze/thaw attack, or latent flaws in design, fabrication, or installation. Below-ground ruptures are most likely to result from settling, latent defects, or the driving of heavy equipment across the site. These rupture mechanisms are different, but we have assumed that their combined probabilities are approximately equal for above- and below-ground systems.

In addition, we have assumed that rupture probabilities are independent of tank capacity and pipe length. We make this assumption because components are designed to accommodate the normal range of operating stresses. Thus, design strengths should increase with tank capacity and pipe strength. We assume that the increased design strength for larger components cancels out the increased stresses to which they are subject, so that rupture probabilities are independent of system design.

Table 13 also lists rupture probabilities for double-walled tanks and pipes and concrete tanks. For double-walled components, we model the inner and the outer walls separately, but we assume that there is a 50% probability that a breach of the outer wall will also breach the inner wall. Because the inner wall is subject to fewer stresses than is the outer wall, we assume that a rupture is less likely to begin with the inner wall than with the outer wall. In addition, because operating pressures in hazardous waste tanks are generally low, we assume that only an insignificant fraction of ruptures initiating with the inner wall also breach the outer wall.

Concrete tanks are also subject to rupture, though in this case, these failures are more commonly referred to as cracks. Because the cracking of concrete is an age-dependent process, Table 13 lists a time-to-failure distribution rather than a binomial probability. This time-to-failure distribution is N(35,10). We chose it based on telephone conversations with concrete contractors and state highway officials. Our subsequent research has indicated that this time-to-failure distribution should vary with the design life of the tank. Thus, our failure distribution is probably an adequate approximation for the 20-year design life assumed by our original sources, but probably results in too many failures for 30- or 40-year design lives.

4.5 Tank Corrosion Model

Our Monte Carlo model can simulate above-, below-, and in-ground tank systems constructed of carbon steel, stainless steel, fiber-glass reinforced plastic (FRP), or concrete. We can also model a variety of corrosion protection systems, including:

- interior coatings;
- exterior coatings;
- cathodic protection; and
- interior and/or exterior corrosion with cathodic protection.

For ease of reference, the effects of these options are summarized for four different corrosion mechanisms in Tables 14 through 17. The following subsections will discuss these mechanisms in detail.

Underground Tanks

Steel tanks. For underground steel tanks, we have distinguished four basic corrosion mechanisms: localized exterior corrosion, generalized exterior corrosion, localized interior corrosion, and generalized interior corrosion.

Localized exterior corrosion is the most important of these processes. Like the other forms of corrosion, it is an electrochemical reaction involving a flow of current between the tank and the surrounding environment. When localized corrosion occurs, however, one or more irregularities in the tank surface or the surrounding soil channel the normal flow of current through a small area, accelerating the rate of corrosion. These irregularities are called point anodes, and they may result from local variations in soil pH, scratches in the tank wall, or stones or cinders in contact with the tank. In theory, a properly installed tank should have no point anodes. In practice, 70% to 85% of tanks do experience localized corrosion. Our localized exterior corrosion model is based on exterior corrosion data collected by the Petroleum Association for conservation of the Canadian Environment (PACE).

The PACE data consists of a survey of 108 leaking and 192 non-leaking underground service station tanks, giving the age of each tank and the aggressiveness of the soil in which it is buried. This survey data can be

TABLE 14. EFFECT OF TANK DESIGN ON LOCALIZED EXTERIOR CORROSION

Tank Design	Effect on Localized Exterior Corrosion Rate
BELOW-GROUND	
Carbon Steel	PACE Baseline corrosion rate, increased by $(A/440)^{.16}$ to account for tank surface area variations.
Stainless steel	Corrosion rate is 25% of the rate applicable to below-ground carbon steel tanks.
Fiberglass reinforced plastic (FRP)	Does not corrode. Probabilities of rupture and installation damage are double those used for steel.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Exterior coating	Delays onset of localized exterior corrosion by N(7,3) years (for all tank sizes). Localized corrosion begins with certainty following coating failure.
Cathodic protection	Delays onset of corrosion by m·N(10,5) years, where m = FNU (1,3) is a stochastically determins the level of cathodic protection maintenance. Once cathodic protection fails, corrosion follows PACE baseline.
Exterior coating with cathodic protection	Delays onset of corrosion until both cathodic protection and coating fail. Localized corrosion begins with certainty following corrosion-protection failure.
Stray currents	There is a 10% chance of stray currents at the site. If they exist, they will increase corrosion rate by a factor of x = B(1,2,4)

TABLE 14. EFFECT OF TANK DESIGN ON LOCALIZED EXTERIOR CORROSION (Continued)

Tank Design	Effect on Localized Exterior Corrosion Rate
ABOVE-GROUND (on cradles)	
Carbon steel	Corrode like low-SAV underground tanks of 5% as large a surface area.
Stainless steel	Corrodes at 25% of the rate applicable to above-ground carbon steel tanks.
Fiberglass reinforced plastic (FRP)	Does not corrode. Probabilities of rupture and installation damage are double those used for steel.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Exterior coating	Delays onset of corrosion by N(9,3) years (for all tank sizes). Localized corrosion begins with certainty following coating failure.
Cathodic protection	Does not affect above-ground tanks.
Stray currents	Do not affect above-ground tanks.
ABOVE-GROUND (on-grade)	Above-grade section corrodes like an above-ground tank of similar surface area; on-grade section corrodes like a below-ground tank of similar surface area. We only model the below-ground section, however, because it corrodes more quickly.
IN-GROUND	Above-grade section corrodes like above-ground tanks of similar surface area; below-grade section corrodes like below-ground tanks of similar surface area. The above- and below-grade portions are modeled independently.

TABLE 15. EFFECT OF TANK DESIGN ON GENERALIZED EXTERIOR CORROSION

Tank Design	Effect on Generalized Exterior Corrosion Rate
BELOW-GROUND	
Carbon steel	Corrosion rate in mils/yr is given by: $\max [1.4, \frac{SAV}{10} FNU (1.4,5)]$
Stainless steel	Corrosion rate is 25% of the rate applicable to below-ground carbon steel tanks.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Exterior coating	Delays onset of generalized exterior corrosion by N(7,3) years. After coating fails, generalized exterior corrosion is same as for a new, uncoated tank.
Cathodic protection	Delays onset of generalized exterior corrosion until cathodic protection system fails. (See Table 14). Once the cathodic production system fails, the tank corrodes like a new, unprotected tank.
Exterior coating with cathodic protection	Delays onset of generalized exterior corrosion until both cathodic protection and the coating fail. After corrosion protection fails, generalized exterior corrosion is the same as for a new, unprotected tank.
Stray currents	Increase generalized exterior corrosion rate by same factor as applies to localized exterior corrosion.

TABLE 15. EFFECT OF TANK DESIGN ON GENERALIZED EXTERIOR CORROSION (Continued)

Tank Design	Effect on Generalized Exterior Corrosion Rate
ABOVE-GROUND (on cradles)	
Carbon steel	Corrodes at 1.4 mils/yr.
Stainless steel	Corrodes at .35 mils/yr
Fiberglass reinforced plastic (FRP)	Does not corrode.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Exterior coating	Delays onset of corrosion by N(9,3) years (for all tank sizes). Following coating failure, generalized exterior corrosion is the same as for a new, uncoated, above-ground tank.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once the cathodic protection system fails, the tank corrodes like a new, unprotected tank.
Exterior coating with cathodic protection	Delays onset of corrosion until both cathodic protection and coating fail. After corrosion-protection fails, generalized exterior corrosion is the same as for a new, unprotected tank.
Stray currents	No effect on above-ground tanks.
ABOVE-GROUND (on-grade)	Above-grade section corrodes like an above-ground tank of similar surface area; on-grade section corrodes like a below-ground tank of similar surface area. We only model the below-ground section, however, because it corrodes more quickly.
IN-GROUND	Above-ground section corrodes like above-ground tank; below-ground section corrodes like below-ground tank. We only model the below-ground section, however, because it corrodes more quickly.

TABLE 16. EFFECT OF TANK DESIGN ON LOCALIZED INTERIOR CORROSION

Tank Design	Effect on Localized Interior Corrosion Rate
BELOW-, ABOVE-, and IN-GROUND	
Carbon steel	Corrodes beneath fill pipe with a conditional normal distribution of .15N(8,5) years. Tank surface area has no effect.
Stainless steel	Corrodes at 25% of the rate applicable to carbon steel tanks.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Interior coating	Delays onset of corrosion by N(7,3) years. After the coating fails, interior corrosion occurs at the rate applicable to a new, uncoated tank.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once the cathodic protection system fails, the tank corrodes like a new, unprotected tank.
Interior coating with cathodic protection	Delays onset of corrosion until both cathodic protection and coating fail. After corrosion-protection fails, tank corrodes like a new, unprotected tank.
Stray currents	Have no effect on interior corrosion.

TABLE 17. EFFECT OF TANK DESIGN ON GENERALIZED INTERIOR CORROSION

Tank Design	Effect on Generalized Interior Corrosion
BELOW-, ABOVE-, or IN-GROUND	
Carbon steel	Corrode according to the following empirical distribution:
	Probability: 0.00 to .65 — Corrosion rate (mils/yr): 2
	Probability: .65 to .90 — Corrosion rate (mils/yr): FNU(2,10)
	Probability: .90 to 1.00 — Corrosion rate (mils/yr): FNU(10,20)
Stainless steel	Corrodes at 25% of the rate applicable to carbon steel.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Concrete	Generalized break-up (modeled as a rupture) after N(35,10) years. Seeps continuously.
Interior coating	Delays onset of corrosion by N(7,3) years. After coating fails, corrosion occurs at the rate applicable to a new, uncoated tank.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once the cathodic protection system fails, the tank corrodes like a new, unprotected tank.
Interior coating with cathodic protection	Delays onset of corrosion until both cathodic protection and coating fail. After corrosion-protection fails, tank corrodes like a new, unprotected tank.
Stray currents	Have no effect on interior corrosion.

converted into time-to-failure distributions for tanks in aggressive, moderate, and benign soils. The resulting distributions are presented in Table 18. In this table, soils are classified according to soil aggressiveness value (SAV), which is a numerical index developed by PACE to measure soil corrosivity. The calculation of SAV is detailed in Table 19. Further information about the PACE data, including the derivation of the time-to-failure distributions, is presented in Appendix A.

These time-to-failure distributions, however, are merely the starting points for the corrosion model. These distributions apply directly only to existing service station tanks, which at the time of the survey (1977) were usually constructed of quarter-inch bare steel. Since hazardous waste tanks may have other wall thicknesses, the PACE time-to-failure distributions must therefore be generalized. We accomplish this by sampling a time-to-failure from the PACE distribution and then dividing it into .25 inches to obtain a stochastically-determined corrosion rate, which we can then apply to tanks of thickness other than .25 inches. We then tally annual corrosion allotments, and when remaining wall-thickness reaches zero, the model determines that a corrosion failure has occurred.

We account for the fact that some tanks do not experience point corrosion by assuming that those tanks which have not failed by the end of 30 years are free of point anodes. Thus, 30.1% of the tanks in benign soils have a localized corrosion rate of zero, as do 23.4% of those in moderate soils, and 16.7% of those in aggressive soils. (We obtained these percentages by subtracting the year-30 cumulative failure probabilities from 1.00.) This does not mean that exterior corrosion does not occur in these tanks; rather, it means that corrosion will occur by a slower mechanism. This mechanism is generalized exterior corrosion.

Generalized exterior corrosion is a gradual loss of material over the entire tank surface. We assume that generalized exterior corrosion occurs at least as quickly underground as it does in air, but that except in unusually aggressive soils, it alone is unlikely to cause a quarter-inch tank to fail in less than 50 years. (Source: "Rogers Finds Leaks by Using Statistics," Petroleum Marketer, Nov./Dec., 1982, pp. 17-19.) This means

TABLE 18. CUMULATIVE TIME-TO-FAILURE DISTRIBUTIONS FOR QUARTER-INCH UNDERGROUND STEEL TANKS

	Cumulative Probability of Failure (%)		
Tank Age	Benign Soil (SAV ≤ 6)	Moderate Soil (7 ≤ SAV ≤ 12)	Agressive Soil (SAV > 13)
4	0	0	0
9	0	11.1	26.7
14	6.3	29.1	49.9
19	24.0	54.3	76.5
24	48.3	67.3	79.9
30	69.9	76.6	83.3

Note: the model obtains intermediate values by interpolation.

Source: PACE and Appendix A and F.

Caveat: This data applies only to 5,000 and 10,000 gallon service station tanks. Furthermore, the PACE survey was not conducted under statistically controlled methodologies, so the results may be biased. See Appendix F for further caveats.

Table 19. COMPUTATION OF SAV

		POINTS
I. BASIC CHARACTERISTICS		
• Soil Resistivity	<300	12
	300 - 1,000	10
	1,000 - 2,000	8
	2,000 - 5,000	6
	5,000 - 10,000	3
	10,000 - 25,000	1
	>25,000	0
• Soil pH	<3	8
	3 - 5	6
	5 - 6.5	4
	6.5 - 7.5	2
	7.5 - 9	1
	>9	0
• Soil Moisture	Saturated	3
	Damp	2
	Dry	0
II. DIFFERENTIAL CHARACTERISTICS		
• Soil Resistivity (ratio of extremes)	>1:10	3
	>1: 5	2
	>1: 3	1
	<1: 3	0
• Soil pH (Difference in pH Value)	3	2
	1.5 - 3	1
	0 - 1.5	0
III. SULFIDES		
	Positive	4
	Negative	0

Source: Petroleum Association for Conservation of the Canadian Environment (1983).

that the generalized exterior corrosion rate lies somewhere between 1.4 mils per year (the generalized corrosion rate in an air environment according to Ailor, 1982) and 5.0 mils per year (the rate required for a quarter-inch tank to fail in 50 years). We assume that the corrosion rate is uniformly distributed between these two values. In addition we assume that this corrosion rate varies proportionally to SAV, but that even in the most benign soils, the generalized exterior corrosion rate cannot be less than 1.4 mils per year. Mathematically, all of these assumptions can be expressed in a single equation:

$$\text{corrosion rate (in mil/yr)} = \max[1.4, \frac{\text{SAV}}{10} \text{FNU}(1.4,5)]$$

where 10 is the average value of SAV for all 300 of the PACE tanks, and the notation max[ ] means the maximum of the two values in the brackets. Note that for the average tank (SAV = 10), this distribution collapses to FNU(1.4,5).

Because both generalized and localized exterior corrosion are electrochemical processes, they may be accelerated by stray DC currents from improperly grounded motors or nearby electric rail lines. Based on conversations with Warren Rogers of Warren Rogers Associates, we have concluded that there is approximately a 10% chance that such equipment will be close enough to interfere with any given tank system. In addition, we have concluded that stray currents approximately double the rates of both localized and generalized exterior corrosion. More specifically, we have assumed that stray currents increase the corrosion rate by a multiplicative factor of x, where x is a random number drawn from a beta distribution with a minimum of 1, a mode of 2, and a maximum of 4. The resulting distribution could be termed a "conditional beta," where the 10% binomial probability determines the existence of stray currents and the beta distribution determines their intensity. Since these results will apply to the entire tank facility, we use the same value of x for all of the system's underground components, including tanks, pipes, and ancillary equipment.

In addition to exterior corrosion, tanks are also vulnerable to interior corrosion. This corrosion may be localized or generalized, and may result from a variety of causes, including materials defects, poor seam construction, accumulated grit or sludge, or acids generated by anaerobic bacteria living near the bottom of the tank.

Data collected by the American Petroleum Institute (API) indicates that localized interior corrosion occurs in only 15% of service station tanks. If it occurs, localized internal corrosion is probably a more rapid process than localized external corrosion, so we have assigned it a conditional time-to-failure distribution of .15 N(8,5) (see Appendix A). We can obtain an average corrosion rate by sampling this distribution and dividing the time-to-failure into .25", as we did for localized exterior corrosion. We can then apply this corrosion rate to tanks of any thickness. Note that for the 85% of tanks which do not experience localized interior corrosion, the localized internal corrosion rate is zero.

Generalized interior corrosion, however, always occurs at a non-zero rate. According to the sources cited in Appendix A, this form of corrosion is likely to range from 2 to 20 mils per year. Because we believe that lower corrosion rates are the most likely, we have used this information to construct the following empirical distribution of generalized interior corrosion rates:

Cumulative Probability	Corrosion rate (mils/yr)
0 to .65	2
.65 to .90	FNU(2, 10)
.90 to 1.00	FNU(10, 20)

All four corrosion mechanisms may act simultaneously. If this is the case, we must combine their individual corrosion rates to determine the overall effect. In doing this however, it is not proper to simply add all four corrosion rates together; that would implicitly assume that localized interior and localized exterior pits occur at the same place -- a highly unlikely event. Furthermore, because the PACE and API data were obtained from empirical observations rather than theoretical computations, it is likely that our localized exterior and localized interior corrosion rates already include their respective generalized corrosion rates.

Thus, only certain combinations of corrosion mechanisms need to be considered. Generalized interior corrosion must be added to localized exterior corrosion (in most cases this will have little effect on the failure date, but in a few instances it will allow a localized exterior pit to corrode through more quickly if the interior wall is undergoing unusually rapid generalized corrosion), and generalized exterior corrosion must be added to localized interior corrosion (accounting for those occasions when an interior pit reaches a rapidly corroding exterior wall). If there is no localized corrosion, then generalized interior and exterior corrosion rates must be combined to determine the date at which generalized corrosion causes a failure in a large segment of the wall.

Coated underground tanks. Tanks may be coated in an attempt to impede corrosion by preventing corrosive materials from reaching the tank surface. Coatings may be applied to either the interior or the exterior of the tank, and as long as they are intact, they effectively prevent the onset of either localized or generalized corrosion.

Coatings, however, do not last indefinitely. Instead, the sources identified in Appendix A indicate that both interior and exterior coatings fail with a time-to-failure of N(7,3) years. When failure occurs, the coating must be replaced, or corrosion will begin. Replacement of an interior coating is relatively easy, but replacing an exterior coating requires that the tank first be exhumed. Furthermore, the detection of an exterior coating failure requires careful inspection -- also requiring that the tank be exhumed. For these reasons, we have assumed that failed exterior coatings will not be repaired. Since the tank will therefore begin corroding from the outside at about the same time as the interior coating fails, we assume that the owner will not bother to repair a failed interior coating without also repairing the exterior coating. It is therefore relatively unlikely that either interior or exterior coatings will be repaired, and we have not included any form of coating repair or replacement in our underground tank model.

Once an exterior coating fails, the onset of localized corrosion becomes a certainty, for gaps in the coating provide a ready supply of point anodes.

(Source: National Association of Corrosion Engineers, personal communication.) Thus, the time-to-failure distributions presented in Table 18 must be rescaled so that for all three soil types the cumulative probability of failure eventually reaches 100%. The rescaled time-to-failure distributions are presented in Table 20. For interior coatings, however, the effect of coating gaps is less certain; for want of better data, we assume that following a coating failure, the tank corrodes like a new, uncoated tank.

Because large tanks are more likely to have unusually deep localized exterior corrosion holes, tank size will influence the localized exterior corrosion rate once an exterior coating fails. This will not be the case for interior coatings, however, because localized interior corrosion will generally be confined to the region beneath the fill tube. As before, we assume that the area of this region does not vary significantly with tank capacity.

For exterior coatings, we assume that the area correction factor is $A/A_0^{.16}$, where A is the surface area of the typical service station tank (approximately 440 square feet). The value of A to be used in this formula is the area of the entire tank surface, not merely the area of the coating failures. This is because the area correction factor is merely a scaling factor which we can use simply by assuming that the area of coating failure is proportional to the tank's surface area. We therefore never need to know the actual area or number of coating failures.

Cathodic protection. Cathodic protection is an entirely different form of corrosion protection. Rather than attempting to prevent corrosion by precluding contact with corrosive materials, it imposes a reverse electrical current on the protected components, inhibiting the electrochemical reactions that cause corrosion. Cathodic protection may be used on both the exterior and interior of the tank. Exterior cathodic-protection systems obtain the desired current flow by using a charged electrode in the surrounding soil; interior systems suspend an electrode in the waste. We assume that a cathodically protected tank uses both exterior and interior electrodes. We also assume that these electrodes are driven by the same

TABLE 20. COATED UNDERGROUND TANKS: TIME-TO-FAILURE DISTRIBUTION FOR QUARTER-INCH STEEL TANKS FOLLOWING THE FAILURE OF AN EXTERIOR COATING

Tank Age	Cumulative Probability of Failure (%) Benign soil (SAV ≤ 6)	Moderate Soil (7 ≤ SAV ≤ 12)	Aggressive Soil (SAV ≥ 13)
4	0	0	0
9	0	14.5	32.0
14	9.0	38.0	59.9
19	34.3	70.9	91.8
24	69.1	87.9	95.9
30	100.0	100.0	100.0

Note: the model obtains intermediate values by interpolation.

power supply. If this power supply fails and is not repaired, cathodic protection will fail simultaneously for both tank surfaces. Since power supply failure is an important cause of cathodic-protection failure, we therefore assume that these two systems always fail in tandem.

Properly installed and maintained, cathodic protection systems should prevent corrosion indefinitely. They require regular monitoring, however, and prompt repair or replacement of failed components. According to the National Association of Corrosion Engineers, the leading cause of cathodic-protection failure is poor maintenance. Furthermore, once localized corrosion has started, repair of the cathodic-protection system will be ineffective, for it is difficult to get proper current density into the center of an existing pit. For these reasons, we have assigned cathodic-protection systems a time-to-failure distribution of (m)·N(10,5) where m is a random number between 1 and 3 indicating the quality of the maintenance effort. A value of 1 means that no maintenance is undertaken; a value of 3 indicates that the operator carefully follows the prescribed maintenance schedule. We multiply this number by the sampled time to failure in order to delay failure for well-maintained systems.

Once cathodic protection fails, the tank begins to corrode in the same manner as a new, unprotected tank. If the tank has both a coating and cathodic protection, it does not begin to corrode until both the coating and the cathodic-protection system have failed; it then corrodes like a coated tank whose coating has failed.

Construction materials. A third way to prevent corrosion is by constructructing tank shells from fiberglass, stainless steel, or concrete, because fiberglass and concrete do not corrode, and stainless steel corrodes at only 25% the rate applicable to carbon steel (Peters and Timmerhaus, 1980). The use of these materials is not without its drawbacks, however. Stainless steel is expensive, concrete seeps continuously and may develop cracks (See Section 4.4), and fiberglass is twice as vulnerable to rupture or installation damage as is carbon steel (see Section 4.4).

The seepage rate for a concrete tank is given by the following formula:

$$dQ/dt = A(1 + d/t)K \left[\frac{\mu_{H_2O}}{\mu_{waste}}\right]\left[\frac{\varphi_{waste}}{\varphi_{H_2O}}\right]$$

where:

dQ/dt = the rate of leakage

A = the surface area of the tank (sides and bottom only)

d = the average fluid depth in the tank

t = the thickness of the concrete

K = the permeability of the concrete to water (2.5×10^{-9} cm/sec)

μ_{H_2O} = the viscosity of water

μ_{waste} = the viscosity of the waste

φ_{waste} = the density of the waste

φ_{H_2O} = the density of water

Using this equation, we find that a rectangular 10,000-gallon concrete tank containing an aqueous waste with an average fluid depth of 6 feet will have a seepage rate of about 90 gallons per year. This seepage rate will continue throughout the tank's operating life.

In addition to continuous seepage, concrete tanks are also subject to a type of gradual disintegration that is often referred to as "corrosion." (U.S. Department of the Interior, Concrete Manual, 1981). The result of this process, however, is generalized cracking rather than isolated corrosion holes, so we have included it in the time-to-failure distribution for concrete tank ruptures (Section 4.4), rather than in this section.

Tank Size. In addition to the modifications necessary to account for corrosion protection and the use of alternative construction materials, the underground tank corrosion model must also be modified to account for variations in tank size. The PACE data were obtained from service station tanks, most of which probably had capacities of approximastely 5,000 gallons. Hazardous waste tanks, however, can range from 200 gallons to millions of gallons. The larger a tank is, the more likely it is to develop an unusually deep corrosion pit, and the sooner will be its first failure.

There are no good data describing the effect of tank size on time-to-failure. The best data source is a pipeline corrosion model developed by Rossum. This model indicates that the deepest pit in an area of A square feet is given by:

$$x = x_0 \left(\frac{A}{A_0}\right)^{.16}$$

where

x = the depth of the deepest pit in an area of A square feet, and

x_0 = the depth of the deepest pit in an area of A_0 square feet.

We can easily incorporate this equation into the PACE model. A_0 is now the surface area of a 5000-gallon service station tank (about 440 square feet), A is the area of the hazardous waste tank under consideration, and x_0 is the localized exterior corrosion rate (which is linearly related to the depth of the deepest pit). Therefore, the localized exterior corrosion rate is related to the PACE baseline rate by a scaling factor of $(A/A_0)^{.16}$.

This area correction factor applies only to localized exterior corrosion, for that is the only type of tank corrosion which is affected by area. Generalized exterior corrosion and generalized interior corrosion are by definition area-independent, and the API data indicates that localized interior corrosion is confined to the region beneath the fill tube. The area of this region is not strongly affected by variations in the tank capacity.

<u>Above-ground Tanks on Cradles</u>. Like underground tanks, above-ground tanks are vulnerable to localized exterior, generalized exterior, localized interior, and generalized interior corrosion. Both types of interior corrosion will be the same for these tanks as for underground tanks, and generalized exterior corrosion will occur at the rate appropriate for an air environment (1.4 mil/yr).

Because the atmosphere does not contain point anodes, localized exterior corrosion will be unlikely on most of the tank's surface. The tank's seams and its points of contact with its support cradles, however, provide surface irregularities, and even in an air environment, these can serve as point anodes (National Association of Corrosion Engineers, telephone conversation). Thus these portions of the tank's surface are vulnerable to localized pitting (Perry and Chilton, 1973, p. 23-3). We assume that these vulner- able regions account for about 5% of the tank's surface. Because air environments are probably less corrosive than most soils, we have assumed that localized exterior corrosion at these locations is similar to localized exterior corrosion of a below-ground tank in a benign soil. To account for the limited locales at which such corrosion is likely, we use the $(A/440)^{.16}$ adjustment factor to reduce the effective surface area of the tank to 5% of its actual value.

If there is an exterior coating, exterior corrosion will not begin until the coating fails. This will occur after N(9,3) years (see Appendix A). Once the coating fails, exterior corrosion will occur with certainty at the points of failure. Generalized exterior corrosion will occur at 1.4 mils per year; localized exterior corrosion will occur at the rate applicable to exterior coating failures on low-SAV underground tanks with 5% as large a surface area.

Instead of using coatings, above-ground tank facilities may reduce corrosion failures by using corrosion-resistant construction materials. These materials are modeled like their below-ground counterparts. Thus, above-ground stainless steel tanks corrode only 25% as quickly as above-ground carbon steel tanks, while above-ground concrete tanks are subject to the same seepage losses and cracking problems as underground concrete tanks. Fiberglass tanks do not corrode, but they are twice as likely to rupture as their carbon steel counterparts.

<u>In-ground Tanks and On-grade, Above-ground Tanks</u>. In-ground tanks and on-grade, above-ground tanks can be modeled by combining our above-ground and below-ground corrosion models. We assume that the below- or on-grade portions of such tanks corrode like below-ground tanks of similar surface area. Their above-ground portions corrode like above-ground tanks, but

instead of experiencing localized corrosion at their seams and points of contact with cradles, these tanks corrode at their seams and near their points of contact with the ground. Because above-ground corrosion is generally a slower process than below-ground corrosion, however, we have only modeled the on-or below-grade sections of such tanks.

Multiple-Tank Systems. If a hazardous waste facility has more than one tank, we model each tank independently, re-sampling the probability distribution for all forms of corrosion and all forms of corrosion-protection failure. If there is a cathodic-protection system, we assume that it includes all of the tanks. In addition, we assume that the entire cathodic-protection system is connected to the same power supply. If this power supply fails and is not repaired, cathodic protection will fail for all of the tanks.

4.6 Pipe Corrosion

Like tanks, pipes are subject to four forms of corrosion: localized exterior corrosion, generalized exterior corrosion, localized interior corrosion, and generalized interior corrosion. Also like tanks, pipes may or may not be coated or cathodically protected, and may be constructed of carbon steel, stainless steel, or fiberglass. They may be above-ground or below-ground. We model these various pipe designs similarly to the equivalent tank designs, first determining the time to corrosion-protection failure, then using time-to-failure or corrosion-rate distributions to calculate corrosion rates for each of the corrosion mechanisms. We then combine these corrosion rates to calculate the total effect of all of these mechanisms on pipes of varying thicknesses.

Our pipe-corrosion model, however, has some important differences from our tank-corrosion model. First, it assumes that the pipes from which our baseline corrosion data were obtained have a thickness of .19 inches rather than the .25 inches applicable to tanks. In addition, in order to take full advantage of available data, our pipe model uses a combination of the PACE tank-corrosion data and a pipe-corrosion formula developed by Rossum

(1968). Thus, our pipe-corrosion model involves somewhat different time-to-failure distributions than does our tank corrosion model.

For convenience of reference, Tables 21 through 24 summarize the effects of pipe system design on corrosion rates for localized exterior, generalized exterior, localized interior, and generalized interior corrosion, respectively. We will describe these effects in more detail in the remainder of this section; complete derivations of the time-to-failure distributions may be found in Appendix A.

Localized exterior corrosion. The Rossum pipe corrosion model is directly applicable to pitting corrosion (i.e., localized exterior corrosion) of underground, uncoated, carbon steel pipes. According to this model, the expected number of leaks at time t is given by:

$$L = A\left[\frac{1.06\ K}{z}\right]^{6.25}\left[\frac{t(10 - pH)}{\varphi}\right]^{6.25n}$$

where

L = the number of leaks at time t
A = the surface area of the pipe (square feet)
K = 170 for soils of good aeration
= 196 for soils of moderate aeration*
= 222 for soils of fair aeration
= 355 for soils of poor aeration
z = the thickness of the pipe in mils
t = the age of the pipe (in years)
pH= the soil pH (must be between 5 and 9)
φ= the soil resistivity
n = 1/6 for soils of good aeration
= .236 for soils of moderate aeration**
= 1/3 for soils of fair aeration
= 1/2 for soils of poor aeration

* We have obtained this value by averaging the values for good and fair aeration.
** We have obtained this value by taking the geometric mean of the values for good and fair aeration.

TABLE 21. EFFECT OF PIPE SYSTEM DESIGN ON LOCALIZED EXTERIOR CORROSION

Pipe System	Effect on Localized Exterior Corrosion Rate
BELOW-GROUND	
Carbon steel	Time-to-failure is predicted by a stochastic modification of a leak-prediction formula by Rossum (1968).
Stainless steel	Corrodes at 25% of the rate applicable to below-ground carbon steel pipes.
Fiberglass reinforced plastic (FRP)	Does not corrode. Probabilities of rupture and installation damage are double those applying to steel pipes.
Exterior coating	Delays onset of localized exterior corrosion by N(7,3) years. Localized corrosion begins with certainty following coating failure.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once cathodic protection fails, pipe corrodes like a new, unprotected pipe.
Exterior coating with cathodic protection	Delays onset of corrosion until both cathodic protection and coating fail. Localized corrosion begins with certainty following corrosion protection failure.
Stray currents	If stray currents are present, they will have the same effect on pipes as they do on underground tanks.

TABLE 21. EFFECT OF PIPE SYSTEM DESIGN ON LOCALIZED EXTERIOR CORROSION (Continued)

Pipe System	Effect on Localized Exterior Corrosion Rate
ABOVE-GROUND	
Carbon steel	Corrodes with conditional time-to-failure distribution given by: $T= .11\ (A/10)^{.16} N \left[16(10/A)^{.16},\ 6.6(10/A)^{.16}\right]$ where T is the time to failure.
Stainless steel	Corrodes at 25% of the rate applicable to above-ground carbon steel pipes.
Fiberglass reinforced plastic (FRP)	Does not corrode. Probabilities of rupture and installation damage are double those applicable to carbon steel.
Exterior coating	Delays onset of corrosion by N(9,3) years (for all pipe lengths). Localized corrosion begins with certainty following coating failure.
Cathodic protection	Has no effect above-ground.
Stray currents	Have no effect above-ground.

TABLE 22. EFFECT OF PIPE SYSTEM DESIGN ON GENERALIZED EXTERIOR CORROSION

Pipe Design	Effect on Generalized Exterior Corrosion Rate
BELOW-GROUND	
Carbon steel	Corrosion rate in mils/yr = $\max\left[1.4, \frac{SAV}{10} FNU(1.4,5)\right]$
Stainless steel	Corrosion rate is 25% of the rate applicable to below-ground carbon steel pipes.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Exterior coating	Delays onset of generalized corrosion by N(7,3) years. After coating fails, generalized corrosion is the same as for new, uncoated pipes.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once cathodic protection fails, pipe corrodes like a new, unprotected pipe.
Exterior coating with cathodic protection	Delays onset of generalized exterior corrosion until both cathodic protection and the coating fail. After corrosion-protection fails, generalized exterior corrosion is the same as for a new, unprotected pipe.
Stray currents	Will increase the generalized exterior corrosion rate by the same factor as applies to tanks.

TABLE 22. EFFECT OF PIPE SYSTEM DESIGN ON GENERALIZED EXTERIOR CORROSION (Continued)

Pipe Design	Effect on Generalized Exterior Corrosion Rate
ABOVE-GROUND	
Carbon steel	Corrodes at 1.4 mils/yr.
Stainless steel	Corrodes at .35 mils/yr.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Exterior coating	Delays onset of corrosion by N(9,3) years (for all pipe lengths). Following coating failure, generalized exterior corrosion is the same as for a new, uncoated, above-ground pipe.
Cathodic protection	Has no effect above-ground.
Stray currents	Have no effect above-ground.

TABLE 23. EFFECT OF PIPE SYSTEM DESIGN ON LOCALIZED INTERIOR CORROSION

Pipe System Design	Effect on Localized Interior Corrosion Rate
BELOW- or ABOVE-GROUND	
Carbon steel	The probability of localized interior corrosion is given by: $p = .024\ (A/10)^{.16}$ The corrosion rate for pipes which experience this form of corrosion is $(A/10)^{.16}$ times the corrosion rate obtained by sampling a time-to-failure distribution of N(8,5) for 190-mil pipes.
Stainless steel	Corrodes at 25% of the rate applicable to carbon steel pipes.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Interior coating	Delays the onset of corrosion by N(9,3) years. After the coating fails, interior corrosion occurs at the rate applicable to a new, uncoated pipe.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once cathodic protection fails, pipe corrodes like a new, unprotected pipe.
Interior coating with cathodic protection	Delays onset of interior corrosion until both the cathodic-protection system and the coating fail. After corrosion-protection failure, localized interior corrosion is the same as for a new, unprotected pipe.
Stray currents	Have no effect on interior corrosion.

TABLE 24. EFFECT OF PIPE SYSTEM DESIGN ON GENERALIZED INTERIOR CORROSION

Pipe System Design	Effect on Generalized Interior Corrosion Rate
BELOW- or ABOVE-GROUND	
Carbon steel	Corrodes according to the following formula: corrosion rate = $(1-f)(1.4) + fr_T$ where f is the fraction of the time the pipe is in contact with the fluid (including a 30-minute drying time), and r_T is a corrosion rate sampled from the same generalized interior corrosion distribution as is used for tanks.
Stainless steel	Corrodes at 25% of the rate applicable to carbon steel.
Fiberglass reinforced plastic (FRP)	Does not corrode.
Interior coating	Delays onset of corrosion by N(9,3) years. After coating fails, corrosion occurs at the rate applicable to a new, uncoated tank.
Cathodic protection	Delays onset of corrosion until cathodic protection system fails (see Table 14). Once cathodic protection fails, pipe corrodes like a new, unprotected pipe.
Interior coating with cathodic protection	Delays onset of interior corrosion until both the cathodic-protection system and the coating fail. After corrosion-protection failure, generalized interior corrosion is the same as for a new, unprotected pipe.
Stray currents	Have no effect on interior corrosion.

This formula is very sensitive to soil resistivity and soil pH; doubling the resistivity, for example, will cut the expected number of leaks in half, while decreasing the pH from 7 to 6 will increase the expected number of leaks by 33%. In addition, since the chemical processes underlying corrosion vary with the amount of oxygen present, Rossum's formula is highly dependent on soil aeration. For 100 feet of 2-inch diameter, 190-mil pipe, in a soil with a resistivity of 5000 ohm-cm and a pH of 6, this equation gives the following values:

	Expected Number of Leaks		
Aeration	Year 10	Year 20	Year 40
good	.025	.51	1.04
moderate	.072	.20	.56
fair	.0084	.040	.16
poor	.001	.0092	.08

This model, however, merely predicts the expected number of holes. It does not give a stochastic distribution of times to failure. We have therefore converted it into a cumulative probability distribution by assuming that the nth hole develops at a random time between the dates when L = n - 1 and L = n + 1. We convert fractional values of L into probabilities to determine when during this interval the nth hole develops. Thus, at the date when L = 1, there is a 50% probability that the first leak has occurred, for L = 1 is half-way between L = 0 and L = 2. Similarly at L = 1.5, there is a 75% probablity that the first leak has occurred, for 1.5 is 75% of the way between 0 and 2. Furthermore, if the first leak has occurred at L = 1.5, there is a 25% chance that a second leak has also developed. There is no chance, however, that a third leak will develop before L = 2.0.

This discussion reveals one important difference between the pipe-corrosion model and the tank-corrosion model: the pipe-corrosion model allows for multiple leaks, while the tank corrosion model only predicts the date at which the first leak occurs. If suitable data can be found, future versions of the tank-corrosion model will also allow for the development of multiple corrosion holes.

There is another important difference between the tank- and pipe-corrosion models. The tank-corrosion model is based on the soil's resistivity, pH, moisture content, and sulfide content, while the pipe-corrosion model uses the soil's resistivity, pH, and aeration instead. Thus the two models require different parameters, and changes in the non-overlapping parameters (moisture, sulfides, and aeration) can have significant effects on corrosion rates. The two models are not incompatible, however, because several of the parameters are strongly correlated. High moisture content, for example, is usually accompanied by relatively low resistivity and relatively poor aeration. In each of our simulation runs, therefore, we have taken care to specify a consistent set of soil characteristics.

Generalized exterior, localized interior, and generalized interior corrosion. Generalized exterior corrosion is very similar for pipes and tanks. We have therefore assigned the same probability distribution to both types of components. Because we assume that corrosion proceeds independently on separate pieces of equipment, however, we sample this distribution independently for each tank and each pipe. Thus, while tanks and pipes have the same probability distributions for generalized exterior corrosion, they need not have identical corrosion rates.

Generalized interior corrosion, however, does not have the same distribution for pipes and tanks. In pipes, fluid is seldom present, and generalized interior corrosion proceeds largely from atmospheric effects. We therefore use a corrosion rate of 1.4 mils per year (the rate appropriate for an air environment, Ailor, 1982), with a correction factor for the fraction of time that the pipe is in contact with the fluid. We obtain this correction factor in two steps. First, we compute the fraction of time when fluid is in contact with the pipe (including a 30-minute drying time following each pipe usage). We denote this fraction as f. Then we sample a generalized interior corrosion rate from the same distributions that we use for the generalized interior corrosion of tanks. We denote this corrosion rate as r_T. We then combine r_T and f in the following formula:

$$r \text{ (in mils/yr)} = (1-f)(.14) + fr_T$$

Where r is the generalized interior corrosion rate. Note that this expression degenerates to 1.4 mils per year if f = o (i.e. if fluid is never present).

Localized interior corrosion is a bit more difficult to model. In tanks, the API data show that this form of corrosion is 19% as likely as localized exterior corrosion, but tanks are always in contact with the fluid, while pipes are usually in contact with the air. On the other hand, localized interior corrosion appears to be strongly influenced by fluid motion. That is why tanks that fail due to localized interior corrosion generally do so at locations immediately below their fill tubes.

Fluid motion in tanks and in pipes only occurs during periods of fluid transfer. For a fill pipe, these periods correspond exactly to the periods of most significant fluid motion in the tank (because the tank experiences significant fluid motion only during filling). For a discharge pipe, differences in pumping rates may cause the fraction of the time during which fluid is in motion to differ from that applicable to the fill pipe. Since the same volume of fluid must pass through all three components, however, we assume that these variations are unimportant, and that like tanks, fill and discharge pipes are 19% as likely to undergo localized interior as localized exterior corrosion.

In order to use this percentage, however, we must first reconcile a difference between the Rossum underground pipe formula and the API service station data. According to the Rossum formula, all pipes undergo some degree of localized corrosion. Yet according to the API data, only 15% of service station pipes experience corrosion failure (see Appendix A for our derivation of this percentage). first consideration, these two predictions appear incompatible. The difference, however, is in the time period. The API data considered tank systems with an average age of 11 years; for many soil conditions, the Rossum formula often does not predict failure until considerably later. Thus, within the time horizon of the API data set, the Rossum formula does not predict 100% failure, and depending on assumptions about pipe length and soil characteristics, the two data sources can be readily reconciled. For example, according to our stochastic version of the Rossum formula, pipe segments with a surface area of 10 square feet in a moderate-aeration soil with a resistivity of 2000 ohm-cm and a pH of 5 show an 11% 20-year failure rate. Since this is well within the range indicated by the API data, we can use that data without introducing any serious inconsistencies into our model.

To derive an interior corrosion model, we therefore begin with the API data's indication that interior corrosion is 19% as common as exterior corrosion and that 15% of service station pipes fail due to corrosion. Since the 15% figure includes both interior and exterior corrosion failures, this means that 2.4% of service station pipes should experience interior corrosion failure.

This 2.4% figure, however, is valid only for pipes similar to those in service stations. We have assumed these pipes to have an area of 10 square feet (10 feet of 4" pipe or 20 feet of 2" pipe). Hazardous waste tank pipes may be much longer or much shorter. Consequently, we have used the surface-area adjustment factor that we had previously derived for tanks to also adjust for pipe-length variations. Thus, the probability of localized interior corrosion is 0.024 $(A/A_0)^{.16}$, where A_0 = 10 square feet.

In addition, we have assumed that like tanks, those pipes which develop localized interior corrosion have a baseline time-to-failure distribution of N(8,5). In order to account for the fact that longer pipes are more likely to develop unusually deep pits, we have adjusted the corrosion rate obtained from this distribution by $(A/10)^{.16}$.

Above-ground Pipes. Above-ground pipes also experience all four forms of corrosion. Three of these corrosion mechanisms, however, are easily described: generalized and localized interior corrosion are the same for above-ground pipes as they are for underground pipes, while generalized exterior corrosion is the same for above-ground pipes as it is for above-ground tanks (1.4 mils/yr). In order to model localized exterior corrosion, however, we have been forced to develop a new corrosion model, for the localized exterior model which we developed for underground pipes is inapplicable above-ground.

We have used a combination of the PACE tank data and the API service station data to develop this model. According to our underground pipe model, 15% of underground pipes fail due to corrosion. Since the probability of interior corrosion is 2.4%, we assume that the remaining 12.6% failure rate is due to localized exterior corrosion. Furthermore, the API data indicates that the time-to-failure distribution for pipes which do fail (due to either cause) is N(12,5) (see Appendix A). Although this distribution contains a mixture of internal and external corrosion failures, it will be dominated by localized exterior corrosion failures (because they are more common), and we can apply this distribution directly to this class of failures. Thus, according to the API data, the time-to-failure distribution for localized exterior corrosion of underground pipes is .126N(12,5).

Above-ground pipes, however, will not follow this distribution. Instead, based on reasoning parallel to that which we used for above-ground tanks, we assume that above-ground pipes will corrode like pipes in low-SAV soils, but only at the 5% of their surface areas accounted for by seams and points of support. We must therefore adjust the API time-to-failure distribution to account for surface area and SAV.

We adjust for surface area by applying an area adjustment factor of $(.05A/10)^{.16}$ to both the binomial probability of failure and the baseline corrosion rate obtained from sampling the conditional time-to-failure distribution. We correct for SAV by noting that according to the PACE data, 77% of medium-SAV and 70% of low-SAV tanks fail by localized exterior corrosion within 30 years. Assuming that the average pipe in the API study was buried in medium-SAV soil, and assuming that the effects of SAV on underground pipes and tanks are proportional, this means that 11% of low-SAV service station pipes should develop localized exterior corrosion (11% = 12.6% x (70% / 77%)). Furthermore, the PACE data (see Table 19, above) indicates that the average failure date for medium-SAV tanks experiencing point corrosion is 16 years. The average for low-SAV tanks is

21 years. Again assuming proportionality, this means that the time-to-failure distribution for low-SAV service station pipes should be N(16,6.6). Combining our SAV assumptions with our area adjustment factor, we obtain the following conditional normal distribution for above-ground pipes:

$$\text{time to failure} = .11(A/10)^{.16}\ N[16(10/A)^{.16},\ 6.6(10/A)^{.16}]$$

This adjustment factor applies to the time to failure, rather than the corrosion rate. Since time to failure and corrosion rate are inversely related, applying a factor of $(10/A)^{.16}$ to the time to failure is mathematically equivalent to applying a factor of $(A/10)^{.16}$ to the corrosion rate.

A note on area effects. As a comparison of our pipe- and tank-corrosion models would indicate, our use of area correction factors is different for pipes and tanks. For pipes, we have used an area correction factor for both the baseline probability and the baseline corrosion rate. For tanks, we only apply it to the corrosion rates.

We have modeled pipes and tanks differently because we believe that three factors control the onset of localized corrosion. One of these is the surface area of the buried metal. The others are the corrosivity of the soil and the care with which the component is installed. We have assumed that surface area is an important factor for localized corrosion events with low probabilities. In other words, we have assumed that the probability of pipe corrosion is relatively low because a pipe is small enough that it is relatively unlikely to experience a point anode. For tanks, however, the baseline probabilities of localized corrosion are on the order of 70-85%. We assume therefore, that the principal factors influencing the onset of tank corrosion are the corrosivity of the soil and the care with which the tank is installed. Surface area will be important, but its primary effect will be to determine the number of point anodes and thus the depth of the deepest pit.

We have generalized the preceding discussion to obtain the following rule of thumb: whenever the baseline probability of a corrosion event is less than 50%, we assume that component surface area will influence the probability of the onset of corrosion; whenever the baseline corrosion probability is over 50%, we assume that the component is already large enough that surface area has little influence on probability. Since all of our relevant baseline probabilities are either greater than 70% or less than 12%, we never had to elaborate this rule of thumb by developing a model to deal with intermediate cases. In addition, since our area adjustment factor requires an area more than 5000 times larger than baseline to increase a 12% probability to 50%, we did not need to modify that factor to assure that our area adjustments do not increase the failure probability by too much. For similar reasons, our model is insensitive to any choice of cutoff probabilities between 25% and 70%, so it is unnecessary for us to be precise in our determination of what value in that range is the theoretically best choice.

<u>Corrosion protection</u>. Pipes may be coated, cathodically protected, or constructed of fiberglass, concrete, or stainless steel. These corrosion protection techniques have the same effect on pipes as they have on tanks. Fiberglass pipes are corrosion-resistent; stainless steel pipes corrode one-fourth as rapidly as bare steel pipes; and cathodically protected pipes do not corrode until the cathodic-protection system fails. If there is cathodic protection for tanks, we assume that there is also cathodic protection for pipes. In addition, we assume that the pipes cathodic-protection system uses the same power supply as the tank's. If that power supply fails and is not repaired, cathodic protection will fail for both tanks and pipes.

Interior and exterior coatings also have the same effect on pipes as they do on tanks, delaying the time of failure by a time of N(7,3) years for exterior coatings on underground pipes, or N(9,3) years for coatings exposed primarily to an air environment (interior coatings or exterior coatings on above-ground pipes). Once the coating fails, interior corrosion and generalized exterior corrosion proceeds as for new, uncoated pipes, but localized exterior corrosion commences with certainty at the gaps in the coating. Since the Rossum model does not incorporate this effect even for underground pipes, we used the API and PACE data to determine the time-to-failure distributions following coating failure. As we discussed earlier, these distributions indicate that uncoated, medium-SAV pipes have a conditional time-to-failure distribution of N(12,5), while uncoated, low-SAV pipes have a conditional time-to-failure distribution of N(16,6). We have not previously calculated a conditional time-to-failure distribution for uncoated, high-SAV pipes, but calculations similar to those which we used for low-SAV pipes provide a conditional time-to-failure distribution of N(9,4).

We can apply these same time-to-failure distributions to coated pipes, for the effect of coating failures is to assure the onset of corrosion, not to alter its conditional time-to-failure distrubition. Therefore, following coating failure, we assume that coated pipes corrode with certainty according to the time-to-failure distribution appropriate for their locations. We account for variations in their lengths by multiplying the baseline corrosion rate by $(A/A_0)^{.16}$ where A_0 = 10 square feet, the typical surface area of a service station pipe.

Multiple-Pipe Systems. If a hazardous waste facility has more than one pipe, we model each pipe independently, re-sampling the probability distributions for all forms of corrosion and all forms of corrosion protection failure. If there is cathodic protection, however, we assume that the entire cathodic-protection system will fail simultaneously. Thus, we use the same date of failure for each pipe's cathodic-protection system. This date of failure is also the same as the date of failure for the tank's cathodic-protection system.

4.7 Pump and Valve Corrosion

Pumps and valves corrode similarly to short pipe segments. The effect of pump corrosion, however, depends on whether the pump is submersible or above-ground. Submersible pumps are located inside the tank, where even if they corrode they cannot release fluid to the exterior environment. Above-ground pumps, however, may be the source of releases. Corrosion of these pumps is very similar to above-ground pipe corrosion, with a few minor changes to higher interior corrosion rates to account for the pump's complex shape. The details of our pump-corrosion model are present in Appendix D.

It should be noted that pumps are unnecessary for underground waste storage tanks. These tanks are generally constructed so that they will be gravity-fed by drainage from a collection tank located at a higher elevation. They are discharged through a flexible hose connected to a portable pump on the pump-out truck. Thus, such systems do not contain on-site pumps, and we have generally not included pump corrosion in our underground storage tank simulations.

Valves are housed in short lengths of pipe that are physically distinct from the rest of the pipe. In theory, we could model these valve segments separately, but such an approach would needlessly complicate our model. Instead, we have treated each valve as a portion of the pipe to which it is attached, and have not distinguished between corrosion of the pipe and corrosion of the valve.

4.8 Erosion

In addition to corrosion, pipes and pumps are also subject to erosion. This process, which has effects very similar to generalized interior corrosion, results from mechanical abrasion by suspended solids in a flowing fluid. Wastes with low suspended solids will therefore cause little erosion, while wastes that are high in suspended solids will be much more erosive. Since our baseline interior tank-corrosion data were obtained from service station tanks, we assume that this data does not already account for erosion, for petroleum products are generally non-erosive.

We modeled erosion by adding the erosion rate to the interior corrosion rate. Although we did not model erosion as a localized process, we used it to augment both the localized and the generalized interior corrosion rates. We did this because in both cases our baseline data had applied only to non-erosive fluids.

The erosion rates which we used are listed in Table 25. Based on the fraction of suspended solids, this table distinguishes between three types of fluids: non-erosive, moderately erosive, and highly erosive. Most of the wastes under consideration in this study will be non-erosive, but a few sludges may be moderately or even highly erosive. The erosion rates in Table 25 are appropriate only if the fluid is always in motion. Thus, these values may be applied directly to continuous treatment tanks, but for other system the erosion rate must be multiplied by f, the fraction of the time during which fluid motion occurs in the component under consideration. Because fluid motion is not as rapid in tanks as it is in pipes, we have not modeled erosion in tanks. Future versions of our model, however, may be revised to account for turbulence beneath the fill pipe.

4.9 Gasket Disintegration

Gaskets gradually disintegrate due to the combination of chemical attack and erosion. We have modeled gasket aging as an erosion-like process with a baseline disintegration rate between 0 and 50 mils/year. Since we believe that lower disintegration rates are more likely, we use the following empirical distribution:

Cumulative Probability	Gasket Disintegration rate (mils/yr)
0.00 to 0.77	FNU(0,12.5)
0.77 to 0.83	FNU(12.5,25)
0.83 to 1.00	FNU(25,50)

Because gaskets can trap or absorb fluid, this disintegration process continues even when fluid is not present in the pipe. Therefore, we assume that the fraction of time when fluid is present is irrelevant for this type of failure.

Gasket disintegration may be greatly accellerated by incompatability between the waste and the gasket (EPA, Case Study No. 4, 1984). We account

TABLE 25. EROSION RATES FOR TANKS, PIPES, AND PUMPS

Component	Erosion rate (mils/year) Non-erosive fluid (<1 ppm solids)	Moderately erosive fluid (between 1 and 10,000 ppm solids)	Highly erosive fluid (>10,000 ppm solids)
Tanks	0	FNU(0,5)	FNU(5,10)
Pipes	0	FNU(0,5)	FNU(5,10)
Pumps	FNU(0,10)	FNU(0,10)	FNU(10,20)

for this possibility by multiplying our baseline disintegration rates by a random number x sampled from FNU(1,20). If x is low, the gasket is compatable with the waste; if x is high, the gasket disintegrates unusually quickly.

A gaskets fails when its thicknesses reaches zero. Since a gasket is a flat, washer-like disk, the point of attack will be at its inside edge, which initially will be flush with the interior surface of the pipe. The gasket will fail when the difference between its inner and outer radii reaches zero. For gaskets for 2" pipes, this initial difference is 1.06 inches; for gaskets for 4" pipes, it is 1.44 inches (Perry and Chilton, 1973). Thus, gaskets can fail as early as year 2, or they may last for the entire lifetime of the facility.

4.10 Hole Sizes and Locations

Whenever a release occurs, the Monte Carlo model interrupts the fault tree sampling process to determine the release rate from the new leak. The first step in this procedure is to set the dimensions of the hole through which the fluid is leaking.

Hole sizes for all relevant failure events are given in Table 26. For most events, these hole sizes are stochastic and are determined by sampling the distributions listed in the table. For overflows, however, hole size is not a limiting factor in determining the loss rate. These loss rates are instead determined by the rate at which fluid is being pumped into the tank. Similarly, losses from external catastrophes are determined by the volumes of fluid present in the tank at the time of the catastrophe. For these events, therefore, Table 26 does not include hole sizes, but instead identifies the other factors (such as tank capacity) that determine the loss rate.

Hole size alone does not determine the leak rate. The density and viscosity of the waste are also important factors, as are the operating pressure inside the failed component and the nature of the medium into which the leak occurs. Two of these factors, density and viscosity, are determined

TABLE 26. INITIAL HOLE DIMENSIONS AND HOLE LOCATIONS FOR VARIOUS CLASSES OF FAILURES

Type of Failure (with event label)[1]	Dimensions of Hole (in inches)	Location of Hole
CORROSION HOLES		
• Tanks		
- Localized exterior corrosion (T1121)	diameter = B(1/64, 1/32, 1/4)	Bottom of tank
- Localized interior corrosion (T1123)	diameter = B(1/64, 1/32, 1/4)	Bottom of tank
- Generalized corrosion (T1127)	diameter = B(1/64, 1/32, 1/4)	Bottom of tank
• Pipes		
- Localized exterior corrosion (B13)	diameter = B(1/64, 1/32, 1/4)	Midpoint of pipe
- Localized interior corrosion (B13)	width = FNU(.1, .25) length = FNU(1, 10)	Midpoint of pipe
- Generalized corrosion (B13)	width = FNU(.1, .25) length = FNU(1, 10)	Midpoint of pipe
• Pumps		
- Localized exterior corrosion (A2116)	diameter = B(1/64, 1/32, 1/4)	Pump outlet
- Localized interior corrosion (A2116)	diameter = B(1/64, 1/32, 1/4)	Pump outlet
- Generalized corrosion (A2116)	diameter = B(1/64, 1/32, 1/4)	Pump outlet

TABLE 26. INITIAL HOLE DIMENSIONS AND HOLE LOCATIONS FOR VARIOUS CLASSES OF FAILURES (Continued)

Type of Failure (with event label)[1]	Dimensions of Hole (in inches)	Location of Hole
OTHER LEAKS AND RUPTURES (including installation damage)		
• Tanks (T1124)		
- seam leak (75% of cases)	width = FNU(0, 1/16) length = FNU(0, 60)	Bottom of tank
- major rupture (25% of cases)	width = FNU(0, 3) length = FNU(3, 36)	Bottom of tank
• Pipes (B11)	width = FNU(1, .25) length = FNU(1, 10)	Midpoint of pipe
• Flanges (B121)	width = FNU(0, 1/8) length = FNU(0, 50% of flange circumference	Varies with tank size, location, configuration, and process for which tank is used. See Appendix D.
• Gaskets (B122)	width = FNU(0,1/8) length = FNU(0, 50% of gasket circumference	Varies with tank size, location, configuration, and process for which tank is used. See Appendix D.
SECONDARY CONTAINMENT BREACHES		
• All secondary containment components[2]	Large enough to allow entire spill volume to escape before remedial action can be taken.	Lowest elevation in secondary-containment system, allowing the entire spill volume to escape.

TABLE 26. INITIAL HOLE DIMENSIONS AND HOLE LOCATIONS FOR VARIOUS CLASSES OF FAILURES (Continued)

Type of Failure (with event label)[1]	Dimensions of Hole (in inches)	Location of Hole
OTHER LOSS MECHANISMS		
• External catastrophe (all ANUCAT events)	Large enough to lose entire contents of tank.	Bottom of tank
• Overflow through vent or over sides of open-topped tank (A210 or A211)	Large enough that the overflow rate equals the rate at which fluid is being pumped into the system.	Top of tank
• Strainer drain left open (A11111)	Large enough that the spill rate equals the pumping rate	At location of pump
• Pump drain left open (A11112)	Large enough that the spill rate equals the pumping rate	At location of pump
• Flexible hose ruptures (A1112)	Leak rate = FNU(0, pumping rate)	At midpoint of hose
• Loose flexible hose connection (A1115)	Leak rate = FNU(0, pumping rate)	At tank's pump-out port

[1]These labels correspond to the labels in the fault trees. They are also used in Appendix A. That Appendix explains the derivation of these hole sizes.

[2]If a system contains two secondary containment systems (such as a vault with a synthetic liner), both must fail before a release can occur.

by the identity of the waste, and will be the same for all leak locations. Similarly, the nature of the medium into which the leak occurs will be determined by the choice of backfill material, and will be the same for all underground leaks. The operating pressure at the site of the hole, however, varies with the hole's location. Table 26 identifies the locations where we have assumed each of the possible leaks or ruptures occur. From these location assumptions the operating pressures can be calculated according to standard engineering formulas. These formulas are too complex to present here, but have instead been included in Appendix A. These formulas are dependent on design factors (such as average fluid depth, pressure added by the pump, or the relative locations of tanks and pipes) which are also too complex to present in the main body of this report. These design details are given in Appendix D.

Most of the hole sizes listed in Table 26 are self-explanatory. Corrosion holes and secondary-containment breaches, however, require additional discussions.

Corrosion Holes. As Table 26 indicates, we have assumed that corrosion holes in tanks, pumps and above-ground pipes are generally circles, ranging in initial diameter from 1/64" to 1/4". We also use this size distribution for exterior corrosion holes in below-ground pipes. Due to the combination of soil corrosivity and the action of flowing fluid, however, we have assumed that interior and generalized corrosion holes in pipes are larger and more elongated, ranging in initial size from .1" x 1" to .25" x 10".

These hole sizes apply to new holes. With time, however, these holes will grow larger and larger until eventually their leak rates become large enough to be detected. We model the growth of corrosion holes by increasing the hole's radius at the end of each model year. For localized exterior corrosion failures, we assume that the hole continues to grow according to localized exterior corrosion but is now subject to attack from the inside as well. Thus, its hole growth rate is the sum of the generalized exterior corrosion rate, the generalized interior corrosion rate, and the erosion rate. We apply this growth rate to the hole's radius because corrosion will occur simultaneously on all parts of the hole's circumference. Based on similar reasoning, we assume that localized interior corrosion holes will grow at the sum of the localized interior corrosion rate, the erosion rate, and the generalized exterior corrosion rate, while generalized corrosion holes in tanks will grow at the sum of this generalized exterior and generalized interior corrosion rates, plus erosion. Due to the combination of soil corrosivity and the action of flowing fluid, however, we assume that generalized corrosion holes will grow rapidly, doubling in length and width each year until they are either detected and repaired or until the entire bottom of the tank has corroded.

Secondary Containment Breaches. Secondary containment breaches are also included in Table 26. For our present version of the model, we have assumed that a breach in the secondary-containment system will result in total non-containment. In practice, fluid might drain through the breach slowly enough that an emergency clean-up could be arranged in time to prevent a release of the entire volume, but we have made the conservative assumption that this is unlikely.

4.11 Leak-Rate Calculations

Leak rate formulas depend on whether the leaking components are above-ground or below-ground. For above-ground leaks (or leaks from underground tanks in vaults), the leakage occurs into an air environment, and the Bernoulli equation applies. According to this equation:

(4.1) $$Q = .6A(2gz)^{.5}$$

where

Q = the leak rate;

.6 = a coefficient appropriate for sharp-edged orifices;

A = the area of the crack or hole;

g = the accelleration due to gravity; and

z = the equivalent static hydraulic head (i.e., the equivalent height of the fluid surface above the hole, taking into account pressure additions due to pumps, or losses due to friction or suction when fluid is flowing through pipes). This is calculated according to the operating-pressure equations in Appendix A.

For underground leaks, however, the surrounding soil or backfill material will impede the flow of fluid, dramatically reducing the leak rate. In these circumstances, the Bernoulli equation no longer applies.

Unfortunately, there are no textbook formulas directly applicable to losses from underground tanks. Thus, we were forced to develop our own model for soil impedance, basing it on published studies of packed columns and fluid beds. The derivation of this model is contained in Appendix A. The final equation is:

$$Q = \frac{-B + (B^2 - 4AC)^{.5}}{2A} \text{ (Area)} \qquad (4.2)$$

where

Area = The area of the hole

$$A = \frac{1.75\ (1-E_m)}{E_m^3} \frac{\varphi}{\emptyset_s d_p}$$

$$B = \frac{150\ (1-E_m)^2 \mu}{E_m^3\ (\emptyset_s d_p)^2}$$

$$C = \frac{-\Delta P}{L} g_c$$

in which

E_m = void fraction of the soil particles; (i.e. E_m is the ratio of the total void space to the volume occupied by the soil particles themselves)

φ = density of the fluid;

$\emptyset_s$ = sphericity of the soil particles;

d_p = average diameter of the soil particles;

μ = viscosity of the fluid

ΔP = the pressure drop between the inside of the hole and the surrounding soil; and

g_c = a conversion factor which is 1 in metric units and 32.17 in English units;

L = the distance required for leaking fluid to disperse (i.e. for its pressure to drop to that of the surrounding soil).

Our model included four basic types of backfill: gravel, sand, silt and clay. The relevant parameters for each of these soil types are presented in Table 27. The basic soil parameters were readily obtainable from hydrogeolo gic texts, but dispersion distances for underground leaks have never been published. The figures presented in Table 27 are therefore only estimates based on our own engineering judgement. In making these estimates, we began by noting that for cylindrical fluid beds, the dispersion length is linearly related to the bed diameter (Perry and Chilton, 1973). We assumed that a similar linear relation carried over to the conical or wedge-shaped dispersion patterns likely from corosion holes and underground cracks, respectively. Thus, the dispersion-length figures presented in Table 27 are given as multiplicative factors of hole diameter (for circular holes) or crack width (for elongated cracks). We further assumed that the dispersion length will be larger for a crack than it will be for a hole with a diameter equal to the crack's width. We made this assumption because fluid leaking from a hole will be able to disperse in all directions, but fluid leaking from an elongated crack will only be able to disperse in directions perpendicular to the crack. In addition, we noted that fine-grained materials like silt and clay offer a greater resistance to fluid flow than do coarse-grained materials like sand and gravel. Thus, dispersion lengths will be smaller for fine-grained materials than they will be for coarse-grained materials. These observations are reflected in the dispersion-length coefficients listed in Table 27.

The precise arithmetic values for these coefficients were difficult to determine. We based our choices of coefficients on our engineering assessment of published tank failure case studies (see Appendix C for sum-

Table 27. SOIL PARAMETERS FOR UNDERGROUND LEAKS

Parameter	Backfill Material Gravel	Sand	Silt	Clay
DISPERSION LENGTH				
• Circular holes (diameter d)	100 x d	20 x d	7.5 x d	2 x d
(maximun value)	(100cm)	(20cm)	(7.5cm)	(2cm)
• Elongated cracks[1] (width w)	100 x w	40 x w	10 x w	4 x w
(maximum value)	(100cm)	(40cm)	(10cm)	(4cm)
VOID FRACTION[2]	.50	.53	.75	.95
PARTICLE SIZE[2]	9.4	.25	.064	.002
SPHERICITY[2]	.70	.65	.34	.075

---

1 Cracks will have a longer dispersion length than holes because dispersion can only occur in directions perpendicular to the crack.

2 Source: Kunii and Levensaul (1969)

maries of 21 of these case studies). From these case studies, we concluded that a moderately large (1 cm) hole in a 10,000-gallon tank buried in sandy soil should produce a leak rate of approximately 1,500 gallons per month. This will occur (assuming 4 feet of hydraulic head) if the dispersion length is 20 cm, i.e. if the dispersion length coefficient is 20. We then chose other dispersion length coefficients to be consistent with both that value and our assumptions about the effects of hole shape and soil particle size. In addition, we have assigned maximum values to each dispersion-length coefficient. These maximum values, which are listed in Table 27, are the maximum lengths that our formulas would predict for hole diameters or crack widths of 1 cm.

As equation (4.2) and Table 27 indicate, our underground leak-rate model is quite complex, depending on several variables. The most important variables, however, are the soil parameters and the hole size. Figures 26A through 26D examine the effects of these parameters by plotting leak rates versus hole sizes for a 10,000-gallon storage tank in each of the four representative soils. These graphs show that leak rates are highest for gravel, and lowest for clay, as would be expected. In addition, these graphs show that despite the complexity of equation (4.2), leak rates are almost linearly dependent on hole diameters, at least for holes greater than 1/8 inch in diameter. This linear relation results because an increase in hole size has two opposing effects on leak rates: it increases leakage by increasing the hole's surface area; and it decreases the leak rate by lengthening the dispersion distance. According to Figures 26A through 26D, the net result of these two effects is that leak rates are almost linearly related to hole diameters.

4.12 Leak Detection

Once a leak develops, it will continue until it is detected. Detection may occur immediately, or it may be delayed for weeks or even months. If the leak is small enough, it may never be detected.

We have considered 9 possible leak detection options. These options, which may be used in any combination are:

FIGURE 26A. THE EFFECT OF HOLE DIAMETER ON LEAK RATES IN CLAY

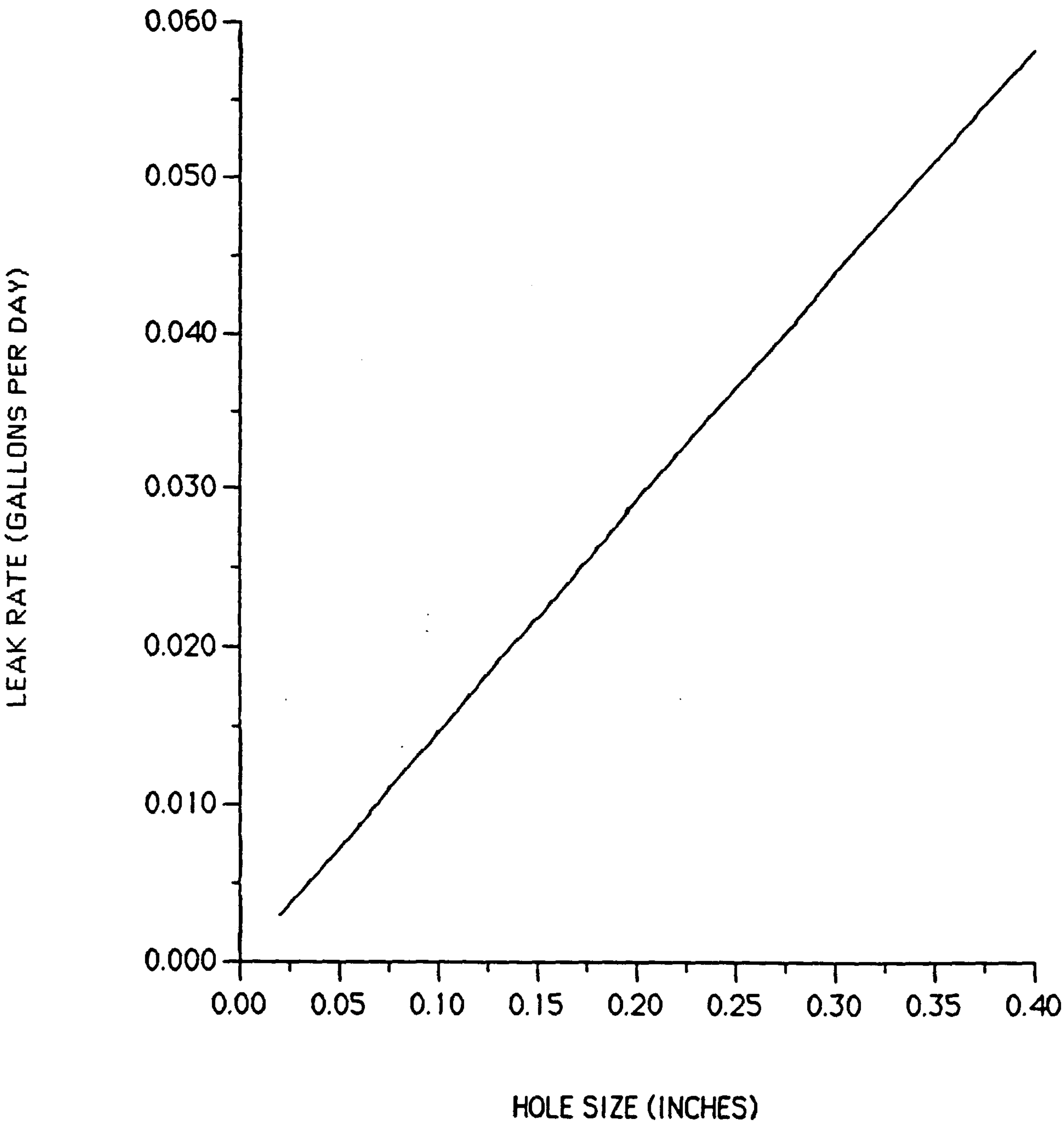


FIGURE 26B. THE EFFECT OF HOLE DIAMETER ON LEAK RATES IN SILT

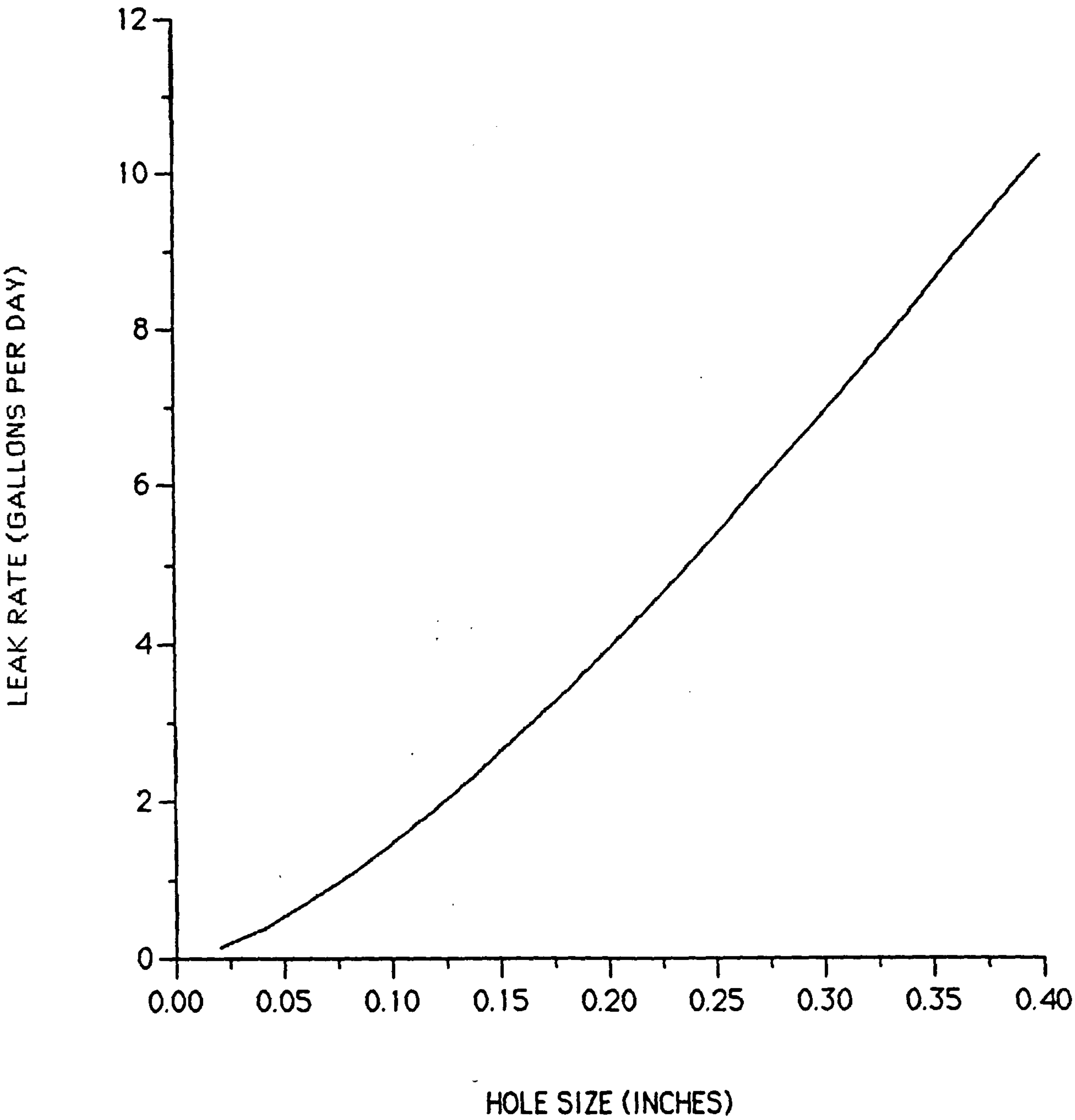


FIGURE 26C. THE EFFECT OF HOLE DIAMETER ON LEAK RATES IN SAND

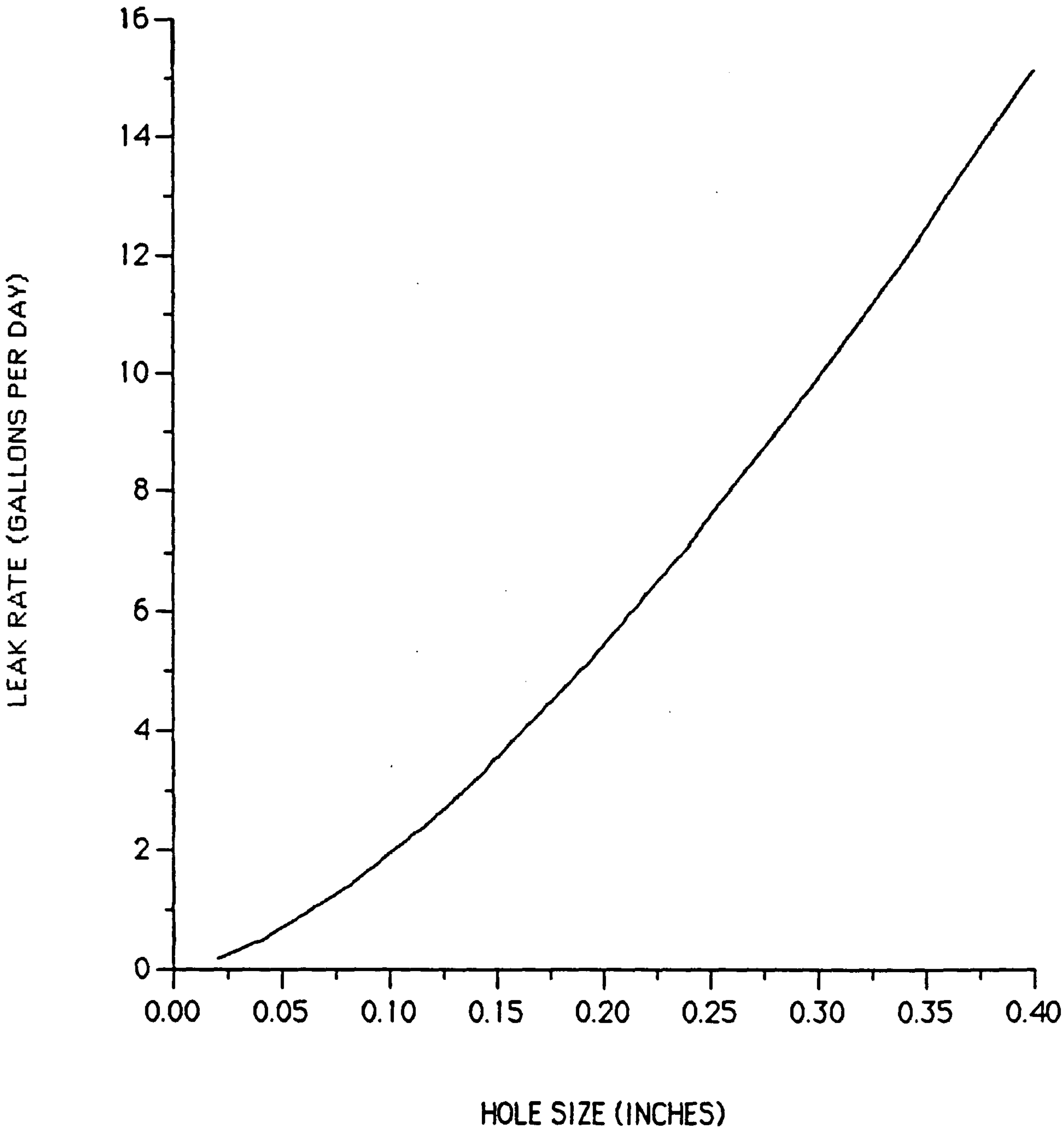
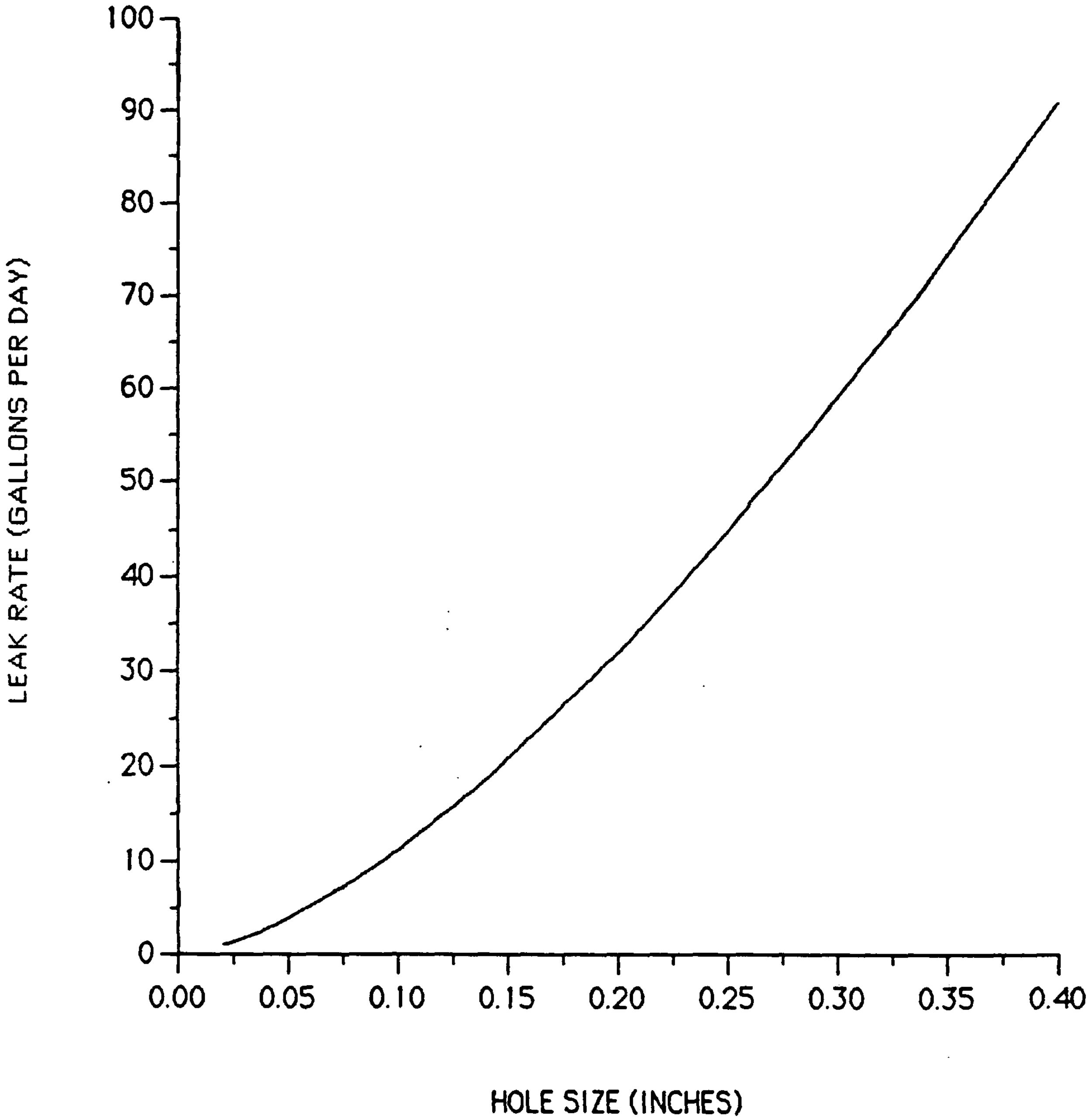


FIGURE 26D. THE EFFECT OF HOLE DIAMETER ON LEAK RATES IN GRAVEL



- Visual inspection,
- Inventory monitoring,
- Vapor wells,
- Interstitial monitoring,
- U-tubes,
- Pollulert monitoring,
- Continuous pipe monitoring,
- Groundwater monitoring, or
- Unsaturated zone monitoring.

With the exception of groundwater monitoring and unsaturated zone monitoring (which the Agency has decided to model using the contaminant transport subroutines of ICF's Tank Risk Model) we have incorporated each of these options into our Tank Failure Model. In modeling these leak detection systems, we have been primarily concerned with three parameters: the minimum volume of release which can be detected, the time lag until detection occurs, and the probability that the system will fail to detect a release which is large enough to be detectable. Table 28 presents these parameters for each of the modeled leak detection systems. The remainder of this section explains these systems in greater detail.

Visual Inspection. Our model permits the simulation of two types of visual inspection. One of these is a casual "walk-around" inspection which we assume occurs daily at all facilities. The other is a more thorough periodic inspection, which is optional. Generally, this inspection is carried out on a weekly or monthly basis, but the model allows us to specify any desired inspection cycle. The probability of detecting a leak depends on the leak rate, and is different for each type of inspection. We have assumed that casual inspection (or normal operating routine) will always be sufficient to detect a leak larger than a slowly running faucet (approximately 100 cm^3/minute). For leaks with rates between 10 drops per minute (approximately .5 cm^3/minute) and 100 cm^3/minute, we have assumed that there is a 50% probability of detection by casual inspection. Smaller leaks will not be detectable by this method. Periodic inspection, however, will have a 95% chance of detecting any above-ground leak.

The time lag between the onset of a leak and its detection depends on the size of the leak and when during the inspection cycle the leak begins. In

TABLE 28. LEAK DETECTION PARAMETERS

Leak Detection System	Threshold Level Necessary for Detection	Time Lag Until Detection	Failure Probability
VISUAL INSPECTION			
• Casual	100 cm^3/min	FNU(.25,60) min	0
	.5 cm^3/min to 100 cm^3/min	FNU(0,24) hrs	.50
	<.5 cm^3/min	Not detectable	1.00
• Careful	No limit	FNU(0,7) days	.05
• Visual detection of overflows	No limit	FNU(0, fill time)	0
• Visual detection of pump drain or strainer spills	No limit	FNU(0, fill time)	0
• Visual detection of flexible hose ruptures or loose connections	No limit	FNU(0, pump-out time)	0
INVENTORY MONITORING			
• Casual (daily)	Determined by user input (0-100% of tank capacity).	FNU(0,48) hours	0
• Weekly, monthly, or at pump-out	Determined by user input (0-100% of tank capacity).	Depends on when during inspection cycle leak begins.	0

TABLE 28. LEAK DETECTION PARAMETERS

Leak Detection System	Threshold Level Necessary for Detection	Time Lag Until Detection	Failure Probability
TIGHTNESS TESTING	Determined by user input (generally .10 gal hr).	FNU(0,interval between tightness tests).	0
VAPOR WELLS	Determined by user input (250 ppm is typical).	Given by solving Thibodeaux's equation for t.	.10
U-TUBES	Conservatively estimated as the volume of fluid needed to saturate all of the soil between the tank bottom and the tubes.	Depends on the porosity at the back-fill, depth to the U-Tubes, soil permeability, soil moisture content, leak rate, and identity of the waste.	0
POLLULERT MONITORING	Conservatively estimated as the volume of fluid needed to saturate all of the soil between the tank bottom and the water table.	Depends on the porosity at the back-fill, depth to the groundwater, soil permeability, soil moisture content, leak rate, and identity of the waste.	0
CONTINUOUS PIPE MONITORING	0.2 gal/hr.	0	0
INTERSTITIAL ALARMS	no limit	Detection is immediate if the alarm functions.	.10
LEAK DETECTORS IN VAULTS	no limit	FNU (1,12) hrs	.10

general, leaks detected by casual inspection will be detected in FNU(0,24) hours, leaks detected by weekly inspection will be detected in FNU(0,7) days, and leaks detected by monthly inspection will be detected in FNU(0,30) days. For leaks in excess of 100 cm^3/minute, however, detection will be in FNU(.25,60) minutes.

Visual inspection will also lead to detection of overflow or accidental spills. Because we assume that the operator is likely to observe these types of leaks without taking a walk-around inspection, we assign them shorter detection periods. These detection periods are listed in Table 28.

Inventory Monitoring. Inventory monitoring programs are designed to detect shortfalls in the amount of fluid contained in a tank by comparing the actual volume to that which is predicted by tallying fill volumes and discharge volumes. This type of leak detection is useful only for storage and accumulation tanks, however, for the short time period between pump-outs for treatment tanks (even continuous systems are emptied once a day) means that any leaks large enough to cause a detectable inventory shortfall would also be large enough to be immediately obvious to the operator.

In theory, the detection threshold for inventory monitoring depends on the monitoring frequency and the care with which records are maintained. If monitoring is carried out frequently, with accurate records, it is possible to apply statistical techniques to detect relatively low loss rates from product storage tanks. These techniques have not been developed for above-, in-ground, open-topped, or hazardous waste tanks. Since there is no reliable method for hazardous waste materials of the aforementioned tank types, we have assumed that monitoring is carried out casually, with a much higher detection threshold than would apply for more sophisticated inventory control programs. This is the level of inventory control we expect to find at existing hazardous waste tank facilities.

We have modeled two types of inventory monitoring. The more sophisticated of the two is daily monitoring. This type of monitoring involves a daily inspection of the fluid level, but requires no record-keeping or statistical analysis. The detection threshold for this type of monitoring is specified as a percentage of tank capacity, and is set by user input. Because of the casual nature of this type of monitoring, we recommend the use of a fairly large detection threshold, perhaps 10-25% of tank capacity. This threshold applies to the sum of all losses occurring between monitorings. Thus, if a tank has two leaks, neither of which alone would be large enough to trigger detection, their sum may nevertheless exceed the threshold level, and both leaks would then be detected and repaired.

The second type of inventory monitoring is periodic monitoring. For this type of monitoring, the operator periodically computes the expected volume of waste in the tank and compares it to the actual volume. If he detects a shortfall, he assumes that a leak has developed. The detection threshold for this type of monitoring depends on the accuracy of the operator's records and the care with which he measures the volume of waste contained in the tank. For simplicity, we specify this detection threshold is a fraction of tank capacity. This fraction is determined by user input. Because we are assuming that this is a fairly casual type of inspection carried out by poorly trained operators, we recommend the use of a fairly large detection level (at least 10% of tank capacity).

The detection lag for this type of monitoring depends on when during the inspection cycle the leak begins. If the leak begins early, there is a higher chance that the accumulated loss volume will be large enough for detection at the next scheduled inventory reconciliation. Otherwise, even if the leak rate is fairly rapid, the leak may not be detected until the following reconciliation. We account for this possibility by randomly setting the time during the monitoring cycle when the leak develops. The minimum detection delay is therefore zero (for a large leak developing immediately before the inventory is reconciled), while the maximum is two full inspection cycles (for a leak that is barely large enough to be detected and which begins too late in the monitoring cycle to be detected at the first inventory reconciliation). The interval between inventory reconciliations is set by user input, and may range from one month to the entire period between pump-outs.

Vapor Wells. Vapor wells detect leaks by sensing hazardous waste vapors in the soil near the leaking component. This detection method is appropriate for volatile waste streams. According to Thibodeaux (1979), the concentration of hazardous waste vapor at an underground distance z from the source is given by:

$$C = C_0 \left[1 - \text{erf} \left(\frac{z}{4Dt(\epsilon/1.73)} \right) \right]$$

where

C = the concentration of the contaminant at the sensor

C_0 = the concentration of the contaminant at the source (we assume that the air there is saturated with the vapor)

z = the distance from the source to the sensor

D = the diffusivity of the contaminant in air

t = the elapsed time since the leak began

ϵ = the porosity of the soil

erf = the standard Gaussian error function

We obtain the time to failure by setting C equal to the detection threshold of the vapor sensor (150 ppm for a Sensidyne detector). We then solve Thibodeaux's equation for t, the elapsed time until the concentration at the sensor reaches this level. This time t is the detection lag; C is the detection threshold.

Thibodeaux's equation is based on the assumption that there is enough liquid at the source to keep the nearby air saturated. The model checks this assumption by calculating the radius of the smallest sphere that could contain the vapor if the entire leak evaporated. If that sphere is not large enough to reach the sensor, then no detection has occurred regardless of the results of the Thibodeaux equation.

Vapor wells are not 100% effective. We assume that they have a 10% per-demand probability of failure. If the sensor fails, the leak will continue for 1 month, at which time we assume that the sensor will be repaired and the leak will be detected.

Tightness Testing. Tightness testing is capable of detecting very slow leaks in either tanks or pipes. In theory, because tightness tests use careful surface-level measurements to detect leaks by detecting minute changes in fluid level, the sensitivity of this leak detection technique should be inversely related to the size of the tank. Because the manufacturers claim the same detection limits for all tank sizes, however, we have not attempted to adjust for tank size. Instead, we have left the threshold level as a user input, so that sensitivity analyses may be performed easily. We have also allowed the testing schedule to be determined by user input.

Tightness testing has not been proven reliable for hazardous wastes to achieve suggested reliability levels. As a consequence, tank facilities may need to replace the tank fluid with water to perform such a test. We will assume that our tightness testing results represent the use of water, not hazardous waste. As a result, our costs must include cleaning the tank and possibly the installation of a manhole.

U-Tubes. U-tubes are porous tubes running beneath an underground or in-ground tank. Usually, these tubes are located one or two feet beneath the tank, but the the model allows us to specify any desired depth. These tubes collect leaking waste and channel it to an underground sump where it can be monitored at any specified interval (generally weekly or monthly). As an alternative, U-tubes can be continuously monitored by including a liquid sensor in the sump.

The detection lag for U-tubes is a combination of two factors: the time lag until the waste reaches the tubes, and the time lag between the arrival of the waste in the sump and its detection there.

The detection lag for the percolation of waste through the intervening backfill is given by the following expression (EPA, Liner Location Report, 1984):

$$t = \left[\frac{z(\xi - \theta_i)}{(dQ/dt)} \right] \left(\frac{dQ/dt}{K} \right)^{.25}$$

where

t = the time required for leaking waste to penetrate to the U-tubes

z = the depth of the U-tubes beneath the tank

dQ/dt = the leak rate

ξ = the porosity of the backfill

θ_i = the moisture content of the backfill (before the spill)

K = the permeability of the soil to water

The values of K, ξ, and θ_i for each of our four types of backfill are listed in Table 29. For U-tubes lying beneath 1 foot of sand backfill, it will take 32 hours for waste to reach the tubes from a 1-gallon-per-day leak.

TABLE 29. HYDROGEOLOGIC PARAMETERS FOR VARIOUS SOIL TYPES[1]

Soil Type	Porosity Porosity	Moisture Content	Permeability (cm/sec)[2,3]	Residual Saturation
Gravel	0.25	.09	$1 \times 10^{-2}(.4^N)C$	1.0
Sand	0.35	.09	$1 \times 10^{-2}(.6^N)C$	1.0
Silt	0.35	.27	$1 \times 10^{-8}(.02^N)C$	1.0
Clay	0.5	.30	$1 \times 10^{-8}(.12^N)C$	1.0

[1]Source: Fetter, (1980).

[2]C is an adjustment factor for viscosity and density variations:

$$C = \frac{\text{water}}{\text{waste}} \times \text{specific gravity of waste}$$

where denotes viscosity

[3]N=1 if petrochemical, otherwise N=0.

We have conservatively estimated the detection threshold for U-tube monitoring as the volume required to saturate all of the soil between the tank bottom and the U tubes. This volume is given by the following formula (EPA, Liner Location Report, 1984):

$$Q = z(\xi)(\theta_p)(A)$$

where

Q = the threshold release volume,

θ_p = the residual saturation of the backfill; and

A = the cross-sectional area of the leak source

The value of θ_p depends on the nature of the backfill. Representative values of θ_p are included in Table 29 for aqueous wastes and toluene. For U-tubes located 1 foot beneath a horizontal, 10,000-gallon tank, this detection threshold for an aqueous waste is 445 gallons.

In addition, the detection threshold for U-tube monitoring is also governed by the sensitivity of the technique used to monitor the sump. We have assumed that this threshold is insignificant compared to the threshold volume required for the liquid to initially reach the U-tubes. We have also assumed that the sump monitoring method has a near-zero failure rate.

Pollulert Monitoring. A pollulert system is a monitoring device located in a well reaching to the water table. This monitoring system detects leaks by sensing organic wastes floating on top of the water table. We have modeled Pollulert systems in the same way as we have modeled U-tubes, except that for Pollulert systems the sensor is always monitored continuously.

Continuous Pipe Monitoring. Continuous pipe monitoring systems use electrical sensors on the pipes to detect changes in soil conductivity caused by leaks. They can detect leaks as small as 0.2 gal/hr (Sobotka, 1984), and we assume that they will react immediately to detectable leaks. There are a variety of such pipe monitoring techniques, but the present version of our model has not attempted to distinguish among them.

Interstitial Alarms and Alarms in Vaults. Interstitial alarms are leak sensors placed between the walls of double-walled tank's or pipes. If either of the walls is breached, such an alarm will react immediately to the influx of waste (for breaches of the inner wall) or soil monitor (for breaches of the outer wall). This allows the operator to take the proper remedial action. In many cases, no waste will have been released to the environment because one of the walls will still be intact.

Alarms in vaults are similar, except that they are not sensitive enough to detect infiltrating soil moisture (otherwise they would also react to atmospheric condensation). Thus these alarms give immediate notice of breaches in the tank, but they give no notice of breaches in secondary containment. By detecting the leak from the tank, however, they prevent the leak from continuing undetected for long periods of time.

All types of alarms are subject to failure. Since interstitial alarms and alarms in vaults are physically very similar to high-level alarms, we have given them the same failure probability as we used for high-level alarms. This probability is 10% per demand. The derivation is presented in Appendix A under event MOALARM.

Remedial Action. Once a leak has been detected, the operator must take action to prevent it from continuing. Generally, such action requires that operating procedures be changed until the leak can be repaired. We have conservatively assumed that except for overflows, accidental spills, or external catastrophes, such remedial action requires 2 days to implement. Overflows and spills can be remedied immediately, however, and remedial action delays are irrelevant for external catastrophes because these events have already resulted in the loss of the system's entire contents.

5.0 RECOMMENDATIONS FOR ADDITIONAL RESEARCH

5.1 Possible Modifications to the Model

A complex simulation model such as ours is always open to refinements designed to increase the accuracy with which it reflects the complexities of the real world. Table 30 lists a number of refinements which we deem to be worthy of further consideration. Most of these changes could be implemented with very little effort. These easily implemented changes are:

- Improving our hole-size estimates for generalized exterior corrosion holes;
- Including erosion (beneath the fill pipe) in our tank model;
- Separate modeling of the above-grade and on- or below-grade sections of on-grade or in-ground tanks;
- Using a separate cathodic-protection system for each protected component;
- Allowing inspection and repair of coatings on above-ground tanks;
- Including sophisticated inventory-monitoring systems as a leak-detection option;
- Allowing the efficacy of careful visual inspections to vary with the leak rate;
- Including ultrasonic testing as a leak prevention option; and
- Modifying our pipe-rupture model to account for variations in pipe-length.

Other changes would require more effort, either because good data may be difficult to locate, or because these changes would require revisions of substantial segments of the computer code. Nevertheless, these changes are useful enough that we recommend that at least some of them be carried out. The details of these proposed revisions are given in Table 30, which lists the present modeling approach, the proposed revision, and the effects of the proposed change. It also discusses the difficulties likely to be encountered in implementing each of these changes. These changes are:

o Modeling the possibility of multiple corrosion holes for exterior tank corrosion;

TABLE 30. CHANGES WHICH MAY BE INCORPORATED INTO FUTURE VERSIONS OF OUR MODEL

Model Element	Present Modeling Approach	Proposed Revision	Effect of Proposed Revision	Difficulty of Implementation
TANK CORROSION				
• Multiple localized exterior corrosion holes	We only model one localized exterior corrosion hole per failure incident.	Include the possibility of multiple corrosion holes.	This would increase leak rates.	Could be accomplished by assuming that tank corrosion is similar to pipe corrosion, and by applying the appropriate elements of the Rossum pipe corrosion model to tanks.
• Multiple interior corrosion holes	We only model one interior corrosion hole per failure incident.	Include the possibility of multiple corrosion holes.	This would increase leak rates.	Unknown
• Hole sizes for generalized corrosion holes	We use the same hole-size distribution as we use for localized corrosion holes.	Make these holes large and rapidly growing.	Would increase the leak rates.	We already make this distinction for pipes. We could easily use the same approach for tanks.
• Erosion	We do not model erosion of tanks.	Allow tanks to erode beneath the fill pipe.	Would increase the interior corrosion rate slightly.	We already model erorion in pipes and pumps. We could easily use the same approach for tanks.
• Effect of waste pH on tank corrosion	Our present corrosion rates are derived from data for gasoline, and therefore apply for normal environments.	Model acidic wastes as more corrosive.	Would substantially increase interior corrosion rates for tanks containing acidic wastes.	Would require additional library research.
• In-ground tanks and above-ground tanks on-grade	We only model corrosion for the below- or on-grade segments of these tanks. tanks.	Model the corrosion of both of these segments.	Would increase the number of corrosion failures for these tanks.	Requires only minor changes in the computer code.
PIPE AND PUMP CORROSION				
• Multiple interior corrosion holes	We only model one interior corrosion hole per failure incident.	Include the possibility of multiple corrosion holes.	This change would increase leak rates.	Unknown. Data might be very difficult to locate.
• Effect of waste pH on pipe corrosion.	Our present corrosion rates are derived from data for gasoline, and therefore apply for normal environments.	Increase the corrosity of acidic wastes.	This change would substantially increase interior corrosion rates for pipes containing acidic wastes.	Would require additional library research.

TABLE 30. CHANGES WHICH MAY BE INCORPORATED INTO FUTURE VERSIONS OF OUR MODEL (Continued)

Model Element	Present Modeling Approach	Proposed Revision	Effect of Proposed Revision	Difficulty of Implementation
PIPE AND PUMP CORROSION (Continued)				
• Time-to-failure distribution for localized exterior corrosion of underground pipes	We assume that the date of the nth failure is uniformly distributed between the time when the expected number of corrosion holes is n-1 and when it is n+1.	Double the probability that the n'th hole develops at time t.	This would assure that the nth corrosion hole develops by the time predicted by Rossum and would give the same number of expected releases as he predicts.	Simple.
CORROSION PROTECTION				
• Cathodic protection	We presently assume that all components of the tank system are connected to the same cathodic-protection system.	Use a different cathodic-protection system for each of the protected components.	This would reduce the number of components affected by a cathodic-protection system failure but would increase the number of systems subject to failure.	Fairly simple.
LEAK DETECTION AND SECONDARY CONTAINMENT				
• Coatings on above-ground tanks and pipes	We presently assume that like underground coatings, these coatings receive no maintenance.	Model the maintenance of such coatings.	This would increase the service life of above-ground coatings.	Fairly simple.
• Sophisticated inventory modeling (using statistical analysis of time-series data)	Not included in present model.	Include it as a leak detection option.	The model would be more flexible.	Simple—we have already modeled this leak detection method in another computer model.
• Casual inventory monitoring	We presently assume that the operator will take no action until the leak is confirmed by two successive days of shortfalls. Thus, we use a detection lag of FNU(24,48) hours.	Eliminate the assumption that the operator will await confirmation.	Reduces loss volume by changing the detection lag to FNU(0,24) hours.	Trivial.
• Careful visual inspection	We presently assume that this method has a 90% probability of detecting even the smallest leak.	Allow the effectiveness of this method to depend on the leak rate.	In our present model, this method is too effective for detecting very small leaks.	Trivial.

TABLE 30. CHANGES WHICH MAY BE INCORPORATED INTO FUTURE VERSIONS OF OUR MODEL (Continued)

Model Element	Present Modeling Approach	Proposed Revision	Effect of Proposed Revision	Difficulty of Implementation
MISCELLANEOUS				
• Ultrasonic testing	Not presently included in the model.	Include this inspection option in the model.	Would allow the inspector to detect thin spots before corrosion holes develop.	Trivial.
• Pipe rupture	We presently assume that the probability of pipe rupture is independent of pipe length.	Let longer pipes be more vulnerable to rupture.	Would increase the probability of rupture for long pipes and decrease it for short pipes.	Simple, although it may be difficult to obtain authoritative documentation.
• Cracking of concrete tanks	The distribution used in our model was derived for tanks with 20-year design lives.	Let the time-to-failure distribution vary with design life.	Would substantially reduce the number of failures for concrete tanks designed for 30 or 40 years.	Depends on level of sophistication desired. Might require additional library research and might be difficult to document.

- Modeling the possibility of multiple interior corrosion holes for both tanks and pipes;
- Including the waste's pH as a parameter in our interior corrosion models for pipes and tanks;
- Changing our time-to-failure distribution for underground localized exterior pipe corrosion to eliminate a present bias in favor of belated development of corrosion holes; and
- Designing a more sophisticated model for the cracking of concrete tanks.

5.2 Caveats

There are other refinements which would be useful if adequate data could be found. Because such data are unlikely to be available, however, we have not included these refinements in Table 30. Instead, we will discuss them in this section as caveats.

Use of Uniform Corrosion Rates. Both our tank- and pipe-corrosion models are based on the assumption that localized exterior corrosion holes grow at constant rates throughout their life-spans. Thus, we have assumed that corrosion rates are independent of pit depth. Rossum's article, however, indicates that corrosion rates slow down as the pit surface area gets larger and as the pit fills with scale. Thus, pits grow rapidly at first, but slower later on. Since our corrosion rates are the averages obtained from .25-inch tanks (or .19-inch pipes), they still correctly predict dates of failure for pipes of these thick- nesses, but if Rossum's non-linear model is correct, our average corrosion rates are too rapid for thicker materials and too low for thinner materials. In addition, our attempts to combine generalized interior corrosion with localized exterior corrosion also result in delayed failure dates if Rossum's non-linear model is correct. This bias occurs because generalized interior corrosion effectively reduces the thickness of the component wall over the period of time during which corrosion is occurring.

As an example, consider a .25-inch tank with a 5-mil-per-year interior corrosion rate and an exterior corrosion time-to-failure of 25 years (obtained by sampling the PACE corrosion data). According to our model, this tank will have an exterior corrosion rate of 10 mils per year, for a combined corrosion rate of 15 mils per year. Under our uniform corrosion-rate assumption, failure will occur in 17 years.

Suppose, however, that the corrosion rate decreases with pit depth. A 25-year time-to-failure might then correspond to the following corrosion rates:

Years Since Onset of Corrosion	Annual Corrosion Rate
1-5	15 mils/yr
6-10	12 mils/yr
11-15	10 mils/yr
16-20	8 mils/yr
21-25	5 mils/yr

If this tank is now given a 5-mil/yr interior corrosion rate, failure will occur in year 14, somewhat earlier than the year-17 prediction obtained from the uniform corrosion example.

It should be noted that the above example is an extreme case. It involves both a very high interior corrosion rate and a 3-fold change in the annual corrosion rate with pit depth. And even with these extreme effects, it only alters the time-to-failure by 18% from that obtained from the purely linear approximation. This indicates that the model is fairly robust to non-uniform corrosion rates, at least as long as the tank wall-thickness remains at .25 inches. If the initial tank wall-thickness is substantially altered, however, the uniform corrosion-rate predictions are not as robust. Since non-uniformities have been observed for localized interior corrosion (Ishikawa, et al, 1981) as well as localized exterior corrosion (Rossum, 1968), future versions of our model could be improved by exploring these non-uniformities and incorporating them into the interior and exterior pit-growth models. Adequate data, however, might be very difficult to locate.

Baseline Corrosion Data for Tanks. The tank corrosion time-to-failure data is based on the PACE survey data. PACE obtained this data from three sources:

- Over a 6-month period in 1977, PACE requested its member companies to report leak incidents.

- During this same time period, PACE requested the member companies to report tank decommissionings. PACE then tested the decommissioned tanks for leaks.
- If one tank on a particular site was leaking or decommissioned, PACE also tested all other tanks on the same site.

The PACE survey is therefore a combination of two non-random samples, one of leaking tanks (and other tanks on the same site) and the other of decommissioned tanks (and tanks near them). The first sample is biased toward leaking tanks; the second is biased toward tanks old enough to be decommissioned. In addition, the second sample is biased toward non-leaking tanks, for in 1977, most gasoline storage tank decommissionings probably resulted from the closing down of non-profitable service stations, or the replacement of undersized tanks, rather than the removal of tanks that were known to be leaking.

The net effect of these two biases is unclear. The resulting time-to-failure distributions look reasonable, so the net bias is probably not severe. Nevertheless, the model could be revised if an unbiased time-to-failure survey becomes available.

Air Quality and Corrosion of Above-Ground Tanks and Pipes. Our above-ground exterior corrosion models do not take local air quality into account. Air quality, however, may be very poor in the vicinity of certain process tanks, and this poor air quality could substantially increase both the generalized and the localized exterior corrosion rates. Since our model does not include this effect, it does not presently apply to tanks or pipes located near process equipment which produces corrosive fumes. Future versions of the model could be generalized to take these effects into account if adequate data could be located.

Initial hole sizes for localized corrosion failures. We have assumed that localized corrosion holes initially range between 1/64 and 1/4 inches in diameter. This assumption is based on anecdotal data and personal observations. It could be improved if a better data set were available.

Corrosion hole growth rates. In our corrosion model, we have modeled corrosion holes as circles that expand in radius as continued corrosion consumes the surrounding metal. This model presents a good approximation of the behavior of corrosion holes, but a more sophisticated approach would be to model corrosion holes as hemispherical pits, growing at the appropriate corrosion rate. When failure occurs, the metal around the edges of such a hole would be very thin, and would corrode rapidly. We could account for this by allowing the corrosion hole to continue growing as an imaginary hemisphere, with the edges of the hole representing the points of intersection between the hemisphere and the tank wall. The effect of this would be to cause the corrosion hole to expand rapidly at first, then slower and slower. The growth rate, however, would always be somewhat higher than that predicted by our present model.

Underground leak rate model. Our underground leak rate is based on our engineering estimates of the effects of hole diameter and backfill material on the dispersion distance. Our estimates produce reasonable leak rates that exhibit the anticipated sensitivites to changes in key variables, but our estimates could be improved if our leak rate formulas were verified by bench-scale testing.

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