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SPILL PREVENTION PRIORITY ANALYSIS FOR REDUCING ACCIDENTAL RELEASE RISKS DURING PIPELINE TRANSPORT

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ABSTRACT

Spill risk during pipeline transportation is about 4 times higher in comparison to transportation by barges, and about 7 times higher in comparison to transport by rail. Since accidental spills cannot be eliminated, efforts to reduce risks of accidental releases during pipeline transportation and adequacy of the resources allocated for managing accidental releases should be periodically evaluated. A simple risk assessment technique was developed to evaluate the risks of leakage during pipeline transportation. The spill prevention priority analysis (SPPA) developed in this study is a flexible, risk based approach which can be used to develop strategies to gradually reduce spills during pipeline transport. The method developed incorporates failure probabilities, detection capabilities for failures, and significance of the consequences due to a spill to estimate a set of spill prevention priority numbers (SPPN) for possible failure modes which could lead to a spill. The relative magnitudes of the SPPNs can be used for development of risk management strategies and in decision making for allocating resources to reduce the spill risks to acceptable levels.

INTRODUCTION

Pipelines are the primary mode of transport for crude oil, refined petroleum based fuels, and processed materials. In addition to their efficiency, pipelines also have important environmental and transportation-safety benefits. Compared to other inland transport modes, pipeline transport does not create additional traffic on the highways and rivers, and produces negligible air pollution. However, pipeline spills are very common and the number of chemical spills reported during pipeline transport is higher in comparison to the number of spills reported during highway or railroad transportation, as shown in Table 1. Spill risk per mile of transport during pipeline transportation is about 4 times higher in comparison to transportation by barges, and about 7 times higher in comparison to transport by rail, as shown in Table 2. Since accidental spills cannot be eliminated, efforts to reduce risks of accidental releases during pipeline transportation and the adequacy of the resources allocated for managing accidental releases should be periodically evaluated. Prevention and reduction of accidental release risks during pipeline transportation of chemicals require understanding, development, and application of engineering solutions for the hazards associated with design and operation of the pipeline transportation facilities, as well as hazards associated with environmental factors and natural phenomena. Despite the efforts to prevent spills, almost 14,000 oil spills are reported each year in the United States [1]. Relative risks due to human error and mechanical failures resulting in a spill could be significant depending on the conditions of the facility and the expectations from the employees. As shown in Table 3, checklist inspection, failure to observe, and general omissions in routine monitoring procedures are the most common human errors. Valve and electric motor failures are among the most common mechanical failures.

Table 1. Source of Chemical Spills Reported to the National Response Center in 1990 [1]

Source of spill	Number of spills
Fixed facility	4,466
Offshore	2,654
Marine	2,163
Unknown	2,025
Pipeline	1,514
Highway	1,165
Unknown offshore	955
Railroad	229
Aircraft	117
Underground storage tank	34

Table 2. Oil Spills Risks per Mile of Transport

Hazard	Average size (Gal)	Frequency	Reference
Barge spills	12,800	0.420×10^{-6} per mile	[2, 3]
Railroad car derailment		0.231×10^{-6} per mile	[2, 3]
Tank truck accident	3,000	0.027×10^{-6} per mile	[2, 3]
Pipeline	6,000	1.7×10^{-6} per mile	[2, 3]

Table 3. Risks of Human Errors and Mechanical Failures that May Result in an Oil Spill

Cause	Risk	Reference
Human errors		
Failure to observe	5×10^{-2} per task	[3, 4, 5]
Failure to act	3×10^{-4} per demand	[3, 4, 5]
Checklist inspection	1×10^{-1} per task	[3, 4, 5]
Critical routine task	1×10^{-3} per task	[3, 4, 5]
General omission	1×10^{-2} per task	[3, 4, 5]
Mechanical failures		
Electronic system failure	1×10^{-6} per hour	[3, 5, 6]
Joint ruptures	1×10^{-8} per hour	[3, 5, 6]
Pump ruptures	1×10^{-8} per hour	[3, 5, 6]
Electric motor failure	1×10^{-3} per demand	[3, 5, 6]
Piping failure	1.8×10^{-9} per ft per year	[3, 5, 6]
Shutdown failure	1×10^{-4} per demand	[3, 5, 6]
Audible alarm failure	1×10^{-5} per demand	[3, 5, 6]
Valve failure	4×10^{-3} per year	[7]
Valve failure	8.76×10^{-5} per year	[3, 5, 6]
Relief valve opens early	1×10^{-5} per hour	[3, 5, 6]
Tank rupture	2×10^{-4} per year	[7]
Tank rupture	1×10^{-6} per year	[3, 5, 6]
Break in piping	9×10^{-7} per year	[7]

Risk assessment for environmental management is an important decision-making tool that can be used by both the environmental regulators and the regulated industries. Developments in environmental protection and legislation tend to follow an evolutionary process, due in part to the facts that many environmental concerns are long term and the environmental disasters which have occurred have resulted in slow changes in legislation. There are potential benefits to adopting a risk-based goal-setting approach to environmental management, but there are also limitations in the application of risk assessment to the environment [8]. Based on the analysis of the enforcement efforts for the effectiveness of the U.S. Coast Guard in reducing oil spills, it has been concluded that the behavioral changes to prevent spills increase with monitoring [9]. A number of studies have been conducted to evaluate the spill risks and development of risk reduction strategies. Performance of both gas and liquid transmission lines in Europe, the United States, and the former Soviet Union in terms of failures has shown a progressive improvement, but the severity of consequences following gas releases and oil spills have not shown any changes in the last fifteen years [10]. External interference is not always the predominant cause of failures in pipeline transmission systems. Failures with casualties in gas transmission have not shown any significant decrease over the last decade, and there is a clear indication that many are connected with the parts and functions—other than the main body—of the pipelines [10]. There is a need to improve risk assessment methods by integrating people into a unified assessment and to build a risk model of the whole system, including multiple species, stressors, and cumulative effects. It is also necessary to look at how this integration can occur within the problem formulation step wherein the system is defined, a conceptual model created, a subset of components and functions selected, and the analytical framework decided in a context that includes the management decisions. The risk assessment process should help address the urgent needs of society to provide a format to communicate knowledge and understanding, and to develop a basis for policy and management decisions [11]. A number of mathematical analysis programs have been developed for assessment of risks during transportation of chemicals. Stam et al. [12] developed two software applications for analysis of accident-related information and for managing risks of small and large facilities that may pollute surface waters through accidents. The two perspectives used include safety management aspects and surface water vulnerability. Bruzzone et al. [13] developed a maritime environment for simulation analysis for different types of emergency events, such as oil spills, hazardous material spills, fires, and explosions specifically connected to port operations. Bonvicini et al. [14] used a fuzzy logic approach to assess the risks of hazardous materials transport by road and pipelines, evaluating the uncertainties affecting both individual and societal risks.

In this article, a simple risk assessment technique was developed to evaluate the risks of leakage during pipeline transportation. The method developed incorporates failure probabilities, detection capabilities for failures, and significance of the consequences of a spill, to estimate a set of spill prevention priority numbers (SPPN) for possible failure modes which could lead to a spill. The relative magnitudes of the SPPNs can be used to develop risk management strategies and to make decisions allocating resources to reduce spill risks to acceptable levels.

SPILL PREVENTION PRIORITY ANALYSIS

Risk can be expressed as the probability of occurrence of an event and its consequences or as the magnitude of the consequences expected over some period of time [15]. Risk assessment is a systematic process used to identify, describe sources, and causes and consequences of a risk. Its purpose is to provide information to decision makers in a way that allows comparisons of different risk reduction alternatives and their costs. In most cases risks cannot be eliminated, only reduced to an acceptable level, when weighed against the advantages and disadvantages of the activity or the process. Occurrence of a spill usually requires a combination of several elements to go wrong at the same time. The consequence of the spills during transportation could be significant depending on the vulnerability of the spill locations. Therefore, the assessment of pipeline spill risks requires consideration of hazard factors, detectability measures, and vulnerability of the spill locations.

The spill prevention priority analysis (SPPA) developed in s study is a flexible, risk-based approach which can be used to develop strategies to gradually reduce spills during pipeline transport. This risk-based approach incorporates the important hazard elements into a framework to estimate a set of spill prevention priority numbers (SPPN) which can be used for risk management and decision making. The SPPA can be used for both old and new systems and should be periodically revised for updating the system risks. The periodic upgrades in the system can be incorporated into the system evaluation and the sequential improvements in the risk factors can be incorporated into the risk analysis. Figure 1 presents the general flow diagram for SPPA for pipeline transportation. The SPPA involves the following steps:

1. Identification of Hazard Modes

This step involves identification of the modes or the manners in which any element of the pipeline transport system can fail to accomplish its function. As shown in Figure 2, hazards for pipeline spills could include the general failure categories such as design factors, operational factors, environmental factors, and acts of God. For each general category the following hazard factors should be identified.

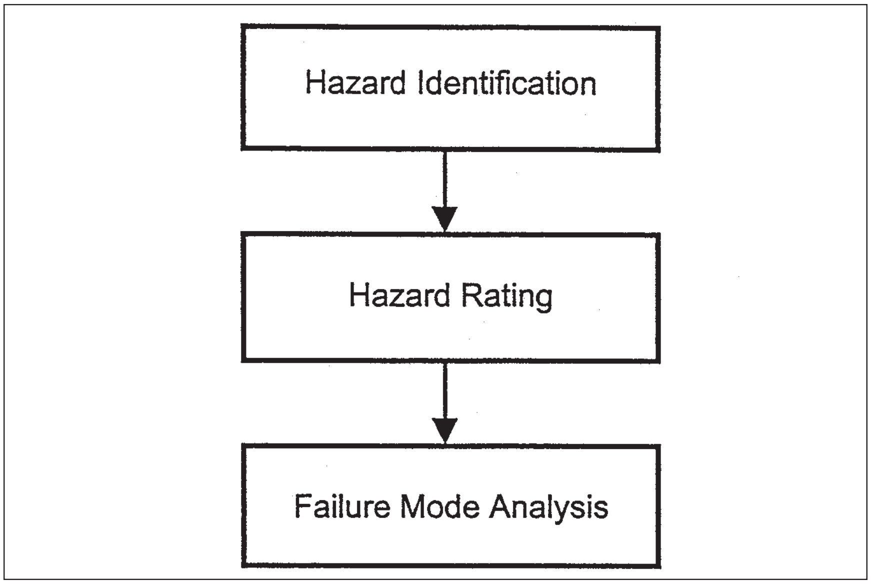

Figure 1. General schematic of SPPA.

1.a. Identification of Causes of Spill (Specific Hazard Elements)

After the general hazards are identified, the actual cause(s) that result in occurrence of a system failure and subsequently a spill should be identified. Typical causes might include design failures such as equipment stresses during operation, aging and wear out, a software coding error, human errors like poor attention to work requirements, materials damage because of transportation and handling, or operator-and-maintenance-induced factors.

1.b. Identification of Spill Detection Means

This step involves the identification of mechanisms that would detect a failure with ease and in a timely manner. If the likelihood of occurrence of a spill can be identified at an early stage, measures can be taken to prevent any further damage. When even a small spill is detected after many days or weeks, it may cause serious damage.

1.c. Identification of Effects of Spill

In this step, the potential consequences from a spill are identified. These consequences could include contamination of soil, water source, fires, explosions, and toxic material releases.

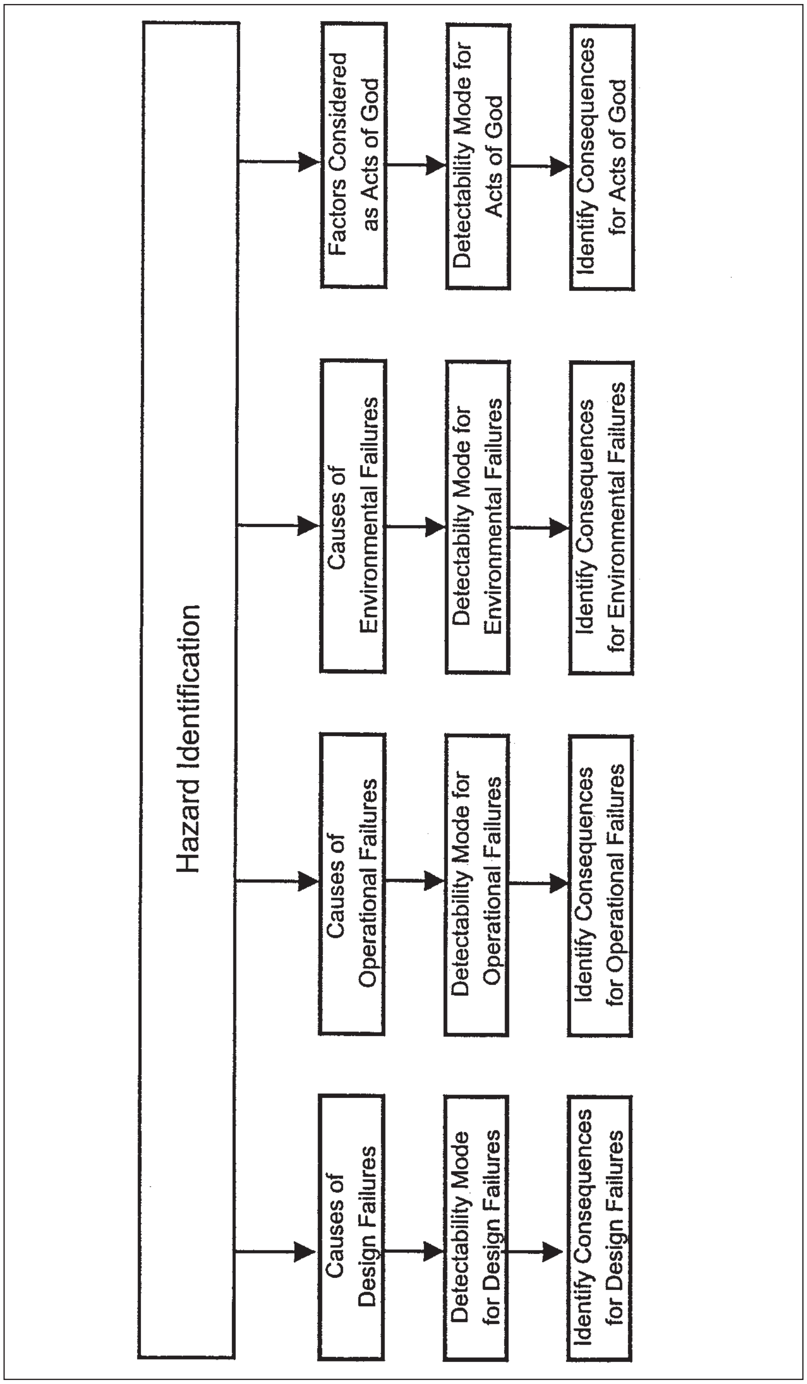

Figure 2. Flow diagram for hazard identification.

2. Rating of Hazard Modes

After identification of each hazard mode, each failure mode should be rated in a systematic manner as shown in Figure 3. The rating procedure for each hazard mode is explained below:

2.a. Allocation of Weights for Failure Frequency

This step addresses the frequency of occurrence of each failure mechanisms which could lead to a spill. For the purposes of quantification, a scale of 1 to 10 was used as follows:

a) Remote (spill is unlikely) = 1
b) Low (relatively low possibility of a spill) = 2 to 3
c) Moderate (occasional spills are likely) = 4 to 6
d) High (spills would occur) = 7 to 8
e) Very high (spill is inevitable) = 9 to 10.

These ratings can be based on the expected number of spills per unit of time, or equivalent.

2.b. Allocation of Weights for Spill Mode Detection Probability

This pertains to the probability that a detection mechanism such as process control instruments; design features/aids and verification procedures will detect potential spills in time to prevent a major spill occurrence. For the purposes of quantification, again a scale of 1 to 10 was used as follows:

a) Very high detectability = 1 to 2
b) High detectability = 3 to 4
c) Moderate detectability = 5 to 6
d) Low detectability = 7 to 8
e) Very low detectability = 9
f) Absolute certainty of non-detection = 10.

2.c. Allocation of Weights for Spill Severity (Consequence Rating)

This refers to the seriousness of the effect or impact of a particular spill. For the purpose of quantification, the degree of severity can be related to issues pertaining to environmental damage and human health and safety risks. The consequence of a spill can be rated quantitatively on a scale of 1 to 10 as follows:

a) Minor effects = 1 to 2
b) Moderate effects = 3 to 4
c) Severe effects = 5 to 6
d) Very severe effects = 7 to 8
e) Catastrophic effects = 9 to 10.

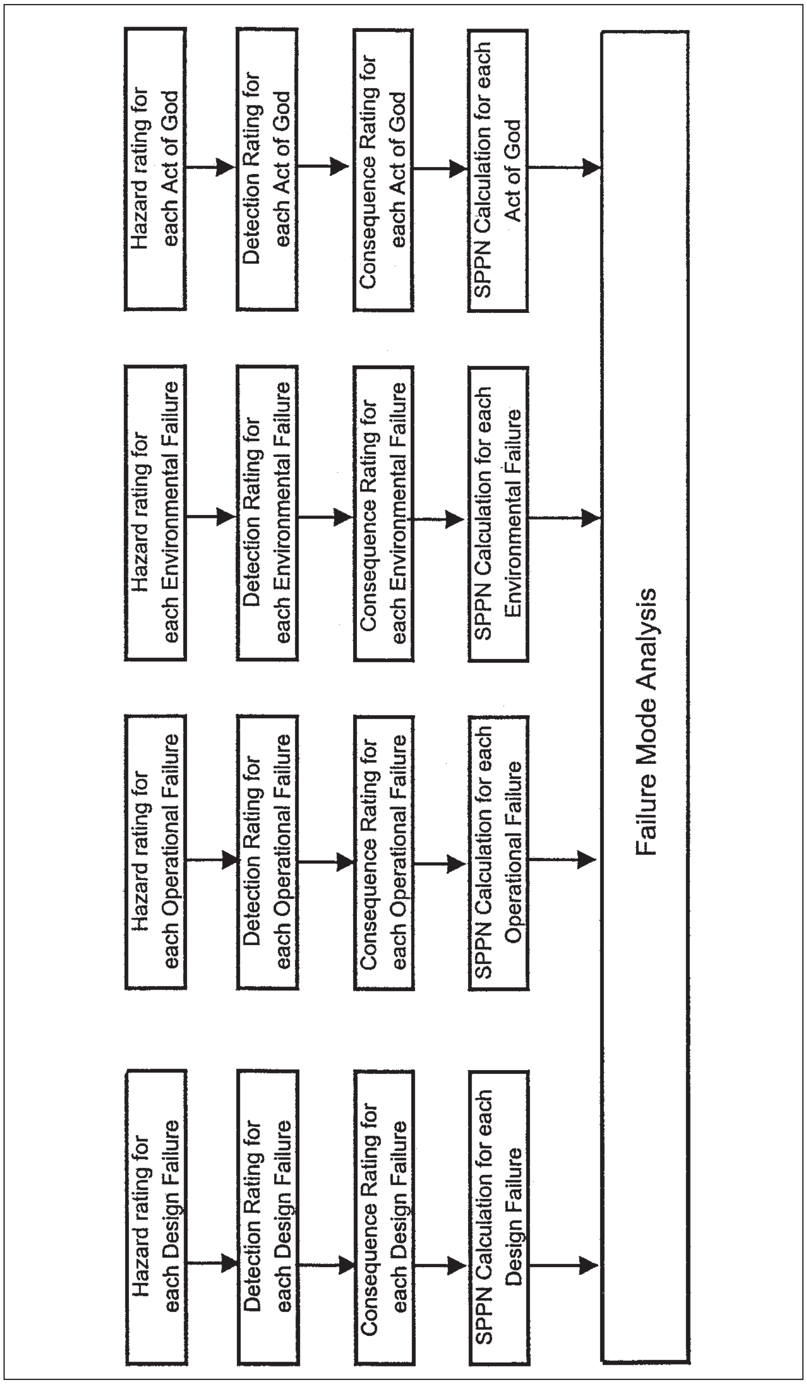

Figure 3. Flow diagram for rating assignments for failure mode analysis.

3. Calculation of SPPNs

This step involves the analysis of information from the preceding steps to quantify the possible spill scenarios due to each failure mechanisms. A spill prevention priority number (SPPN) is calculated based on severity and frequency, probability of detection of the failure and seriousness of possible consequences due to the specific failure can be calculated as follows:

$$\text{SPPN} = (\text{failure mode frequency rating}) \times (\text{detectability rating}) \times (\text{severity rating})$$

4. Analysis of Spill Modes

The SPPN is a measure of relative significance of the spill mode criticality. On inspection, one can see that a spill mode with a high frequency of occurrence, with significant impact on system performance, and which is difficult to detect is likely to have a very high SPPN. The risk assessment method is based on the development of spill prevention priority numbers to identify the areas that require immediate attention for risk reduction. The values of SPPNs can be analyzed by developing a histogram of the SPPNs and how the management plans to reduce the SPPN profile in the future. An analysis of the SPPNs corresponding to hazard factors can provide information to identify areas which need to be addressed for risk reduction. For example, if the SPPNs with high values correspond to design related factors, a partial or full system upgrade and installation of spill detection instruments could help reduce the spill risks significantly.

NUMERICAL EXAMPLES

Two numerical examples are provided below to illustrate the application of the SPPA.

Example 1. Older Facility

The spill risk factors at for an older system are rated based on possibility of failure, detectability, and spill consequence as shown in Table 4. This system can fail in four different modes: design, operational, environmental, and acts of God. For example, if the facility fails by design mode, due to excessive pipe pressure, based on the existing knowledge about the facility the following ratings can be given:

Risk factor score = 7
Detectability score = 6
Consequence score = 7

Table 4. Calculation of SPPNs for the Old Facility Described in Example 1

Origin	Spill risk factor	Risk factor score	Detectabiilty score	Consequence score	SPPN
Design	No. of components (D1)	8	5	8	320
	Age (D2)	9	4	9	324
	Pipe material (D3)	8	4	9	288
	Pipe length (D4)	7	4	8	224
	Pipe capacity (D5)	8	4	8	256
	System redundancy (D6)	6	4	6	144
	Degree of automation (D7)	8	7	8	448
	Pipe pressure (D8)	7	6	7	294
	Material being piped (D9)	7	3	6	126
Operational	No. of people employed (O1)	5	2	5	50
	Quantification (O2)	4	2	5	40
	Periodic training program (O3)	5	1	5	25
	Frequency of inspection (O4)	5	1	6	30
	Work hours (O5)	5	3	6	90
	Morale (O6)	3	1	3	9
	Work ethics (O7)	3	1	3	9
Environmental	Geology (E1)	4	3	6	72
	Geography (E2)	4	3	6	72
	Weather[a] (E3)	4	3	6	72
	Vibration (E4)	5	3	6	90
	Nearby activities[b] (E5)	5	3	6	90
Acts of God	Earthquake (G1)	2	9	9	162
	Arson (G2)	2	4	9	72
	Flood (G3)	2	8	9	144
	Hurricane (G4)	2	3	9	54

[a]Rain, snow, ice, temperature, frost, and other seasonal variations. [b]Such as construction, road repairs.

Hence the SPPN can be calculated as:

SPPN = $7 \times 6 \times 7 = 294$

The estimates of the SPPNs for each hazard factor for this facility range from 9 to 448 as shown in Table 4. The average value of the SPPNs was 140.20 with a standard deviation of 118.87. Figure 4a presents the estimated SPPNs plotted as a histogram. The analysis of the histogram could provide guidance for decision-makers. For example, if a facility desires to reduce the risk factors with SPPNs greater than 250, the management can decide to focus on those hazard areas. Figure 5 presents the SPPNs for individual risk factors in an increasing order. In older facilities the spill risk factors would typically be design related due to the age of the components, inadequate number of installed spill detection instruments and the operational limitations of the system components.

Case 2: New Facility

The spill risk factors for a new system are rated based on possibility of failure, detectability, spill consequence, and the estimates SPPNs are presented in Table 5. For this facility, the SPPNs range from 2 to 162, as shown in Table 5. The average value of the SPPNs was 30.44 with a standard deviation of 41.47. Figure 4b presents the estimated SPPNs plotted as a histogram. The analysis of the histogram shows that only two risk factors have a SPPN of above 140, and that these two risk factors are significantly higher than the other the values of SPPN for other hazard factors. Figure 6 presents the SPPNs for individual risk factors in an increasing order. Analysis of this figure shows that the two factors with the higher SPPNs correspond to acts of God. For such cases, the management may chose to increase insurance or develop measures to minimize damages due to natural hazards.

CONCLUSIONS

Risks associated with pipeline transportation should be evaluated in terms of design and operations variables (which include both human and mechanical components), environmental variables, and natural phenomena. Since each of these factors is time dependent, risk management for oil spill prevention requires periodic updates and revisions of the operating procedures and risk management plans. The consequence of an oil spill due to pipeline failure depends on the amount and type of material handled, the number of mechanical units in the

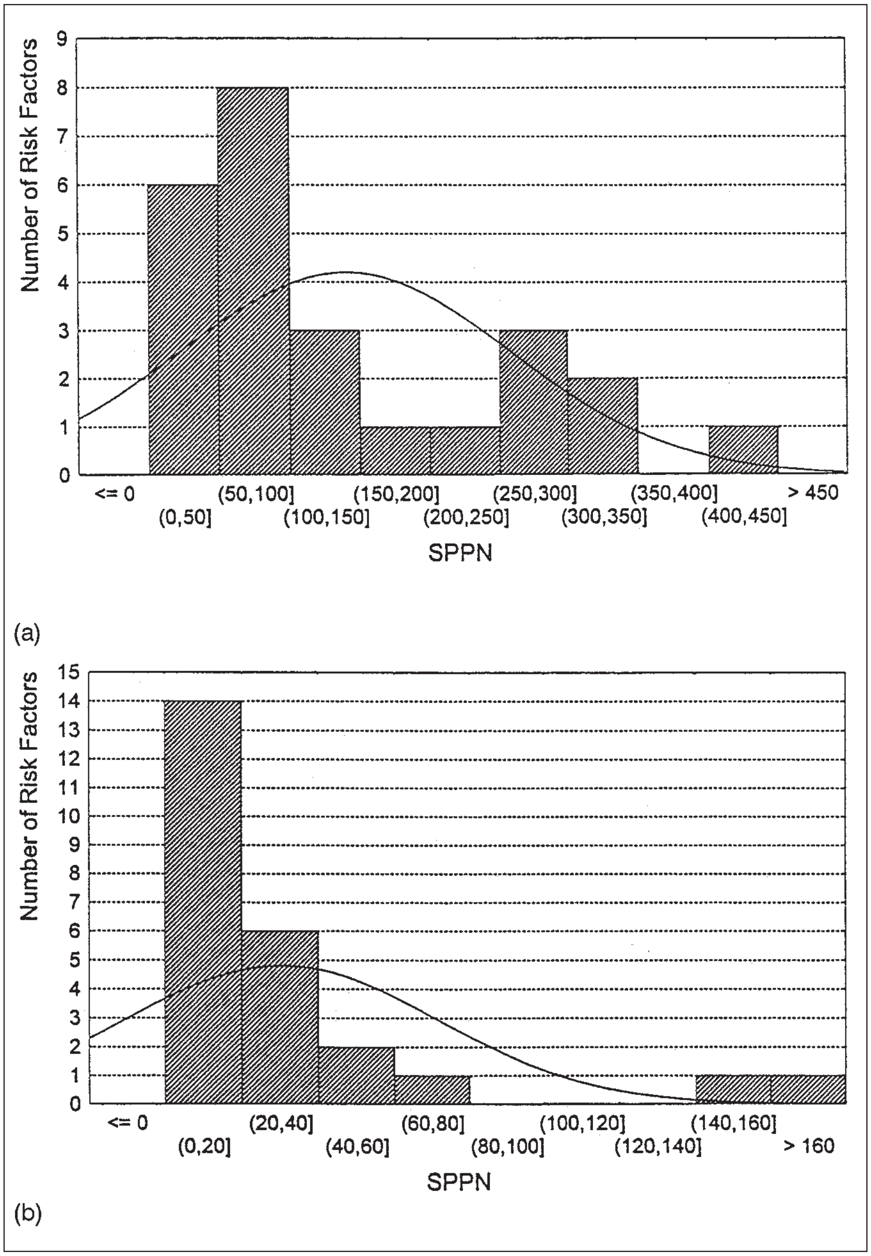

Figure 4. Histogram of SPPNs for: (a) an older facility, (b) a new facility.

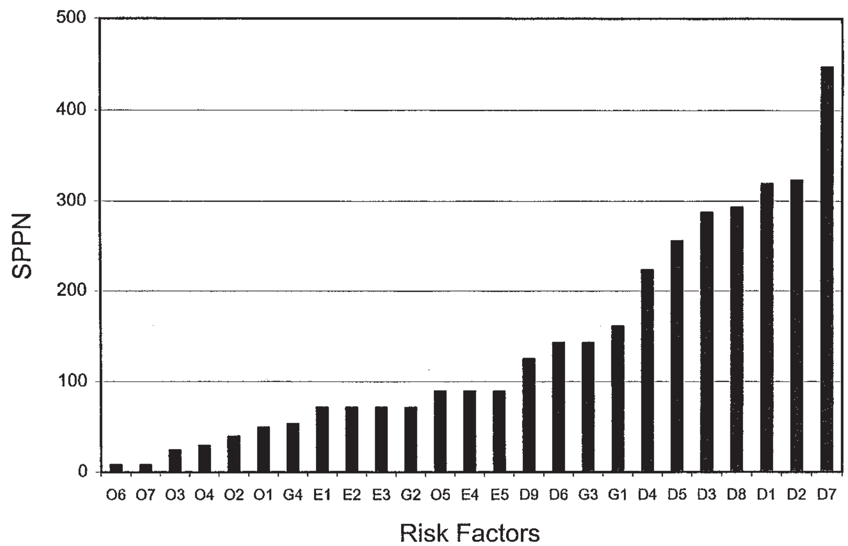

Figure 5. Relative significance of SPPNs vs. risk factors for an older facility.

system, number and level of training of personnel, and the vulnerability of the specific location at each stage of the operation.

Spills occurring during pipeline transport require specific attention due to the environmental vulnerability of the oil transportation routes and public exposure. Reducing spill risks during pipeline transport involves reduction of possible failure factors and increasing measures for detecting system failures. Based on the probability of each variable, preventive measures can be identified and evaluated for implementation. The spill prevention priority analysis developed can be used as a preliminary guideline to allocate resources for risk reduction. For example, the spills due to human errors can be reduced by periodic training of personnel on system operation, risk measures and handling emergency situations, proficiency in handling specific tasks, system limitations, and use of the monitoring instruments. Both the risk assessment and preventive measures should be evaluated periodically for each stage of operation. Periodic inspection and maintenance and installation of proper warning instruments can reduce failures due to mechanical system components.

Table 5. Calculation of SPPNs for the New Facility Described in Example 2

Origin	Spill risk factor	Risk factor score	Detectabiilty score	Consequence score	SPPN
Design	No. of components (D1)	2	2	5	20
	Age (D2)	1	1	5	5
	Pipe material (D3)	1	1	6	6
	Pipe length (D4)	1	1	5	5
	Pipe capacity (D5)	2	2	6	24
	System redundancy (D6)	2	2	6	24
	Degree of automation (D7)	1	2	5	10
	Pipe pressure (D8)	2	2	4	16
	Material being piped (D9)	2	2	4	16
Operational	No. of people employed (O1)	2	1	4	8
	Quantification (O2)	2	1	4	8
	Periodic training program (O3)	1	1	4	4
	Frequency of inspection (O4)	1	1	4	4
	Work hours (O5)	1	1	3	3
	Morale (O6)	1	1	2	2
	Work ethics (O7)	1	1	2	2
Environmental	Geology (E1)	2	3	4	24
	Geography (E2)	2	3	4	24
	Weather (E3)	2	5	4	40
	Vibration (E4)	3	3	4	24
	Nearby activities (E5)	3	5	4	60
Acts of God	Earthquake (G1)	2	9	9	162
	Arson (G2)	2	4	9	72
	Flood (G3)	2	8	9	144
	Hurricane (G4)	2	3	9	54

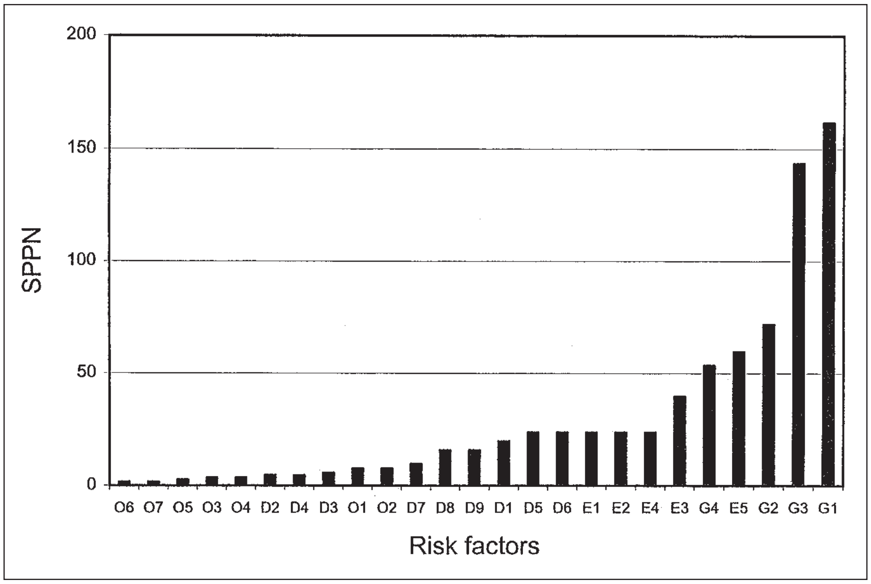

Figure 6. Relative significance of SPPNs vs. risk factors for a new facility.

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