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RISK ANALYSIS METHODS FOR DEEPWATER PORT OIL TRANSFER SYSTEMS

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16. Abstract

This report deals with the risk analysis methodology for oil spills from the oil transfer systems in deepwater ports. Failure mode and effect analysis in combination with fault tree analysis are identified as the methods best suited for the assessment of comparative risk from different technical alternatives.

The necessary methodology and analytical expressions are developed and their application is demonstrated in some general sample calculations.

Basic data sources are listed, and the quality of the data is discussed. It is shown that the available data are not sufficiently complete for quantitative calculations of the risk for the entire system. Comparative calculations, however, can be made, and a systematic qualitative examination of the system is possible.

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PREFACE

With the enactment of the Deepwater Ports Act of 1974 the Department of Transportation and, through delegation, the United States Coast Guard became responsible for regulation of most aspects of deepwater ports, from licensing through construction, testing, and operations. The Transportation Systems Center is providing technical support to the Coast Guard in this area of its responsibility.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

CALM	Catenary Anchor Leg Mooring
DWP	Deep Water Port
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
OCIMF	Oil Companies International Marine Forum
OTC	Offshore Technology Conference
OTS	Oil Transfer System
PLEM	Pipeline End Manifold
PPC	Pumping Platform Complex
SALM	Single Anchor Leg Mooring
SPM	Single Point Mooring
λ	Failure Rate Per Unit Time
λ^1	Failure Rate Per Demand
λ^*	Effective Failure Rate at AND and OR Gates
τ	Time of Duration of Failure
τ^*	Effective Duration for Combined Failures
ℓ	Last Failure in Sequence
	AND Gate
	OR Gate
	Input Event
	Description of Derived Failure Condition
	Transferred Input or Output

1. INTRODUCTION

1.1 OBJECTIVES AND SCOPE

The following tasks were assigned to TSC:

1. To review existing methods of risk and reliability analysis for their applicability to the DWP oil transfer system (OTS).

2. To select a risk analysis technique which, when applied to a DWP transfer system, will allow the identification of potential problem areas, and will serve as a basis from which to promulgate regulations designed to eliminate or minimize any problems in the design, construction, test, and operation of DWP transfer systems.

3. To demonstrate the practical application of the selected method.

In accordance with these tasks the literature of DWP's and risk analysis was reviewed, and the bibliography is contained in Appendix A.

A general schematic of the transfer system was constructed on the basis of technical reports and existing DOT DWP regulations.[1] This schematic is shown in Figure 1-1. The DWP transfer system is defined as beginning at the suction side of the tanker's cargo pump and ending at the storage tank ashore. The rigid pipelines from the single point mooring (SPM) to the pumping platform and from the pumping platform to shore will be regarded as conduit only; that is, the inherent failure modes of such lines and stresses and strains resulting from various events such as soil movements, laying methods, etc., will not be considered.

1.2 RISK ANALYSIS AND PERFORMANCE SPECIFICATIONS

The general objective of rules-making in the context of DWP's is to insure safe operation and protection of the environment. These objectives can largely be met by providing performance standards for components and operating procedures. This approach does not impose any undue restrictions on technological innovations.

Technical specifications as to the arrangement of components may be necessary in some instances. On the other hand, an excessive use of technical specifications of this kind would tend to restrict the permissible designs on the basis of existing technologies. This is clearly undesirable. The specific arrangements considered in this report are chosen only to illustrate the methods of risk analysis.

2.1.3 Rules and Procedures

The method must allow for the examination of the effects of rules and procedures, since operating procedures will have a bearing on the risk of oil spills. This may be illustrated by the simple example of a rule requiring the shutting of valves at the tanker end of transfer hoses when the waveheight is in excess of some safe limit.

2.1.4 Level of Detail

The method must be suitable for dealing with several levels of complexity or sophistication while allowing for small changes in the system design and incorporating, among other things, several modes of operation, the effects of wear, external stress, etc.

2.1.5 Failure Modes

The method should enable identification of all modes of failure.

2.1.6 Human Error

The method must allow for the inclusion of human error, since a large number of manual operations are involved in an oil transfer. This is true even for highly automated systems, in part because the operations of mooring and connecting to the ship's manifold are manual and in part because communications between the various sites (such as the tanker and the control center on the pumping platform) are involved.

2.2 REVIEW OF ALTERNATIVE METHODS

In reviewing the various system safety risk analysis methods in detail, it is apparent that many of the methods differ only in name. The different organizations that either developed or employed the various methods named them to suit their own needs. For this reason, although there appear to be many risk analysis methods, only a limited number of them represent different methods. The following methods were reviewed:

A similar analysis technique is that of "Operations Safety Analysis," which is primarily a means of identifying tasks that are hazardous in the operation of a system. Again, as in mission analysis, these techniques do not provide the necessary flexibility to examine the transfer system as desired in the criteria presented in Sections 2.1.1 to 2.1.6

2.2.3 Interface Safety Analysis and Flow Analysis [4]

Additional methods of risk analysis available for use in analyzing a DWP transfer system are "Interface Safety Analysis" and "Flow Analysis." Interface safety analyses are performed to insure that incompatibilities between units of a system do not generate hazards that could result in accident. In a safety analysis of this type, it is not possible to look at the overall system as well as the desired detail. An interface safety analysis is aimed at adjacent or interface systems or components. Additionally, inclusion of the human element or determination of a quantitative evaluation is not possible. Flow analysis considers the flow of fluid, energy, or both from one location to another and the hazardous conditions associated with this transport. This form of analysis could be part of an interface analysis. This method of analysis does not allow sufficient scope and is too restrictive to provide credible results. The criteria outlined in Section 2.1 cannot be met by either of the above methods.

2.2.4 Failure Mode and Effect Analysis (FMEA)

This method was originally developed to examine the consequences of the failure or the failure modes of a given component. FMEA is primarily employed in the analysis of equipment. The system is examined, one component or assembly at a time, for possible failure modes and subsequent effects. A limitation of this approach is that it often happens that simultaneous failures of two components are involved in a event leading to serious consequences. Additionally, human error is not a consideration in a FMEA. The general approach to FMEA is first to perform a qualitative analysis and then, utilizing available data and however, it considers only one component at a time, and it does not provide for other factors. For purposes of DWP risk analysis, the standard FMEA will be modified to reduce the qualitative aspects of the analysis and incorporate into FMEA the factors of human error and environmental effects.

In summary, the selected FTA and FMEA methods provide the desired tools for both a qualitative and quantitative evaluation from which to judge the merits of a transfer system.

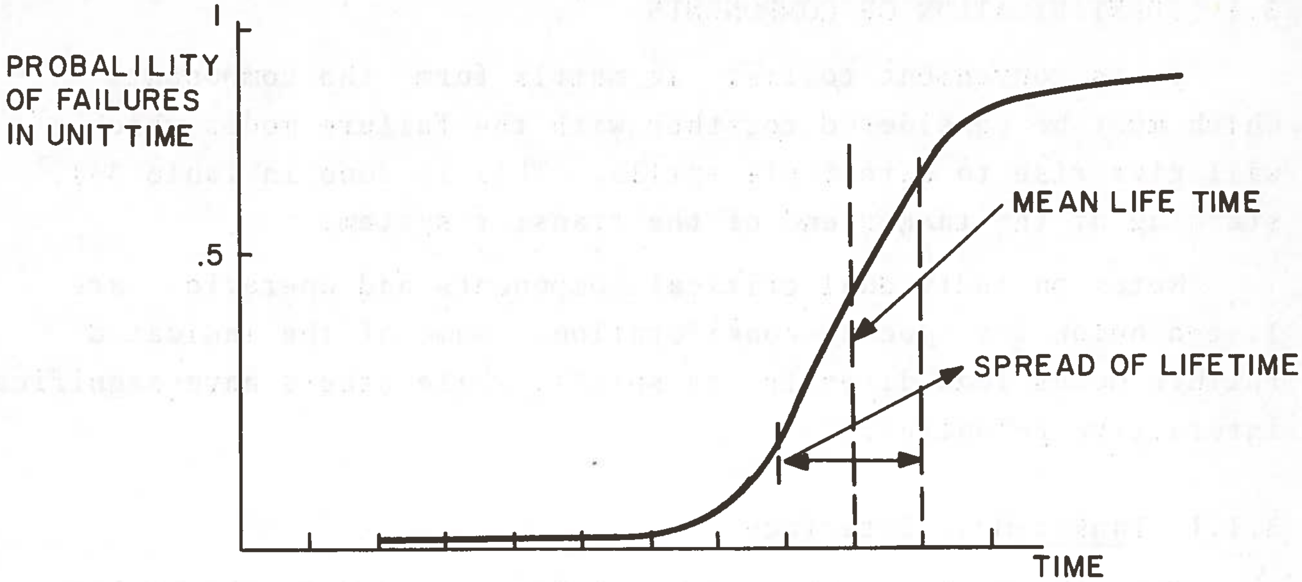

FIGURE 3-1. PROBABILITY OF FAILURE FOR COMPONENT WITH A WELL-DEFINED MEAN LIFE

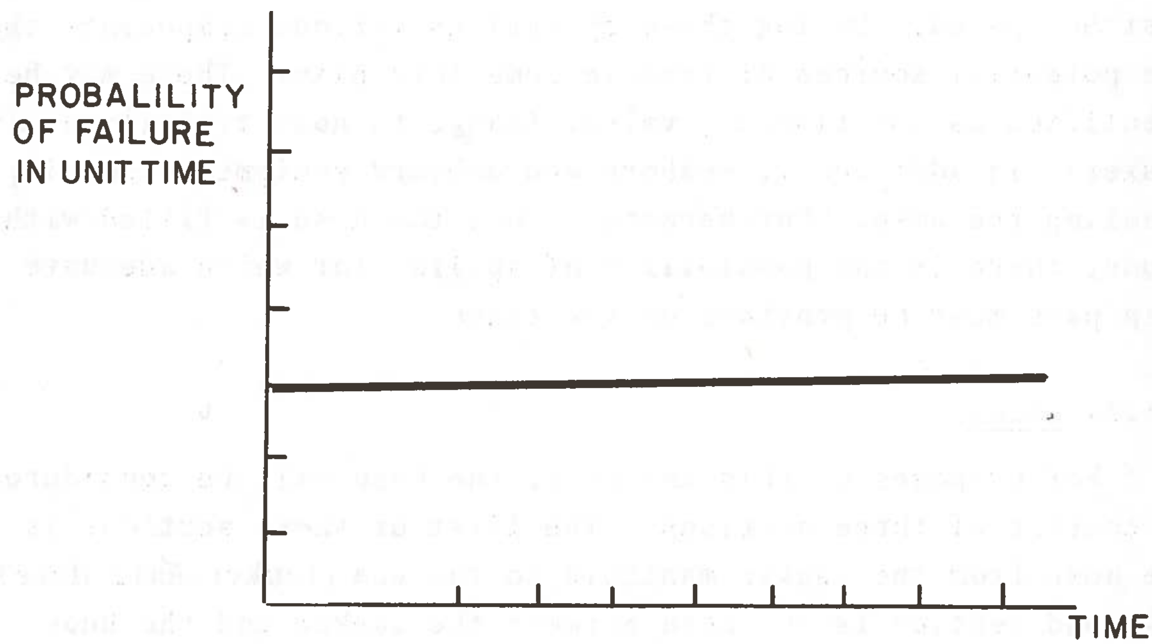

FIGURE 3-2. PROBABILITY OF FAILURE PER UNIT TIME OF A COMPONENT SUBJECT TO RANDOM FAILURE

TABLE 3-1. SINGLE COMPONENT FAILURE-MODES CAUSING SPILLS DIRECTLY FROM THE FAILED COMPONENT

COMPONENT	MODE 1	MODE 2	MODE 3
End Gasket	Rupture	Deterioration	
End Flange	Break	Faulty Weld	Deterioration
End Valve	Leaking Stem	Cracked Housing	Leaking Flanges
Tanker Rail Hose	Damaged Hose	Burst Support	Separation of Liner
Floating Hose	Damaged Hose	Leaking Flange	Separation from Nipple
Buoy Hose	Kinked & Cracked	Leaking Flange	Separation from Nipple
Under Buoy Hose*	Kinked & Cracked	Leaking Flange	Separation from Nipple
Buoy End Valve	Leaking Stem	Cracked Housing	Leaking Flanges
Riser End Valve**	Leaking Stem	Cracked Housing	Leaking Flanges
Cargo Swivel	Leaking Seal		
Hose to Pipe	Deterioration	Leak in Connections	Separation from Nipple
Scraper Launcher	Leaking Connections		
Gaskets at at PLEM+	Rupture	Deterioration	
Riser at PPC++	Cracks	Leaking Connections	
Expansion Joints	Over extension	Over extension	Pressure surge

Notes:

*CALM only
**SALM only
+PLEM = Pipeline End Manifold
++PPC = Pumping Platform Complex

Generally, buoyancy is provided by plastic foam (polyurethane, polystyrene, etc.) and this floatation material must be adequately protected. There have been incidents where ships have run over floating hoses, and signal lights or markings are therefore required on the hose.

The underbuoy hose lengths are subject to abuse similar to that experienced by the other hose sections. In addition, the region of the hose which connects to the swivel at the SPM is subject to strong bending moments and should be inspected thoroughly. Underbuoy hoses may also be damaged by chafing with each other or by contacting the ocean floor. The design configuration chosen (SALM or CALM) [8] will determine which of the problems might be encountered with the SPM hose system.

3.1.3 Single Point Mooring Buoy

The basic connection between the floating hose and the pipeline end manifold (PLEM) is accomplished through the use of a fluid swivel. In the case of the CALM the swivel is located on the buoy, whereas in the SALM the swivel is located underwater. Fluid swivel joints are potential sources of leaks and presumably will require some maintenance. Other problems such as swivel binding and excessive wear may be experienced and must be considered in the analysis.

In many SPM designs fluid swivels are used in addition to the main fluid swivel on the buoy to connect the buoy to the underbuoy hose. These swivels allow for increased movement of the underbuoy hose relative to the fixed connection on the buoy. In the case of the SALM system, where the swivel joint is underwater, special problems are created in the inspection and maintenance of this joint.

In examining the failure modes of an SPM buoy, it is important to consider the integrity of both the buoy structure and its several components, such as buoy piping, bearings and valves. Failure of the structural integrity of a buoy, which can lead to pollution, may be initiated by failure of buoy moorings or by collision with a seaborne vessel.

The manifolds interconnecting the various components of the system, such as pipelines to pumps, are subject to stresses from pressurization and possibly from shock and vibration; thus mechanical or welded joints may develop small leaks. Valves and manifolds will be exposed to seawater and oil products, so that the corrosion effects of these substances, as well as the possibility of damage from solid materials, must be considered.

3.1.6 Turbine Flow Meters

Turbine flow meters are likely to be used in various locations to meter the flow through hoses, pipelines, and manifolds. In addition, flow meters have been mentioned in connection with such uses as balancing the flow through parallel sections of manifolds, detecting leaks, and totalizing the flow through the system. Used in this way, the flow meters will be part of an interacting subsystem and will be discussed in Section 4. However, flow meters are moving systems in an otherwise static arrangement of hardware, and there is always a possibility of the disintegration of moving parts. Thus, the mechanical failure modes of such devices must be examined.

3.1.7 Strainers

Strainers must be included in the hydraulic system to intercept inner linings of hoses, which occasionally flake, and solids carried in the product stream. Strainers may be located ahead of valves, pumps, and other sensitive components. The requirements of such strainers under conditions of full pressure and under surge conditions must be considered.

3.1.8 Bypasses

It is possible that there will be a need to include bypass relief valves around strainers, pumps, and valves in order to relieve conditions of overpressure. Such bypasses may be springpossible, though not probable, that the tank structure could rupture and result directly in a spill.

3.1.11 Metering and Control

Metering and control will be discussed, to the extent currently possible, under the headings of interacting subsystems and operational procedures. Viscosity and temperature are of interest for the calibration of flowmeters. System pressure is a parameter required to actuate various controls. Flowmeter readings are also subject to viscosity corrections. Leaks of major proportions could, in principle, be detected by flow or pressure sensors along the line. Small leaks, however, cannot be detected by flow metering.

3.1.12 Storage Tanks

Storage tanks, whether onshore or at sea, must be considered as a possible source of failure. The most probable cause of a spill from a storage tank is not a rupture of the tank, but the possible overflow due to errors in filling or due to failure of tank level indicating devices. For purposes of a risk analysis, all possible storage tank failure modes must be considered.

3.1.13 Shipboard Piping

As previously defined, the DWP transfer system extends from the suction side of the shipboard cargo pumps to the onshore tank farm facility. Any risk analysis must therefore include the shipboard piping and its associated fittings. Spills due to leaks or rupture of the piping, or as a result of rupture of an expansion joint or the failure of a gasket, are possible events and must therefore be considered.

If all of the above methods fail, it is necessary to assign a number based on engineering experience. Such an arbitrary number is useful for the purpose of comparing one installation to another.

For consistency, it is necessary to select a single unit for λ, such as number of failures per unit time or per unit of oil unloaded. This presents no great problem at this point where the application is to single components. Later on, when the question of human error is considered, it will be necessary to give a different interpretation, since human error is related to the demand frequency of the operation leading to the error.

Because "time to repair" or failure duration is more logically expressed in units of time than in any other unit, time has been chosen as the unit for the proposed method. If the unit of time is chosen large enough, say one year, the conversion should present no great difficulties. To convert "human error per action" to human error per unit time, one only need determine how often in the course of one year the action under consideration is performed.

One other caveat must be added. The probability of failure is frequently a function of operating parameters. Thus, the life of a liner in a hose will depend on the oil flow velocity and on the properties of the oil, while the life of the support body of the hose will be a function of prevailing average sea states.

3.2.2 Restoration Time or Time to Repair (τ)

The effective duration of a failure is an important quantity in determining the amount of spillage in each event. Additionally, when dealing with interacting systems where more than one component may have to fail before a spill will occur, the effective duration of a failure is an important quantity in determining the probability of undesirable events. In the latter application, the concept of repair times is important. It is desirable to keep the concepts and symbols used to a minimum, 3.2.3.2 Technical Factors Determining Q - The determination of Q on a technical basis will depend on factors peculiar to each failure mode and on the technical details of the installation.

A complete break of a floating hose for instance will lead to a Q depending on:

1. The velocity, v, of the fluid, and the diameter, D, of the hose
2. The time to detection and shutdown τ.

Thus, $Q = v(D/2)^2\pi\tau$

The case of a leak is more complicated. If the detection of leaks is based on flowmeters, for example, then any leak smaller than one part in 10^2 or 10^3 will not be detected, since one part in 10^2 or 10^3 represents the limit of sensitivity of such instruments at the present state of the art. Thus, if 100,000 bbl are unloaded per hour, then a leak of 100 bbl per hour may go undetected. Alternate means of detection, such as periodic visual inspection by helicopter over-flights, will be available.* In that case, Q will depend on the frequency of such inspection flights. Finally, in the case of a leak that is not detected during visual inspection flights, the duration of the leak will be determined by the maintenance and inspection schedule for the component in question.

For comparative purposes it is therefore necessary to deal with the questions of leak detection sensitivities and with the inspection schedules when considering such failures as partial nipple detachment or flange-nipple weld leaks.

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*Fluorescence detectors using laser illumination are currently under development. Devices of this kind are easily airborne.

flakes from the hose. In the event of rapid blockage the entire momentum of liquid moving in the hose would build up a large surge at the end closest to the strainer. The amount of pressure built up as a result of the surge depends upon the speed with which the liquid is moving and the suddenness with which the flow is blocked,[9] (see Figure 4-1). Instances have been reported where a hose ruptured or became detached from nipples as a result of surges occuring when a butterfly valve closed suddenly. Any such arrangement should be analyzed and a risk assigned to it.

The situation described in the preceeding paragraph can best be avoided by providing bypasses around strainers. Such bypasses could either bridge the strainer into the main line or provide access into an accumulator tank or overflow. In the case of a bypass leading to an overflow there is always the possibility of a leak or tank overflow. In the case where the bypass leads into an accumulator tank and where such a tank may contain, a gas-pressure-buffering system the dynamic properties of such a system must be analyzed.

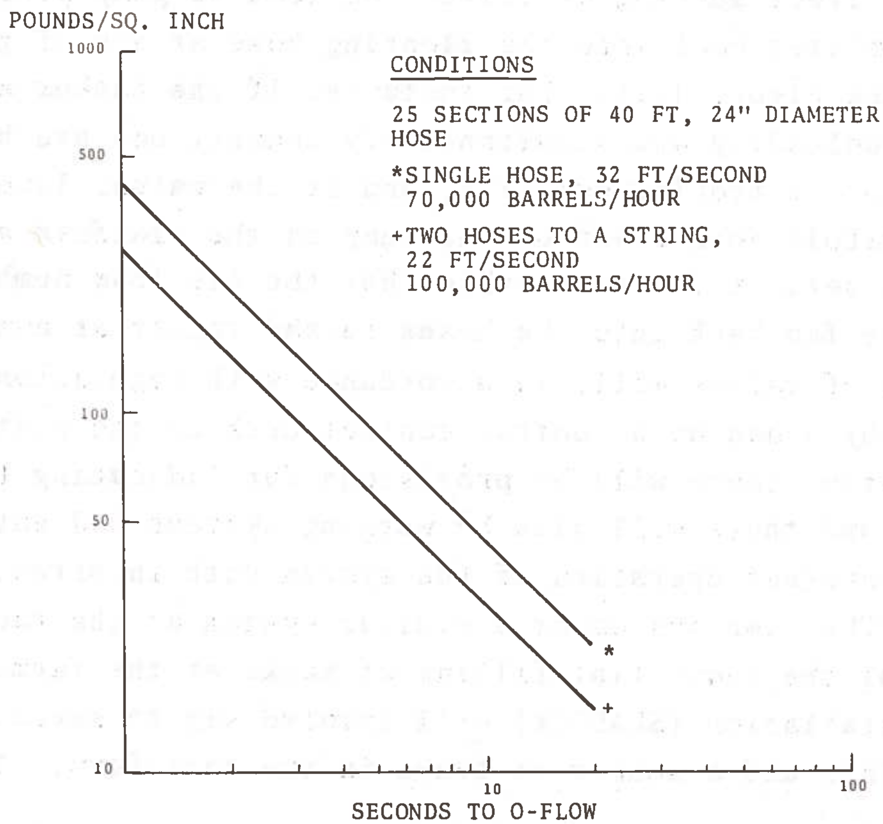

FIGURE 4-1. SURGE-PRESSURE RESULTING FROM SUDDEN FLOW STOPPAGE

manifold systems interconnecting the various parts of the oil transfer system will necessitate a fairly complicated control system. It is likely that computer logic will be used and that this logic will receive inputs from various level sensors and from flow meters, pressure gauges, and other instrumentation. The failure modes of this entire man-computer hydraulic system-interface must be carefully analyzed.

4.5 FLOW METERS

The malfunction of the flow metering system may lead to an unbalanced operation of the hydraulic system. Where the flow meter is used in an automated system to provide inputs for the control of the system, dangerous situations may arise if a flow meter malfunction is not detected. Similarily, if flow meters are used to totalize the flow into or out of tanks, particularily tanks of irregular crossection, such as the salt domes proposed by Loop, there is the possibility of a tank overflow because of an incorrect reading from the flow meter. Turbine flow meters are provided with proving facilities by the manufacturers. However, the reading of flow meters is subject to change due to temperature, pressure, and viscosity. The use of flow meters in a situation of this kind must be considered in the risk analysis.

4.6 COMMUNICATION DEVICES

Links between major components such as the tanker, the platform, and the onshore tank farm are required for normal as well as emergency situations. Failure of a link could result in overflow of a tank or overpressure in a line, hose, or separator. Accordingly, the interactive modes of communications links must be considered.

4.7 COMPUTER AND LOGIC DEVICES

It is conceivable that the use of computers and logic devices for the smooth control of the hydraulic system may be contemplated. In general, such a system will consist of at least three functional separator tanks and overflow valves, will be designed for fail-safe operation. Nevertheless, the power plant must be identified as a part of several interactive subsystems.

4.10 OPERATIONAL PROCEDURES

The sense in which operational procedures are to be considered interactively related to the functional parts of the system may be illustrated by the following example. The product transport through the proposed systems will be on the order of 4×10^6 gallons per hour. If instrumentation were provided to detect leaks automatically by, say, a differential flow measuring process at two points with a precision of one part in 10^4, then a leak of 4×10^2 gallons per hour would remain undetected. To detect the escape of 100 gallons due to failure of the floating hoses, the area of the hose would have to be inspected every 15 minutes by visual means. On the other hand, if the flow meter had the more conventional precision of one part in 10^2 then continuous monitoring would be required in addition to the flow metering at two points. Thus, procedures must be linked to the characteristics of the mechanical devices and to the rules specifying the detection capabilities of surveillance devices at various points of the DWP.

4.11 HUMAN FACTORS

Consideration of human factors will enter into a number of operations. In the case where a human operator is working in parallel with an automated system, there is always the danger of the human operator having too little to do to remain alert. Thus the system should be examined to ascertain that the division of labor between machine and man is such as to provide a sufficient rate of activity for the man to maintain his alertness.

Other factors entering the analysis would be training, qualification of personnel, and adequacy of staffing. This latter factor is of special significance for emergency situations in automated systems. Since such systems will generally have fewer personnel available to deal with emergencies, special training and methods to meet such contingencies are called for.

It is sometimes claimed that certain components never fail. New pipelines, pumps, or valves, for instance, have been subject to such assertions by their manufacturers. A study of actual accidents, however, does not justify such absolute confidence, since one finds frequent references by users to "manufacturers defect," "faulty weld," etc.

It is reasonable to expect, and has been confirmed by experience, that older facilities are more prone to chronic malfunctions than new facilities. This is true even where an effective and careful system of maintenance and replacement is practiced. In what follows it is important to keep in mind that a risk analysis can serve at best to prevent gross omissions in design and that any predictions of spill which may be attempted will not apply throughout the life of the facility. Nor can one be sure that after all due care is taken in the design and operation of a facility, a spill of say 10,000 gallons will not occur during the very first hour of operation. It has been pointed out by several authors that the incidence of large spills is sufficiently low and the causes sufficiently diverse to make a meaningful statistical analysis difficult and a definitive prediction impossible.

What, then, is the useful information that can be obtained from the data? The answer to that question is best illustrated by means of a fictitious example. Suppose, for instance, that it turns out that several large spills have occurred because of pump casing rupturing. Since the flow of oil can not be stopped immediately one might require a fast-acting bypass system to shut off the flow to the pump and open the bypass. Now, suppose on the other hand that the data indicate that pump cases never rupture but butterfly valves occasionally shut against the flow of oil, thereby causing surges that rupture hoses. In that case one would certainly eliminate the fast shutoff valve and, depending on the other failure mode of pumps, equip the bypass with an automatic relief valve.

according to class of accident — i.e., collision, explosion, or grounding — and then according to narratives of the events and the circumstances surrounding the accident and of the damage which ensued. The third category, "Assistance and Recommendations," is self-explanatory.

Subsequently, the Coast Guard investigates the accident and files a "Finding of Fact Conclusions" and recommendations as to whether the case should be closed or investigated further. The two sets of reports, namely, Forms CG 2692 and the Coast Guard narrative report, are filed together in the Office of Merchant Marine Safety. The information on CG 2692 is stored on tape.

The question of completeness comes up in connection with the accident data maintained by the Office of Merchant Marine Safety, as it does for similar compilations of accident statistics. From the point of view of hazardous materials, all ocean going vessels and tank barges must be certified by the Coast Guard when they are new and periodically thereafter. If one of these vessels is in an accident and requires repairs at a shipyard, a Coast Guard inspection is required before the vessel can put to sea again. Therefore, the Coast Guard has a mechanism to insure that accidents of any significance whatsoever are detected.

5.2.1.2 <u>Office of Marine Environment and Systems</u> - One of the functions of this office is to maintain records on all incidents that result in the discharge of environmentally hazardous substances into the waters of the United States. These reports originate in the various Coast Guard Districts and are entered directly into the master file by remote terminals at the District Office. A great many of the items in the report are of interest for accident analysis.

These files are crosschecked with the Merchant Marine Safety files to determine the degree to which both cover incidents that should be common to both files. However, there is to date no universally accepted estimate of the completeness of either of these two Coast Guard files.

TABLE 5-1. COAST GUARD DATA, 1972

SOURCE AND CAUSE

Number of incidents / Volume in Gallons

SOURCE \ CAUSE	Collision	Grounding	Capsizing/ Overturning	Fire/Explosion	Other Casualty	Tank Rupture	Hull Structural Failure	Storage Tank Rupture or Leak	Hose Rupture	Line Leak
Vessels										
Dry Cargo	2/125	5/705	1/500	10/821	3/5	1/0	2/102	3/1,262	6/44	7/253
Tankships	7/105,315	9/319,100	X	1/0	3/212	13/2,877	18/23,326	17/1,801	9/2,206	5/130
Tank Barges	45/1,294,732	23/422,207	1/0	2/92	15/1,690,249	81/46,825	70/121,461	35/11,259	31/8,361	19/8,861
Combatant	1/20	X	X	X	3/53	2/2,045	2/22	4/415	7/406	8/55
Other	10/1,118	8/1,670	1/37	4/1,000	68/7,930	2/2,030	6/299	5/92	4/375	7/132
Land Vehicles	22/17,943	X	37/91,613	1/250	5/15,030	7/31,110	5/3,250	1/50	X	2/20
ONSHORE FACILITIES										
Refineries	X	X	X	X	1/50	1/300	X	X	6/952	12/502
Bulk Storage	1/100	1/20,000	1/3,000	1/0	1/5	7/42,505	X	17/58,429	3/193	20/5,941
Waterfront Transportation Facilities	6/1,263	X	X	1/0	2/50	7/46,615	2/280	10/267	45/16,464	36/29,575
Non-Transport. Facilities	1/20	X	1/800	5/7,275	3/4,005	7/25,350	1/0	13/2,781	13/742	50/8,192
Other Land Transportation Facilities	X	X	X	X	3/167	X	X	1/0	2/55	2/400
Pipelines	6/33,910	X	X	1/0	2/24	X	X	X	1/1	41/6,035
OFFSHORE FACILITIES	9/901	X	X	5/21,300	17/18,077	5/477	2/47	18/3,805	19/575	791/42,157
MISCELLANEOUS	1/20	X	X	2/0	2/400	2/400	X	5/43,820	2/30	7/1,784
UNKNOWN	X	X	X	X	X	X	X	X	X	X
TOTAL	111/1,455,467	46/763,682	42/95,950	33/30,738	128/1,736,257	135/600,534	108/148,787	129/123,981	148/30,404	1,007/104,037

TABLE 5-2. COAST GUARD DATA SUMMARY, 1972

CAUSE	NUMBER OF INCIDENTS	% of TOTAL	VOLUME IN GALLONS	% of TOTAL
COLLISON	62	0.7	1,455,900	16.5
GROUNDING	54	0.6	898,039	10.1
CAPSIZING OR OVERTURNING	21	0.2	32,575	0.4
FIRE & EXPLOSION	9	0.1	398,400	4.5
OTHER CASUALTY	68	0.8	260,805	2.9
TANK RUPTURE	70	0.8	2,081,443	23.5
STRUCTURAL FAILURE	26	0.3	7,620	0.1
STORAGE TANK RUPTURE OR LEAK	123	1.4	146,815	1.7
HOSE RUPTURE	110	1.2	50,347	0.6
LINE LEAK	1,529	17.5	562,896	6.4
PIPE RUPTURE OR LEAK	588	6.7	674,506	7.6
OTHER RUPTURE OR LEAK	311	3.6	191,440	2.2
VALVE FAILURE	461	5.3	141,578	1.6
PUMP FAILURE	207	2.4	14,142	0.2
OTHER EQUIPMENT FAILURE	279	3.2	118,329	1.3
TANK OVERFLOW	253	2.9	100,787	1.1
IMPROPER HOSE CONNECTION	71	0.8	8,476	0.1
OTHER PERSONNEL FAILURE	505	5.8	926,687	10.5
INTENTIONAL DISCHARGE	359	4.1	50,652	0.6
NATURAL PHENOMENON	94	1.1	5,805	0.1
UNKNOWN	3,536	40.5	712,281	8.0
TOTAL	8,736	100.0	8,839,523	100.0

Source: "Polluting Incidents In and Around U.S. Waters, Calendar Year 1971," U.S. Coast Guard, Washington DC [n.d.], p. 7

The Lloyd's data are collected and analyzed by the Tanker Advisory Center, 315 West 70th Street, New York NY 10029. The Center publishes quarterly and annual world-wide tanker casualty returns. These returns list the incidents which result in pollution and the number of tons of oil spilled.

Some questions about the completeness of the data arise because when there is not enough damage to exceed the recent deductability provisions of the marine insurance policies, the casualty may go unreported. Also, spills are not included when there has been no casualty. Hence the Lloyd's data are probably biased toward larger spill incidents.

5.2.4 Atomic Energy Commission ("Rasmussen Report," Failure Rates, Repair Times, and Methodology)

Probably the most extensive compilation of data on failure rates for components similar to those used in DWP's is the Reactor Safety Study.* This study reports on an assessment of accident rates in U.S. commercial nuclear power plants. In addition to the data, there is much valuable material in it on the subject of risk assessment and fault tree analysis pertaining to construction and maintenance. Appendixes II and III to the Study contain the bulk of the the information on failures rates and fault trees.

Appendix III is almost entirely devoted to failure origins and validity of the data. A very extensive list of references is provided. The failure rates are given in units appropriate to the type of component and the function which it performs. How to take into account the effect of maintenance is discussed in this appendix and in Appendix II as well. Sample data are reproduced in Table 5-3.

5.2.5 SPM Spill Data Contained in MIT Report MIT SG 74-20 (April 1974)[10]

This report contains a compilation of spill data from overall sources as follows:

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*Prepared for the U.S. Atomic Energy Commission. The draft was issued in August 1974.

5.2.5.1 SPM Forum Data - These data were supplied to the investigators by ECO Inc. Originally supplied by the SPM forum, they represent 55 spills and are reproduced in Table 5-4.

5.2.5.2 "Durban Data" - The "Durban Data" were evidence submitted to the House of Lords (U.K.) on accidents at Shell's Durban (Union of South Africa) SPM facility during the inquiry by the select committee on the Anglesey Marine Terminal Bill.

The data, Table 5-5, list 23 spills and give the causes of each spill, its location, and estimated size.

The data confirm that the floating hoses are the principal sources of spills. In the case of Durban, 11 out of 23 spills were hose-related. Another set of data given in the same reference for SPBM's showed 33 out of 51 spills to be hose-related.

5.2.5.3 Shell-Oil SPM Spill Experience - These data, made available by the Anglesey Defense Action Group, contain information on 200 spills from all the Shell Oil SPM installations and were also submitted by Shell as evidence during the hearings in the House of Lords. These data are reproduced in Tables 5-6 and 5-7.

5.2.5.4 Exxon Data - These data, submitted by Exxon to the investigators, cover their offshore installations and are reproduced in Table 5-8.

5.2.6 Southwest Research Institute (Hose Failures)

The Southwest Research Institute of San Antonio, Texas, is currently concluding a study of worldwide floating hose failures at single point mooring buoys. This study should be available shortly and will be of value in assigning risk values to the floating hose and the under-buoy-hose.

TABLE 5-5. LISTING OF FIRST 23 DURBAN SPILLS

NUMBER	DATE	AMOUNT	TIME TO DISCOVERY (MINUTES)	CAUSE
1	9/21/1970	20	10	Bolts on 16" blind flange loosened
2	9/29/1970	250	nil	Tanker hull leak, no. 5 port wing tank
3	9/30/1970	85	5	Underwater hose leak, manufacturer's defect
4	10/4/1970	6	nil	Spill from hose end during connect operation
5	10/10/1970	1	nil	Underwater hose leak, manufacturer's defect
6	10/11/1970	20	nil	Tanker ballast discharge valve leaking
7	11/18/1970	1,470	nil	Floating hose rupture at buoy, manufacturer's defect
8	12/12/1970	2,940	nil	Hull leak due to contact with SBM ballast box
9	12/22/1970	42	nil	Underwater hose nipple, manufacturer's defect
10	1/3/1971	24	5	Tanker "World Friendship" overboard discharge
11	1/3/1971	85	5	Tanker "World Friendship" overboard discharge
12	2/6/1971	4,410	nil	Butterfly valve shut against ship pumps blowing 24" deckline out of expansion joint
13	2/16/1971	2,940	nil	Both end hoses parted when mooring lines broke in 40 knot squall, light condition
14	2/17/1971	20	nil	During repair due to spill 13
15	2/18/1971	20	nil	During repair due to spill 13
16	3/27/1971	20	nil	Hose connection during heavy rain
17	3/31/1971	880	nil	Floating hose nipple blew during discharge
18	5/6/1971	1	5	Tanker hull leak, no. 2 port wing tank
19	5/15/1971	20	5	Main sea valve leak, port pumproom
20	5/25/1971	1,470	2	Main seal valve leak
21	6/14/1971	620	nil	Tanker overflow from no. 3 starboard tank during discharge
22	7/11/1971	72	nil	Tanker overflow from no. 1 port wing tank during discharge
23	10/24/1971	600	nil	Floating hose repture, ship end, Manufacturer's defect

5.2.7 Office of Pipeline Safety (Accidents to U.S. Pipeline)

These reports are issued annually on the basis of data submitted by the pipeline companies to the Office of Pipeline Safety in the Department of Transportation.

Excerpts from the 1972 data are shown in Tables 5-9, 5-10, and 5-11. Reported details range from year to year, and it appears that the more recent data (see Table 5-12 for 1974) have less information as far as failure mode is concerned. The industry reports from which the annual statistics are compiled are on file at the Office of Pipeline Safety. The reports submitted by various carriers between 1968 and 1975 were examined in detail in order to obtain a better insight into the failures.

Approximately 350 reports were examined. Most of the accidents reported are due to (a) corrosion of oil pipe and (b) road building or construction equipment crossing the pipeline path. Another broad category of accidents arises from faulty welds withering around the girth of the line or along longitudinal seams along the pipe. Accidents in the latter category and also those due to corrosion were noted only when other factors, such as human error in operating valves or manifolds, contributed to the spill. Approximately 10 percent of all the accidents, however, are caused by the failure of components, either singular or as a part of interacting systems, and are therefore of interest to our work.

Apart from the understanding of the failure modes of the particular components or systems provided by these reports, it was also interesting to learn to what extent the primary component responsible for a failure can be identified from the statistics eventually published in the annual reports of the Office of Pipeline Safety. This matter is of some interest since these data, together with the data published by the Coast Guard, are the only large scale statistical data available for OTS's. In this respect it is noteworthy that several accidents were reported as "tank accidents" or "tank overflows" when in fact the accidents had been caused by the failure of other equipment. Specifically,

TABLE 5-10. PIPELINE DATA, 1972 (OFFICE OF PIPELINE SAFETY) SUMMARY — CORROSION AS CAUSE

Commodity Involved	No. of Accidents	
	External Corrosion	Internal Corrosion
Crude Oil	52	24
Gasoline	11	1
L.P.G.	6	0
Fuel Oil	4	0
Diesel Fuel	1	0
Condensate	1	0
Total	75	25

Corrosion Control	External Corrosion Only	
	No. of Accidents	% of Total
Line bare - no cathodic protection	28	37.3
Line bare - with cathodic protection	29	38.7
Line coated - no cathodic protection	2	2.7
Line coated - with cathodic protection	16	21.3
Total	75	100.0

TABLE 5-11. COMPARISON OF COATING AND YEAR OF INSTALLATIONS (EXTERNAL ONLY). NO. OF ACCIDENTS IN 1972 BY YEAR OF INSTALLATION

	Before 1920	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1972	Total
Coated	1	1	5	4	6	1	0	18
Not Coated	17	20	10	8	2	0	0	57
Total	18	21	15	12	8	1	0	75

Source: "Summary of Liquid Pipeline Accidents Reported on DOT Form 7000-1 From January 1, 1972, Through December 31, 1972," Office of Pipeline Safety, [U.S.] Dept. of Transportation, [Washington DC], April 2, 1973, p. 3.

in two such cases discharge pumps failed during the simultaneous charging and discharging operation of a tank, resulting in the overflow of the tank. Apparently in both of these instances, no warning devices were available to notify personnel concerned with the charging of the tank of the failure that had occurred on the discharging side. There were several reports on accidents involving interacting systems. For instance, in one case a failure of communications resulted in the opening of a valve at the delivery station into a receiving line of which the end valve was still closed. This resulted in an overpressure in the line. At the same time a relief valve set at a pressure of 950 psi failed to open; this sequence resulted in a ruptured pipe.

Scraper traps and launchers were involved in several accidents. In one instance a scraper trap was used to route the oil past a booster pump during a bypass operation, and a small relief valve in the trap opened up. The oil escaping through the valve went into a sump tank, which eventually overflowed; since the orifice was quite small, the pressure drop was not noted, and a considerable quantity of oil escaped. A somewhat similar accident, which caused a very large spill, occurred when a one-half-inch pressure-sensing line at the pump station was sheared off. The pressure drop at the gauge was not noticed. Such accidents indicate that large quantities of oil can be spilled from relatively small auxiliary lines; e.g., the attachment points of pressure gauges or relief valves when these are located in areas where the small resulting leak is not easily detected.

Several accidents were reported in which the failure and the spill occurred at single components. In this category it is worth mentioning the mechanical failure of two pumps. In one case, the pump housing cracked as a result of stresses in the line. In another case a reciprocating piston pump threw a rod, which cracked the cylinder head. Accidents arising from strain or thermal expansion or overpressure arising from unrelieved thermal expansion of the oil have also occurred. In two such accidents gaskets blew. In one instance the gasket of an

d. Shutting off the high-pressure regulator

e. Shutting the valve to the tank.

4. Each segment is assigned a probability of success (reliability). Many of these probabilities have been established empirically. (A few values are indicated in Table 5-13.) Where alternative actions are possible, suitable assignment of values is necessary for each.

5. The probability of successful accomplishment of each task is obtained by multiplying the probabilities for each segment. In certain instances, the task segments must be examined to decide whether they are dependent or independent events and to establish suitable mathematical relationships.

6. The probability of successful accomplishment of each procedure is obtained by multiplying the probabilities for each task.

At present the chief drawback to using this method is the accuracy of the probabilities for each segment. Almost all of these probabilities were derived from laboratory tests, and values for the probable success may be low. This fact may be due to the desire of research personnel to show measurable differences between events, especially with the limited number of tests undertaken. In addition, not only will field conditions vary from those in the laboratory but field personnel will also have different capabilities than laboratory workers. Variations in temperature, vibration, noise, and stresses will also cause field results to differ from theoretical or test considerations. It should be emphasized here, however, that it is not the methodology that is at fault but the data employed. This problem may eventually be overcome once more experience has been gained in this area.

6. STEPS IN A RISK ANALYSIS

In previous sections, general methodology was discussed and the concepts of various failure modes of individual components and interacting subsystems were introduced. In the following sections, the implementation of the method in the form of logical analysis and numerical analysis will be considered. The method employed in systematizing risk considerations in the following sections is Fault Tree Analysis and a modified version of FMEA illustrated in Table 6-1. A convenient tool for the qualitative and quantitative evaluation of risk is the FAULT TREE (FT), which is shown in Figure 6-1. The information presented in Figure 6-1 corresponds exactly to that in Table 6-1, but the presentation via "AND" and "OR" gates is easier to follow and facilitates numerical evaluation.

6.1 THE CONSTRUCTION OF FAULT TREES

Fault Tree Analysis (FTA) was originally developed in 1962 by the Bell Telephone Laboratories. The Bell Telephone Laboratories' development was sponsored by the United States Air Force for use with the Minuteman ICBM. Since then, considerable work has been done on the further development of FTA, the Boeing Company being a major contributor. Considerable literature is available on FTA, and the reader is directed to a portion of this literature.[2,12,13] With the literature available for the reader's review, the FTA methods will be only briefly reviewed in this report.

Fault trees, the principal tools used in the analysis, are employed in two types of applications. First, the FT is used to assess the overall risk of occurrence of certain undesirable events. Second, the fault tree serves as a means for the systematic examination of a system for the purpose of discovering ways in which the reliability of the system can be improved and to identify critical areas.

Before the analysis can begin it is necessary to have a schematic of the proposed installation, such as Figure 1-1, in which all components through which the oil must flow, starting at the tanker and ending at the tank farm, are delineated. In addition to this diagram it will be necessary to have separate diagrams for all the

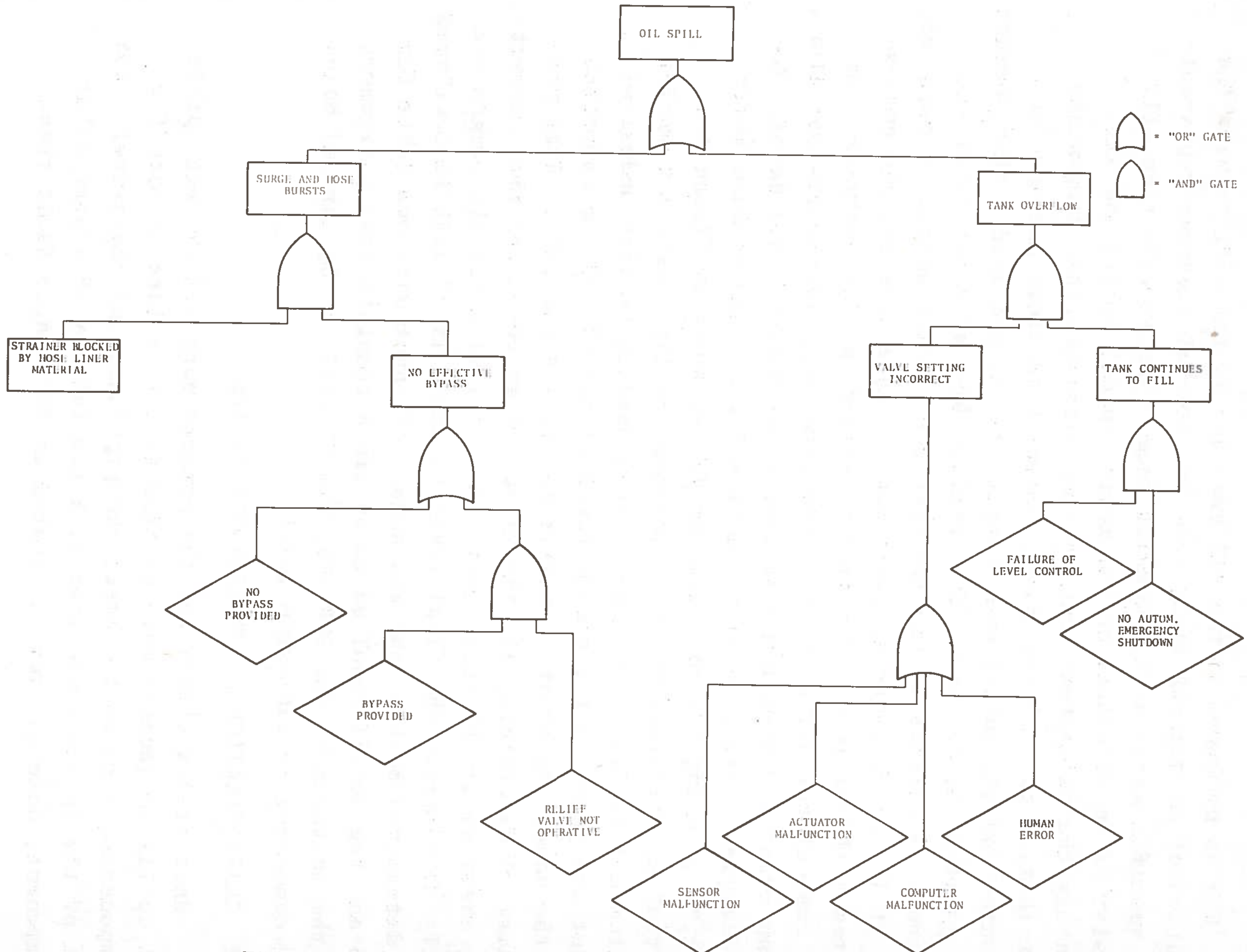

FIGURE 6-1. FAULT TREE CORRESPONDING TO TABLE 6-1

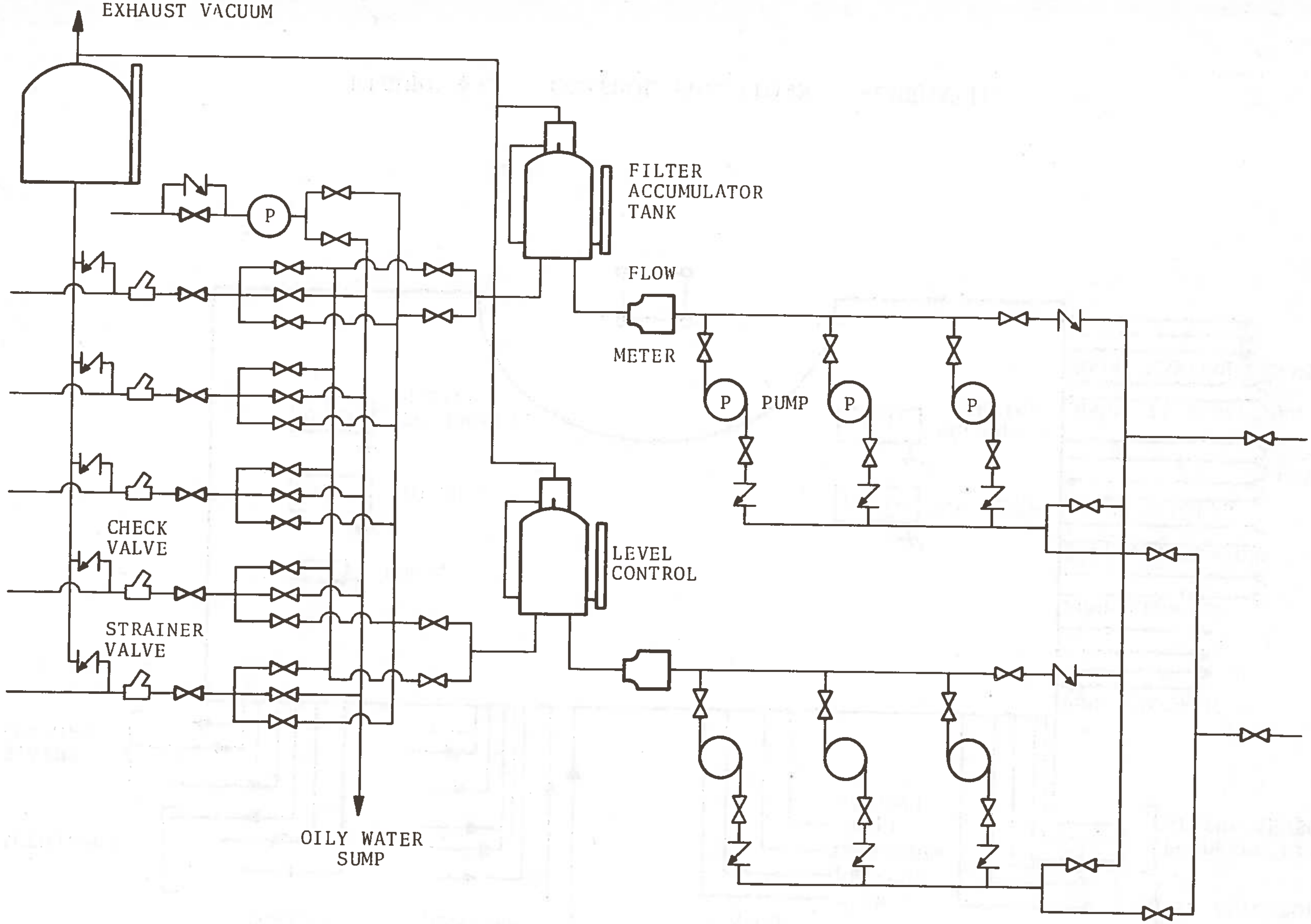

FIGURE 6-2. PLATFORM – GENERAL SCHEMATIC

Examples of classification by component and by type of failure are illustrated in Sections 6.2.1 and 6.2.2 below.

6.2.1 Classification by Components

In considering spills resulting from a failure of the hoses, one must distinguish between those spills which occur under static conditions, that is, when no oil is flowing in the system, and those situations when oil is actually flowing.

Figure 6-4 illustrates a hose spill fault tree under static conditions. Figure 6-5 on the other hand, shows a fault tree for a complete break while oil is flowing at a fixed rate. The reason for setting up separate FTs in those two instances is that an approximate amount for the spill in each of these two ultimate events can be predicted.

Thus, under static conditions it is likely that the contents of only one or two sections of the hose will actually be spilled into the sea. In the case of a break under operating conditions, however, the amount of oil spilled will depend upon the time it takes the spill to be detected and the amount of oil actually flowing through the hose, as shown in Figure 6-6.

6.2.2 Classification by Type of Failure

In the previous two examples it was assumed that the hose breaks completely. It is necessary, however, to allow also for other types of failures. This is illustrated in Figure 6-7, which shows a partial fault tree for hose spills under flow conditions caused by a leak in the hose. The reason for the separate consideration of this type of failure of a hose under operating conditions is that the spill size for these events depends on entirely different factors than in the case of a complete break. In general, these leaks will be small and the spill size will therefore depend upon the minimum quantity of oil that can be detected. This, in turn, is a function of the provisions (if any) for detecting oil on the water (or the frequency with which the lines are inspected) and the state of the sea during the period in which the leak occurs.

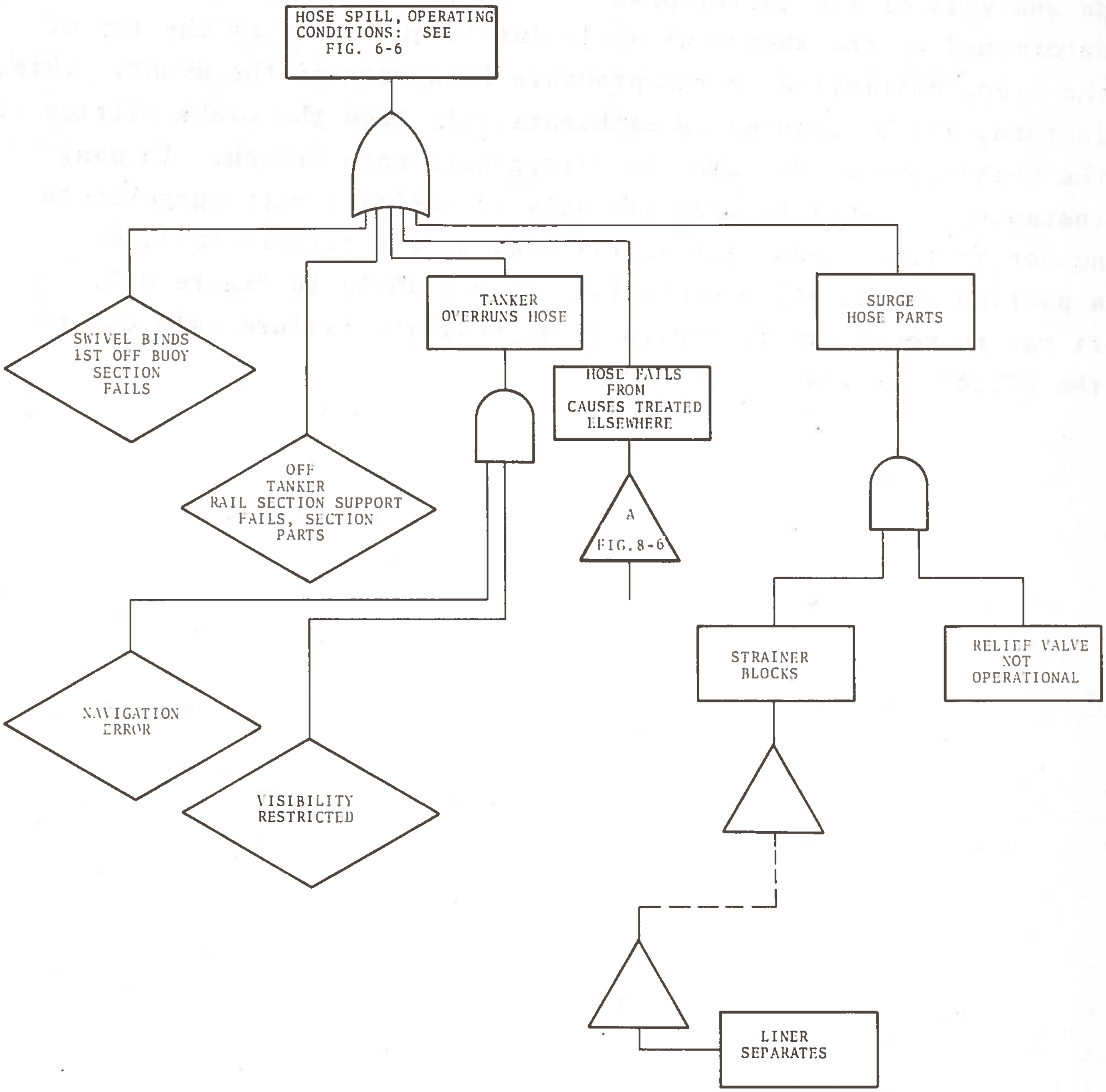

FIGURE 6-5. HOSE-BREAK FAULT TREE — OPERATING CONDITIONS

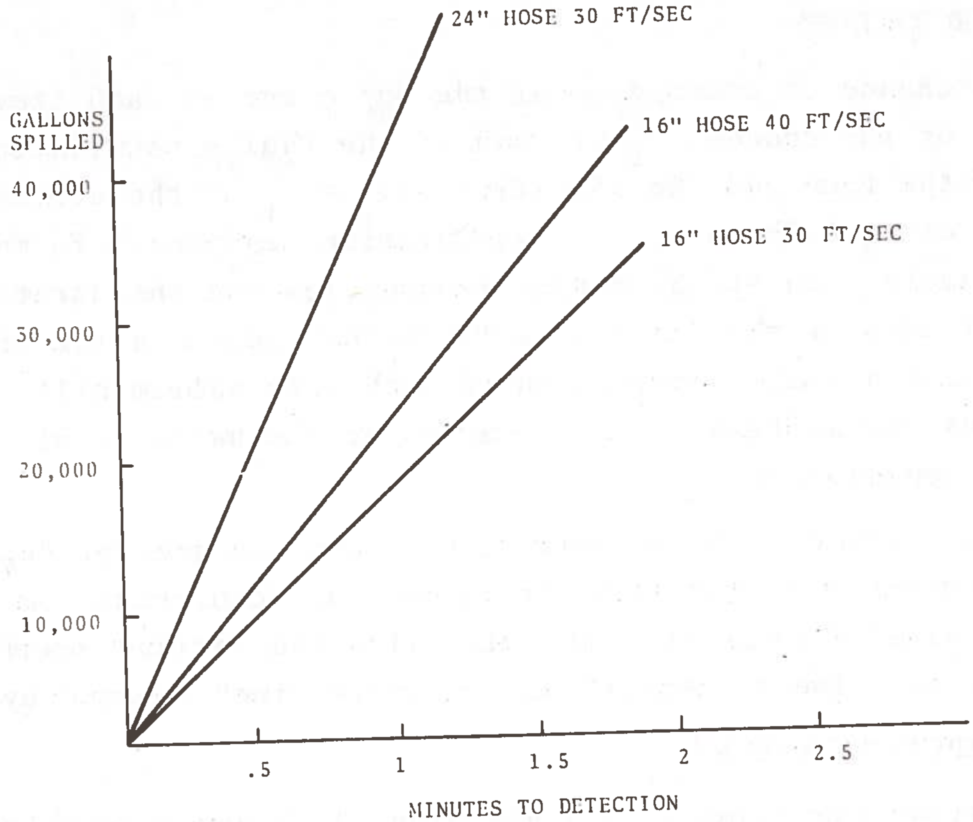

FIGURE 6-6. SPILLSIZE AS A FUNCTION OF "TIME TO DETECTION"

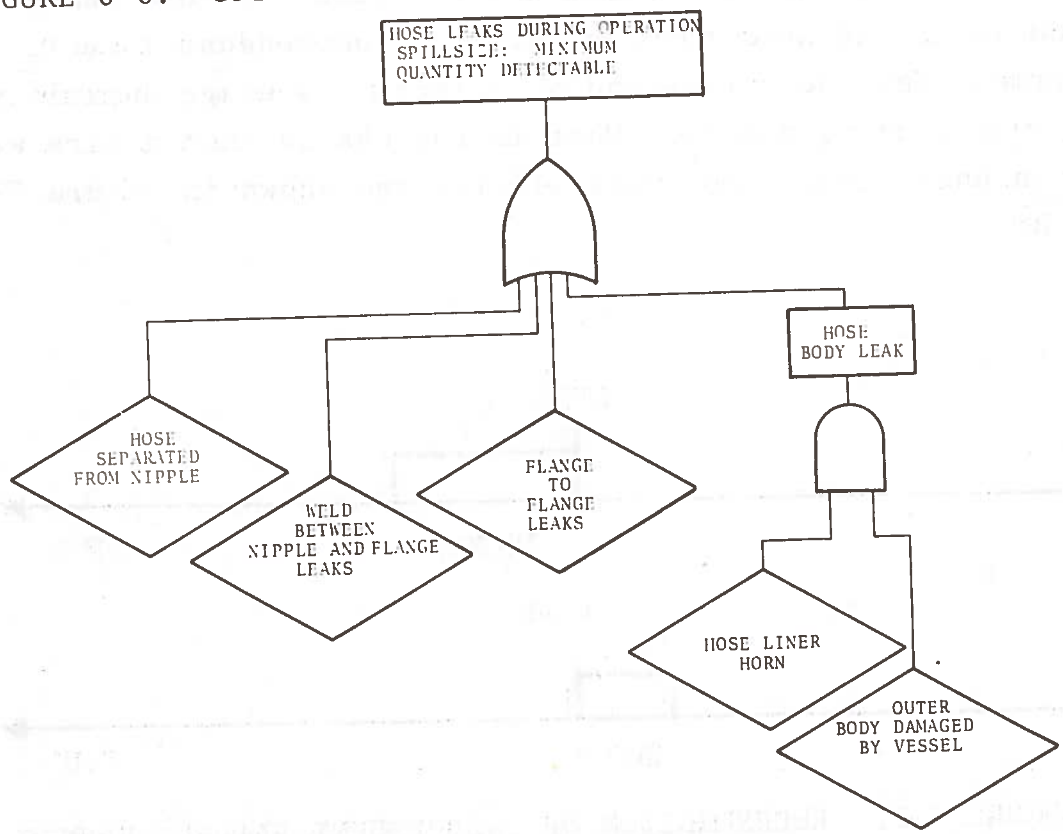

FIGURE 6-7. HOSE-LEAK FAULT TREE — OPERATING CONDITIONS

either (A) the leak occurs first and the match is struck during the effective time of the leak, or (B) the match is struck first and the leak occurs during the effective time for the match to be lit. In A, the resulting accident rate for fire is given by:

$$P_B = \lambda_1 (\lambda_2 \tau_1) \qquad (7\text{-}1)$$

In B, the rate for this sequence of the independent events is:

$$P_B = \lambda_2 (\lambda_1 \tau_2) \qquad (7\text{-}2)$$

The overall rate P is: $P_A + P_B$ or

$$P = \lambda_1 \lambda_2 (\tau_1 + \tau_2) \qquad (7\text{-}3)$$

7.3 ORDERED EVENTS

Consider next the case of an overflow resulting from the failure of a level control in a tank a short time after an emergency valve has become inoperative and therefore fails to close (Figure 7-2). If the valve had operated at the time when the level control

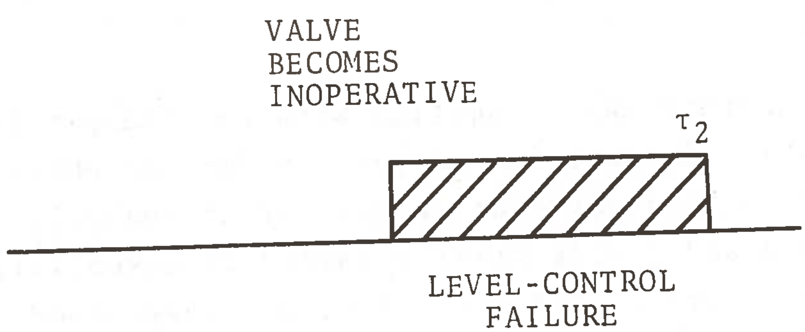

FIGURE 7-2. ILLUSTRATION OF ORDERED FAILURE EVENTS

failed, there would have been no overflow, even if conditions which might have led to a failure of the valve had occurred after it closed in response to the failure of the level control. Denoting the corresponding parameters for the level control and valve again by λ_1, τ_1 and λ_2, τ_2, respectively, in this case clearly

$$P = \lambda_2 (\lambda_1 \tau_2) \qquad (7\text{-}4)$$

probability of an overflow in unit time may be calculated as follows (see Figure 7-3).

FIGURE 7-3. DEPENDENT FAILURES

The frequency f_1 of occurrence of failure of the level control determines the number of demands placed on the valve. Therefore, in unit time, λ_1 demands are placed on the valve; i.e.,

$$f_1 = \lambda_1. \tag{7-7}$$

The overflow rate is therefore simply

$$P = f_1\lambda_2' = \lambda_1\lambda_2'. \tag{7-8}$$

In this treatment neither τ_1 nor τ_2 appear explicitly in the calculation of P, but τ_1 retains its importance as a parameter describing the repair time or recovery time as required for further calculations, such as the quantity spilled into the overflow.

7.5 EQUIVALENCE, UNEQUIVALENCE, AND UNCERTAINTY

It is possible to transform ordered events into dependent events and vice versa, but fundamental problems remain unresolved. The question of transformation will be treated first, and a discussion of the uncertainty will follow.

Suppose the valve in Section 7.4 were subjected to regular maintenance checks at n periods per unit time. The chance P_v of finding the valve in a failed condition in unit time is borne in mind when analyzing actual deepwater port proposals. In effect, it is not safe to assume that valves or other components that fail with a rate λ' per demand in one system will exhibit the same failure rate in DWP application.

7.7 COEXISTENCE OF INDEPENDENT FAILURES

Consider an "AND" gate with n input Failure possibilities F_1 to F_n and let each be characterized by failure rate, λ, and a time interval, τ_i, before repair or detection (see Figure 7-4).

Suppose at time 0 all systems/components are functioning and operation commences. We wish to calculate the chance that at some time, t, long compared to any τ_i, all failures have coexisted.*

Assume F_ℓ occurred last. Then, if the failure rate is random the chance of F_ℓ is:

$$P_\ell = t\lambda_\ell \qquad (7\text{-}13)$$

while the chance that F_i existed at the time that F_ℓ occurred is

$$P_i = \lambda_i\tau_i. \qquad (7\text{-}14)$$

The chance that F_ℓ occurred some time in the interval and tha F_i existed at that time is the product of P_ℓ and P_i.

The chance that all possible failures existed at some time between 0 and t with F_ℓ having occurred last is the product of P_ℓ with all such possible P_i's.

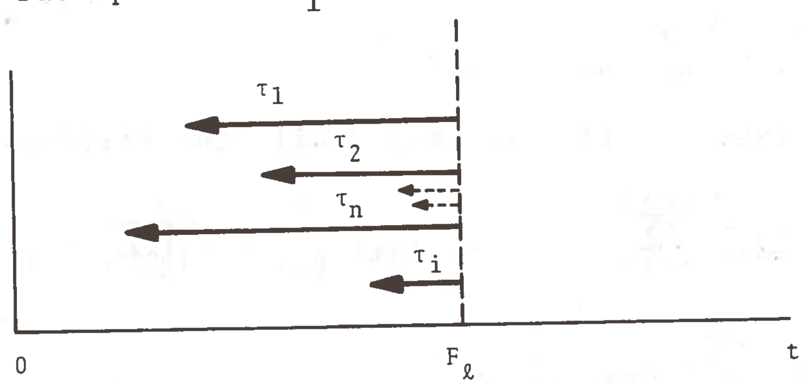

FIGURE 7-4. n INDEPENDENT FAILURES

*Actually, it must be assumed that $\lambda_i\tau_i$<<1.

$$\tau_n^* = \lambda_n^{*-1} \prod_{\ell=1}^{n} \lambda_\ell \tau_\ell$$

and using (7-18) to substitute for λ_n^* finally gives

$$\tau_n^* = \left(\sum_{i-1}^{n} \tau_i^{-1} \right)^{-1} . \tag{7-21}$$

7.7.3 <u>"OR" Gate λ_n^*</u>

The effective combined failure rate at the output of an "OR" gate is clearly

$$\lambda_n^* = \sum_{i=1}^{n} \lambda_i \tag{7-22}$$

since the events are independent.

7.7.4 <u>"OR" Gate τ_n^*</u>

Using a fictitious event F_{n+1} and proceeding as in Section 7.7.2 again gives

$$\lambda_{n+1}^* = \lambda_n^* \lambda_{n+1} \left(\tau_{n+1} + \tau^* \right) \tag{7-23}$$

in terms of the effective value of λ^* and τ^*, while considering all failure pairs F_i, F_{n+1} now gives

$$\lambda_{n+1}^* + \sum_{i=1}^{n} \lambda_i \lambda_{n+1} \left(\tau_{n+1} + \tau_i \right) \tag{7-24}$$

since each of the n failures at the input to the gate now represents an output coexisting with F_{n+1}. Using (7-22) to eliminate λ_n^* in (7-23) gives

$$\lambda_{n+1}^* + \sum_{i=1}^{n} \lambda_i \lambda_{n+1} \left(\tau_{n+1} + \tau^* \right) . \tag{7-25}$$

Eliminating λ_{n+1}^* between (7-24) and (7-25) and solving for τ_n^* gives:

$$\tau_n^* = \left(\sum_{i=1}^{n} \lambda_i \tau_i \right) \left(\sum_{j=1}^{n} \lambda_j \right)^{-1} . \tag{7-26}$$

order, so that

$$P_B^* = (1/2)\ \lambda_3\ t\ (\lambda_1\tau_2)\ (\lambda_2\tau_2) \tag{7-29}$$

and the combined probability for the cases "A" and "B" is

$$P_3^* = t \prod_{i=1}^{3} \lambda_i\ (\tau_1\tau_2 - \tau_2^2/2). \tag{7-30}$$

Note that the probability for the sequence of failure $F_2 \rightarrow F_1 \rightarrow F_3$ is

$$P_3^{*1} = t \prod_{i=1}^{3} \lambda_i\ \tau_2^2/2 \tag{7-31}$$

since both F_1 and F_2 must now occur in the interval τ_2 prior to the occurence of F_3.

The combination of (7-30) and (7-31) gives all possible orderings of failure when F_3 fails last and is

$$\sum P_3^* = t \prod_{i=1}^{3} \lambda_i\ (\tau_1\tau_2). \tag{7-32}$$

Finally, all possible sequences of failure with any of the F_i's failing last can be obtained by summation:

$$\sum\sum P_3^* = t\ \lambda_1\lambda_2\lambda_3\ (\tau_2\tau_3 + \tau_1\tau_2 + \tau_1\tau_3). \tag{7-33}$$

This is identical with (7-16) as applied to three cases.

This last result is obvious since (7-16) represents all possible sequences of failure. A similar relationship exists between equations (7-15) and (7-32).

7.9 USE OF LAMBDA-TAU METHOD IN OIL SPILL ANALYSIS

The equations derived in the previous section are very general in this application to fault tree analysis. However, when applying them to specific situations careful attention must always be paid to insuring that parameters used are consistent with the type of fault being considered. Specifically, it is essential to distinguish between the chance that a failure will occur in a functioning component (e.g., meter stops functioning) and the existence of a failed state (e.g., the meter is not functioning). The first of these is a rate — the average number of failures per variety of the situations encountered is sufficiently wide that such a set of rules is impracticable. On the other hand, fault tree analysis is basically an application of the theory of probability. Consequently, since the concepts and methodology that it employs are always consistent with that branch of mathematics, the general rules are to be found therein. A summary of formulas used appears in Table 7-1.

8. RISK ANALYSIS DEMONSTRATION

8.1 INTRODUCTION TO DEEPWATER PORT EVALUATION TECHNIQUES

This section shows how the methods and data presented earlier in this report can be used to estimate the safety of a DWP with respect to spills of oil. The aim here is not to evaluate the total spill hazard in DWP as such, but rather to illustrate the approach to conducting such an analysis. The evaluation for a real port will involve the assembly of detailed data about the specific port and analyzing it in the context of its actual environment. In this section we shall deal only with a few of the systems that can be extended to encompass all the systems of the port and any potential spill situations that can occur.

When the task of evaluating a proposal for a real port finally arises, it will be apparent that analytical methodology will not be a limiting factor. Rather, for the present and probably for some time to come, data will be the major limitations to the evaluation process. Hence, in developing a capability for risk analysis in connection with DWP, most of the attention should be focused on improving the data base.

The schematic drawing of the DWP, Figure 1-1, shows that the basic elements of the system are the tanker, floating hoses, single point mooring buoy with an adjacent pumping platform, and the on-shore storage tanks. Undersea pipelines connect the SPM to the pumping platform and the pumping platform to the storage tanks. Table 8-1 lists some pertinent characteristics of this DWP which are necessary in the subsequent analysis.

The examples presented in this section are concerned with material failures that lead to significant spills of oil from the general hydraulic system. Specifically, they involve catastrophic events in this system that would lead to significant spills if associated systems do not function properly when these events occur.

TABLE 8-1. CHARACTERISTICS OF DEEPWATER PORT

BASIC DATA	
Tanker Size	250,000 dwt ~ 1.75 x 10^6 bbl
Ton/Barrel Ratio	7 (Abaqaiq Arabian Crude)
Hoses Per SPMB Hose String	2
Hose Section Dimension	Inside Diameter, 2 ft; Length, 40 ft
Number of Sections Per Hose	50
Pumping Rate/Hose	35,000 bbl/Hose/hr
Storage Tank Volume	1,000,000 bbl
Underwater Pipeline Length	50 Mi
Annual Volume	3.7 x 10^8 bbl
DERIVED DATA	
Volume Per Hose	6283.19 ft^3
Volume Per Hose	1168 bbl
Velocity of Oil	16.7 ft/sec. 11.4 mi/hr
Number of Tanks Filled Per Tanker Discharge	1.75
Pumping Time Per Tank Discharge	25 hr
Tanker Discharge Per Year	211

seas. Other events also pose perils to the hose, such as its being struck by a vessel. Moreover, a hose section failure can be the result of a defect in its manufacture.

Hose sections are therefore subject to three kinds of failure events: early failures resulting from defects in manufacture, chance events such as accidental striking by a vessel, and wearout, which results from the combined stresses imposed by the operations of the system and from the environment. Figure 8-1 shows how the failure rate of a hose section varies with time after its installation.

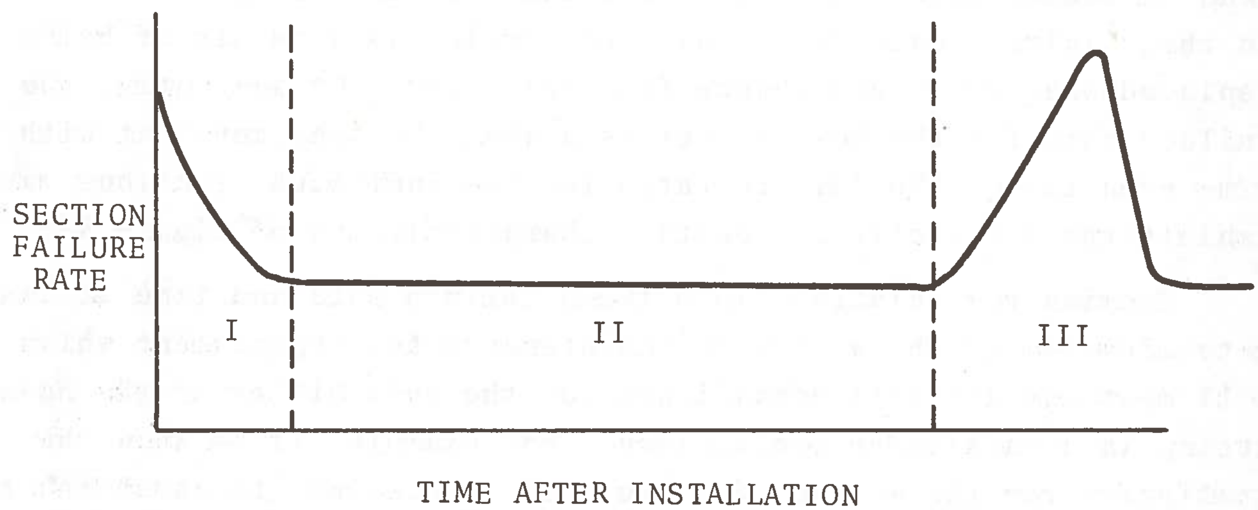

FIGURE 8-1. THREE REGIMES IN THE FAILURE HISTOGRAM OF A COMPONENT*

Figure 8-1 shows three regimes in the lifetime of the hose section as follows:

I. In this regime the hose is subject to change failures caused by exogenous events and to "early failures" due to defects in manufacturing or in installation.

II. This is the part of the lifetime when only the chance failures are predominant. The hose has survived the infant mortality phase and the effects of wearout are not yet a very significant factor. Exogenous event are the principal source of injury to the hoses during this regime.

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*A single section of hose under "normal" usage has here been chosen for illustration. In general a hosestring will more nearly exhibit the random failure mode corresponding to Fig. 3-2.

replacement is quite feasible and can lead to dramatic increases in the reliability of the system.

From the fault tree point of view, a hose string is describable as an OR gate in which each individual section provides an independent input. If all sections are assumed to have the same failure rate λ and there are a total of S such sections, the overall failure rate for the hoses is $S\lambda$. The rate λ is the sum of the individual rates for the three failure modes; namely, (λ_e) early, (λ_c) chance, and (λ_w) wearout.

As mentioned before, wearout failures are the only type which can be prevented by replacement. The typical rate for this type of failure is shown in Figure 8-2.

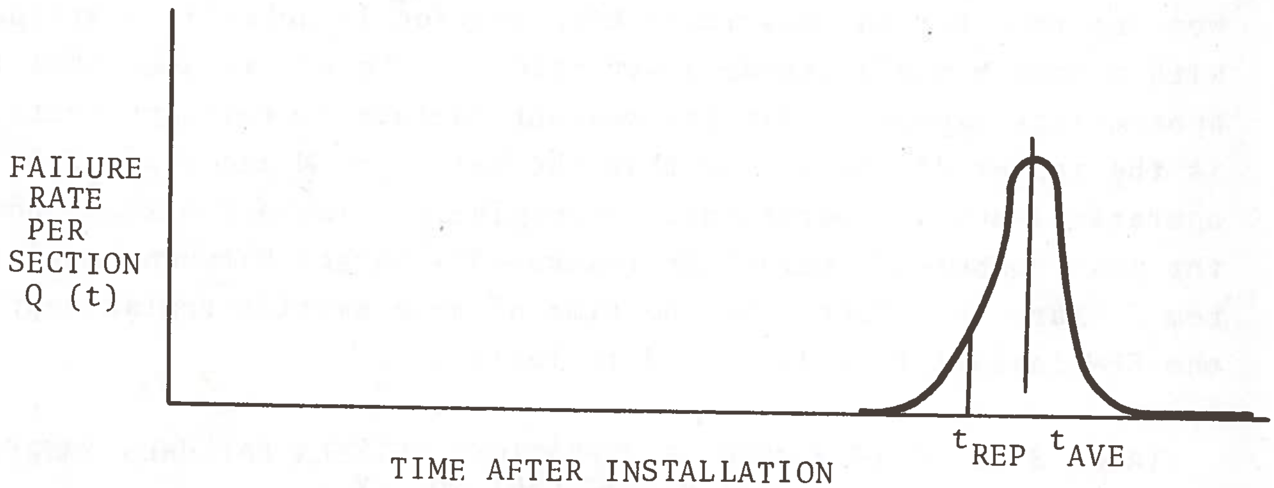

FIGURE 8-2. WEAROUT FAILURE RATES OF HOSE SECTIONS AS A FUNCTION OF TIME AFTER INSTALLATION

If t_{ave}, is the average time in the system at which wearout occurs and if the distribution is symmetrical about this time, the following three statements can be made about wearout replacement policy:

1. If the section is replaced at wearout failure, the failure rate λ will be $1/t_{ave}$.
2. If the section is replaced when its time in the system is t_{ave} the failure rate will be $1/2\ t_{ave}$.

One of these is that anticipatory replacement deals only with wear-out. Improvement by replacement is not worthwhile when chance failures become the dominant causes of unreliability.

The second limitation is the cost of replacement. At some point it may be economically more advantageous to accept a failure probability on the basis that, ceteris paribus, the cost of dealing with spills is less than the cost of increasing the hose section replacement rate. This trade-off will be examined below.

The cost of replacement is made up of such elements as down time, materials, and labor. The cost of a failure may be measured by various quantities, one of which is the cost of cleaning up the resultant spill. The optimum time between replacements depends upon balancing these two costs against one another to find the minimum. The formula which gives the costs, C, for any replacement time interval, τ, is:

$$C = \frac{C_1 \left[1 - G(\tau)\right] + C_2 G(\tau)^*}{\int_0^{\tau} G(t)\, dt} \qquad (8\text{-}2)$$

where C_1 is the total cost of the consequences of a failure and C_2 is the total cost of a replacement. For a normal distribution with mean, M, and standard deviation, σ,

$$G(Z) = \frac{1}{\sqrt{2\pi\sigma}} \int_Z^{\infty} e^{-\frac{(t-M)^2}{2\sigma^2}}\, dt. \qquad (8\text{-}3)$$

Since our interest is in finding a minimum, we shall measure C in units of C_2, the replacement cost, in which case the coefficient of the first term becomes the ratio of the cost of cleanup to the cost of replacement. Figure 8-3 shows the cost index (C/C_2) as a function of replacement interval for four values of the cleanup/replacement cost ratio C_1/C_2: 1000, 100, 10, and 1. In this example we assume a mean life of 200 operations with a standard deviation of 40.

As would be expected, the higher the ratio of cleanup cost to replacement cost the shorter would be the time to replacement. When the cost ratio is unity, there is obviously no advantage to replacement before failure.

8.3 EXAMPLES OF SPILL PROBABILITY CALCULATIONS

This section will evaluate fault trees for typical event sequences that could lead to large spills of oil in DWP installations. In the material which follows, the event sequences will be evaluated individually to determine an estimate of the annual rate at which large spills could occur in the context of the DWP specified in Table 8-1. In connection with each of the event sequences, a scenario will be presented which establishes the relationships in time and space of the equipment and events that the fault tree describes. Next, the failure probabilities will be specified and the source of these probabilities described. Finally, the overall fault tree itself will be evaluated to obtain the required estimate of the annual large spill rate and volume.

The examples presented do not necessarily represent, either in detail or in function, spill events for actual DWP's; they have been selected primarily to demonstrate the basic concepts involved in the formulation and analysis of fault trees in the context of DWP's.

8.3.1 Fault Tree Analysis No. 1 — Accumulator Tank Overflow

The fault tree of Figure 8-4, based on the subsystem shown in Figure 8-5, represents one set of circumstances that could lead to a large spill of oil into the sea from the pumping platform while a tanker is being discharged. The undesirable event shown at the top is an oil spill from the platform into the sea. In this case, such an event could occur if there were a serious spill of oil on the platform and a simultaneous blockage of the drain to a sump, which would normally collect the oil prior to its overflowing the platform and contaminating the sea.

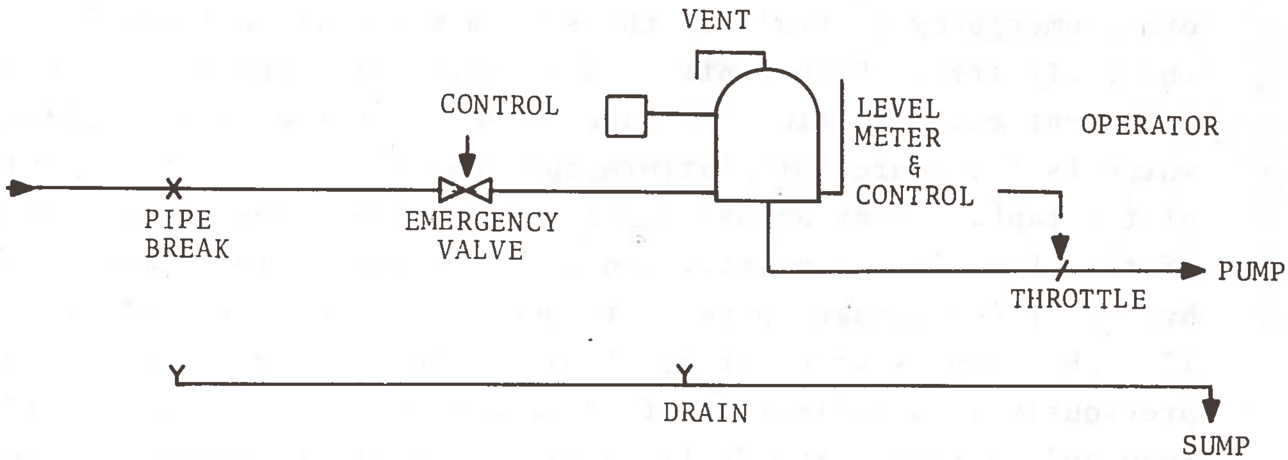

FIGURE 8-5. TANK SYSTEM

The fault tree identifies two failure events on the platform, either of which could cause a spill: the overfilling of an accumulator tank <u>or</u> the failure of a pipe in the primary hydraulic system. There are two events necessary to cause the tank to overflow: a failure of the meter which measures and controls the oil level in the tank, <u>and</u> a failure of an emergency valve to operate properly and thereby prevent a spill by shutting down the oil flow into the tank. There are two independent faults which lead to valve failure: a failure in the communications to the valve operator <u>or</u> failure of the valve to be closed properly. As shown on the fault tree, these events can result from either an equipment failure (e.g., the valve is frozen) or an operator error (e.g., the wrong valve is turned).

There are recovery times associated with the events shown in the fault tree. With respect to the valve, for example, the recovery time is that time required to detect the fault and take the necessary corrective action (close a valve in series with the inoperative one if the fault is in its mechanical function, or if a wrong valve were closed, to close the right one).

The measures of hazard assumed for the specific fault tree of Figure 8-4 are the annual numbers and volumes of spills into the sea. Before approaching the determination of these measures,

$$\lambda_C = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4{}^*$$

$$\tau_C = \frac{1}{\lambda_C} (\lambda_1 \tau_1 + \lambda_2 \tau_2 + \lambda_3 \tau_3 + \lambda_4 \tau_4)$$

The evaluation of the "AND" Gate D requires some special considerations because the two events are not independent. The right input is conditional upon the left input event occurring. Hence, the output of D is (see Section 7.4):

$$\lambda_D = \lambda_5 \lambda_C$$

$$\tau_D = \frac{1}{\frac{1}{\tau_5} + \frac{1}{\tau_C}}$$

Gate E is an "OR" gate with independent events as inputs and the formulas of Table 7-1 apply directly. Hence,

$$\lambda_E = \lambda_D + \lambda_6$$

$$\tau_E = \frac{\lambda_D}{\lambda_E} \tau_D + \frac{\lambda_6}{\lambda_E} \tau_6 .$$

The final calculation to be made is for the "AND" gate at the top of the fault tree. The inputs are both independent of one another and so the formulas of Table 7-1 apply directly. Hence,

$$\lambda_F = \lambda_E \lambda_7 (\tau_E + \tau_7)$$

$$\tau_F = \frac{1}{\frac{1}{\tau_E} + \frac{1}{\tau_7}}$$

*The inputs to an "OR" gate that is itself an input to an "OR" gate can be considered as direct inputs to the latter.

Table 7-1). This quantity is equivalent to failures per demand in this context, and for this case is 5×10^{-7}.

Substitution of the values in Table 8-4 into the formulas just developed leads to the results presented in Table 8-5. The units are per hour or per demand for rates and hours for recovery times.

TABLE 8-5. NUMERICAL RESULTS

GATE	RATE	RECOVERY TIME (HOURS)
C	6.3×10^{-3} per demand	0.05
D	6.3×10^{-7} per hour	0.05
E	1.6×10^{-6} per hour	0.05
F	1.6×10^{-10} per hour	0.025

Table 1 indicates a flow of 2 x 35,000 bbl/hour and a total flow of 3.7×10^8 bbl/year, so that the number of operating hours is 5300 on the average. Hence, the contribution which will be made to the annual spill rate by the fault configuration of Figure 8-4 will be: F x 5300, or

$$\text{Fail/hr} \times \text{hr} = \text{fail}$$

$$(1.6 \times 10^{-10})\ (5300) = 8.5 \times 10^{-7}$$

which is roughly equivalent to one spill per million years.

8.3.2 Fault Tree Analysis No. 2 — Major Hose Spill

The FT of Figure 8-6 is based directly on the DWP schematic, Figure 1-1, and represents the most likely events leading to major spills. The "OR" gate A represents three events leading to hose rupture. These are labeled surge, manufacturer's defect, and wear. Since none of these defects have a repair time the effective spill-time is set by the closing of the emergency valve, which does not appear explicitly on this branch. It will be assumed that this time is .01 hours.

The center input via the "AND" gate B represents the same basic failures of the hose aggravated by the failure of the emergency valve system. This combination of events is not likely to occur as frequently, but the spill size will be larger since it will take time to shut down the flow of oil by such measures as stopping the pumps. The events at the "OR" gates G are contingent upon the events at the "OR" gate E so that λ_B must be calculated as a function of λ_E and λ_G as dependent events. The duration τ_B of the spill will depend of τ_G the time required to recover from the failures at the gate G. It should be noted (see Table 8-6) that the "recovery times" associated with the events 1, 2, and 3 are not identical with the "repair times" associated with the same events in 4, 5, and 6. At gate A the emergency system operates and limits the spillage in .01 hours, thus effectively repairing the fault. Since the operation of the emergency valve does not appear on the branch 4 explicitly the recovery time must be introduced at events 1, 2, and 3 in place of the intrinsic repair time for the hoses, which is approximately 24 hours. At gate B, on the other hand, the true repair times may be used because the recovery time for the valve failure appears explicitly at the gate G.

The right hand input to F represents the parting of the hose as a result of the parting of the mooring line, while the dependent failure of the emergency system at the "OR" gate D is still unrepaired. In this case there will be a time interval between the parting of the line and the parting of the hose, so that no spill will occur if the emergency valve operates. Furthermore, the output frequency from gate D may be assumed to be much lower than that of gate G, which represents the same basic events. This is because, in general, there will be time available to recover from the valve failure before the hose parts. As it turns out the contribution of a gate A is very much larger than that of the other inputs to F, so that the exact value of the parameters for events 4 to 11 is not important. On the basis of the discussion the following equations apply:

oil will also be lost out of the two parted ends of the hose after the flow is stopped. This quantity can be estimated by means of a separate tree.

8.4 DISTRIBUTION OF SPILL SIZES

A curious phenomenon appears almost invariably whenever a collection of data listing sizes of observed individual spills is plotted on logarithmic probability paper — namely, over most of the range (and this may be many orders of magnitude) a straight line is obtained. Figure 8-7 shows such a plot. The data involved were spills reported in the Anglesey Hearings for the SPBM at Durban, South Africa. There was a total of 23 spills in this set of data. This straight line relationship was found in every set of spill data examined.

There is no convincing explanation for the log-normal behavior of spill size, nor can much be said about the utility of knowing that this behavior exists. There are some conveniences in computation that arise from the fact that only two parameters are required to specify the distribution, and extensive tables are available on its various properties.

Now, the log-normal distribution is very common and probably can be used to describe many more phenomena than it has already. A few examples of where it has been found to be useful include:

a. Particle sizes when a mass is broken up by use of force
b. Luminosity of stars
c. Daily discharges of rivers
d. Annual maxima of river heights
e. Annual sales of items by a firm
f. Corporation sizes in the U.S. and Britain.

Finally, one distinction should be noted. The normal distribution arises when the variable under consideration is the sum of a number of variables, each randomly distributed. With the log-normal distribution, on the other hand, the variable under consideration is the product of a number of variables, each again randomly distributed.

APPENDIX A. LITERATURE SEARCH

The attached literature search ranged over many abstracts and indexes. The following indexes were searched:

ASCE Index 1971-1975

British Ship Research Assoc. Ocean Engineering 1969-75

British Technology Index 1969-1975

Engineering Index 1969-1975

Fuel Abstracts 1969-1975

Government Reports Abstracts 1968-1975

Institute of Petroleum Abstracts 1969-1971

Lockheed Information Retrieval Service

Marine Engineering/Shipbuilding Abstracts 1969-1974

Maritime Research Information Services (MRIS) 1970-1975

National Technical Information Service

Ocean Abstracts 1973-1975

Ship Abstracts 1973-1975

Transportation Research Information Service (TRIS)

The terms used in the search were as follows:

single point mooring

deepwater port

mooring buoys

tanker moorings

offshore mooring devices

ports habors

tankers-ships-terminals

In many instances several combinations of these terms were employed to ferret out information.

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APPENDIX B - FAULT TREE ANALYSIS (RIGOROUS TREATMENT)

B.1 BASIC PROBABILISTIC ASSUMPTION

It will be assumed that each component of the system has a constant failure rate that applies when the component is in working order and a constant repair rate that applies when it is out of order. The failure rate is translated as "probability of failure per unit time" and the repair rate as "probability per unit time that if the component is out of order it will be restored to working order." The rates of failure and repair differ from one component to another.

These assumptions provide a reasonably good representation of the working of the system if the effects of initial (or start-up) failure are discounted by replacement of the component if it fails because of initial weaknesses, and if each component is replaced before its age begins to impair its reliability. Under these conditions, failures will be random with respect to time. The repair cycle includes a lapse of time needed before a failure is detected, and a further lapse of time needed for repair or replacement. It is assumed that the sum of these two time-lapses will be exponentially distributed; i.e., the repair process is also a Poisson process.

B.2 THEORY OF THE POISSON PROCESS

Under the above assumptions the probabilities attached to the AND and OR gates of the system will be derived by a logical combination of the Poisson processes involved in the inputs to the gates. The probability distribution of the outputs of the gates can best be understood after the Poisson process for a single component has been explored. Accordingly, this section is devoted to an examination of the probabilistic behavior of a single component under quite general conditions.

Let E represent an event that can occur at any time, and suppose that if it has not occurred at time T, the probability that it will occur in the interval T + dt is k dt. Further, let

The waiting time is the reciprocal of the occurrence rate in a Poisson process. It is so on the average for any failure law.

Thus, if a component is in working order, its mean time to failure is the reciprocal of the failure rate; if it is out of order, its mean time to repair is the reciprocal of the repair rate.

If a component is in working order, with failure rate k, the probability per unit time that it will first fail at the end of a lapse of time T is p(T) = k exp(-kT).

These two results are fundamental to the further derivations.

B.3 THE TWO-STATE PROCESS

It is now necessary to consider the passage of the component from a state of working order to a state of failure, and from failure to working order. The notation for the rates of failure and repair will be as follows:

Failure rate:	λ
Repair rate:	μ
Mean time to repair:	$\tau = 1/\mu$.

The state of failure will be termed "State 0," and the state of being in working order "State 1." The state of failure is also the state of being under repair, if the detection time is included in the repair time, as has been done in Section B.1.

In addition, let $P_o(t)$ be the probability that the component will be found in state 0 if observed at time t, and let $P_1(t)$ be the corresponding probability for state 1. Then, since the component is either working or not working, with no third state, it must be true at all times that

$$P_0(t) + P_1(t) = 1. \qquad \text{(B-6)}$$

Now consider the rate of change of P_0, as follows: If the component is out of order at time t, the probability that it remains out of order during the following interval of length dt is $(1 - \mu dt)$.

In this form they allow an intuitively appealing interpretation: The life cycle of the component consists of two phases, one of length m during which it is in working order, and one of length τ during which it is out of service. The steady state probabilities are just the ratios of the two time periods to the length of the total cycle.

B.4 THE COMBINATION OF POISSON PROCESSES

The fundamental equations derived in the preceding section can now be applied to the derivation of the output probabilities for AND gates and OR gates. The AND gate in a fault tree is emitting a signal (contributing a fault) if all of its inputs are in state 0; i.e., if all the components involved in it are in a state of failure. The probability that an AND gate, observed at a random time, is emitting a signal is therefore the product of the steady state probabilities that its components are in state 0. The OR gate emits a signal if at least one of its inputs is in state 0; the steady state probability that it is emitting a signal is the complement of the probability that all of its components are in state 1. The mathematical consequences of these conditions will now be derived.

The derivations are valid, as first-order approximations, and they are logically sound. However, there are some difficult mathematical questions that are avoided by means of the arguments as presented; the reader should consult any standard text for a complete and rigorous derivation.

B.4.1 Deactivation of Time and an AND Gate

If an AND gate is activated, all its components are in a state of outage. The gate will be deactivated as soon as one component returns from state 0 to state 1. We are therefore looking for the smallest of the realized repair delays; this is equivalent to asking for the smallest of a set of N values drawn

B.4.2 Mean Activation Time of an AND Gate

Consider an AND gate with N components, in which the i-th component has the failure and repair rates λ_i and μ_i. Assume that the failure rates are small enough so that the probability that two components will change state in the time interval dt is negligible. Then the gate will change its condition only by the change of state of a single component. If more than one component is in state 1, the gate cannot change from no output to an output. Therefore, in computing the activation probability, one must assume that N-1 of the components is in state 0, and the remaining component is in state 1. Assume for the moment that the i-th component is functioning and the others are not. Then the probability of activation through failure of the i-th component is the product of three factors:

Failure rate:	λ_i
Steady state probability:	$\dfrac{\mu_i}{\mu_i + \lambda_i}$
Joint Probability $P_{0,1} \ldots P_{0,N}$:	$\left(\dfrac{\lambda_1}{\mu_1 + \lambda_1}\right) \ldots \left(\dfrac{\lambda_N}{\mu_N + \lambda_N}\right)$

where the i-th term is omitted from the product in the third line.

By putting the factor λ_i into the numerator of the fraction in the second row, and removing the μ_i to a separate position, it can be seen that the product of all three factors reduces to the product of μ_i and a factor consisting of the product of all the steady state probabilities P_0 for all N components.

This result can be derived in another way, which may yield a better insight into the process. Consider the AND gate as a single unit, with an activation and deactivation probability and mean time between activation and deactivation denoted by τ, and mean time between deactivation and activation denoted by m. Then, in accordance with the results derived in Section 7.4, the probability P_1 that the gate is active can be expressed as

$$P_1 = \frac{\tau}{m + \tau} \tag{B-17}$$

We now want to find the value of 1/m, which is the instantaneous activation rate. We therefore solve the above equation for 1/m, obtaining

$$1/m = \left(\frac{1}{\tau}\right) \left(\frac{P_1}{1 - P_1}\right) \tag{B-18}$$

The value of τ was derived in the preceding section as $1/\Sigma\mu_i$.

If the value of P_1 has already been calculated for the AND gate, the calculation of 1/m becomes very simple. On the other hand, the expression for P_1 can be expanded in terms of the λ's and τ's, as follows: First, P_1 is the probability that all components making up the AND gate are out of service. This is the product of the probabilities that the individual components are out of service, namely

$$P_1 = \left(\frac{\tau_1}{m_1 + \tau_1}\right) \left(\frac{\tau_2}{m_2 + \tau_2}\right) \cdot\cdot \left(\frac{\tau_N}{m + \tau_N}\right) \tag{B-19}$$

The following chain of algebraic manipulations leads to an expression involving the λ's and τ's.

B.4.4 Mean Life of an OR Gate

The mean life of an OR gate is most easily derived by the second of the methods used in Section 7.7.2. Let P by the steady state probability that an OR gate is inactive; then

$$P = \frac{m}{m + \tau}$$

where τ is the mean life of the activity state, and m is the mean time between deactivation and activation. From the preceding section, it is known that $m = 1/\Sigma\lambda_i$. The equation for P can be solved to yield

$$\tau = m\left(\frac{1}{P}\right) - 1, \qquad \text{(B-23)}$$

The value of P is the product of the steady state probabilities that all the components are in working order; i.e.,

$$P = \left(\frac{\mu_1}{\mu_1 + \lambda_1}\right)\left(\frac{\mu_2}{\mu_2 + \lambda_2}\right) \cdots \left(\frac{\mu_N}{\mu_N + \lambda_N}\right) \qquad \text{(B-24)}$$

The value of τ can be computed directly once the value of P is known, or it can be expressed in terms of the λ's and τ's by a process like that used in Section B.4.2. The manipulations are as follows:

$$\frac{\mu_i}{\mu_i + \lambda_i} = \frac{1}{1 + \lambda_i\tau_i} ;$$

$$\frac{1}{P} = (1 + \lambda_1\tau_1)(1 + \lambda_2\tau_2) \cdots (1 + \lambda_N\tau_N); \qquad \text{(B-25)}$$

$$\frac{1}{P} - 1 \sim \Sigma\lambda_i\tau_i ; \qquad \text{(B-26)}$$

APPENDIX C

THE CONVERSION FROM λ TO λ' (RIGOROUS TREATMENT)

A valve having a constant failure rate λ is checked at regular intervals τ_m. The problem is to calculate the effective value of the demand failure rate λ'.

The average time to failure after an inspection is:

$$t_f = \left\{\int_0^{\tau_m} te^{-\lambda t} \lambda dt\right\} + \left\{\tau_m e^{-\lambda\tau_m}\right\} . \qquad \text{(C-1)}$$

The integral gives the average time for failures occurring between inspections, and the second term accounts for survivals. Evaluating (C-1) gives:

$$t_f = \frac{1}{\lambda}\left[1 - e^{-\lambda\tau_m}\right] \qquad \text{(C-2)}$$

The time fraction during which the valve is in operative is then

$$F = \frac{\tau_m - \frac{1}{\lambda}\left[1 - e^{-\lambda\tau_m}\right]}{\tau_m} \qquad \text{(C-3)}$$

and if $\lambda\tau \ll 1$

$$F \approx \lambda\tau_m/2. \qquad \text{(C-4)}$$

Regarding the system now as prone to failure on demand only and denoting the demand failure rate by λ' one finds

$$\lambda' = n(\lambda\tau_m/2)(1/n) \qquad \text{(C-5)}$$

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