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RISK ANALYSIS OF LIQUEFIED NATURAL GAS TRANSPORT

The importation of liquefied natural gas (LNG) by tanker ships into a storage facility on the Chesapeake Bay is discussed from the viewpoint of the risk analysis of a new, large-scale technology.

INTRODUCTION

In response to a request from Calvert County, Md., we have made an assessment for the Maryland Energy and Coastal Zone Administration of several issues associated with the transport of liquefied natural gas (LNG) to Cove Point, including risk, to identify cost-effective means for improving the safety of the present system operation and to provide insight that may contribute to the evaluation of additional proposed LNG capacity. This article is a brief review of the information collected and results obtained during these studies.

Accidents that lead to injury, death, or property loss are caused by human errors, design weaknesses, or unforeseen happenings. For example, ships may collide or run aground because of navigational mistakes, or they may capsize or break apart in severe weather that stresses them beyond their design limits. Explosions in coal mines, dam bursts, and building collapses take their toll. Fires are caused by personal misjudgments or by faulty equipment. No human activity is entirely without the potential for accidents that can lead to unwanted losses.

Our technological society has learned to cope with accidents by devising a host of safety procedures and standards. Traffic rules are designed to reduce automobile collisions to a "tolerable" level, even though the total number of accidents remains inexcusably large. Building codes are promulgated to reduce damage, but the evidence from occasional mass fires and earthquakes shows that those codes may be inadequate.

Ordinarily, accident statistics provide a valuable record of accident frequency, severity, and probable causes. Actuarial accident and mortality data are useful guideposts by means of which countermeasures can be designed, although the precise links between cause and effect, as in the case of smoking, may be difficult to establish in detail. If an accident is spectacular in its consequences, thorough investigations are instituted that may lead to significant changes in practice. Or if, by legislative action, new safety measures are mandated, as was the case with coal mine accidents, the rate of incidents may show a dramatic decline.

The introduction of a new technology, particularly a large-scale one, poses a dilemma. In the absence of historic accident records, how can the magnitude of a hazard that is about to be introduced be estimated? What safety standards or rules are called for? How can public concern be allayed?

A variety of risk assessment procedures has been developed to provide a framework within which these concerns can be quantitatively addressed. The procedures are briefly summarized in the following pages. A particular example, the introduction of shipments of large quantities of LNG by tankers into the Chesapeake Bay, is then discussed in greater detail.

TECHNOLOGY RISK ASSESSMENT

Evaluation of the safety aspects of a complex technical system presents a challenge when operational data are often either scarce or unavailable. The assessment of the risk of a system need not be restricted to only its negative aspects. It is preferable also to study and provide a perspective on the lost benefits of the system (or action) if it were not used (or performed), in addition to an account of the potential hazards and benefits of alternative systems that could meet the same demands.[1,2] Unfortunately, there is no consensus on a method for assessing the benefits of newly introduced technologies.

Most assessments dealing with energy technology risks are concerned with the relative risks of different conversion options or the absolute risk levels of a single option, together with comparisons to "background" or natural hazards. It has been shown that it is also important to account for the risks involved in producing the materials used to construct the entire energy system.[3,4]

A risk assessment may be divided into several distinguishable components: (a) identification and development of new risks or changes in risk parameters; (b) estimation of the likelihood and magnitude of occurrence of the risks; and (c) evaluation of the degree of acceptability of the levels of risk.[5] These components will be discussed, with examples drawn from marine transportation of potentially hazardous materials such as LNG.

Risk Identification

Accidents can occur during any phase of the LNG importation and distribution process. Numerous reports and environmental impact statements have been generated that focus on accident occurrence during transport by tank ship, loading and unloading of the ship at the terminal, storage in tanks at a shore-based facility, or distribution by pipeline or cryogenic tank trucks.

Various initiating events that can lead to large LNG spills during the phases of importation and distribution can be defined. The initiating events include severe storms, earthquakes, meteorites, ship collisions, groundings or rammings, aircraft crashes, missile impact, normal and operating equipment failure, operator error, and sabotage. The identification and selection of the initiating events are the result of intuition, scientific reasoning, and engineering judgment.

Risk Estimation

Risk estimation refers to the process of quantifying the probability distribution and uncertainties of each accident occurrence, magnitude of the consequence, and social group affected. However, the conceptual framework for risk estimation assumes that the distribution for the probability of occurrence and the consequence magnitude are statistically independent.

Most risk-assessment studies for marine transportation of oil and other hazardous materials estimate the risk by combining the following elements:

1. Probability of a vessel casualty;
2. Probability of a spill (of a given size or distribution of sizes) as a result of a casualty;
3. Spill effects (physical results for the dynamics of a spill) and exposure pathways;
4. Consequences of risk exposure in terms of the probability that consequences will occur (potential fatalities, property damage, etc., based on spill effects).

Methods for evaluating the probabilities of a vessel casualty have been categorized,[6,7] and representative studies that fit those categories are listed in Table 1. Analytic methods use kinematic equations and usually assume random motion to express the probability of collision, ramming, or grounding in terms of system variables, including traffic density, ship length, and speed-distribution data. Risk assessments that have used analytic models for vessel-casualty probability estimation typically apply factors on the order of 10^{-4} to make the model results consistent with historical data. The usefulness of *analytic* methods to asses the value (risk reduction) of various safety measures appears limited. The *simulation* (statistical) approach uses historical accident data bases to calculate a probability of occurrence. However, it is sometimes necessary to use a surrogate data base; that is, accident data for liquefied petroleum gas tank ships may have to be modified and substituted for an LNG ship accident analysis. Difficulties involving trends in the data versus time (nonstationarity) can arise, and a sufficient data sample may not be available.

Rather than derive probability estimates from system-level information, as proposed by the statistical inference method, logic-tree (fault-tree/event-tree) methods may be applied to express the possible sequences of events that lead to a casualty, and then basic component (or event) level probability information may be used.[17] Failure-rate information on components or events that comprise a complex system may be difficult to obtain. Fault-tree analyses are successful as descriptive aids in understanding accident events and are extremely useful during the conceptual design phase of the development of a large technological system.

Table 1 — Categorization of vessel casualty estimation methods.[4,5]

Method	*Study*
Analytic	*Spill Risk Analysis Program* (scenario model), Operations Research, Inc. (1977)[8]
	LNG Risk Assessment Study for Point Conception, Calif., Science Applications, Inc. (1976)[9]
Simulation	*Vessel Safety Model*, Transportation Systems Center (1974)[10]
Fault-tree/ event-tree	*Reactor Safety Study*, U.S. Nuclear Regulatory Commission (1975)[11]
	The Effect of U.S. Coast Guard Rules in Reducing the Probability of LNG Tanker-Ship Collision in Boston Harbor, Tera Corp. (1979)[12]
Casualty report analysis	*Spill Risk Analysis Program* (quasi-experimental method), Operations Research, Inc. (1977)[8]
Subjective	*Cargo Spill Probability Analysis for the Deep-Water Port Project,* Woodward, Lundgren, and Associates (1973)[13]
Statistical	Risk Assessment for LNG Terminal at Matagorda Bay, Federal Power Commission (1977)[14]
	Offshore Petroleum Transfer Systems for Washington State, Oceanographic Commission of Washington (1974)[15]
	Spill Probability Analysis for Outer Continental Shelf Environmental Assessment, Council on Environmental Quality (1974)[16]

The incorporation of the human element into logic-tree risk assessments is undergoing active development.[18,19] Simulation on computers (digital, analog, or hybrid) is another approach that can be used to estimate the probability. To date, full Monte Carlo simulation studies are quite expensive and appear limited in assessing the effects of safety measures. The *subjective* method uses information from questionnaires or from interviews with experts (Delphi approach) to develop a probability estimate or to modify a scientific inference.[20] Apparently it is generally easier to estimate probabilities of relatively large magnitude (e.g., 1/10) rather than those of small magnitude (e.g., 1/10,000). Thus, this technique is more appropriate for estimating the effects (in terms of a probability or risk factor) associated with safety measures than estimating an accident probability-of-occurrence. Finally, the *casualty report analysis* approach involves detailed evaluations of narrative vessel-casualty reports, a method that is time-consuming and has validity that is contingent upon the accuracy and completeness of the reports.

For a range of consequence magnitudes (damage levels) with various likelihoods associated with a given action, a commonly used measure of risk is a curve that graphically displays a probability distribution function versus the magnitude of damage. Figure 1 presents several risk curves as complementary cumulative distribution functions in which the ordinate represents the probability that "damage" of "level x or greater" will be produced. The Point Conception, Calif., LNG operations risk curve is included.[21] When several types of consequences (i.e., number of deaths or property damage in dollars) are considered, this risk curve may be generalized to several dimensions.

Risk calculated by summing the products of the probabilities and consequences provides an expected value (or mean) of the damage under study. It has been pointed out that reducing the information in the risk curve to a single statistical number may not be appropriate for relative risk comparisons because enormously different curves may have the same expected value. However, the single statistical number continues to be favored in many practical applications; that is, typically the risk R is given in the linear form:

$$R = \sum_{i=1}^{n} P_i C_i \ . \tag{1}$$

Equation 2 is another simple model to express risk:

$$R = \sum_{i=1}^{n} P_i C_i^{K} \ , \tag{2}$$

where P_i is the probability per unit time of the ith type of accident, C_i represents the consequences, n is the total number of accident types, and K is a parameter that could weight high-consequence accidents more than low-consequence ones, thereby explicitly representing via a power law the public's perception of risk. If society views a single large accident as being more significant than many small accidents that have the same total consequence, the society is said to be risk-averse. When the exponent K is taken to be greater than 1, large accidents would be weighted to reflect society's aversion to high-consequence events ($K = 1$ corresponds to an absence of risk aversion). In measuring the societal risk of early death from radiological incidents, the Advisory Committee on Reactor Safeguards[22] recommends use of the latter formula with $K = 1.2$. Some argue that the use of risk aversion factors may result in a wrong "prioritization" and in misallocation of both regulatory and industry resources being focused on high-consequence low-probability events rather than in providing adequate attention to accident sequences that are in fact more likely to occur.

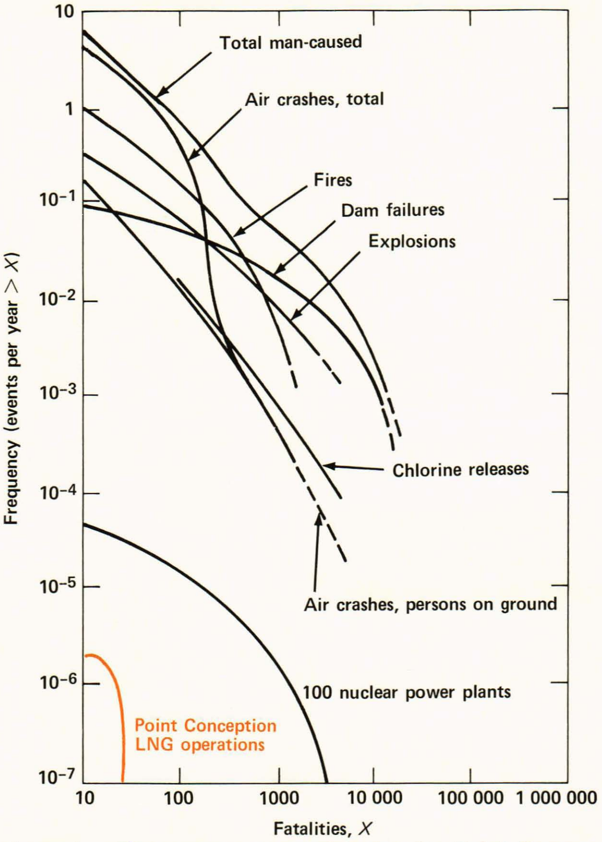

Figure 1 — Risk curves comparing risk for Point Conception LNG operations with man-caused events involving fatalities. (From the LNG Safety Study[21] and the Reactor Safety Study.[11])

Risk Evaluation, Acceptance, and Decision Making

The most difficult part of a total risk assessment of the operations of an LNG terminal is the evaluation of the acceptability of the calculated risks. Factors that are thought to influence the perception of risk include the following:

- The difference between technical and perceived risk
- Whether the risk is from a common or "dread" hazard
- Whether the risks are assumed voluntarily
- The time span between exposure and effect
- The available alternatives
- The degree of uncertainty about the risk
- Whether the risks are occupational
- Whether the health effects occur to identifiable people or statistical people
- The degree of controllability
- Those to whom the benefits accrue

These factors are interrelated in a complex way that makes decision making for risk management very difficult. Both the risks to the exposed individual or group and the risk imposed upon society are clearly important. Minimizing general risk to the public may increase (adversely affect) occupational risks. Furthermore, those who benefit from a risk activity do not necessarily incur the risks.

Few cases exist where quantitative safety goals or acceptable levels of risk for regulatory decision making have been used by a government agency. Several risk levels set by governments include a 10^{-2} to 10^{-3} per year risk of overflowing the Thames Valley flooding defense, and a risk of 10^{-4} per year for the Netherlands sea defense. Also, MIL-STD-1316, "Fuzes, Navy, Design Safety Criteria For," states that "a safety failure rate not to exceed one in a million (1×10^{-6}) should be used as a goal in the design of a fuze and, to the extent possible, in its evolution." According to this military standard, 10^{-6} may thus be taken as an order of magnitude that is the maximum acceptable probability of an accident for a catastrophic hazard (i.e., one involving death or severe injury to personnel, or system loss). The Food and Drug Administration (44 FR 17092; March 20, 1979) had concluded that a risk of 1 in 1 million over a lifetime would constitute an acceptable level for the presence of carcinogens in food additives.

The public may not recognize differences between annual mortality risks of 10^{-3}, 10^{-6}, and 10^{-9}, and therefore it has been suggested that risk be cast in more understandable terms (e.g., in terms of days of life expectancy lost). Fatalities per year among the public resulting from several energy-generating technologies are given in Table 2, and a comparison of the loss-of-life expectancy resulting from various causes (including generation of energy) is provided in Table 3.[23]

Table 2 — Fatalities per year among public due to energy generation.[23]

Source	*Fatalities Per Year*	*Reduction in Life Expectancy (Years)*	*Days of Reduced Life Expectancy*
Coal			
Air pollution	10,000	10	11.5
Transport accidents	300	35	1.0
Total			12.5
Oil			
Air pollution	2000	10	2.2
Fires	500	35	2.0
Total			4.2
Gas			
Air pollution	200	10	0.2
Explosions	100	35	0.4
Fires	100	35	0.4
Asphyxiation	500	25	1.5
Total			2.5
Hydroelectric dam failures	50	35	0.2
Nuclear (400 GW)			
Routine emissions	8	20	0.02
Accidents	8	20	0.02
Transport	<0.01	20	—
Waste	0.4	20	—
Plutonium toxicity	<0.01	20	—
Total			0.04
Electrocution	1200	35	5.0
Grand total			~24

Basic approaches for risk evaluation and decision making are listed in Table 4. Each of the decision-making methods is conventional and relatively easy to understand, except perhaps those classified as *multiobjective techniques*. In general, multiobjective planning can be categorized into "prior preference" and "postanalysis preference" methods, as discussed by Cohon[24] and outlined in the box insert on p. 330. The former method is exemplified by utility theory and attempts to elicit the decision makers' preferences regarding a set of objectives and constraints, using this information to reach a decision[25] (see Fig. 2, taken from Ref. 26).

In comparison, the latter method first attempts to develop the range of choices (or noninferior set) involved in the problem by using mathematical programming. Preferences are then elicited from decision makers after they see the implications of their preferences in terms of trade-offs. A best compromise solution can then be found, based on these preferences.[24] In a multiobjective analysis framework, risk (to each group affected) can be incorporated as

Table 3 — Loss of life expectancy (ΔE) due to various causes.[23]

Cause	*Days of Reduced Life Expectancy*
Being unmarried (male)	3500
Cigarette smoking (male)	2250
Heart disease	2100
Being unmarried (female)	1600
Being 30% overweight	1300
Being a coal miner	1110
Cancer	980
Being 20% overweight	900
<8th grade education	850
Cigarette smoking (female)	800
Low socioeconomic status	700
Stroke	520
Living in unfavorable state	500
Army in Vietnam	400
Cigar smoking	330
Dangerous job (accidents)	300
Pipe smoking	220
Increasing food intake 100 cal/day	210
Motor vehicle accidents	207
Pneumonia/influenza	141
Alcohol (U.S. average)	130
Accidents in home	95
Suicide	95
Diabetes	95
Being murdered (homicide)	95
Legal drug misuse	90
Average job (accidents)	74
Drowning	41
Job with radiation exposure	40
Falls	39
Accidents to pedestrians	37
Safest jobs (accidents)	30
Fire	27
Generation of energy	24
Illicit drugs (U.S. average)	18
Poison (solid, liquid)	17
Suffocation	13
Firearms accidents	11
Natural radiation	8
Medical X rays	6
Poisonous gases	7
Coffee	6
Oral contraceptives	5
Accidents to pedalcycles	5
All catastrophes combined	3.5
Diet drinks	2
Reactor accidents (UCS*)	2†
Reactor accidents (Rasmussen)	0.02†
Radiation from nuclear industry	0.02†
PAP test	−4
Smoke alarm in home	−10
Air bags in car	−50
Safety improvements 1966-76	−110
Mobile coronary care units	−125

†These items assume that all U.S. electricity is generated by nuclear power.

*UCS is the Union of Concerned Scientists, the most prominent group of nuclear critics.

Table 4 — Risk evaluation/acceptance.

Method/Technique	*Risk Management*
Risk aversion	Determine maximum degree of risk reduction with little or no comparison to other risks or benefits.
Balance risks	Compare risk values to other appropriate risk cases or to other risks previously determined to be acceptable.
Cost effectiveness of risk reduction	Attempts to maximize the reduction in risk for each dollar expenditure for safety (e.g., equipment, operating or emergency procedures, etc.).
Benefit-risk analysis (cost-benefit)	Detailed cost balance of the benefits of an activity or technology against the level of risk (cost) it presents.
Matrix analysis	This approach can be used in risk acceptance because of difficulties in estimating dollar equivalents. One can keep separate the types of consequences (e.g., deaths, injuries, property damage, etc.).
Multiobjective techniques	These techniques provide a framework to address multiple conflicting objectives and the preferences of the decision makers to show trade-offs between the different objectives (e.g., cost versus population proximity to an LNG facility when siting facilities to meet demands on a regional scale).

MULTIOBJECTIVE PROGRAMMING AND PLANNING

There are two basic categories of multiobjective problem-solving techniques.[24] First, generating methods are designed for multiobjective analysis with mathematical programming formulations. For example, the general multiobjective maximization problem can be stated as

$$\text{Max } [z_1(\underline{x}), z_2(\underline{x}) \ldots z_p(\underline{x})], \quad \underline{x} \text{ feasible}$$

where $\underline{x}$ is an n-dimensional vector of decision variables and $z_k(\underline{x})$ is the kth objective, which is a function of the n decision variables. Thus, the problem is to maximize all of the p objectives simultaneously while maintaining feasibility, which is defined by constraints on the decision variables. Conventional single-objective problems differ only in the dimensionality of the objective function. The generating techniques, sometimes called "postanalysis preference" methods, emphasize information transfer by focusing on the generation of the trade-off curve. Preference information is not formally developed; instead, preferences may be articulated, perhaps implicitly, when a solution is chosen from the generated noninferior set.

Generating methods of significance include the weighting and constraint methods, the noninferior set estimation method, and the multiobjective simplex method. Cohon reviews the entire range of multiobjective programming techniques in detail.[24]

Second, by contrast, preference-oriented methods, such as multiattribute decision analysis,[25] suggest formal procedures that attempt to quantify preference information. This "prior preference" method proceeds more or less directly to a supposed preferred solution without generating the noninferior set. Refer to Fig. 2 and consider impact vectors consisting of two components: y cost measured in dollars, and x damage measured in fatalities. For a given option, A, there are various possible outcomes with associated probabilities. All the impact vectors (for that option) have the same benefit, Y_A, but the degree of damage varies along with its associated probability. The probability-damage relationship for each option (e.g., A, B, etc.) can be expressed in the form of a risk curve similar to those shown in Fig. 1. To decide which risk option is preferable requires that a utility function, $u(x,y)$, be formulated to map the impact vector into a scalar quantity (utility). This decision model chooses the option with the maximum expected utility, which is defined as the sum of the possible outcomes of the utility of each outcome weighted by the probability of that outcome.

Several complications arise in the application of multiattribute decision analysis, particularly in the public sector. Uncertainty exists over which preferences to use because of the multiplicity of decision makers. The approach may fail to provide sufficient information on the choices represented by the noninferior set.

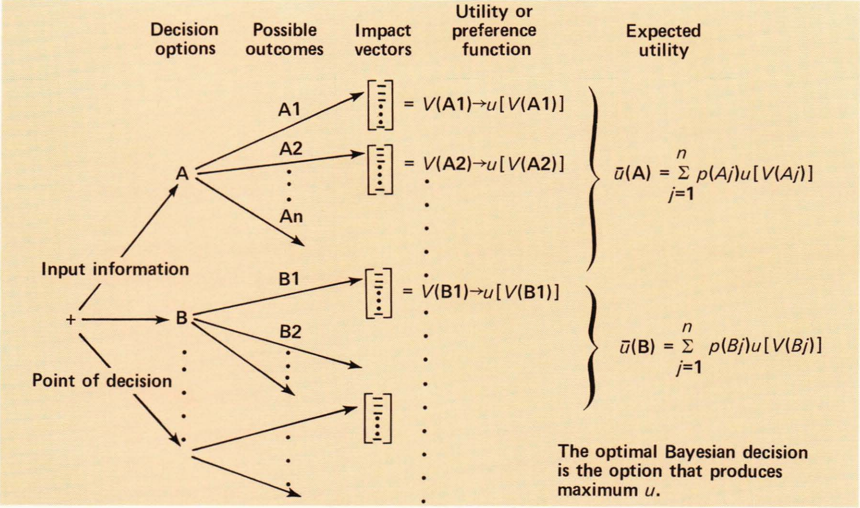

Figure 2 — The anatomy of the multiattribute utility preference approach. (From Okrent.[26])

one of several objectives to be optimized. Acceptable risk is properly assessed in the context of alternatives.

Some terminology and concepts from multiobjective programming (the new specialty of operations research and mathematical programming) are introduced below. When there are multiple conflicting objectives, there can be no plan that is clearly best. Instead, there is a range of solutions that perform with varying degrees of success on the various objectives. (Attributes and criteria are synonymous with objectives.) The central notion in a multiobjective problem is that of noninferiority, which replaces the idea of optimality in single-objective programs. Consider the graphs in Figs. 3 and 4, which show a trade-off curve or noninferior set (''Pareto optimum'' and ''efficient'' are equivalent concepts). The points on the curve represent different plans (i.e., courses of action for a decision maker).

A solution is noninferior if there is no other feasible solution that yields a higher value of one objective without yielding lower values of at least one other objective. Inferior solutions, therefore, are dominated solutions in the sense that there exist feasible alternatives that are better on the basis of all objectives. As shown in Fig. 4, point D is clearly inferior since there exist feasible solutions such as B and C that dominate D; e.g., Z_2 can be increased by moving from D to B without decreasing Z_1. Points A, B, and C are noninferior because there are no feasible points that dominate them. The collection of noninferior solutions is called the noninferior set, which is shown as the colored portion of the boundary of the feasible region in Fig. 4. As one moves along the noninferior set, one objective is continually traded off against the other; one objective must be sacrificed to achieve an improvement in the other objective. Graphically, the trade-off corresponds to the slope of the trade-off curve, which changes as we move along the curve.

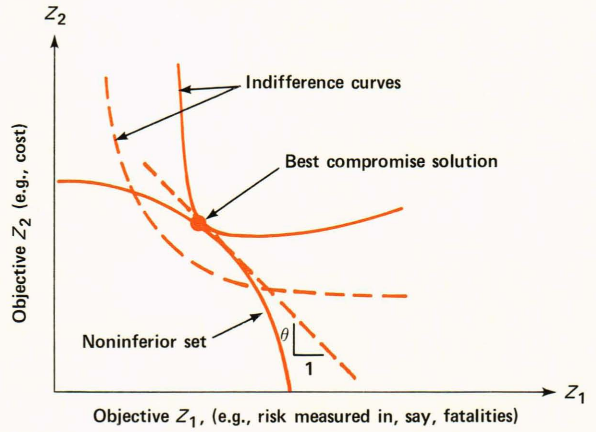

Figure 3 — Geometry of the noninferior set, the indifference curves, and the best compromise solution. (From Cohon.[24])

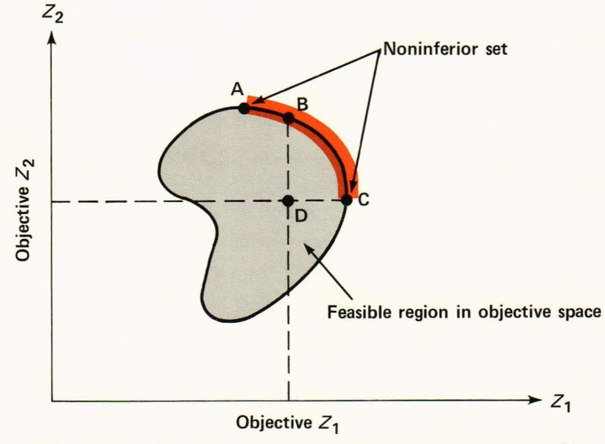

Figure 4 — Noninferior set geometry. (From Cohon.[24])

It is also interesting to note two other basic approaches to determine acceptable societal risks: the *revealed preferences* method discussed in publications by Starr beginning in 1972[27] and the *expressed preference* method of Frischhoff *et al.*,[28] which extends Starr's work. Starr's work assumes that society has achieved an essentially optimum balance between risks and benefits associated with any activity and also that historical data may be used to reveal acceptable risk-benefit patterns (Fig. 5). Starr's results, which are sometimes referred to as the ''laws of acceptable risk,'' include the following:

1. The acceptability of the risk is proportional to the third power of the benefits;
2. The public is willing to accept much greater risks from voluntary activities (approximately 1000 times) than it would from involuntary ones;
3. The acceptable level of risk is inversely related to the number of persons exposed to the risk activity.

The data base from which Starr derived the above results has been reexamined by Otway and Cohen[29] and Rowe,[5] who found different power-law relationships between risk and benefit. For example, Rowe concluded that $R \sim B$ for involuntary risks and $R \sim B^{0.5}$ for voluntary risks. Starr's concepts have been used to establish acceptable risk levels for petrochemical[30] and energy plants.[31]

Another approach to determine what level of risk is acceptable to people consists of asking them to express their preferences directly. This method of expressed preferences has been applied to rate the total risk or the total benefit to society for each of 30 activities. The results indicate that people believe that more beneficial activities should have higher risk levels and that characteristics of risks, including the degree to which the risk appears voluntary, controllable, familiar, known, and immediate, have double standards (Fig. 6).

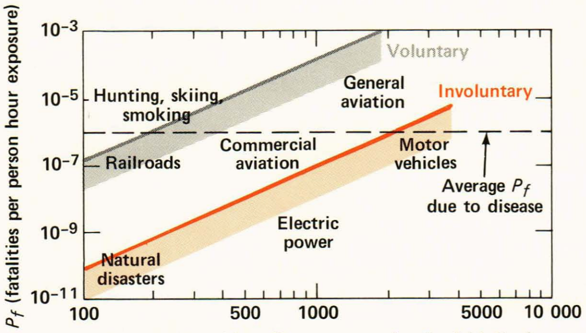

Figure 5 — Acceptable risk as determined by revealed preferences. The best fitting lines were eyeballed; error bands indicate that the lines are approximations. (From Starr.[27])

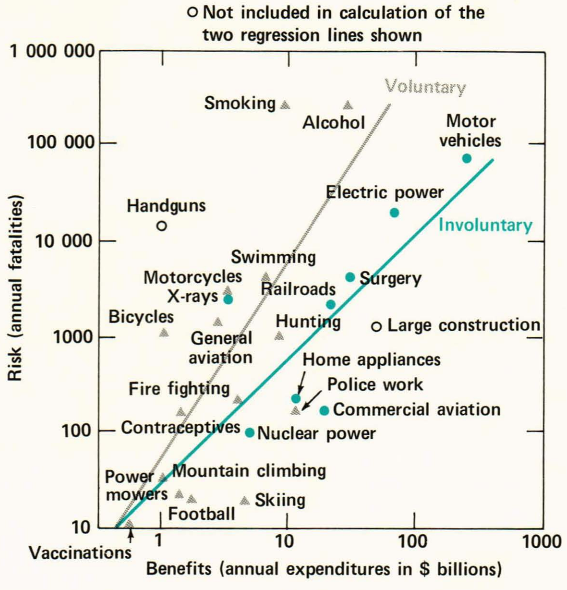

Figure 6 — Acceptable risk as determined by expressed preferences. (From Frischhoff *et al.*[28])

Equivalent Safety Concept

By using a simple quantitative method developed by Danahay and Gathy,[32] an attempt can be made to contrast potential hazards of LNG to other common chemicals or commodities carried by vessels in waterways under U.S. Coast Guard jurisdiction. The method, called the equivalent safety concept (ESC), is meant to aid the Captain of the Port in deciding whether to permit a particular harbor transit. The ESC is not officially required for use by the U.S. Coast Guard and is undergoing study by a panel of the National Academy of Sciences. The method consists of calculating several indices for the chosen cargo, vessel, and port, i.e., the Cargo Hazard Index (CHI), the Vessel Index, and the Port Safety Index. It is intentionally a simple basic formulation rather than a complete mathematical risk-analysis model. Table 5 presents a ranking of cargoes using the CHI, which is based on physical, chemical, and toxicological properties. The higher the relative value for CHI, the greater the relative hazard. Where materials have both a toxic and a flammable hazard, the higher of the CHI's is listed. Apparently this approach indicates that LNG has a much lower consequence potential than the other chemicals.

Table 5 — Relative hazard ratings.[32]

Commodity	*Basic Hazard**	*Cargo Hazard Index (CHI)*
Phosgene	T	150.0
Chlorine	T	51.0
Acrolein	T	42.6
Hydrogen chloride	T	19.7
Allyl chloride	T	18.2
Ethyleneimine	T	16.7
Ethylene oxide	F	12.7
Methyl bromide	T	12.55
Carbon disulfide	F	11.4
Dimethylamine	T	10.9
Hydrogen fluoride	T	10.2
Ethyl ether	F	7.95
Acetaldehyde	F	6.2
Ethylene	F	5.63
Ammonia (anhydrous)	T	4.96
Vinyl chloride	F	4.6
Butadiene	F	4.5
Propylene	F	4.4
Methyl chloride	T	4.24
Butane	F	4.0
Propane	F	3.74
Carbon tetrachloride	T	3.37
Methane	F	2.69
Benzene	T	2.08
Acrylonitrile	T	1.3

*T = Toxic
F = Flammable

LNG TRANSPORTATION SYSTEM

The United States is faced with complex problems associated with management and growth in its coastal areas. Issues related to the safety and environmental impact of transport of energy-related materials, including LNG, as well as other hazardous materials, and the siting of major facilities of regional importance need to be addressed on a continuing systematic basis.[33-35] (Japan and various European countries have been importing substantial quantities of LNG from the Middle East, Indonesia, and Australia, and Canada will soon become a large exporter.)

Cove Point, Md., is one of four receiving terminals in the United States for LNG. The others are located in Everett, Mass.; Savannah, Ga.; and Lake Charles, La. In addition, the United States has been exporting relatively small quantities of LNG from Nikiski, Alaska, to Japan since 1969. Operations began at Cove Point with the arrival of the first LNG tanker on March 13, 1978. The facility is authorized to receive 92 tanker deliveries per year from Algeria, which corresponds to approximately two shiploads per week, and to send out 650 million cubic feet of gas per day into the nearby gas transmission pipeline. At present, imports have been suspended because of a contractual impasse on pricing policy.

The importation of LNG into the Cove Point terminal and its subsequent distribution involve

1. Transportation of natural gas from the Sahara Desert gas deposits to Arzew, Algeria, located on the Mediterranean;

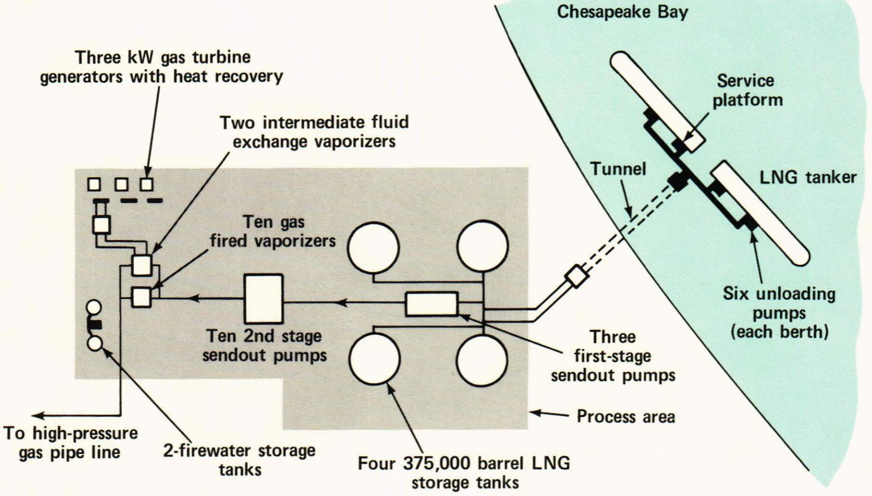

Figure 7 — Schematic of the Cove Point, Md., LNG receiving terminal and off-shore unloading and berthing facilities.

2. Liquefaction at Arzew and shipment across the Atlantic Ocean (3570 nautical miles) using a fleet of nine tank ships;
3. Unloading, storage, and regasification at the land-based terminal at Cove Point.

Cove Point LNG Terminal

The Cove Point LNG terminal (Fig. 7) is located on 1022 acres in Calvert County, 60 miles south of Baltimore and 40 miles south of Annapolis, near the mouth of the Patuxent River. Structures now occupy approximately 60 acres. The terminal includes a berthing facility with space for two 1000-foot tankers for unloading, a tankage area with four 375,000-barrel tanks in place and with space for two additional tanks, and an operations area for pumping and regasification. The vaporized LNG is routed by an 87-mile, 36-inch pipeline to connect with existing transmission facilities west of Dulles International Airport (Fig. 8). It is intended to serve Ohio, Pennsylvania, Virginia, West Virginia, New York, Maryland, and Kentucky, and the District of Columbia. At full operation, 12.2% of the natural gas needs in Maryland will be met by LNG.[36]

The Cove Point terminal is for baseload operation, in contrast to "peak-shaving" LNG operations. The latter store LNG and supply gas during periods of peak demand, such as during the winter season, whereas a baseload plant provides supplies throughout the year. At present, there are approximately 50 peak-shaving plants located in or around major cities, capable of storing 12 million barrels of liquid.[35] Two peak-shaving facilities are located in Baltimore, with a storage capacity of 145,000 barrels of LNG (equivalent to about 500 million cubic feet of gas).

Population and Wind Patterns Surrounding Cove Point

Calculations of the population distribution near the Cove Point LNG facility have been prepared. Approximately 6000 persons lived within six miles of the site in 1980; it is predicted that 8200 and 9100 persons will live there (in the off-peak season) in 1990 and 2000, respectively. During the summer months (on weekends), the population increases by 50%. Figures 9 and 10 present the 1990 projected population by radial distance and sector from the terminal and the nearby wind direction frequency (or annual wind rose) pattern.

Tank Ships

Each ship has a capacity of 125,000 cubic meters of LNG or 2½ billion cubic feet of gas. One shipload is approximately equivalent to the annual gas needs of 17,000 residential customers in the Baltimore-Washington area.

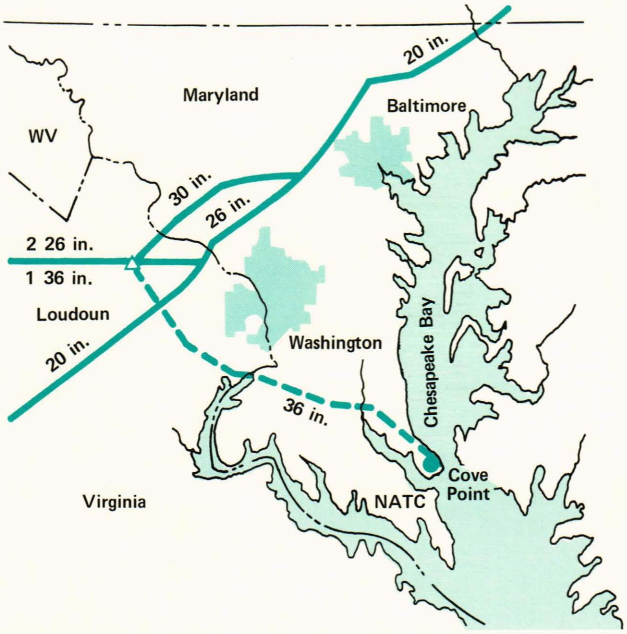

Figure 8 — The gas pipeline distribution system from the Cove Point LNG terminal.

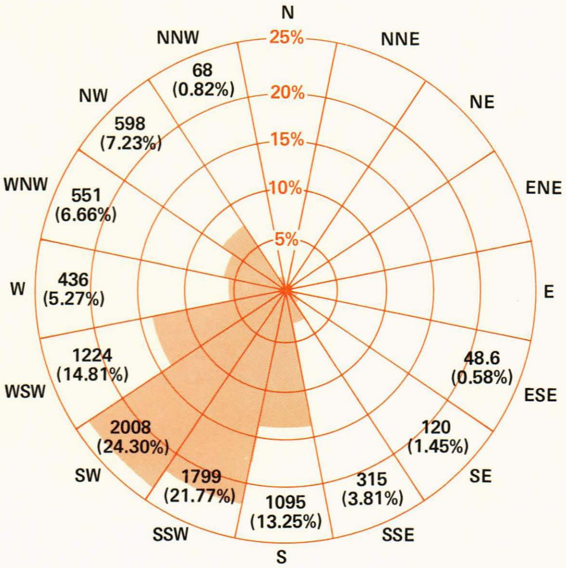

Figure 9 — The number and percentage of residents for the year 1990 by compass section living within a mile radius from the Cove Point LNG facility.

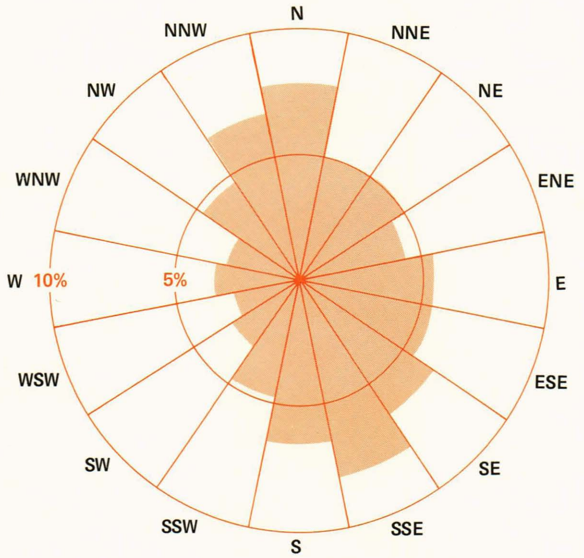

Figure 10 — The annual frequency of occurrence of winds blowing from each compass sector. Wind rose statistics are based on Patuxent Naval Air Station data (1967-71).

The vessels are about a thousand feet long, with a loaded draft of 36 feet. Because of the relatively low density of LNG (one-half the weight of water) a fully loaded LNG vessel rides higher out of the water than does a petroleum carrier of comparable capacity. The tankers have insulated containment systems to maintain the LNG at cryogenic temperatures, with an approximate vaporization rate (boil-off) of 0.25% per day by volume; the vapor is burned in the ship's boilers as fuel. The round trip time for vessels traveling between Arzew and Cove Point is about three weeks. The total investment for the nine tank ships is about 1.2 billion dollars.

BACKGROUND INFORMATION

Composition and Ignition Properties of Natural Gas

Methane gas, when cooled to a temperature of approximately −260°F (−162°C) at atmospheric pressure, condenses to a liquid and reduces in volume by approximately 600 times. This large volume reduction makes bulk marine transport of LNG economically feasible.

The LNG delivered to Cove Point is actually a mixture of hydrocarbons containing approximately 84 to 92% methane. The percentages of the major constituents of LNG supplied from Algeria are:

Component of LNG	*Percentage*
Methane	84.0 to 92.0
Ethane	6.0 to 8.5
Propane	2.2 to 3.0
Nitrogen	0.6 to 1.4

A flammable mixture needs a minimum threshold energy for ignition, which depends on several factors, including characteristics of the energy source, composition of the mixture, and rate of flow of gas. With a high-temperature source, such as a spark discharge from a capacitor bank between two electrodes, the energy is very small (less than 1 millijoule for a stoichiometric mixture). This energy rises steeply near the flammability limits (Fig. 11). Methane-air can also be ignited by a hot surface. Safety guides (National Fire Protection Association Guide, Number 325M) indicate that a 537°C (999°F) surface would ignite methane, assuming negligible flow rate of gas over the surface. Surface temperatures on the order of 1200°F or more would be required for moderate flow velocities past a surface or for gas containing small particles.

LNG Experience and Incident Record

The LNG shipping industry is not new. Over 5200 voyages have been made without any large LNG releases. The first shipment of LNG in a specially insulated tank ship was made in February 1959 from a refrigeration plant in Lake Charles, La., to London, England, as a demonstration of the technical feasibility of bulk marine transport.[37] The Phillips-Marathon Project has been exporting LNG from Alaska to Japan since 1969, and the Distrigas Project in Boston has been importing LNG from Algeria since 1971. Minor accidental LNG releases have occurred during transportation on LNG tankers.

The most serious LNG accident occurred at a liquefaction, storage, and regasification plant in Cleveland in 1944, where the contents of two tanks totaling less than 6300 cubic meters were released. The cause was probably shock-initiated brittle failure of a 3% nickel steel alloy used as the tanks' structural material.[38] Today's tanks are constructed with a 9% nickel steel or aluminum that provides fracture toughness down to temperatures of liquid nitrogen (−320°F).

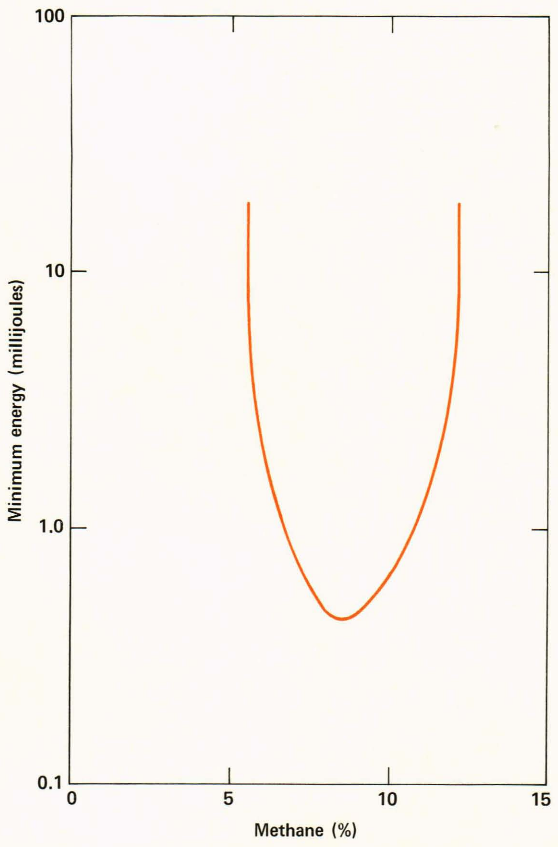

Figure 11 — Minimum spark ignition energies for methane-air mixtures.[33]

The Cleveland accident resulted in 130 deaths, 225 injuries, and property damage estimated at $7 million. Containment dikes that could have prevented spillage into the storm-drain system were absent (and not required at that time).

A small natural gas explosion occurred in 1979 at the Cove Point terminal. Its cause was LNG leaking past an inadequately tightened pressure seal on one of the second-stage sendout pumps to the switchgear and motor-control building. A spark ignited the gas vapors, killing one person and seriously injuring another. Contributing to the accident was the absence of combustible gas indicators to detect the flammable vapors in the substation. Damage to the facility was estimated at about $3 million.

Spills in the Chesapeake Bay Area

The U.S. Coast Guard's Pollution Incident Reporting System (PIRS), which was implemented in 1970,[39] maintains a computerized record of spill incidents, including oil and other hazardous materials. Figure 12 shows the distribution of spill volumes (gallons) over a four-year period (1974-77) in the Chesapeake Bay. Approximately 67 and 78% of the spills were less than 50 gallons and 100 gallons, respectively. During that four-year period, approximately 24 spills per year were greater than 1000 gallons, which represents 5% of the spills in that period. Other data show that most of the spills reported occurred during daylight hours.

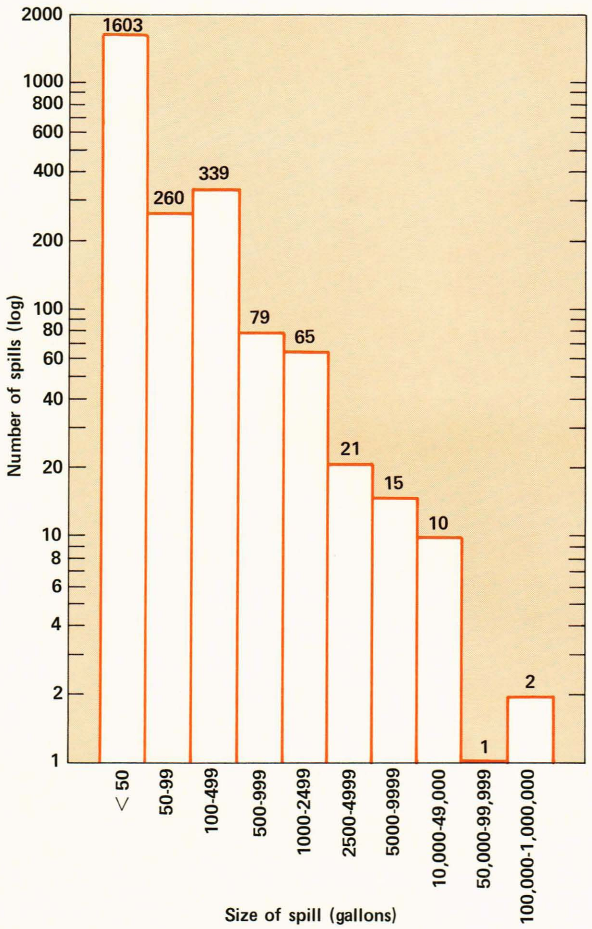

Figure 12 — Size distribution of spills in the Chesapeake Bay during 1974-77. (From U.S. Coast Guard Pollution Incident Reporting System data.)

PROBABILISTIC RISK OF LNG TRANSPORT TO COVE POINT

Public Risk

A risk assessment of the Cove Point LNG operations estimating the public risk in terms of the expected number (mean number) of fatalities per year has been performed.[40,41]

The types of accidents identified include those initiated by either a ship accident or aircraft accident. Specifically, the ship collision analysis pertains to an LNG ship collision with another moving vessel and ship ramming while the LNG ship is docked. Aircraft crashes into LNG storage tanks, pipelines, or a ship while transiting up the Bay were also assessed. The aircraft crash model takes into account air carrier traffic on nearby flight paths and nonairway traffic from general aviation and airport operations, as well as military flights. Each analysis for the probability of a tank rupture resulting in a spill includes both the probability of the initiating event and a penetration analysis, given that event, to arrive at a probability of rupture.

The probabilities of a tank rupture are summarized in Table 6 for accident scenarios while the LNG tanker is docked and while in transit, assuming 92 transits per year. For land-based tanks, the estimated probability of a tank rupture by aircraft is one chance in 400,000 and for a ship's tank rupture by aircraft is one chance in 200,000.

To calculate the risk, an evaluation of the consequences to the general public of an LNG spill was made for three spill rates from a land storage tank into an earthen berm as well as for one- and two-ship tank sizes.

Table 6 — Cove Point accident scenarios, initiating event probability summary (accidents/year), based on 92 transits per year.

Description			*Probability of Accidents/Year*
Ship rupture at dock	4.1×10^{-6}	1 in	240,000
Aircraft penetration at dock	4.3×10^{-6}	1 in	230,000
Total at dock	8.4×10^{-6}	1 in	120,000
Ship collision and upture in transit	5.5×10^{-6}	1 in	180,000
Aircraft penetration in transit	1.7×10^{-9}	1 in	5.9×10^{8}
Total in transit	5.5×10^{-6}	1 in	180,000
Cumulative rupture probability at Cove Point	1.4×10^{-5}	1 in	70,000

Unconfined Water Spills

For LNG spills on water of 25,000 and 50,000 cubic meters, the maximum distances of gas-cloud travel prior to dilution below the Lower Flammability Limit calculated by the Science Applications Inc. (SAI) vapor-cloud dispersion model are 4.8 and 5.5 miles, respectively. The probability of no immediate ignition in the event of a tank rupture is assumed to be 10%. The risk calculations (i.e., number of fatalities) were then based on the frequency of occurrence of combinations of wind speed and wind direction, using the National Weather Service data at Patuxent River Naval Air Station, in addition to the population exposed to the burning plume and the thermal radiation from a plume fire. Evacuation is not assumed, and people within the fire radiation zone are assumed to be fatalities, where the radiation zone is determined by a flux level greater than 5700 Btu per square foot per hour. This exposure level will cause blistering of the skin in 5 seconds but is not sufficient to ignite a building. Two percentages (i.e., 25% and 100%) of the population exposed to the burning plume were used in the fatality calculations. The calculated risk to a person near Cove Point is presented in Table 7 in terms of the parameter fatalities per person at risk per year. These numbers are two orders of magnitude lower (1/100 of the value) than those calculated for the maximum risks to a member of the public in the Virginia Beach/Cape Henry area. The risk to the population along the route was estimated to be less than 1×10^{-11} fatalities per year. The calculated annual probabilities of an accident at other LNG terminals causing one or more fatalities are given in Table 8.

Confined Spills on Land

Based on a hydrodynamic model developed by SAI, the vapor-dispersion and thermal-radiation effects in the event of a fully diked spill would not produce fatal effects beyond the plant-site boundary and therefore did not contribute to the risk calculation. This analysis assumes that the LNG is confined. A report by the General Accounting Office (GAO)[35] gave special attention to the fact that dikes are not designed to contain an instantaneous spill. The maximum possible spillage from overflow is believed to be 52% for the case of the Cove Point, Md., terminal, assuming an idealized model of an instantaneous tank-wall rupture. An inviscid, nonlinear

Table 7 — Fatality calculation risks for 100% and 25% of the Cove Point population exposed to a burning plume.[40] (Radius from spill, 0 to 5.5 miles.)

Spill Size	*100%*	*25%*
25,000 m^3 (157,000 bbls)	2.4×10^{-9}	7.6×10^{-10}
50,000 m^3 (314,000 bbls)	3.3×10^{-10}	8.8×10^{-11}
Average risk	2.7×10^{-9}	8.5×10^{-10}

Table 8 — Calculated annual probability of an accident at LNG terminals causing one or more fatalities.[42]

Location	*Probability*
Canvey Island, U.K.	2×10^{-3}
Everett, Mass.	2×10^{-5}
Point Conception, Calif.	1×10^{-6}
Matagorda Bay, Tex.	5×10^{-7}

shallow-water theory approach for a two-dimensional case that neglects turbulence, ground resistance, and evaporation predicts that approximately 21,200 cubic meters could overflow the present dikes. Other than GAO, no authority believes that such an instantaneous spill is a credible event. Also, the GAO study estimated that 12,000 cubic meters of LNG was the maximum possible spillage from horizontal spigot flow (i.e., from a puncture in the tank at an optimal height above the ground and in a location close to the dike). Friction effects in the hole, air resistance, and vaporization would reduce the amount of the spill; however, their effects are extremely difficult to quantify and were not included in the model.

SAI compared these fatality estimates to statistical information on death in the United States. For example, it is pointed out that the individual fatality probability from fires and hot substances is one chance in 25,000 per person per year. Also, the probability of electric shock fatalities in residences is one chance in one million per person per year. SAI concluded that these everyday risk levels are considerably higher than those posed by the LNG operations. However, a 1977 study by the California Energy Resources Conservation and Development Commission concluded that "risks from LNG technology cannot be compared to everyday risks because the differences in reliability between these two types of assessment preclude comparability. This is not to say that the risks from LNG technology are greater or less than everyday risks; rather, the uncertainties inherent to the calculation of risks due to LNG technology preclude any valid comparison."[43] Furthermore, it was recommended that risk assessments for LNG terminals be used only for alternative site comparisons.

Risk to a Nuclear Plant

Several studies have examined the potential risk posed by the relative proximity of the LNG transportation route and terminal to the Calvert Cliffs Nuclear Plant.[41,44-46] In particular, the probability that an accidental offshore spill of LNG could result in a flammable cloud reaching the nuclear plant has been addressed. The Cove Point dock is approximately 3.7 miles southeast of the power plant. In general, the probabilistic models use a simple representation of a complex interaction of situation parameters. The low probability of spill is the main contributor to the argument that this scenario is a low-probability event (i.e., a flammable LNG cloud reaching the nuclear plant). Assuming a probability of spill (vessel collision and tank rupture) of less than 1.5×10^{-4} and a relatively wide range of probability variations for risk reduction due to special LNG operations, weather, and nonignition, the annual expected number of occurrences of this potentially hazardous water spill event extending to the nuclear site is less than 1×10^{-6} per year. The effectiveness of Coast Guard procedures, crew training, and ship navigation, communication, and control systems was evaluated by Operations Research, Inc.,[47] who concluded that the collision probability of an LNG ship operating in the Chesapeake Bay is about 8.3% of that of other large commercial vessels operating in similar areas.

If a gas cloud with a flammable concentration (5 to 15%) reaches Calvert Cliffs, the cloud probably would not result in radiological releases in excess of federal guidelines for reactor site criteria (10 CFR 100). It has been concluded that heat loads associated with a burning vapor cloud passing over plant structures would not result in significant or unacceptable damage to the structures.[44-48] Other unlikely scenarios include asphyxiation of plant operators and deflagration inside critical structures. In order for an asphyxiating level to exist inside the control room, a proportionately higher level must exist outside for an extended period of time. A closed-cycle control-room ventilation system can be used to control air-exchange pathways. For a flammable cloud concentration to exist inside plant structures, the outside concentration must be greater than the Lower Flammability Limit and the gas cloud must remain in the vicinity for some time without igniting.

SAFETY MEASURES RELATED TO NAVIGATION OF LNG VESSELS

Navigation is the process for safely directing the movements of a vessel. The LNG vessel is navigated on Chesapeake Bay using the pilotage method, which involves directing the vessel primarily by reference to land and sea marks.[49] It is based on the detailed familiarity of the pilot with the waterway system and traffic. To navigate safely, the pilot must know, for example, his own ship's position in the waterway and its handling characteristics, as well as the position, speed, course, and intentions of other vessels encountered during a voyage.

Aids to Navigation

Aids to navigation are devices external to a vessel, intended to assist the navigator in determining his position, finding a safe course, or warning him of dangers (obstructions to navigation). Satellite navigation systems aboard LNG ships are used for proper position fixing for arrival at the mouth of the Bay. The primary short-range aids are fixed lights, lighted and unlighted buoys, fog signals, day beacons, and radio beacons. These aids appear to be uniformly distributed along the route (Fig. 13). In addition, the Chesapeake Bay is covered by a LORAN system. (This system employs the difference in the time of arrival of coded radio signals to locate a vessel's position.) The position-fixing accuracy represented by the circle within which 50% of the estimated fixes lie, using the ground wave transmission, is on the order of 825 to 1200 feet.

Vessel-to-Vessel Communication

The Vessel Bridge-to-Bridge Radiotelephone Act (passed in 1971) requires that all power-driven vessels

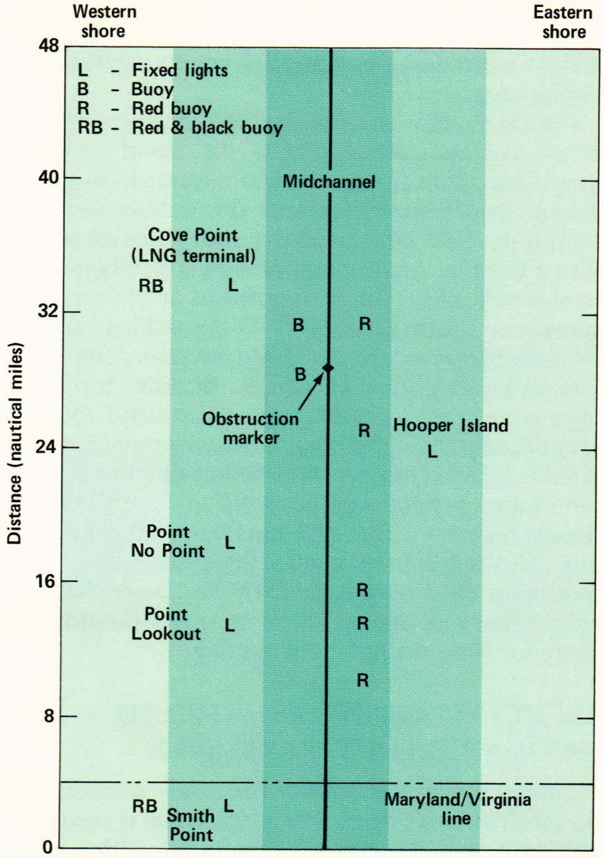

Figure 13 — Schematic representation of major navigation aids in the Chesapeake Bay area for LNG marine transport.

greater than 300 gross tons, all passenger-carrying vessels for hire greater than 100 gross tons, and all towing vessels longer than 26 feet, while navigating, be equipped with a radiotelephone, capable of receiving and transmitting on VHF-FM Channel 13 (156.65 megahertz), that can be operated from the vessel's navigation bridge. The vessel is required to maintain a listening watch on the channel and to reserve its use exclusively for the master (or person in charge of the vessel). The purpose of this special channel is to facilitate the exchange of information between vessels, including intentions and arrangements of safe passings.

The LNG vessels are equipped with multiple radios capable of providing communications on Channel 13. Each pilot also carries a portable transceiver that he uses to monitor Channel 13 and communicate thereon.

It should be noted that the Bridge-to-Bridge Radiotelephone Act does not require vessels to contact one another. The Coast Guard Regulation (Title 33, Code of Federal Regulations Part 26) implementing the Act states that vessels covered by the Act shall "when necessary" transmit and confirm information for safe navigation. In general, the determination of "when necessary" is left to the judgment of the vessel operators. However, special Coast Guard operational procedures for the Chesapeake Bay require that ships intending to pass within one mile of the LNG carrier must communicate their intentions before they approach within three miles.

Even when vessels desire to communicate, the level of radio traffic and the duration of transmissions could impede timely communications. The U.S. Coast Guard has compiled statistics for one day's transmissions at various points in the Chesapeake Bay.[50] The data show that the utilization of Channel 13 during the period when an LNG vessel would be passing through the area of Point Lookout (1000 to 1600 hours) is very low (generally less than 5%). These data, in general, correlate with the low level of vessel traffic that has been reported by observers during the same time. The average length of a transmission was determined to be 2.36 seconds, while 98% are no longer than 10 seconds. A study performed by Operations Research, Inc. (1977) for the U.S. Coast Guard concludes that the bridge-to-bridge radiotelephone does provide an effective decrease in collision rate. Review of a sample of collision reports for FY 71-74 from the casualty record files of the U.S. Coast Guard using a systematic logical model determined that 20% could have been prevented by using the system properly.

Crew Training

Crews receive training both prior to joining the LNG carriers and aboard the vessels.[49] Use is made of the Marine Safety International (MSI) Bridge Simulator. It provides a full-scale ship bridge with standard operating equipment and a full-scale visual presentation of the vessel and its environment. The vessel-handling characteristics are incorporated through ship hydrodynamic models in a digital computer. The MSI visual projection is obtained through a small television camera probe that is magnetically guided in accord with controls from the ship bridge over a scaled model board of selected geographic areas. Models have been constructed for the Chesapeake Bay approach, with emphasis on the Chesapeake Bay Bridge, the tunnel complex at Norfolk, and several narrow channels in the Virginia area of the Bay.

Scenarios include low-visibility navigation, piloting with and without a pilot, docking, and undocking. These scenarios can also incorporate limited meeting and crossing traffic and simulated engine and rudder failures.

Members of the Maryland Pilots Association have indicated that in their opinion the simulator ship hydrodynamic model did not adequately represent the shallow-water ship-handling characteristics (especially low-speed and backing conditions) appropriate for the Chesapeake Bay operations.

Special Operational Procedures and Regulations

The Coast Guard has instituted a number of special procedures and regulations[51] directed at minimizing the risk of a collision for LNG carriers. In order to make masters and pilots aware of the LNG vessel's transit, the time of arrival of the LNG vessel is issued in the local Notice to Mariners. At the Virginia Pilot Station, a Coast Guard representative is put aboard to make safety checks prior to and during the vessel's transit. This is supplemented with a more extensive examination that is required every two years.

The Coast Guard also provides an escort for the LNG vessel up the Bay to act as a mobile traffic system to ensure that the needed communications and safe navigation are carried out by the LNG vessel and other vessels it meets during its transit.

In addition, Coast Guard regulations require that a loaded LNG vessel make the Bay transit during daylight hours only. The LNG vessel must not commence its trip from the Virginia Pilot Station until sunrise and must not start less than eight hours before sunset. Also, the transit cannot take place unless visibility in the Cape Henry area is more than three miles.

Docking cannot take place in sustained winds greater than 35 knots. When the vessel is moored and transferring LNG, operations must be halted if the sustained (i.e., 10 minutes or longer) wind speed is greater than 35 knots. A docked LNG vessel must stop off-loading and get under way when the sustained wind speed exceeds 45 knots.

At the Cove Point terminal, a "safety zone" has been established to minimize the risk of collision between LNG carriers and other vessels while the LNG vessel is maneuvering in the vicinity of, or moored to, the offshore terminal.[52] While the LNG carrier is maneuvering, the safety zone extends parallel to the shore for approximately one-half mile from each end of the pier and extends approximately one-half mile to seaward, perpendicular to the pier face. When the LNG vessel is moored to the pier, a safety zone radius of 200 yards to the seaward is maintained. With no vessels at the terminal, a 50-yard safety zone about the pier is in effect. A special emergency anchorage location for the LNG carriers in the vicinity of the Cove Point terminal is located about two miles south-southeast of the prohibited area off the western shore below the Patuxent Naval Test Center.[53]

Future Systems for Improving Navigation

Vessel Traffic Systems. Traffic monitoring and control is one of the most significant factors in minimizing the possibility of serious collisions and groundings. The Chesapeake Bay has been studied by the Coast Guard, which decided that the cost effectiveness of a shore-based radar surveillance system was not sufficient to warrant installation. The primary reason for its high cost lies in the need for several radar stations to cover the Bay. Because of recent developments that improve the accuracy of the LORAN-C system, it appears conceivable[54] that the surveillance function might be implemented by means of a portable, pilot-carried unit that would determine the LORAN-C coordinates of the ship and transmit them by VHF radio to a shore-based traffic analysis and display station. In addition to the LORAN-C data transmitted by the pilot-carried unit, the device can also send back identification data that would allow the traffic analysis system to identify immediately the vessel associated with the position data. This method reduces the need for voice communication between the vessel and the shore-based system and provides a higher level of confidence in the identification of vessel positions than the radar-based device.

Future Electronic Aids. The LORAN-C navigation system provides position information to vessels. The equipment is generally located in the chart room and not handy for pilotage-type navigation. In addition, current LORAN-C receivers do not provide the accuracy required for coastal and harbor navigation. Peters[55] discussed the development of a new generation of computer-controlled receivers known as the LORAN Navigation Receiving Systems (LONARS). This receiver is excellent at tracking through interference and is capable of providing much-improved accuracy. The expected geodetic accuracy for LONARS as represented by the circle containing 50% of the estimated fixes lies in the 70- to 120-foot range.

Another concept to provide improved ship-to-ship communication is a transponder system. This allows a vessel to identify another ship similarly equipped and receive information regarding its course, speed, and draft, and also question, through codes, its intention. This concept would not require an independent surveillance system but would connect the pilots directly.

CONCLUSIONS

The safety of LNG import and export operations is vitally important to both the public and the owners of the ships and terminal. Indeed, a primary national objective is to develop safety practices for the LNG industry before any accidents are experienced that may affect the surrounding public. The following observations and recommendations are made:

1. U. S. Coast Guard pollution incident (oil and other hazardous materials) data for the Bay indicate that from 1974 to 1977 there was an annual average of 24 spills of greater than 1000 gallons, which represents 5% of the spills in that period. In general, a better perspective on the risk of the transport of LNG as compared to other hazardous materials in the Chesapeake Bay is needed.
2. An evaluation of the risk of a system would in general encompass both its developmental and operational life cycle phases. There now appears to be no formal program by a regulatory body to monitor the performance of officers and crews of LNG vessels and pilots to assure that they are sufficiently safety-conscious over a long period of time.

3. The Calvert Cliffs Nuclear Plant and the Naval Air Station at Patuxent River are examples of facilities sufficiently close to the LNG shipping operations that they could conceivably compound the consequences in the event of a major spill onto water. The probability of a spill (vessel collision and tank rupture) contributes significantly to the overall probability that a flammable cloud might reach the nuclear site.
4. Systems for traffic monitoring that could play a significant role in minimizing the possibility of serious collisions and groundings other than costly shore-based radar systems are feasible. A study of functional requirements for such a system and cost could delineate a potentially attractive option.
5. Research efforts in the area of the physics of vapor dispersion from large LNG releases onto water and the combustion characteristics of incompletely mixed systems could provide a better understanding of LNG risk scenarios.

REFERENCES and NOTES

[1] Assessments of proposed federal actions, i.e., "alternative risks," are an essential part of an environmental impact statement prepared by a federal agency in accordance with the spirit of the National Environmental Policy Act of 1969 (NEPA). The Congressional Office of Technology Assessment was established in 1972 to evaluate the long-term effects of new and existing technologies. Regulation of health risks by the federal government began in 1938 with the creation of the Food and Drug Administration.

[2] A risk assessment is predictive in nature and may be biased by an individual's assessment of present trends and imagined alternative futures. It has been suggested by Starr[27,56] that it may be useful to distinguish between several different kinds of assessments of future risk:

a. *Real risk*, as eventually will be determined by future circumstances when they fully develop;
b. *Statistical risk*, as determined by currently available data, typically as measured actuarially for insurance premium purposes;
c. *Predicted risk*, as analytically predicted from system models structured from historical studies;
d. *Perceived risk*, as intuitively seen by individuals.

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[18] A. D. Swain and H. E. Guttmann, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications,* NUREG/CR-1278 (Oct 1982).

[19] *Conference Record, IEEE Standards Workshop on Human Factors and Nuclear Safety* (Dec 1979).

[20] Risk estimation has provided another platform for stimulating discussions about the meaning of probability and the application of the subjective view of probability. In short, the subjectivist points out that probability should be interpreted as a measure of degree of belief (an old interpretation traceable to Laplace) rather than the more popular "relative frequency" view that is attributed to Von Mises.[57]

[21] "LNG Safety Study, Technical Report No. 16," in *In Support of Point Conception Draft Environmental Impact Report,* Arthur D. Little, Inc. (Feb 1978).

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