LIQUEFIED ENERGY GAS TERMINAL RISK: A COMPARISON AND EVALUATION

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FOREWORD

For some years, IIASA has promoted and udertaken studies of the analytical, institutional, and sociological aspects of the risks associated with new technologies. Since 1979, with the encouragement and generous financial support of the Bundesministerium für Forschung and Technologie of the Federal Republic of Germany, IIASA has made particular studies of the issues associated with siting terminals for the shipping, storage, and processing of liquefied energy gases (LEG). From the beginning, comparative analyses of issues and ways of handling them in different places and under various conditions were judged of capital importance.

Dr. Christoph Mandl, an Austrian operational researcher, and Dr. John Lathrop, an American decision analyst, directed their attention to this aspect of the studies. This report presents their results.

ALEC M. LEE
Former Area Chairman
Management and Technology Area

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SUMMARY

This report has three main goals:

(1) *To present and compare the various risk assessment procedures as they have been applied to liquefied energy gas (LEG) terminal siting, and in so doing to clarify the limits of knowledge and understanding of LEG risks.*

(2) *To quantify and compare the risks estimated in analyses prepared for four LEG terminal sites, namely Eemshaven (Netherlands), Mossmorran–Braefoot Bay (UK), Point Conception (USA), and Wilhelmshaven (FRG).*

(3) *To evaluate the risk assessments undertaken for these four LEG terminal sites and to suggest guidelines on the preparation of a good LEG risk assessment report.*

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1 INTRODUCTION

1.1 Background, Purpose, and Scope

In the last decade a new technology for transporting and storing natural gas has become increasingly accepted: to reduce the temperature of the gas below −162°C, at which point it becomes a liquid at a six-hundredth of its former volume. Liquefied natural gas (LNG) can then be transported by sea from Indonesia, Algeria, and elsewhere to the major markets in the US and Europe at reasonable cost. The LNG can then be stored efficiently in tanks due to its high energy per unit volume.

However, due to the extremely low temperatures required, special ships, transfer terminals, and storage tanks on land are required, all of which are costly, and so are necessarily of considerable size. A typical vessel can contain 125 000 m^3 of LEG, and a transfer terminal up to 60 000 m^3 of gas per day (equivalent to an energy flow of approximately 15 000 MW – the power of about 15 standard nuclear power plants), and storage tanks are planned to contain up to 500 000 m^3. It is therefore not surprising that such a high concentration of LEG in one place has created concern over the potential negative effects, particularly to the environment and to the local population.

This report covers a broader category of terminals than those handling just LNG: one terminal (Mossmorran) is to handle liquefied propane and butane. While LNG is stored at −163°C at very low pressure over ambient, liquefied propane and butane are stored at much higher temperatures and pressures, and thus behave significantly differently when spilled. All three substances involve essentially the same accident scenarios, although with different parameters and probabilities of detonation, so that propane and butane have many of the same risk assessment features and problems as LNG. Since all of these substances are called liquefied energy gases (LEG), the terminals examined in this study will be referred to as LEG terminals.

Many factors are involved in assessing the advantages and disadvantages of an LEG terminal at a specific site, but the risk to the local population is the most crucial question. Because of a lack of historical data on accidents at LEG terminals, however, the frequency of such events and their consequences cannot be readily estimated. Therefore, over the past few years attempts have been made to quantify the local population risk at several planned LEG terminals, using various techniques and models, with different results.

This report reviews the risk assessments undertaken for LEG terminals in four countries, discusses their plausibilities, explains their differences, and compares their risk estimates. Where necessary and appropriate, we describe some of the reports in detail. Because LEG terminal risk assessment is a relatively new technique, there is still disagreement among experts concerning how to quantify risk, which models to use, what factors to include, and what to exclude. A major part of this report therefore evaluates the LEG terminal risk assessments and suggests guidelines for evaluating risk assessments in general.

This report has three main goals:

(1) To present and compare the various risk assessment procedures as they have been applied to LEG terminal siting, and in doing so to clarify the limits of knowledge and understanding of LEG risks.
(2) To quantify and compare the risks at Eemshaven, Mossmorran–Braefoot Bay, Point Conception, and Wilhelmshaven.
(3) To suggest guidelines with which to evaluate LEG terminal risk assessment reports, particularly those for the four terminal sites.

Clearly, no pretense is made that this report provides complete or final answers concerning comparative risks or risk assessments; rather, it describes some initial attempts to address important problems in the field of risk assessment.

1.2 Risk, Probabilities, and Consequences

Before it is possible to quantify risk, we must define it. People mean different things when they talk about risk; therefore our definition (actually a set of definitions) cannot be descriptive, but rather will be prescriptive.

It should be admitted at the outset that risk is a difficult concept to evaluate. Ideally, if one adopts the axioms of rational choice under uncertainty, the evaluation of any decision alternative should consider the probability distribution of the consequences of that alternative, and this may be expressed in several ways (see e.g., Luce and Raiffa 1957). Yet the concept of risk singles out a subset of those consequences for special analysis. The term is typically applied to specific uncertain costs, diverting attention from other costs and uncertain benefits that could be just as important in the evaluation. In the case of LEG, for example, several dimensions are of concern in site selection and facility design, such as land use, environmental quality, air quality benefits of LEG, and dependence on foreign supplies. Some of these involve uncertain costs, such as financial losses to the developer if anything goes wrong (delay in application approval, loss of supply contract, vessel accident); environmental effects due to accidents or even routine disruption; fatalities and injuries due to accidents; property losses due to accidents; and losses to consumers due to supply interruption (e.g., unemployment and health effects). These uncertain costs could be and are referred to as risks, and they can all be analyzed using risk assessment techniques. However, in all the reports reviewed here, the term risk assessment in the context of LEG typically refers only to estimates of fatalities caused by accidents.

One could argue that such a narrow scope reflects a judgment that externalities involving fatalities deserve special attention. However, other effects of LEG could cause loss of lives, such as supply interruption in a severe winter. This narrow scope given to risk assessments is an implicit acknowledgment that special attention should be given to assessing the probability of accidental and/or catastrophic loss of life. We call this particular focus the political perspective of risk, in reference to the fact that realities of the political process of risk management include a special sensitivity to that form of loss of life. It follows that the definition of risk adopted here should be compatible with that focus of attention.

There is an extensive literature that deals with the political perspective of risk (see, e.g., Slovic *et al.* 1980), which identifies particular important dimensions of risk from that perspective. In addition to the possibility of catastrophe itself, the inequity of the burden of risk is important, as is whether or not risk is occupational, and how the risk to an individual compares with other risks commonly experienced. It is beyond the scope of this report to develop a single comprehensive measure of the political perspective of risk, but, in choosing a definition we should be responsive to that perspective and select ones that include these concerns.

The best way to develop a definition of risk is to start by quoting some definitions from the risk assessment literature.

- "Risk is the expected number of fatalities per year resulting from the consequences of an accidental event." (SAI 1976)
- "Risk is the probability of an injurious or destructive event, generated by a hazard, over a specified period of time." (Cremer and Warner 1977)
- Group risk is defined as "the frequency at which certain numbers of acute fatalities are expected from a single accident." The risk to the society as a whole is defined as "the expected total numbers of acute fatalities per year resulting from accidental events in the system." (Battelle 1978)
- "Societal risk – total expected fatalities per year; individual risk – probability of an exposed individual becoming a fatality per year; group risk – probability of an individual in a specific exposed group becoming a fatality per year; risk of multiple fatalities – probability of exceeding specific numbers of fatalities per year." (Keeney *et al.* 1979)

It is of interest to note that these definitions of risk are the only ones used in the risk assessments reviewed. In all other reports not mentioned above, the risk is assessed without ever being explicitly defined. In addition, in SAI (1975) other summary measures are given, including the risk of multiple fatalities, which are not included in the quoted definition. The general assumption of most of the reports seems to be that risk is a multidimensional concept that can be adequately described to a decision maker by various sets of numbers, without an explicit definition.

Although the quoted definitions differ quite substantially, in most cases they agree at least to the extent that risk is related to the probabilities of certain events and their consequences (in terms of number of fatalities). One can identify two polar definitions of risk. One extreme definition (Cremer and Warner) considers only the probabilities of destructive events and does not look at the consequences. Such an approach is only practical as a nonevaluative description of risk, and only makes sense for comparison or evaluation in the very limited case when all destructive events have equal consequences, and risk is defined as the probability that any one of the events would occur in a given time interval. It would be clearly meaningless to label two facilities equally risky if they had equal probabilities of an accident, but if an accident in one facility would have much more serious consequences than one in the other. On the other extreme, risk can be and is sometimes viewed as the worst possible event with the most serious consequences. Again we would argue that focusing on this kind of risk is not meaningful because it omits the probability of an event.

The underlying concept of this report is based on the axioms of rational choice under uncertainty, i.e., that any evaluation of the risk of a decision alternative should depend upon the probability distribution of the consequences of choosing that alternative. While descriptions of political behavior may deviate in important ways from the rational choice paradigm, this report adopts an essentially prescriptive perspective, while remaining sensitive to the political perspective of risk. We do this by adopting definitions of risk that address political perspective concerns, as described by Keeney et al. (1979):

(i) *Risk of multiple fatalities:* the probability of exceeding specific numbers of fatalities per year.
(ii) *Societal risk:* total expected fatalities per year.
(iii) *Group risk:* the probability of an individual in a specific exposed group becoming a fatality per year.
(iv) *Individual risk:* the probability of an exposed individual becoming a fatality per year.

Each of these definitions addresses a different aspect of the political perspective of risk, although they are interrelated (see Section 3.5.1). They can all be derived from the same basic set of data: the annual probability distribution of accidents and the conditional probability that an exposed individual will be killed in an accident. In practice, that data set typically takes the form of conditional probabilities that particular geographic regions are exposed to various physical effects, combined with population density data for each region. The data can be used to calculate the probability distribution of the number of fatalities, which in turn yields the risk of multiple fatalities and the societal risk. The same data can be used to calculate the annual probability that an exposed individual will become a fatality. The sum of those probabilities is the societal risk; the average over all exposed individuals is the individual risk; and the average over each group of individuals, classified by location or occupation (e.g., LEG terminal employees), is the group risk.

Two important aspects of accident risk, injuries and property damage, are not considered separately here because LEG-related accidents are characterized by closely interrelated fatalities, injuries, and property damage. Risk measures based on fatalities can be taken as good relative indicators of all three types of risk, so long as alternatives to LEG have similar ratios between fatalities, injuries, and property damage. We are not saying that this condition holds for the LEG terminals studied here; the information available to us is not adequate to test the validity of such an assumption.

The definition of risk adopted here is by no means an ideal or universal one. Readers from particular disciplines may have other definitions that they find more suitable for their purposes. However, our definition requires estimates of the probability of an event, and its consequences, both of which are discussed in this report. Most readers will be concerned with one or both of these topics, and so will find the report relevant to assessments of risk as he or she defines it.

1.3 LEG Risk Assessments as Decision Aids

It is easy to forget that a risk assessment is not an end unto itself, but is only one element in the complex process of facility siting and design. More importantly, a risk assessment should be an aid for one or more of the decisions that must be made within that process. A knowledge of where risk assessments fit within an LEG siting and design procedure is essential to the understanding of their adequacy and usefulness in the decision process. This procedure is part of a hierarchy of decisions: should LEG be imported to expand the national energy supply and, if so, how much? The sources of natural gas must be then identified: domestic, foreign via pipeline, or foreign via LEG. If it is decided that a new LEG terminal should be built, then the site must be selected, and a detailed design of the facility developed.

There are two features of such a hierarchy of note here. First, population risk is only one dimension of concern; others include cost, land use, environmental quality, dependence on foreign supplies, as well as the risk of supply interruption due to shortage, embargo, accident, earthquake, or bad weather preventing berthing.

The second notable feature of the decision hierarchy is the interdependence of the decisions. While the top-down order presented above may approximate typical chronological order, in fact each decision depends on the outcome of the previous one. For example, the decision to select LEG as a new source of energy depends on cost and risk figures that are dependent on the site and design. In fact, if it were not for that interdependence, the first three decisions would not be relevant to this report. It follows that the decisions are made in an involved order, as tentative decisions based on uncertain estimates filter down the hierarchy and feedback filters back up.

Given the number of decisions involving risk that must be made, it would seem that there are several roles for risk assessment in LEG facility siting and design. Yet most of the processes studied narrowed that role down to a single application: on one dimension, risk to life; and at one level, siting or design (depending on the country). There are several effects of this narrowing. To begin with, it diverts analytical effort and political attention away from those questions not addressed by a risk assessment; for example, supply interruption risk could be a significant factor. In the case of California, supply interruption risk (due to shortage) was the chief argument for initiating the LEG application in the first place, and so was an important consideration.

A second effect of the narrow role given to risk assessment is that the level at which it is applied affects how it is conducted. When a risk assessment is part of the site selection process, as in California, a particular facility design is assumed, and analytical effort concentrates on such aspects as shipping traffic and local population density as site-specific inputs in the calculation of population risk. When a risk assessment is part of the facility design process, the site has already been selected, and the analysis considers the sizes, arrangement, and specifications of components of the facility. In that case technical design variations are considered in terms of incremental risk reductions.

There is a third effect of the narrow role given to risk assessment that is more subtle than those given above, but is perhaps the most important one. Once a site is selected, given the political realities of the situation, the question of the overall acceptability of the risk is more or less settled. If a risk assessment is applied at the design level, it may consider various modifications to reduce the risk in the most cost-effective way. However, given its scope and charter, the assessment is highly unlikely to find that a site cannot be made acceptably safe with current technology and so should be abandoned. On the other hand, if a risk assessment is applied at the site selection level, it would at least be feasible to rule that none of the sites in the current choice set are acceptable. That feasibility arises from the lack of political and economic momentum behind any one site, and from the fact that at least in some cases additional sites could be considered in response to analysis results.

Risk assessment does not exist in a vacuum. It is a decision aid within a much larger process. Any understanding of current methods of assessment, and any suggestions for improvement, also require an understanding of that larger process controlling the role and nature of risk assessment in very basic and important ways.

2 REVIEW OF THE LITERATURE

Before going into quantitative and technical detail, we compare and evaluate in qualitative terms the risk assessments prepared for Eemshaven, Mossmorran–Braefoot Bay, Point Conception, and Wilhelmshaven, with some reference to reports on other sites. We also discuss critical reviews of risk assessments and present their major points of criticism.

2.1 Risk Assessment Reports

In Table 1 we give a comprehensive overview of the most important risk assessment reports available to us. Before discussing various aspects of this table, some comments on the headings might be helpful.

(*a*) *Parts of the system considered.* Not all reports consider all the components of an LEG terminal system, namely vessel, transfer system, and storage tanks. In particular, for Wilhelmshaven there are two reports; one deals only with vessel operation and LNG transfer, and the other deals only with the storage tanks (the latter report cannot be commented on here because it was not available to the authors at the time of writing).

(*b*) *Concept of risk.* As discussed in Section 1.2 there is no unique definition of risk. We have indicated the type of risk analyzed in each report.

(*c*) *Estimation of probabilities of events.* One crucial part of risk assessment is the estimation of probabilities, unless only the consequences are considered. It is therefore necessary to see how this problem has been solved in different reports. Two methods can be used. *Event tree* analysis can identify a logical sequence of events (failures) that could result in unwanted consequences (accidents). Having identified the possible events, *fault tree analysis* helps to identify and determine the probability of a "top-level event" (typically a specific accident) that is the result of a sequence of events (failures). Fault tree analysis evolved in the aerospace industry in the early 1960s and has since become a standard

TABLE 1 Comparison of risk assessment reports.

Issues		TNO	Aberdour	Cremer and Warner	ADL	FERC	SAI
(*a*)	Parts of system considered	Vessel, transfer, storage tank	Vessel	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel	Vessel, transfer, storage tank
(*b*)	Concept of risk	Risk of multiple fatalities and group risk	Group and individual risk	Probability of an injurious or destructive event	Multiple fatalities risk	Societal, group, and individual risk	Risk of multiple fatalities, group & individual risk
	Estimation of:						
(*c*1)	probabilities of events	Yes, quantitative	Yes, quantitative	Only in terms of low, very low, etc.	Yes, quantitative	Yes, quantitative	Yes, quantitative
(*c*2)	event tree analysis used	Yes	No	No	Yes	Yes	Yes
(*c*3)	fault tree analysis used	No	No	No	Yes	No	Yes
(*d*)	Estimation of consequences of events	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, but only physical cons. (eg, spill size); no estimation of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities
(*e*)	Estimation of risk	Societal & individual risk low cf. other man-made risks	Individual risk high cf. other man-made risks	No estimation of expressed fatalities; only of probabilities of events	Yes, quantitative	Yes, quantitative	Yes, quantitative
(*f*)	Final findings	Societal & individual risk low cf. other man-made risks	Individual risk high cf. other man-made risks	"No reason to doubt that installations cannot be built and operated in such a manner as to be acceptable in terms of community safety"	Point Conception suitable with respect to vessel traffic safety. Risk is very low.	Risk comparable to risks from natural events & thus on an acceptable level	"The risk is extremely low"
(*g*)	Uncertainties in final findings	Not mentioned	Not mentioned	Not mentioned	Sensitivity analysis	Disagreement between experts is mentioned	Sensitivity analysis
(*h*)	Single event with highest risk	Grounding of LNG tankers	Not identified	Not identified	Not identified	Not identified	Not identified

TABLE 1 (*continued*).

Issues	Brötz	Krappinger	WSD	Battelle	HSE	Keeney *et al.*	SES
(*a*)	Transfer, storage tank	Vessel	Vessel	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel, transfer, storage tank
(*b*)	Not defined	Not defined	Not defined	Multiple fatalities, societal, and group risk	Multiple fatality and group risk	Multiple fatality, societal, group and individual risk	Multiple fatality risk
(*c*1)	Only in terms of very low	Yes, quantitative	Only in terms of very low	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative
(*c*2)	No	No	No	Yes	Yes	Yes	No
(*c*3)	No	No	No	No	No	No	No
(*d*)	Yes, but only physical cons. (eg, spill size); no estimation of fatalities	No estimation given	Some quantitative statements in terms of few and many fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities
(*e*)	No estimation given	No estimation given	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative
(*f*)	With regard to consequences & their probability there is no danger, cf. relevant laws	No final findings	Risk is not insignificant	Risk about the same as that from the gas distribution network	Risk only acceptable if suggested mitigating measures are undertaken	Risk less than those that the population near terminal is exposed presently	Level of safety cannot be specified accurately
(*g*)	Not mentioned	Not mentioned	Mentioned	Considered, & error bounds given	Not mentioned	Sensitivty analysis conducted to examine effects of variations of 2 parameters	Considered, & error bounds given
(*h*)	Not identified	Not identified	Not identified	Rupture of transfer pipeline with delayed ignition	Not identified	Not identified	Not identified

technique for systems safety analysis. It was also used in the Rasmussen Report (NRC 1975).

(*d*) *Estimation of consequences of events*. The consequences of an event should be stated in terms a decision maker is concerned with. For this reason, and because of the definitions of risk typically assumed, many reports estimate consequences only in terms of the potential number of fatalities a certain event could cause. However, other reports estimate ony the physical consequences (e.g., the size of an LEG spill or the size of a vapor cloud), without relating them to the possible fatalities.

(*e*) *Estimation of risk*. Different estimates of the risk are given, depending on the definition of risk employed; in some cases no estimate is given at all.

(*f*) *Final findings*. As we see it, the ideal result of a risk assessment report is the quantification of the risk (in his case, from LEG) and its comparison with risks from other sources. The ideal, and thus most useful, comparison is between risks from alternatives actually faced in the decision-making process: site A versus site B, site A versus no site, etc. However, decisions concerning the acceptability of the risks from LEG may involve social value trade-offs and perhaps political considerations that go beyond the scope of the risk assessment and the legitimate authority of technical risk analysts. It follows that the final findings of a risk assessment should impart information to enable the decision maker to use them as a basis for a decision, without that decision actually being made for him. If a risk assessment states that a risk is acceptable, then the analysts have made a judgment that they do not have legitimate authority to make, at least in the political systems under study here.

(*g*) *Uncertainties in final findings*. Due to the limited data from LEG accidents there remains substantial uncertainty about the accuracy of the estimates of probabilities and consequences of events. The reports handle this problem in various ways: some ignore uncertainties completely, some give conservative estimates, some perform sensitivity analysis and some give error bounds on the quantified risk.

(*h*) *Single event with highest risk*. If mitigating measures to reduce risk are to be undertaken it is necessary to know which event presents the highest risk, since it is often the case that the highest-risk event offers the most cost-effective opportunities for mitigation.

When comparing risk asessments, however, one should keep in mind that their variations can at least partially be explained by the fact that they were prepared and used as inputs to particular decision processes and therefore each one was developed in a way suited to the particular process it was to serve.

The studies that are essentially different from all the others in Table 1 are Cremer and Warner (1977), Brötz (1978), Krappinger (1978 a,b), and WSD (1978), particularly in terms of the concepts of risk, estimates of consequences, estimates of risk, and final findings. This may be due to the different scientific backgrounds and standards of the analysts, limited resources with which to conduct the analyses, differences in the decision processes at Mossmorran–Braefoot Bay and Wilhelmshaven compared with those at the other sites, or some other reason, but we do not consider these four to be good examples of LEG risk assessments on the basis of the criteria adopted in this study.

2.2 Risk Assessment Reviews

A few publications have already addressed the question of the validity of risk assessment methods. The first major report, often referred to as the Lewis Report (1978), was not concerned with LEG, however, but with the Rasmussen Report on nuclear reactor safety (NRC 1975). The first significant paper specifically reviewing LEG risk assessments was by Fairley (1977), which concerned probability estimates for catastrophic LNG vessel accidents. Schneider (1978) dealt in great detail with specific questions of safety, spill dispersion, and vapor cloud deflagration and detonation. The most recent and most comprehensive review of LNG risk assessments was undertaken by the National Materials Advisory Board of the US Department of Transportation (NMAB 1980). In this section we concentrate on this report because it covers our main points of criticism of the other reports and raises additional questions. The main findings of the NMAB report can be summarized as follows.

(*a*) Many reports seem to focus almost exclusively on low-probability, high-consequence events, and thus tend to underestimate the overall level of risk.

(*b*) Many studies do not consider future patterns of LNG tanker traffic movements (i.e., projected ship sizes and traffic density). Estimates of probabilities of LNG vessel accidents in the vicinity of terminals should take into account the expected changes in traffic patterns over the lifetime of the terminal.

(*c*) Risk-reduction factors are often given too much credit, and estimates of their effectiveness may be arbitrary. Also, these factors are often presented as if they are independent of one another, with the effects of several risk-reduction factors multiplied to give an overall reduction in the accident probability. Such assumptions are not usually adequately justified.

(*d*) Human error is not usually taken into account, and when it is, such events are usually treated as if they are independent, while experience shows that they are not.

(*e*) Confidence limits or error bounds for the probability of LNG spills are rarely given.

(*f*) Differences in the models for predicting LNG vapor cloud sizes lead to large variations in estimates of the consequences.

(*g*) The reports rarely discuss uncertainties in the data or the results; instead, some elements in the analyses are presented as facts so that greater accuracy in the results may be implied than is warranted by the current state of knowledge.

(*h*) In many reports LNG terminal risks are compared with other risks, such as driving and natural hazards, to help to give a feel for the magnitude of the estimate. But such comparisons do not and should not imply that the risks from LNG are acceptable.

(*i*) Whatever flaws LNG risk assessments may have, they are clearly superior to less systematic methods of identifying possible system weaknesses, likely failure modes, and informing decision makers on the topic of risk, which is certainly an important aspect of the whole decision problem.

These nine points can also be taken as a brief introduction to the kind of questions to be discussed here. Although all of these points are certainly very important we feel that some should be looked at in greater detail, which we do in Section 3, and that some additional points should be raised. Taking all factors into account, some general guidelines are then given on how to produce a good risk assessment. The latter two topics are addressed in Sections 4 and 5.

3 ASSESSMENT AND COMPARISON OF LEG TERMINAL RISK

In this section we discuss the probabilities and consequences of different events (failures), following the reports by SAI (1976) and Battelle (1978). After a technical description of the four LEG terminals we divide the rest of this section into three parts. First we consider the estimation of probabilities of events, then estimates of spill sizes, speed, and vapor cloud dispersion as a result of failures, and finally we consider the consequences to the local population by quantifying the overall risk as a result of first two parts, population density, and a few other factors. We compare the results given in the risk assessment reports and discuss their differences in terms of the underlying assumptions of the models used and their plausibility.

However, as we showed in Section 2.1, not all reports are easily comparable, since some do not consider all the events we discuss. Additionally, other reports do not quantify either the probabilities or the consequences of events. This section therefore cannot provide a complete comparison of all events; rather, we want to give some insight into the risk at all the terminals, to show how one should go about preparing a risk assessment, and to identify the open questions in this context.

3.1 Description of the LEG Terminal Systems

In Table 2 we give a brief description of the planned terminals at Eemshaven, Mossmorran–Braefoot Bay, Point Conception, and Wilhelmshaven. Mossmorran is different from the other terminals in that not only is it an export terminal, but the exported gases are LPG (liquefied petroleum gases – mainly propane and butane), while LNG consists mostly (approximately 90%) of methane. As far as one can tell from the available risk studies, the layouts of the four terminals, the LEG tankers (except in size), the storage tanks, and the transfer systems are very much the same.

On a relative scale one would expect that risk will increase with the size of the terminal, and also with the number of people living (or working) within a certain distance. As far as size is concerned, the Point Conception and Wilhelmshaven terminals are larger than the other two, and Wilhelmshaven has the largest total storage capacity, although Eemshaven has the largest individual tanks. Population density is particularly low at Point Conception.

For all sites except Point Conception the LEG tankers have to travel through busy shipping channels close to populated areas. The tanker route to Eemshaven, for example, is only 1.5 km away from the island of Borkum, and tankers en route to Wilhelmshaven pass within 3.5 km of the town of Wangerooge. As shown in Table 2, gases handled at Mossmorran–Braefoot Bay are different from those handled at the three other terminals, so the consequences of accidents will differ, even for the same spill sizes. Some properties of these gases are listed in Table 3. At first, Point Conception appears to be the least risky terminal site because of low population density, but this might be offset by the fact that the terminal will handle the largest amount of gas. The Wilhelmshaven terminal, which is comparable to Point Conception, presents a higher risk because of its higher population density, but the extent of the difference can only be quantified through detailed analysis.

3.2 Events: Probabilities of LEG Spills

One of the most difficult questions in assessing risk is the identification of possible events (failures) and the estimation of their frequencies or probabilities. By definition it is nearly impossible to get enough historical data to estimate the probability of a low-probability event. Rather, one has to build models and rely on data from other, presumably similar, systems. Another difficulty is the identification of events that have never occurred that could have serious consequences; it is certainly impossible to conceive of all possible events, as one can easily demonstrate when looking at the introduction of new technologies, such as airplanes. This problem was acknowledged in the Lewis Report on nuclear safety (NRC 1978):

> It is conceptually impossible to be complete in a mathematical sense in the construction of event-trees and fault-trees; what matters is the approach to completeness and the ability to demonstrate with reasonable assurance that only small contributions are omitted. This inherent limitation means that any calculation using this methodology is always subject to revision and to doubt as to its completeness.

TABLE 2 Descriptions of the four terminals and the sites.

	Eemshaven	Mossmorran–Braefoot Bay	Point Conception	Wilhelmshaven
Type of terminal	Import	Export	Import	Import
Type of transferred material	LNG	Propane/butane (liquefied) and gasoline	LNG	LNG consisting of 90% methane, 5% ethane, propane, and butane
Average transfer per day (in m^3 liquefied, or MW)	18 500 m^3 $\simeq$ 4 900 MW	13 400 m^3	Initial: 58 500 m^3 $\simeq$ 15 500 MW current plan: 41 000 m^3 $\simeq$ 10 900 MW	56 500 m^3 15 000 MW
Maximum capacity of ships	125 000 m^3	60 000 m^3 propane/butane 10 000 m^3 gasoline	130 000 m^3	125 000 m^3
Number of ships per year	54	80 for propane/butane 9 for gasoline	190	170 ships of 125 000 m^3 264 ships of 10 000 m^3
Number and capacity of storage tanks	2 X 120 000 m^3	4 X 60 000 m^3 propane/butane 2 X 31 000 m^3 gasoline	2, later 3, of 77 500 m^3 each	6 X 80 000 m^3
Number of people living within 2 km of terminal	60 (12/km^2)	approx. 350 (50/km^2)	projection for 1990: 14 (2.2/km^2)	0, but recreational area within distance
Number of people living within 5 km of terminal	858 (28.9/km^2)	approx. 8000 (200/km^2)	projection for 1990: 98 (2.5/km^2)	5900 (151/km^2)
Number of people living within 10 km of terminal	9800 (85/km^2)	approx. 100 000 (470/km^2)	data from 1977: 129 (0.9/km^2)	43 000 (275/km^2)

TABLE 3 Some properties of liquefied energy gases.

	Methane	Ethane	Propane	Butane
Boiling point (°C)	−163	−88	−42	−1
Specific gravity at at boiling point	0.466	0.546	0.585	0.601
Vapor density at 0° (air=1)	0.555	1.04	1.56	2.04
Auto-ignition temperature (°C)	540	510	466	430
Flammable limits (concentration in air)	5–15%	3–13%	2.2–9.5%	1.8–8.4%
Gas-to-liquid volume ratio (gas at 0°, liquid at boiling point)	650	410	290	230
Energy content of 1 m^3 liquid at boiling point	6444			

We therefore do not and cannot claim that the events considered here are a complete set of all possible events. However, this set includes all events that were accounted for in the risk assessment literature, e.g., TNO (1978), SAI (1976), ADL (1978), and Battelle (1978). We subdivide events into three groups: vessel accidents, transfer system failures, and events leading to storage tank ruptures.

3.2.1 Vessel accidents

Basically, two types of model are used to estimate accident probabilities, as described by Philipson (1978). First, one must differentiate between the probability of an accident, and the probability of an LEG spill once an accident has occurred. To establish probability estimates of accidents two methods are used in the literature:

(i) *Statistical inference*. Estimates are computed using historical data, first for a particular class of ships, such as oil tankers, and then the estimates are modified to account for the anticipated differences in LEG tankers and their operations at a specific harbor. This is done, for example, by employing judgment and by assessing the proportion of past accidents that would not have occurred if various mitigating measures had been taken. Examples of this type of analysis are given in Ligthart (1980) and FERC (1978).

(ii) *Kinematic modeling*. In SAI (1976) ship collisions are analyzed by assuming ship motions to be random in a zone of interest in the short interval of time preceding an accident. A kinematic model provides the expected number of collisions per year for a harbor with specific

TABLE 4 Estimates of the probabilities of various events.

		TNO	Aberdour	ADL	FERC	SAI	Brötz	Krappinger
(1)	Probability of collision that could lead to a spill per ship approaching the LEG terminal	2.8×10^{-5}		See (14)	5×10^{-4}	1.3×10^{-8}	–	4×10^{-5}
(2)	Probability of grounding that could lead to a spill per ship approaching the LEG terminal	2.5×10^{-4}	1.5×10^{-5} includes (2) and (3)		4×10^{-4}	0	–	7×10^{-5}
(3)	Probability of ramming that could lead to a spill per ship approaching the LEG terminal	–			3×10^{-4}	0	–	3×10^{-7}
(4)	Probability of missile or airplane crash causing one spill per year	–	–		–	4×10^{-7}	8.3×10^{-5}	–
(5)	Probability per year of a meteorite falling on a specific area of 1 m^2	–	–		–	3.3×10^{-13}	–	–
(6)	Probability of internal system failure	–	3.2×10^{-3}		–	1.0×10^{-11}	–	–
(7)	Number of ships per year	54	80	190	190	190	432	432
(8)	Maximum deck size of ship (m^2)	12 000	6600	12 000	12 000	12 000	12 000	12 000
(9)	Length of stay of loaded ship in the vicinity of the terminal (years)	–	–	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}
(10)	Maximum size of one tank (m^3)	25 000	12 000	25 000	25 000	25 000	25 000	25 000

(11)	Probability of different spill sizes given (1)							
	0 ≤ 1 000 m³	0	0	See (14)	0.02	0	–	0.05 spill size not defined
	1 000 ≤ 10 000 m³	0	0		0.026	0		
	10 000 ≤ 25 000 m³	0.56	0.25		2.3×10^{-2}	0.22		
	25 000 ≤ 50 000 m³	0.44	0		0	0.025		
	50 000 ≤ 75 000 m³	0	0		0	0		
(12)	Probability of different spill sizes given (2)							
	0 ≤ 1 000 m³	0	–		0.0024	–	–	0.009 spill size not defined
	1 000 ≤ 10 000 m³	0.33	–		0.0057	–		
	10 000 ≤ 25 000 m³	0	–		3.9×10^{-3}	–		
	25 000 ≤ 50 000 m³	0	–		0	–		
	50 000 ≤ 75 000 m³	0	–		0	–		
(13)	Probability of different spill sizes given (3)							
	0 ≤ 1 000 m³	–	–	See (14)	0.0034	–	–	0.1 spill size not defined
	1 000 ≤ 10 000 m³	–	–		0.0065	–		
	10 000 ≤ 25 000 m³	–	–		0	–		
	25 000 ≤ 50 000 m³	–	–		0	–		
	50 000 ≤ 75 000 m³	–	–		0	–		
(14)	Total probability of different spill sizes per year[a]							
	0 ≤ 1 000 m³	0	0	0	2.3×10^{-3}	0	–	3.8×10^{-3} spill size not defined
	1 000 ≤ 10 000 m³	4.5×10^{-3}	1.1×10^{-3}	0	3.3×10^{-3}	0		
	10 000 ≤ 25 000 m³	8×10^{-4}	0	7.4×10^{-5}	2.5×10^{-3}	8.9×10^{-7}		
	25 000 ≤ 50 000 m³	7×10^{-4}	0	3.2×10^{-6}	0	9.9×10^{-8}		
	50 000 ≤ 75 000 m³	0	0	6.5×10^{-9}	0	0		

[a] = [(1) (11) + (2) (12) + (3) (13) + (5) (8) (9)] (7) + (4) + (6).

configurations and traffic characteristics. A calibration to the actual average conditions of a number of harbors is then made by scaling the model to fit actual past collision frequencies.

In a similar manner the probability of a spill following an accident is either estimated from data from other, but similar tankers or computed using a model by taking the physical characteristics of the ship and the tanks into consideration. Considering specifically the statistical approach, the estimates are criticized by Fairley (1979), who claims that due to remaining uncertainties the actual probability may be substantially higher. The types of accidents estimated by the above methods are collisions, grounding, and ramming, but three other types of accidents also have to be considered: airplane crash, meteorites, and internal system failure. The estimation of all the probabilities due to the six different types of events are given in Table 4. We now discuss how the different reports derived their estimates:

(1) *Collisions, grounding and ramming*. Only SAI uses a kinematic model, calibrated from historical statistics, while in all the other reports, statistical inference alone is used. In NMAB (1980) the work of Ligthart (1980) and Reese (1978) is described as outstanding compared with other reports. TNO (1978) relies on Ligthart, and ADL relies on Reese. The work of Krappinger (1978 a,b,c) relies strongly on TNO. One can certainly not expect the probabilities of (1), (2), and (3) of Table 4 to be the same for all sites, but the difference between FERC (1978) and SAI (1976) is certainly hard to understand. Unfortunately, Cremer and Warner (1977) give no estimates at all on the topics listed in Table 4, and, we therefore excluded this report. The only other report, Aberdour (1979), takes its estimate directly from HSE (1978), which was confirmed by Marshall *et al.* (1979) who reviewed the report.

(2) *Other failures*. Only Aberdour, ADL, SAI, and Brötz consider other events; the estimates of (4) and (5) are based on historical data. Only Aberdour, ADL, and SAI consider internal system failure; Aberdour, (using data from HSE) attribute their internal system failure rate to fire/explosion while the LEG vessel is berthed, although the causes are not clear. System failures in the other reports are due to metallurgical failure.

The estimates in Table 4 were not always taken directly from the reports; in some cases they were adjusted to take additional data into account. For example, SAI used more ships with larger tanks than those currently planned, so the probabilities and spill sizes were reduced accordingly. FERC only considered total spills of one tank (25 000 m^3), although it did provide the data for smaller spill sizes as well, and this was added in Table 4. The three Krappinger reports (1978a,b,c) reported a variety of results using different accident reduction factors, ranging from 1.0 to 0.05. Because the latter factor was not based on any stated reasoning, we used the factor 1.0, as used in Krappinger (1978a).

Findings

The most interesting findings from this comparison of assessments are:

(a) Compared with the probability of collision, grounding and ramming, other events are considered to be unlikely (except for internal failure in the Aberdour report).

(b) The differences in spill probabilities between the three reports for Point Conception are substantial (between 10^{-3} and 10^{-6} for 10000–25000 m^3 spills).

(c) Although tanker traffic patterns at Eemshaven, Braefoot Bay, and Wilhelmshaven are quite different, they all have a total probability of the order 10^{-3}. The spill sizes at Eemshaven and Braefoot Bay differ, and are not even defined for Wilhelmshaven.

3.2.2 Transfer system failure

This type of failure is generally not considered to be critical (compared with vessel accidents and storage tank failure) because the resulting risk is relatively low, so that it is not considered in many reports. Possible events that could lead to transfer system failure are: meteorites, earthquakes, ramming, airplane crashes, and other types of internal system failure. The overall probabilities for different spill sizes are given in Table 5. Because the consequences of an LEG transfer system are no worse than those following a vessel accident (for the same spill size), it is obvious that such an event would not add significantly to the overall risk.

TABLE 5 Estimates of LEG transfer system failure; probability of a spill per year.

Spill size (m^3)	TNO (1978)	Cremer and Warner	SAI	Brötz
0≤30	0	Low	1.6×10^{-3}	Very low
30≤280	0	0	No spill	Very low
280≤460	10^{-4}	0	Size given, but small	0

3.2.3 Storage tank rupture

Finally, we consider the event that could create a very large spill: a storage tank rupture. In the literature, it is assumed that one of the following events could cause a rupture: severe winds, airplane or missile crash, meteorites, earthquakes, internal system failure, and accidents at chemical plants nearby. In Table 6 we list the estimates of the probabilities of such events for the four terminals.

The estimate of TNO (1978) is based on historical data from an LNG peakshaving plant in Rotterdam harbor. Cremer and Warner qualify the probability as "remote", without reference to how this was derived. ADL and SAI derive their estimates from data on weather conditions, earthquake frequencies, and frequencies of airplane crashes in the US. The probabilities for internal system (metallurgical) failure were derived from technical analyses of the metals used and temperature variations that could cause metal fatigue or stress. Using data from the FRG, Brötz estimates the probability of an airplane hitting one of the six tanks at Wilhelmshaven, although no spill sizes are given. But after an airplane crash into a storage tank, complete rupture of this tank can be assumed as a conservative estimate. Only SAI considers the probability of more than one tank rupturing at a time due to a common cause, and the maximum credible spill is considered as a simultaneous rupture of all three storage tanks at Point Conception, each of which will contain 77 500 m^3. SAI adjust their probabilities because the tanks are expected to be empty approximately 40% of the time.

TABLE 6 Estimates of storage tank failure and probabilities of spills of different sizes caused by various events.

Spill sizes (m^3)	TNO	Cremer and Warner	ADL	SAI	Brötz
(1) Due to storms					
0 ≤ 80 000	–	–	$\sim 10^{-6}$	0	–
80 000 ≤ 100 000	–	–	–	0	–
100 000 ≤ 150 000	–	–	–	0	–
(2) Due to airplane crashes, missiles, or meteorites					
0 ≤ 80 000	–	–	$\sim 10^{-5}$	3.6×10^{-7}	5×10^{-5}
80 000 ≤ 100 000	–	–	–	0	–
100 000 ≤ 150 000	–	–	–	0	–
(3) Due to earthquakes					
0 ≤ 80 000	–	–	$\sim 10^{-6}$	5.2×10^{-6}	–
80 000 ≤ 100 000	–	–	–	0	–
100 000 ≤ 150 000	–	–	–	4.7×10^{-6}	–
150 000 ≤ 230 000	–	–	–	3.8×10^{-6}	–
(4) Due to nearby chemical plants					
0 ≤ 80 000	–	very unlikely, and no spill size given	0	0	–
80 000 ≤ 100 000	–		0	0	–
100 000 ≤ 150 000	–		0	0	–
(5) Due to internal system failure					
0 ≤ 80 000	–	–	$\sim 10^{-5}$	2.4×10^{-6}	0
80 000 ≤ 100 000	–	–	–	0	0
100 000 ≤ 150 000	–	–	–	0	0
(6) Overall probability per year					
0 ≤ 9 000	0	"remote"	0	0	5×10^{-5}
9 000 ≤ 80 000	0	0	$\sim 10^{-5}$	8×10^{-6}	
80 000 ≤ 100 000	0	0	–	0	0
100 000 ≤ 150 000	2×10^{-5}	0	–	4.7×10^{-6}	0
150 000 ≤ 230 000	0	0	–	3.8×10^{-6}	0

All LEG storage tanks are built within containment basins that can hold all the contents (in liquefied form) of the tanks. All credible failure scenarios assume that these basins will not break and therefore that all spills will be held.

Findings

(1) The probabilities of a storage tank rupture at all sites (except Mossmorran–Braefoot Bay and possibly Wilhelmshaven, where not all reports are available), are estimated to be of the order of 10^{-5} per year.
(2) A conservative estimate of spill size is generally assumed to be at least the complete contents of one storage tank. However, Cremer and Warner assume that only 15% of the contents of one storage tank will be spilled.
(3) TNO (1978), ADL, and SAI implicitly or explicitly consider the events described in Table 6. In Cremer and Warner it is not clear what type of failures were considered.
(4) There are no major differences in the estimates, except for (2) between ADL and SAI. The reason for this difference is due to changes in missile launch plans at the nearby Vandenburg Air Force base between the times the two reports were written (Elisabeth Drake, ADL, personal communication, 1981).
(5) Common-cause failures that could result in the rupturing of more than one tank are only considered by SAI.

3.3 Physical Consequences of LEG Spills

3.3.1 General remarks

We have so far discussed the probabilities of spills resulting from failures of parts of an LEG system, but before we can quantify the number of fatalities such spills can cause, we have to consider the properties of spilled LEG and how it behaves. Only ignition and consequent burning or detonation of spilled LEG can produce fatalities caused by thermal radiation effects. If rapid burning occurs, explosive blast effects are also possible, but this is more likely with LPG (ethane, propane, butane) than LNG. LEG will immediately start to vaporize after a spill, resulting in a vapor cloud, which, if not ignited, will travel downwind and disperse. All parts of the cloud will eventually reach the lower flammability limit of concentration, below which ignition cannot occur. To estimate ignition probability it is therefore necessary to estimate the size of the vapor cloud, and the downwind travel distance of the part of the cloud that retains a concentration above its lower flammability limit. We first discuss the size of the vapor cloud, which depends on the spill size, on meteorological conditions, and on whether the spill is on land or on water. We then discuss ignition probability estimates for different sites and for different events.

3.3.2 LEG vapor clouds

Among all topics of LEG risk assessment the question of how LEG behaves after a spill has attracted the most scientific interest. So far, empirical studies provide data only for LNG spills of up to 50 m^3 on land, and up to 200 m^3 on water. The prediction of the behavior of large spills has therefore had to rely on theoretical models, which are not easy to validate. Predictions differ for large spills, but they have produced good estimates of observed spills.

Given the amount of effort made in this still very active research area, we do not intend to present a complete review of existing models; rather, we discuss some of the conclusions of reports that have already reviewed the models, present the predictions used in those reports, and try to give some idea of what seem to be plausible predictions.

Spills on Water. Immediately after a spill, LEG starts to vaporize. The first questions are how long it will take until all the LEG has vaporized and how large the vapor cloud will be at that time. There are two types of models on these questions: one assumes an instantaneous release of LEG (so-called puff models) and the other assumes a steady release over a period of time (so-called plume models). Puff models predict a cylindrical vapor cloud with a radius equal to that of the LEG pool. For different LNG spill and pool sizes, vaporization times and vapor cloud sizes immediately after all the liquid has vaporized are given in Table 7 (Havens 1977, FERC 1978).

Meteorological data are not important in the prediction of vaporization, but atmospheric stability and wind speed are important in determining vapor cloud behaviour. The relation of atmospheric stability to weather conditions is shown in Table 8. Havens (1980) predicted the maximum downwind travel distance of a vapor cloud (above its lower flammability limit) using different models, as shown in Table 9. Although the differences the models in this table appear to be great, one should remember that they were made for various levels of atmospheric stability.

Also, as pointed out in ADL, these predictions are only valid for spills on water, because specific landscapes can have different effects on vapor cloud dispersion. Havens (1980) considered that the Germeles–Drake and SAI models were the most plausible. ADL used the Germeles–Drake model, Aberdour used the Feldbauer *et al.* model, while other reports used other models not listed in Tables 7 or 9.

The downwind travel distances of vapor clouds predicted in the various reports are listed in Table 10. Although the predictions depend on spill size, atmospheric stability, and wind speed, not all reports give travel distances for all combinations of these three parameters. It should also be noted that these predictions are again valid primarily over water, which does not influence cloud dispersion in a specific way. Dispersion is likely to be faster over rough terrain than over water, except in the case of LPG vapor clouds, which could accumulate in low-lying areas due to their high density.

In discussing Table 10 one has to bear in mind that the Aberdour report considers LPG, which has a lower flammability limit of approximately 2% in air, in contrast to 5% for LNG. Because this report takes all its information from HSE (1978), which uses the Feldbauer *et al.* model, the greater distances

TABLE 7 Prediction of initial LNG vapor cloud size following different spill sizes on water.
Column headings:
(*a*) Pool radius (m)
(*b*) Vaporization time (min)
(*c*) Vapor cloud radius (m)
(*d*) Vapor cloud height (m)

Model	4 000 m^3 spill				10 000 m^3 spill				25 000 m^3 spill				100 000 m^3 spill			
	(*a*)	(*b*)	(*c*)	(*d*)	(*a*)	(*b*)	(*c*)	(*d*)	(*a*)	(*b*)	(*c*)	(*d*)	(*a*)	(*b*)	(*c*)	(*d*)
Puff models																
A1 Fay/Kalelkar (used by Germeles–Drake)	189	2.8	189	9	267	3.6	267	11	377	4.5	377	13	633	6.3	633	19
A2 Fay	197	2.9	197	8	288	3.9	288	9	425	5.3	425	10	753	8.4	753	14
A3 Hoult	189	2.5	189	9	267	3.2	267	11	372	4.0	372	13	630	5.7	630	19
A4 Ottermann	195	4.0	195	8	274	5.0	274	10	387	6.4	387	12	651	8.9	651	18
A5 Muscari	232	3.4	232	6	328	4.3	328	7	462	5.4	462	9	777	7.6	777	13
Plume models																
B1 Burgess *et al.*	–	–	–	–	–	–	–	–	540	11.9	–	–	–	–	–	–
B2 Feldbauer *et al.*	–	–	–	–	–	–	–	–	610	15.0	–	–	–	–	–	–
B3 FPC	–	–	–	–	–	–	–	–	377	4.5	–	–	–	–	–	–

TABLE 8 Relation of atmospheric stability to weather conditions.

Surface wind speed (km/h)	Daytime insolation: Strong	Moderate	Slight	Night-time conditions: Thin overcast or ≥ 4/8 cloudiness [a]	≤ 3/8 cloudiness
<7.2	A	A–B	B		
7.2	A–B	B	C	E	F
14.4	B	B–C	C	D	E
21.6	C	C–D	D	D	D
>21.6	C	D	D	D	D

A, extremely unstable conditions
B, moderately unstable conditions
C, slightly unstable conditions
D, neutral conditions applicable to heavy overcast; day or night.
E, slightly stable conditions
F, moderately stable conditions

[a] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

TABLE 9 Maximum downwind distance of a flammable vapor cloud following a 25 000 m^3 spill of LNG onto water, given wind speed of 8 km/h.

Model	Atmospheric stability	Distance from spill (km)
Germeles–Drake (Cabot Corporation and ADL)	Stable (F)	18.5
Chris (US Coast Guard)	Stable (F)	26.2
Fay	Very stable	28.0
Burgess *et al.* (US Bureau of Mines)	Stable	40.6–80.9[a]
Feldbauer *et al.* (American Petroleum Institute)	Slightly unstable (C)	8.4
FPC	Neutral (D)	1.2
SAI	Neutral (D)	2.3

[a] Range presented to indicate vaporization uncertainty.

are not surprising. Atmospheric stability level E, in combination with a wind speed of 8 km/h is used in Aberdour because that is claimed to be the worst case. The Cremer and Warner report is not considered here because it does not consider cloud behavior.

Excluding the Aberdour report, the differences between studies are substantial. While SAI and Brötz predict relatively short travel distances, ADL and FERC predict comparable large distances. It is also worth noting that the distance increases with decreasing wind speed in FERC, while for SAI the distance decreases with decreasing wind speed. Also, the data in Table 10 do not seem to be completely consistent with those of Table 9 (taken from Havens 1980) – a point we cannot explain.

TABLE 10 Maximum downwind travel distance of a flammable vapor cloud following an instantaneous LEG spill onto water.

Report	LEG spill size (m^3)	Atmospheric stability[a]	Wind speed (km/h)	Downwind travel distance (km)
Aberdour	800	E	8.0	4.7
ADL	1 000	A	25.0	0.4
		D	21.0	2
		E	19.8	3
		F	10.8	5
Aberdour	20000	E	8.0	19
Brötz	20000	A–F	All wind speeds	2.3
		During night only	All wind speeds	3.5
TNO (1978)	25000	D	–	3.3
		E,F	–	10.0
ADL	25000	A	25.0	1.0
		D	21.0	7.0
		E	19.8	10.0
		F	10.8	20.0
FERC	30000	A	25.0	0.5
			16.0	0.5
			9.0	0.6
		D	25.0	4.2
			16.0	4.9
			9.0	5.9
		E	25.0	7.8
			16.0	9.2
			9.0	11.3
		F	25.0	18.1
			16.0	21.6
			9.0	27.1
SAI	37500	A,D,F	54.0	6.0
		A,D,F	25.0	3.5
		A,D,F	11	2.0
		A,D,F	0	1.0
ADL	50000	A	25.0	1.0
		D	21.0	9.0
		E	19.8	15.0
		F	10.8	25.0
Aberdour	64 000	E	8.0	32.0
SAI	88000	A,D,F	11.0	2.5
ADL	125000	A	25.0	1.5
		D	21.0	11.0
		E	19.8	20.0
		F	10.8	35.0

[a] Atmospheric stability: ranging from A, extremely unstable (rough) to F, moderately stable (calm).

Because the models of TNO (1978), FERC, Aberdour, and Brötz were not reviewed, we cannot make a statement on their validity. Havens (1979) compared the models of ADL and SAI, and concluded that their predictions show agreement within the uncertainty ranges. In other words, given the present state of knowledge both models could be acceptable.

Spills on land. Although possibly larger in size, spills on land are generally considered less dangerous than spills on water because the storage tanks are surrounded by dikes, which are generally not expected to rupture. The second reason is that the vaporization rate of LEG on land is slower than that on water. This vaporization rate can be described by (see NMAB 1980):

$$\frac{\text{vaporization rate}}{\text{area of substrate contacting LEG}} = \frac{F}{\sqrt{t}} ,$$

where t is the time after the spill and F is a parameter characteristic of the substrate contacting the LEG. Only TNO (1978), ADL, and SAI consider vapor cloud behavior after a spill on land, as shown in Table 11. Again the differences between ADL and SAI are substantial.

TABLE 11 Downwind travel distance of a flammable vapor cloud following an instantaneous LNG spill on land.

Report	LNG spill size (m^3)	Atmospheric stability[a]	Wind speed (km/h)	Downwind travel distance (km)
TNO(1978)	150 000	–	–	–
	Only 330 m^3 will evaporate during first 10 minutes after spill, slowing down after this time			
ADL	87 500	A	25.0	0.5
		D	21.0	2.7
		E	19.8	4.6
		F	10.8	15.0
SAI	88 000	A,D,F	25.0	0.6
			10.8	0.6
			0	0.4
	352 000	A,D,F	54.0	1.5
			25.0	1.4
			10.8	1.1
			0	0.6

[a] Atmospheric stability: ranging from A, extremely unstable (rough) to F, moderately stable (calm).

The low vaporization rate given in TNO (1978) is due to the fact that the surrounding dikes are only a small distance (some meters) from the outer wall of the tank. The NMAB report therefore recommends further research to investigate the consequences of a large spill if the dikes are some distance from the tanks, and to compare that of high, close-in dikes. Point Conception and Wilhelmshaven were planned to have low dikes, while plans for Eemshaven and Mossmorran are for high, close-in dikes.

Findings

(1) The reports indicate that there is substantial uncertainty in the maximum downwind travel distance reached by the flammable region of an unignited vapor cloud.

(2) Although Table 9 indicates that some models predict greater travel distances than the Germeles–Drake model, Havens (1979, 1980) suggests that the Germeles–Drake model is one of the most plausible and is therefore reasonably conservative. However, this should not exclude the possibility that downwind travel distances could be greater than those predicted.

3.3.3 Ignition of LEG vapor clouds

Although the LEG vapor is not toxic it can have some effects on humans even if not ignited, including skin irritation (because the vapor is very cold) and suffocation problems (if the concentration of the vapor is high there might not be enough air for breathing). However, compared with the hazards of an ignited vapor cloud these are negligible.

Ignition probability is composed of two parts:

(i) Immediate ignition by the event that caused the spill. As can be seen from Table 12, the probability of immediate ignition, depending on the event, is generally high since an event that can cause a tank to rupture is also likely to create enough frictional heat to ignite the resulting vapor cloud. The probabilities of immediate ignition given in Table 12 are derived from expert judgment, even though the expertise required for this particular task is difficult to characterize.

(ii) Delayed ignition due to some other means. This obviously depends on the presence of ignition sources within the flammable bounds of the cloud, and will in general have far more serious consequences because a vapor cloud increases in size as it travels downwind. In this respect the estimates of TNO (1978) and Aberdour are more conservative than the others; certainly, the immediate ignition probability can be site-dependent. For example, Keeney *et al.* (1979) point out that estimates of immediate ignition probability are high at the specific site studied because collisions would involve large vessels carrying flammable cargoes such as chlorine.

Because data on LEG spills are limited, estimated ignition probabilities can hardly be validated. The reports not listed in Table 12 do not state the ignition probabilities. Neither Cremer and Warner nor Brötz mention ignition probability at all, while ADL does, but does not state the assumptions used.

The same model for delayed ignition probability is used by FERC, SAI, Battelle, and Keeney *et al.* (1979), who assume that each source of ignition has the same probability p of igniting the vapor cloud. Thus the probability

TABLE 12 Probabilities of immediate ignition following different events.

	TNO (1978)	Aberdour	FERC	SAI	Battelle	Keeney *et al.*
Vessel tank rupture caused by:						
collision	0.65	0.66	0.9	0.9	0.8	0.9–0.99
grounding	0.1	–	0.0	–	0.3	–
ramming	–	–	0.9	–	–	–
missile/airplane	–	–	–	0.9	0.9	–
meteorite	–	–	–	0.0	–	–
internal failure	–	0.9	–	0.0	–	–
transfer system failure	0.25	–	–	0.03	–	–
Storage tank rupture caused by:						
storm/waves		–	–	–	–	–
airplane/missile/ meteorites	0.0	–	–	0.89	0.9	–
earthquake		–	–	0.0	–	–
nearby chemical plant		–	–	–	–	–
internal failure		–	–	0.0	–	–

P_n that the vapor cloud will have been ignited within n sources becomes $P_n = 1-(1-p)^n$. Additionally, all the reports using this model (except FERC), assume that all individuals are sources of ignition because they will use facilities (e.g., car, oven, light) that could be direct causes of ignition. FERC assumes that each residence is a source of ignition; however, assuming an average of four persons per residence, then the FERC estimates are comparable with other reports, as shown in Table 13.

TABLE 13 Ignition probabilities per source in case of delayed ignition.

	FERC	SAI	Battelle	Keeney *et al.*
Probability p that each person within a vapour cloud ignites the cloud	0.01	0.1	0.01	0.01–0.1

We present P_n for different p and n in Table 14; estimates of p can be either conservative or nonconservative depending on the number of people (and thus ignition sources) within the bounds of the vapor cloud. The FERC estimate, for example, is less conservative than that of SAI for Point Conception because there are fewer than 130 people (≈ 35 residences) within 10 km of the terminal site. Thus the FERC estimate implies that there is a substantial probability that a vapor cloud will not be ignited at all, while that of SAI implies that it will be ignited with very high probability. On the other hand, using the model for Wilhelmshaven, where there are with 43 000 people living within 10 km of the terminal site (see Table 3), FERC implies that the vapor cloud will be ignited, but only after it has covered a more densely populated area than that predicted using the SAI estimate.

TABLE 14 Probability that a vapor cloud will be ignited within n sources for different values of p.

n	$p = 0.0025$	$p = 0.01$	$p = 0.1$
10	0.02	0.09	0.65
50	0.12	0.39	0.99
100	0.22	0.63	0.9999
500	0.71	0.99	–
1000	0.92	0.9999	–
2000	0.99	–	–
4000	0.999	–	–

The TNO approach is different. It is assumed that a vapor cloud will be immediately ignited when it reaches a populated area, particularly the coast, after a vessel accident, or that it will be ignited at sea by another ship with probability of 0.5, or not at all. The estimated probabilities for Eemshaven are given in Table 15, which was computed by considering that another ship would not necessarily be near the vessel accident site, thus reducing the ignition probability. The delayed ignition probability at the coast is computed assuming that not all vapor clouds will be blown towards a coast.

TABLE 15 Delayed ignition probabilities in TNO (1978).

Delayed ignition at coast after collision	0.05
Delayed ignition at sea after collision	0.2
No delayed ignition after collision	0.75
Delayed ignition at coast after grounding	0.38
Delayed ignition at sea after grounding	0.12
No delayed ignition after grounding	0.5
Delayed ignition after transfer system or storage tank rupture	1.0

Comparing the TNO and other estimates, only the range $p = 0.01 - 0.1$ in Table 14 can explain the immediate ignition at the coast or the 0.5 probability of a ship igniting the vapor cloud, given the population density near Eemshaven and the number of people on a vessel. It thus falls within the range of the estimates given in the other reports.

3.3.4 Fatalities caused by ignited vapor clouds

There are two main effects of ignited vapor clouds: thermal effects and blast effects. There is no doubt that thermal effects exist, but it is an open question whether blast effects due to a deflagration or detonation can occur at all with methane and if so, whether the peak overpressure thus created is great enough to cause damage. TNO considers blast effects to be the only serious danger and that thermal effects are comparatively minor. Cremer and Warner consider both thermal and blast effects, since the Mossmorran–Braefoot Bay terminal will handle propane, butane, propane and ethylene, which are known to explode in certain mixtures with air. ADL considers only thermal effects, because an explosion (either deflagration or detonation) of methane is believed to be very unlikely. FERC and SAI consider only thermal effects. Brötz considers both thermal and blast effects. The NMAB (1980) report concludes that LNG vapor cloud explosions cannot be ruled out completely, even though there is no empirical evidence for such a possibility.

A first step in estimating the number of deaths within certain distances from a spill is to determine the levels of thermal radiation and peak overpressure above which fatalities can be expected. Here one has to distinguish between fatalities caused by primary effects, i.e., those caused directly by thermal radiation and peak overpressure; and secondary effects, i.e., those from fires caused by thermal radiation, and by buildings that have collapsed due to peak overpressure. NMAB concludes that thermal radiation at great distances from a major LNG spill can be estimated with reasonable accuracy (perhaps within ± 30%) from an estimate of the mass burning rate.

All reports consider only fatalities from primary thermal effects and secondary blast effects. Brötz maintains that primary blast effects can be ruled out because the required peak overpressure has never been observed. Secondary thermal effects, however, may affect people sheltered from direct radiation, but these are very difficult to estimate. One way to include them is to assume a low radiation level threshold for fatalities. The only report relating blast effects and fatalities is TNO (1978), including the proportion of fatalities from secondary effects (see Table 16), where it is assumed that the probability of a detonation is 0.01, while the probability for deflagration is 0.99. Brötz does not consider such effects at all.

TABLE 16 Estimated proportion of fatalities, according to TNO (1978).

	Detonation (probability 0.01)		Deflagration (probability 0.99)	
After ignition at coast after 25000–50000 m^3 LNG spill on water	Within 3.3 km of ignition source:	7%	Within 1.2 km of ignition source:	1%
	Within 1.2 km of ignition source:	65%		
After ignition at coast after 10000 m^3 LNG spill on water	Within 2.5 km of ignition source:	7%	Within 0.7 km of ignition source:	1%
	Within 0.7 km of ignition source:	65%		
After ignition at spill site after transfer system or storage tank rupture, resulting in 460 m^3 evaporated LNG	Within 2 km of ignition source:	7%	Within 0.8 km of ignition source:	1%
	Within 0.8 km of ignition source:	65%		

The estimated effects of different radiation levels are presented in Table 17. Given that the radiation level can be described by (see ADL):

$$I = F\,(1/X^2)\ ,$$

where I is the radiation level and X is the distance from the center of the fire.

Table 17 implies that the distance from the center of the fire to the lower fatality level is about twice as large in ADL than in FERC and SAI. Neither Cremer and Warner nor Brötz give a lower fatality level.

TABLE 17 Effects of different thermal radiation levels.

Radiation level (kW/m^2)	Cremer and Warner	ADL (exposure time, 30 s)	FERC (exposure time, 10 s)	SAI (exposure time, 5 s)
4.7	Lower level of pain on skin	Lower fatality level	–	–
16.5	–	–	Lower fatality level	–
17.7	–	–	–	Lower fatality level

ADL and FERC consider only the case when vapor cloud ignition occurs, shortly after the spill, when the cloud can still be considered cylindrical in shape. In Table 18 the distance from the center of the fire to the lower fatality level is given for different spill sizes on water (ADL and FERC), although distances only apply to people not sheltered. Moreover, a conservative estimate is that all people within certain distances are unsheltered and thus become fatalities. ADL also considers fires resulting from a storage tank spill into the surrounding dikes, and concludes that the distance from the center of the fire to the lower fatality level is 550 m. SAI uses a complex model to compute radiation levels, including the case of delayed ignition.

TABLE 18 Distance from point of LNG spill to lower fatality level in case of ignition at the spill site on water for different spill sizes.

Spill size (m^3)	Distance to lower fatality level of radiation from the point of spill (km)	
	ADL	FERC
1 000	0.8	–
25 000	2.9	1.0
37 500	3.5	1.3
50 000	3.9	1.4
125 000	5.5	1.9

Findings

(1) The reports disagree on the major causes of fatalities. While TNO (1976) assumes that all fatalities will be caused by secondary effects of vapor cloud explosions, ADL, FERC, and SAI assume that all fatalities will be caused by thermal radiation. Neither Brötz nor Cremer and Warner estimate the number of fatalities resulting from ignited vapor clouds.

(2) There is also some disagreement as to the radiation level above which there will be fatalities, but ADL adopts the most conservative estimate.

(3) Only TNO (1976) and SAI include the effects of delayed ignition in their calculations. While ADL and FERC do consider delayed ignition, they only include immediate ignition at the spill site.

(4) The effects of LNG and LPG vapor clouds differ because it is known that LPG vapor clouds can explode more easily. Because thermal radiation levels are about the same, an LPG vapour cloud is thus potentially much more hazardous than an LNG vapor cloud of the same size.

3.3.5 Effects on nearby industries

The ignition of an LEG vapor cloud can have effects on nearby industrial plants, perhaps with serious secondary effects on people living or working in vicinity. Except at Point Conception there are chemical plants near all the LEG terminals. This point was considered by both Brötz and Cremer and Warner, but they concluded that these effects would not increase the overall risk significantly. TNO (1976) points out that in case of detonation a nearby ammonia storage tank could collapse with catastrophic consequences, since a lethal ammonia cloud could extend tens of kilometers.

3.4 Demographic and Meteorological Data

It is necessary to consider meteorological and demographic data for the different sites because wind speeds and atmospheric stability play an important role in determining the movement of unignited vapor clouds. Data on wind direction and population density are necessary to determine the number of people at risk from any given accident; Table 19 gives the relevant data for the four sites.

In addition to the populated areas in the vicinity of Eemshaven, there is the island of Borkum, within 1.5 km of the tanker route to and from the terminal. The island's population is not known to us, but the risk to the inhabitants is considered in TNO (1976). Also, the island of Wangerooge is only 3 km from the main tanker route to Wilhelmshaven. There are about 2000 inhabitants, and this increases substantially during the summer due to tourists.

3.5 Assessment of Population Risk

3.5.1 Implications of the definitions of risk

Each of the definitions of risk adopted in Section 1.2 addresses a different aspect of risk from a social and political perspective. The first two definitions (the probability of exceeding specific numbers of fatalities per year, and the total number of fatalities per year) are measures of societal

TABLE 19 Meteorological and demographic data for the four sites.

	Eemshaven	Mossmorran–Braefoot Bay	Point Conception	Wilhelmshaven
Percentage of different atmospheric stabilities				
A,B,C		23.6	16.9	11
D		61.1	28.2	61
E		5.4	41.5	12
F		9.9	13.4	7 (the remaining 9% are not given)
Percentage of different average wind speeds (km/h)	Not known, but probably similar to Wilhelmshaven			
≤ 5.5		15.4	6	Not given
5.5 ≤ 8.8		18.7	14	
8.8 ≤ 16.1		27.3	26	"Dominant"
16.1 ≤ 24.9		24.5	54	Not given
24.9 ≤ 34.6		10.0		
34.6 ≤ 45.1		3.4		
< 45.1		0.7		
Percentage of time wind is blowing from LEG terminal towards populated area (land)	34 (estimated from data for Wilhelmshaven)	71	34	54
Population density within a given distance of LEG terminal (per km^2)				
≤ 2 km	12	50	2.2	0
≤ 5 km	28.9	200	2.5	151
≤10 km	85	470	0.9	275
Populated area (land) within a given distance of LEG terminal (in km^2) and percentage of total area:				
≤ 2 km	5 (40%)	7 (56%)	6.3 (50%)	6 (48%)
≤ 5 km	29.7 (38%)	40 (51%)	39 (50%)	39 (50%)
≤10 km	115 (37%)	212 (68%)	143 (46%)	156 (50%)

risk, involving impacts that fall on society as a whole, i.e., those directly affected and those observing the effects. The last two definitions (the probability of an individual in a specific group becoming a fatality per year and the probability of an exposed individual becoming a fatality per year) are measures of individual risk dealing with direct impacts.

Risk, by the first definition (risk of multiple fatalities), is typically displayed as a complementary cumulative probability distribution: the probability per year that the number of fatalities will exceed x plotted against x. Such a curve, also called Rasmussen curve, contains information not available in the individual probabilities: the effect of correlations between those probabilities. A Rasmussen curve addresses the sensitivity to catastrophe found in the political perspective of risk. For example, consider two facilities that cause equal numbers of fatalities per year. In one facility these are bunched into very rare catastrophes, and in the other they are spread over common small accidents. The former facility may therefore encounter greater political opposition due to sensitivity to catastrophe. The Rasmussen curve is the only format used to illustrate risk by our adopted definitions that addresses this sensitivity.

The second definition (expected fatalities per year) is appropriate for particular types of analysis, such as cost–benefit or risk–benefit analysis, where social preference is assumed to be linear in terms of the number of lives lost.

The third definition (the probability of an individual in a specific group becoming a fatality per year) could be used to address the sensitivity toward equity found in a political perspective of risk. This measure enables one to determine in some sense how much of the risk is being borne by local residents, tourists, etc., and also allows separate determinations of occupational and nonoccupational risks, which are often treated quite differently in political and social processes.

Risk as defined by the fourth definition (the probability of an exposed individual becoming a fatality per year) is simply an average over the group risk measured by the third definition. This measure is somewhat troublesome because it is dependent on the definition of an exposed population. If "exposed" is defined as meaning an individual probability of death of greater than 10^{-12} per year, the individual risk will be averaged over a region extending not far from the facility. On the other hand, if "exposed" is defined with a cut-off probability of 10^{-30} per year, the individual risk will be averaged over a much larger region, and will be much lower. In spite of this shortcoming, individual risk is a measure that allows a convenient comparison between the measured risk and more routine risks the individual may face, such as those from smoking, driving, etc. While such comparisons do not fit into a decision or choice framework (who decides between smoking and living near a terminal?), they do provide readily understandable benchmarks for judging the risk of a facility.

3.5.2 Quantification of risks

Before presenting the estimated risks from the reports we want to show how these concepts are interrelated and what information is needed to compute them. Here we follow closely Keeney *et al.* (1979).

The probability $Pr(x)$ of x fatalities per year is calculated from

$$Pr(x) = \sum_i Pr\,(x\,|\,S_i)Pr(S_i) \ , \tag{1}$$

where $Pr(x \mid S_i)$ is the probability of x fatalities resulting from an event S_i and $Pr(S_i)$ is the annual probability of event S_i. The expected number of fatalities $F(S_i)$ due to event S_i is calculated from

$$F(S_i) = \sum_x x \, Pr(x \mid S_i). \tag{2}$$

These formulas provide the basis for quantifying all of the public risks.

Societal risk is indicated by the expected number of fatalities F per year, and is calculated from

$$F = \sum_i Pr(S_i) F(S_i) \ , \tag{3}$$

where the contributions of all possible events are summed together.

Individual risk is measured by the annual risk level R to an individual in an exposed population and is found by dividing the expected annual number of fatalities by the total number of people exposed, N, yielding

$$R = F / N. \tag{4}$$

This risk level is the probability that an exposed individual will be a fatality in a specific year.

If for each accident scenario S_i the expected number of fatalities $F_G(S_i)$ in a group G is tabulated, the total fatalities F_G per year in that group G is found to be

$$F_G = \sum_i Pr(S_i) F_G(S_i). \tag{5}$$

The individual risk R_G in a particular group G is

$$R_G = F_G / N_G \ . \tag{6}$$

The risk of multiple fatalities is given by the probability that the number of fatalities in a given year is equal to or greater than a specific level y. This can be calculated directly from eqn. (1), and is simply the sum of the probability of y fatalities, $y+1$ fatalities, and so on. Hence

$$Pr(\text{fatalities} \geq y) = \sum_{x \geq y} Pr(x) \ . \tag{7}$$

In Section 3.2. the different events S_i and their probabilities $Pr(S_i)$ were considered, and the probabilities $Pr(x \mid S_i)$ were discussed in Section 3.3. The resulting estimates of the societal risk, the individual risk and the risk of multiple fatalities are given in Table 20. Estimates of the risks were not given in either Brötz or Cremer and Warner.

TABLE 20 Estimates of risks for the different sites.[a]

	TNO	Aberdour	ADL	FERC	SAI
Societal risk (fatalities per year)	4×10^{-2}	Not estimated	7×10^{-6}	10^{-5}	10^{-6}
Individual risk (probability of fatality per year)	$\leq 7 \times 10^{-6}$	7×10^{-4}	$\leq 9 \times 10^{-8}$	8×10^{-7}	10^{-8}
Number of people at risk	$\geq 5\,000$	Not defined	≥ 80	15	90
Risk of multiple fatalities: probability that number of fatalities per year will be					
$\geq$ 1	3×10^{-3}	Not estimated	10^{-6}	Not estimated	6×10^{-7}
$\geq$ 10	10^{-3}		10^{-8}–6×10^{-7}		3×10^{-11}
$\geq$ 100	5×10^{-6}		0		0
$\geq$ 1 000	5×10^{-6}		0		0
$\geq$ 5 000	3×10^{-7}		0		0

[a] Note that the SAI estimates have not been adjusted to make them compatible with ADL and FERC, as has been done elsewhere in the text. Therefore, the risk of the smaller LNG terminal currently planned, as estimated by SAI, would be lower than those presented here, so that the differences between risk assessments here and in the text are in some sense understated.

Not surprisingly, Point Conception has the lowest risk of the three Californian sites, but the various reports often considered quite different events, and the probabilities $Pr(x \mid S_i)$ and $Pr(S_i)$ also varied for the same event and for the same site.

It should also be noted that the SAI estimate was given for an LNG terminal with more storage tanks and larger tankers than is currently planned. Although we adjusted the estimates in earlier sections to make them comparable with ADL and FERC, this was not done in Table 20. Therefore, the risk of the smaller LNG terminal, as estimated by SAI, would be lower than that stated. The individual risk depends on the total number of people exposed, N, which is not always defined in the same way. Depending on how many people are assumed to be exposed at a specific site, the individual risk can vary between assessments even when the societal risk is the same.

If for each accident scenario S_i the expected number of fatalities $F_G(S_i)$ in a group G is tabulated, the total fatalities F_G per year in that group G is found to be

$$F_G = \sum_i Pr(S_i) F_G(S_i). \tag{5}$$

The individual risk R_G in a particular group G is

$$R_G = F_G / N_G \ . \tag{6}$$

The risk of multiple fatalities is given by the probability that the number of fatalities in a given year is equal to or greater than a specific level

y. This can be calculated directly from eqn. (1), and is simply the sum of the probability of y fatalities, $y+1$ fatalities, and so on. Hence

$$Pr(\text{fatalities} \geq y) = \sum_{x \geq y} Pr(x) \quad . \tag{7}$$

In Section 3.2. the different events S_i and their probabilities $Pr(S_i)$ were considered, and the probabilities $Pr(x \mid S_i)$ were discussed in Section 3.3. The resulting estimates of the societal risk, the individual risk and the risk of multiple fatalities are given in Table 20. Estimates of the risks were not given in either Brötz or Cremer and Warner.

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4 EVALUATION OF LEG TERMINAL RISK ASSESSMENTS

It has become clear that in these reports there are substantial disagreements on both the probabilities and the consequences of events, even for the same site. There also exist discrepancies between sites that cannot be explained by the different LEG terminal systems and the respective locations. However, because risk assessments are produced for specific decision-oriented purposes we also have to ask whether they serve those purposes well. Thus we now evaluate them from two aspects, i.e., their scientific quality, and their usefulness in the decision-making process. Although these are certainly correlated there are specific questions related to each one.

4.1 Shortcomings of LEG Risk Assessments

Two questions are discussed in this section:

(1) Could the scientific quality of the risk assessment reports discussed in Section 2 have been improved, and in what way?

(2) Can a risk assessment, even a scientifically perfect one, be extended or improved to become a more effective aid in the decision-making process?

4.1.1 Scientific quality of risk assessments

The clear objective of a risk assessment is to estimate the level of risk, in this case, that stems from an LEG terminal facility. There are three questions related to the scientific quality of a risk assessment: whether or not a reasonable definition of risk is used; whether or not the estimate of the risk is accurate in some probabilistic sense; and how that accuracy can be verified.

As we have shown in Section 1.2, there is no unique definition of risk, so any report should give a precise definition of the type of risk being estimated and should also explain why that particular definition has been used. In our opinion the risk definition used in Keeney *et al.* (1979) is the most reasonable of all those concerned with fatalities, and the concept behind it should also be applied to consequences other than fatalities, such as financial losses.

Whatever definition of risk is used, the question remains as to the accuracy of the estimate of that risk, which is crucial to the entire area of risk analysis. It was first broadly discussed when the Rasmussen Report (NRC 1975) was published, and has remained an important issue ever since. As we showed in Section 3 there are substantial differences between risk assessments on all three dimensions of risk assessment: the events considered, their probabilities, and their consequences. All reports claim that their estimates are conservatively high and only a few mention uncertainties in the estimates. We now discuss the different problems of accuracy in more detail.

- *Events considered.* The reports disagree substantially on the events considered, even for the same LEG facility. One possible event, sabotage, is not considered in any of them. It would perhaps be scientifically more precise to say that the results of these risk assessments are conditional estimates of the risk, assuming that particular events, such as sabotage, do not happen. It is important to realize that this is a simplification of reality that any scientific model builder has to cope with, since all models require simplification. However, it is important to mention in a risk assessment the assumptions under which the estimate is valid. Clearly, certain events are not considered for good reasons; specifically, some are *a priori* considered unimportant or are nearly impossible to quantify, like sabotage. This results, however, in the notion of risk assessment as being an estimate of risk, conditional on certain assumptions.

- *Estimation of probabilities.* Probabilities are derived from frequency distributions, personal (expert) judgment, and combinations of the two. The use of historical data to estimate probabilities of future events is very appropriate, unless major changes in the likelihood of events occur. If future events are expected to differ from those in the past, or if historical data do not exist, one therefore has to rely on the judgment of experts. This method – the Bayesian approach to probability – is conceptually well founded in the axioms of rational behavior (see Lindley 1973, Luce and Raiffa 1957) and is used extensively in decision analysis under a single important assumption: that the analysis involves a single decision maker. In such a case it is conceptually feasible that the decision maker's personal judgment or a single source of expertise commissioned to generate those probabilities would be adequate, but in our case this assumption is not appropriate. If a risk estimate depends heavily on expert judgment, the results may be biased by the particular expert used. One set of results cannot be readily held to be more reliable than another set generated by another expert who believes in different probabilities. Yet in analyses of processes as poorly understood as LEG accident scenarios, the use of expert judgment in deriving probabilities cannot be avoided. While it is clearly desirable to minimize the role of such estimates, that requires data collection, which is expensive in terms of both time and money. In any decision process such as that involved in LEG terminal siting, trade-offs will be made between cost and decision quality in such a way that expert judgment plays an important role. It follows that in any LEG risk assessment, the sensitivity of the estimates to a range of different expert judgments should be clearly specified.

- *Estimation of consequences*. Before the consequences of an event can be analyzed it must be clear what aspects of risk are to be considered – fatalities, injuries, or financial losses due to an accident. To estimate any one of these risks the consequences of events must be stated in the same terms, i.e., the number of fatalities, number of injuries, or the amount of financial losses. Reports that consider consequences only in terms of the amount of LEG spilled, density of thermal radiation, or the like, cannot estimate risk in terms the public or the decision maker can understand. Many, but not all, reports consider consequences in terms of the number of fatalities; none deals with injuries or financial losses explicitly, and only a few consider the consequences in terms of spill size or thermal radiation. Even those dealing with the number of fatalities differ to some extent with respect to consequences, mainly due to the lack of experience with large LEG spills and doubts as to how to model LEG vapor cloud behavior. Thus it is not known precisely how many people near an LEG terminal are at risk, although it is possible that these uncertainties could be reduced in the near future in the light of current research into large LEG spills.

We now turn to the problem of evaluating the scientific accuracy of risk assessments. Although we have identified some important factors, it is nonetheless very difficult to identify the most accurate reports because they deal with such extremely rare (or low-probability) events.

Crucial to the growth of scientific knowledge is the ability to marshall evidence that a certain scientific statement or theory is false. In fact, as some philosophers such as Karl Popper argue, it is not possible to prove the correctness of a scientific statement, but only to prove its falsity. An example from the history of physics supports this view: a very strongly held theory, Newton's laws of motion, was only shown to be false, or, to be more precise, was shown by Einstein to be a special case of relativity theory after more than 200 years. Not all scientific statements can be shown to be false, for two reasons. One is that a scientific statement may be so accurate that any attempt to prove its falsity fails; the other is that a scientific statement is so imprecise, or concerns such inaccessible events (e.g., in the distant future), that it is not currently possible to prove its falsity. But the latter type of scientific statement is much weaker than the first. While the laws of physics are of the first type, Marx's forecast of the economic development of industrialized countries is a scientific theory of the second type.

Let us now look at LEG risk assessment. It is not difficult to design experiments that could prove that certain predicted consequences are false. This could be achieved, for example by experimenting with large LEG spills. But it is difficult to prove that a risk estimate is incorrect because important events are not considered or because the probabilities are wrong. The reason for this is the fact that, by definition, low-probability events occur very rarely and not in a deterministic manner. Even data on LEG terminal system behavior for 20 or 30 years would provide very little information, because very few accidents, if any, would have occurred. Such experience can only put an upper bound on a probability of occurrence at a particular confidence level, a bound that may be far greater than the very low probabilities involved in LEG risk assessment.

There is no easy way to resolve the problem of validating estimates of low-probability events. For this reason, Weinberg (1982) considers risk assessment to be an "art" because "there are, and will always be, strong trans-scientific elements in risk assessment". However, the fact remains that risk assessment is an "art" that is a more desirable means of estimating risk than any other alternative.

4.1.2 Risk assessments as decision aids

We now discuss the shortcomings of LEG risk assessments as decision aids and how they can be improved. It is first necessary to identify the two types of decision problems for which risk assessments are used: the choice of a specific site for an LEG facility, and the decision as to whether or not certain risk-mitigating measures should be introduced. Although it is not clearly stated, it seems that risk reports prepared for Point Conception and Eemshaven were used as inputs to both types of decisions, whereas those prepared for at Mossmorran–Braefoot Bay and Wilhelmshaven were primarily used for decisions on mitigating measures.

Of course, both decision problems are not only concerned with risk to life; consequences such as costs, benefits, environmental impact, and supply interruption risk are also important dimensions. From a decision analysis point of view one should first clarify the alternatives and then quantify the consequences of each, as shown in the decision trees of Figure 1. The siting decision is of course not independent of the decision on which technical

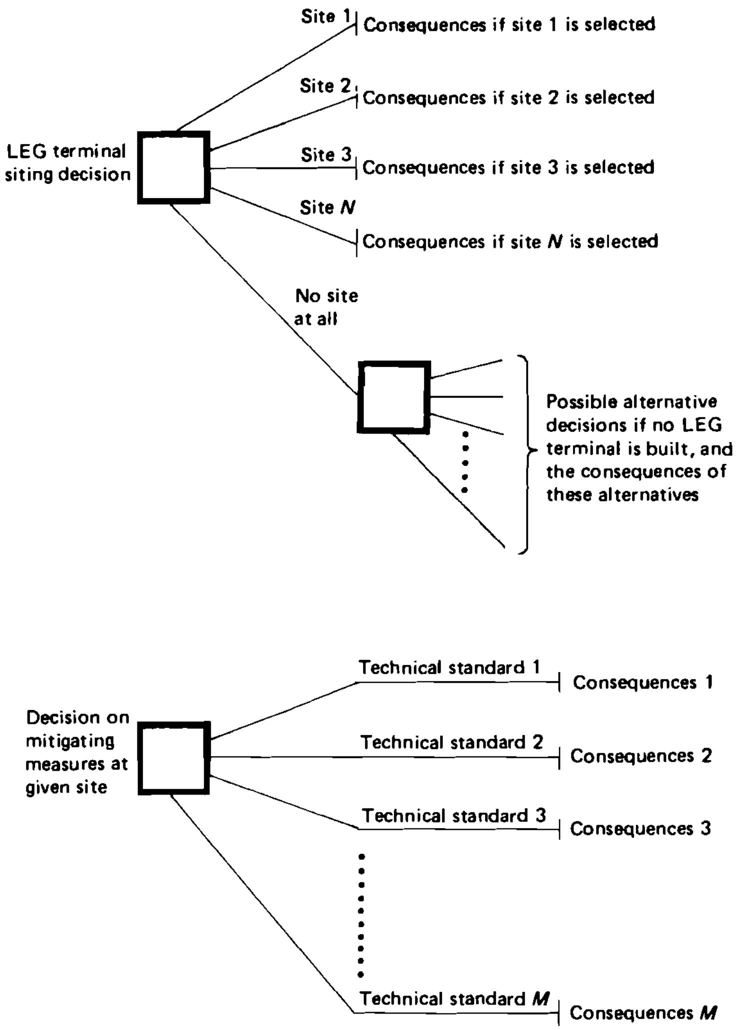

FIGURE 1 Decision trees for the main decisions on LEG terminals

standards to employ for the terminal, a fact that further complicates the process. However, at some point a trade-off has to be made between the consequences of the decision, e.g., costs, benefits, risk, etc. This is exactly the point where questions like "How safe is safe enough?" or "What level of risk is acceptable?" are raised. In a decision analysis framework one should instead ask questions like: "Is it preferable to reduce the expected number of fatalities and to increase the price of natural gas (by specific amounts), or should the expected number of fatalities remain at 10^{-6} per year and the price of gas remain the same as it is now?" There is no scientific approach to answering such questions. In fact, there is not even a unique way of answering such questions for society as a whole, because we do not know of a unique way to aggregate preferences of individuals into a societal preference list. No matter what the results of the risk assessment may be, different people will come up with different solutions to the problems posed in Figure 1 because individual personal trade-offs between risk and other consequences will always differ.

There is no way to make an "objectively correct decision" for society based on a risk assessment or any other scientific method. It is also important to realize that the consequences of decisions vary for different groups of people. For example, not many people are directly exposed to the risk of an LEG terminal, while many receive the benefits, such as the availability of natural gas. On the other hand, if no individual is exposed to the risk because no LEG terminal is built, gas consumers might have to pay a higher price or might not receive it all. Thus there is a conflict of interests that cannot be resolved scientifically. Although this reasoning is not new, some sections of society still tend to believe that risk assessments can make decisions more objective or that the risk analysts can answer the question of whether or not the resulting risk is acceptable.

In the past, decisions concerning technological risk have largely been made by the engineers and companies who plan the facilities: civil engineers decide on the safety level of dams, and airplane industries and regulatory commissions decide on the safety level of airplanes. Although this is a generally accepted practice one must be aware that underlying these decisions are subjective trade-offs between safety (or risk) levels and other factors. If some groups do not accept these trade-offs there is no scientific way to prove them wrong. As shown in Table 1, both Brötz and Cremer and Warner state that the risk of LEG is acceptable, a statement that cannot be defended on scientific grounds. This does not mean, of course, that the risk will be acceptable to all the parties involved.

Risk assessments cannot resolve the conflicting trade-offs between the consequences of decisions relating to LEG; nor can they provide an answer as to whether a risk is acceptable. But they can be an important tool in the decision process. First, they can be used to identify particularly weak or risky components in a system, and so enable the planners to improve facility design, as is often done in airplane design. Secondly, on a political level, risk assessments can be used to analyze LEG risks in detail and compare them with other societal risks such as driving, etc. We believe, however, that risk assessments are most appropriately used within a decision analysis framework to enable decision makers and interest groups to compare the risks and benefits of different decision alternatives, as shown in Figure 1. Although a risk assessment is a prerequisite for doing this, we would argue that its extension to risk—benefit analysis, and ultimately its use within decision analysis, would better suit the decision problems under consideration than risk assessment alone. This is because the absolute risk is never the dominating factor in a decision. What matters is the relative risk compared with the alternatives.

4.2 Significance of Differences Between Risk Assessments

As we have seen in Section 3 there are important differences between risk assessment reports, and it is of interest to identify specific reasons for these, and to determine to what extent and in which direction these affect the risk estimates.

Although there are clear discrepancies between the reports for Wilhelmshaven and Mossmorran–Braefoot Bay on the one hand, and Point Conception and Eemshaven on the other, it is not at all clear whether this is because of differences in cultural styles, in the consulting firms responsible for the reports, in the purposes of the reports, in analytical and financial resources, or some other unknown factors. Although it cannot be substantiated, the expectations of the client, as well as the scientific background of the analyst, are likely to be significant reasons for the differences.

TABLE 21 Ranking of risk assessments for Point Conception in terms of conservatism of estimates on special issues.

	Conservative 1	Less conservative 2	 3
Completeness of events considered	SAI	ADL	FERC
Spill probability due to ship collision	FERC	ADL	SAI
Spill sizes considered	ADL	SAI	FERC
Spill probability due to storage tank failure	SAI	ADL	–
Spill sizes considered	SAI	ADL	–
Maximum travel distance of vapor cloud after a spill on water	ADL	FERC	SAI
Maximum travel distance of vapor cloud after spill on land	ADL	SAI	–
Lower fatality level of thermal radiation	ADL	FERC	SAI
Delayed ignition probability	SAI	FERC	–
Overall risk	FERC	ADL	SAI

While the reasons for the differences cannot be ascertained, their extent indicates the amount of leeway left to analytical judgment. As this report has made clear, several decisions must be made in the course of performing a risk assessment, such as how to characterize risk, what presentation formats to use, what gaps to fill with which assumptions, of what degree of conservatism, which of several conflicting models to use, how to indicate the degree of confidence of the results, and which events simply to omit from the analysis. These decisions can push the results in any direction. Very conservative assumptions increase risk estimates; clear presentations of expert disagreements can reduce confidence in the results; and particular formats highlight particular aspects of the risk. These decisions can push the results of an analysis over such a large range that the final result may be affected more by the predilections of the analyst than the physical features of the site or technology. This same result was found in a comparison of three risk assessments performed for a proposed terminal at Oxnard, California (FPC, SAI, and SES; see Lathrop and Linnerooth 1981).

When looking at the three reports prepared for Point Conception there is no indication that one report is any more (or less) conservative in its overall risk estimate than the others, as shown in Table 21. However, if we take the most conservative estimates of the three reports for each topic the resulting overall risk would be substantially higher than the estimated risk in Table 20.

4.3 Dealing with Uncertainties

There are important problems in determining and portraying the accuracy of risk estimates. Some reports deal with some of the uncertainties, as shown in Table 22, but the greatest uncertainties are acknowledged in Battelle, where it is stated that

> For both the number of expected fatalities per event and the corresponding annual frequencies, the lower limit of the confidence intervals should be considered to be significantly less than 0.1 times the given values, the upper limit over 10 times the given values. In some cases the upper limit is given by the total number of persons at risk.

TABLE 22 Uncertainties in risk estimates.

Report	Range of expected number of fatalities per year	Reasons for range
ADL	$4 \times 10^{-6} - 7 \times 10^{-6}$	Population density — present or future; active time of ignition source
SAI	$1.2 \times 10^{-6} - 1.201 \times 10^{-6}$	Percentage of fatalities among people enveloped by a burning plume, and other conservative assumptions
Battelle	At least $10^{-6} - 10^{-4}$	Probability of vessel accident; probability of immediate and delayed ignition of vapor cloud
Keeney *et al.*	$1.7 \times 10^{-5} - 2 \times 10^{-5}$	Probability of ignition per source; maximum travel distance of flammable vapor cloud
SES	$1.5 \times 10^{-2} - 5.7 \times 10^{0}$	Maximum travel distance of vapor cloud, probability of vessel accident

The reports not listed in Table 22 do not explicitly consider or present uncertainties in their risk estimates at all; even those that do, disagree as to what these are, and the relevant range that these values can take. We consider as particularly uncertain the estimates of probabilities of events stemming from expert judgment. Sensitivity analysis for LEG should therefore involve at least the following parameters:

- probability of an LEG vessel accident resulting in a spill;
- probabilities of immediate and delayed ignition of an LEG vapor cloud;
- probabilities of transfer system and storage tank failure resulting in a spill.

The maximum downwind travel distance of a flammable LEG vapor cloud, seems to us to be a less critical topic because this will be primarily determined by the delayed ignition probability, since the probability that a vapor cloud will be ignited before it reaches its maximum extent is very high over populated areas. This view is also supported by Battelle:

> The uncertainties resulting from the application of simple, experimentally unverified models describing the dynamics of the LEG vapor are not considered to be critical for the assessment of the risk.

To show how large the differences between accident probabilities can be, it is helpful to examine the probability of a spill resulting from a vessel accident per year at Point Conception (see Table 4). This probability was estimated as 9.9×10^{-7} by SAI, as 7.7×10^{-5} by ADL, and as 8.1×10^{-3} by FERC. If this range of the order of 10^4 is taken as the possible range on the probability, the range of the societal risk as given in Table 20 should also be of the order of 10^4, because the probability of a spill on water is essentially multiplicatively related to the expected number of fatalities per year. The reason why the difference between the FERC and SAI estimates in Table 20 is not that great is because FERC makes less conservative assumptions on other issues, as shown in Table 21.

From this small example of sensitivity analyses we would argue that the range of uncertainty given in Battelle and SES of the order of at least 10^2 is defendable as a minimum range for most risk estimates, even if not mentioned explicitly. Of course, this is very rough, and it is certainly necessary to perform thorough sensitivity analyses before making more precise statements on the ranges of uncertainty.

But a more general point should be made here. Each report poses as a representation of the current state of knowledge regarding LEG risks, but because that knowledge is incomplete, at least some of the reports represent it using probabilistic terms or error bounds. Yet each report is based on a different state of knowledge: different assumptions are made, models used, probabilities estimated, etc. No one report in fact represents a comprehensive representation of the current state of knowledge. When SAI gives a probability of 9.9×10^{-7}, and FERC gives 8.1×10^{-3}, the policy maker is somewhat at a loss as to which is the most appropriate probability upon which to base his actions. There is some "societal subjective probability" that most likely lies between those two probabilities, since each represents only a subset of the total state of knowledge. Yet neither report acknowledges that the other estimate exists! What is needed here is a "meta-analysis" combining the different estimates and models, and thus representing a larger fraction of the available knowledge than any one of the existing risk assessments.

A meta-analysis would be more objective than any of the existing reports because if two consulting firms were each asked to do such a meta-analysis, the two reports would then probably be more in agreement than, say, the SAI and FERC. Such an analysis would also have much larger error bounds, or broader probability distributions, than the existing analyses. While policy makers would prefer more precise estimates of risk, our present state of knowledge simply does not warrant such statements. That imprecision in our knowledge about LEG risks should be clearly communicated to readers of risk assessment reports.

5 GUIDELINES FOR STANDARDIZED LEG RISK ASSESSMENTS

In this section we organize our findings in the form of guidelines for preparing a standardized risk assessment. These are meant to suggest ways of improving risk assessments, and also to enable someone unfamiliar with the field to evaluate such reports. The guidelines are intended to improve both scientific and decision-aid aspects of LEG risk assessments. Much of the following has already been stated elsewhere in this report, yet we feel that it is useful to present in summary form:

- *Definition of risk*. Because there are several different definitions and concepts of risk, the particular one used in an assessment should be made clear. In addition, the reason for the choice of that particular risk definition should be explained.

- *Completeness of considered events*. It is conceptually impossible to be sure that all possible hazardous events have been included in an assessment, but the events listed in Tables 4, 5, and 6 should be considered. Other events that could add substantially to the risk (such as sabotage) but were not considered for some reason, should be mentioned, so that the reader can appreciate that the validity of the risk estimate is conditional on certain assumptions.

- *Estimation of probabilities*. Whenever possible, probabilities should be estimated using data rather than judgment, and any judgmental probabilities should be identified. Furthermore, a number of experts should provide estimates so that a range of possible judgmental probabilities is generated.

- *Estimation of consequences*. The consequences should be expressed in terms that concern the decision makers (e.g., fatalities, injuries, financial losses) rather than in physical terms (e.g., spill size, thermal radiation). The possible consequences of domino effects (between an LEG terminal and nearby chemical plants, for example) should also be considered. Whenever possible, consequences should be estimated using data from experiments, rather than theoretical, unverified physical models.

- *Identification of system parts that present the maximum risk*. For considering mitigating measures and engineering design it can be very helpful to identify the parts of the system that present the greatest risk.

- *Sensitivity analysis*. Any risk assessment report should perform sensitivity analysis, particularly on the judgmental probabilities used, to show the possible range of uncertainty of the risk estimate.

- *Assumptions*. The assumptions on which the analysis is based should be made clear. In addition, wherever possible, the implications of each assumption should be presented, to aid comparisons of assessments.

- *Risk–benefit analysis*. Although the estimation of the risk itself increases the understanding of the implications of certain decisions, we feel that the estimation of the risks and benefits of alternatives in the context of LEG terminal decision problems would be more appropriate and useful to the decision makers.

- *Acceptable risk level*. There is no scientific way to decide if a certain risk level is acceptable to society or not. Risk assessment reports should therefore avoid making statements on this question.

REFERENCES

Aberdour and Dalgety Bay Joint Action Group (1979) *Mossmorran–Braefoot Bay: Shipping Hazards* (mimeo).

ADL (1978) *Draft Environmental Impact Report for the Proposed Point Conception LNG Project*, prepared for the California Public Utilities Commission; and *LNG Safety*, Technical Report 16 of Draft EIR for Point Conception (Cambridge, MA: Arthur D. Little, Inc.).

Battelle (1978) *Risk Assessment Study for the Harbor of Gothenburg;* and *Risk Assessment Study for an Assumed LNG Terminal in the Lysekil Area*, prepared for the Swedish Energy Commission (Frankfurt: Battelle Institut eV).

Brötz, W. (1978) *Sicherheitstechnisches Gutachten zum Planfeststellungsverfahren eines Schiffsanlegers vor dem nördlichen Teil des Voslapper Grodens im Norden von Wilhelmshaven* (Stuttgart: Institut für Technische Chemie der Universität Stuttgart).

Cremer and Warner (1977) *The Hazard and Environmental Impact of the Proposed Shell LNG Plant and Esso Ethylene Plant at Mossmorran, and Export Facilities at Braefoot Bay*, Vols I and II (London: Cremer and Warner).

Fairley, W.B. (1977) "Evaluating the 'small' probability of a catastrophic accident from the marine transportation of liquefied natural gas", in W.B. Fairley and F. Mosteller (eds) *Statistics and Public Policy* (London: Addison-Wesley).

Fay, J.A. (1980) "Risks of LNG and LPG" *Annual Review of Energy* (Cambridge, MA: MIT Press).

FERC (1978) *Final Environmental Impact Statement Vol.III, Comments and Appendices*, Western LNG Project, FERC/EIS-0002F (Washington, DC: Federal Energy Regulatory Commission).

FPC (1976) *Pacific-Indonesia Project: Final Environmental Impact Statement* Bureau of Natural Gas, FERC (Washington, DC: Federal Power Commission).

Havens, J.A. (1977) *Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment* (Washington, DC: US Coast Guard).

Havens, J.A. (1979) *A Description and Assessment of the Sigmet LNG Vapor Dispersion Model*. Report No. CG-M-3-79 (Washington, DC: US Coast Guard).

Havens, J.A. (1980) "Assessment of predictability of LNG vapor dispersion from catastrophic spills onto water" *Journal of Hazardous Materials* 3: 267-78.

HSE (1978) *Canvey: An Investigation of Potential Hazards from Operations in the Canvey Island/Thurrock Area* (London: Health and Safety Executive).

Keeney, R., Kulkarni, R., and Nair, K. (1979) "A risk analysis of an LNG terminal" *Omega* 7:191-205.

Krappinger, O. (1978a) *Abschätzung des Risikos, dass Tanker mit gefährlicher Ladung im Jadefahrwasser mit anderen Schiffen kollidieren oder auf Grund laufen* (Hamburg: Hamburgische Schiffbau-Versuchsanstalt GmbH).

Krappinger, O. (1978b) *Risikoanalyse: Über die Gefährdung der an dem Umschlagsbrücken der DFTG und ICI liegenden Schiffe durch den die Anlage passierenden Verkehr auf dem Fahrwasser der Jade* (Hamburg: Hamburgische Schiffbau-Versuchsanstalt GmbH).

Krappinger, O. (1978c) *Ergänzung der Risikoanalyse: Über die Gefährdung der an dem Umschlagsbrücken der DFTG und ICI liegenden Schiffe durch den die Anlage passierenden Verkehr auf dem Fahrwasser der Jade* (Hamburg: Hamburgische Schiffbau-Versuchsanstalt GmbH).

Lathrop, J.W. and Linnerooth, J. (1982) "The role of risk assessment in a political decision process", in P. Humphreys and A. Vari (eds) *Analysing and Aiding Decision Processes* (Amsterdam: North-Holland).

Lewis, H.W. (Chairman) (1978) *Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission* NUREG/CR-0400 (Washington, DC: US Nuclear Regulatory Commission).

Ligthart, V.H.M. (1980) "Determination of probability of marine accidents with respect to carriers proceeding in Dutch coastal and inland waters" *Journal of Hazardous Materials* 3: 233-47.

Lindley, D. (1973) *Making Decisions* (London: Wiley).

Luce, R.D. and Raiffa, H. (1957) *Games and Decisions* (New York: Wiley).

Marshall, Burgoyne and Partners (1979) *Review of a Document Entitled "Part II — Assessment of the Potential Hazard Posed by a Major Spillage of LPG or Ethylene at the Proposed Braefoot Bay Terminal"* (London: J.G. Marshall, Burgoyne, and Partners).

NMAB (1980) *Safety Aspects of Liquefied Natural Gas in the Marine Environment*, National Materials Advisory Board Publication No. NMAB 354 (Washington, DC: US Department of Transportation).

NRC (1975) *Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants*, Rasmussen Report WASH-1400 (Washington, DC: Nuclear Regulatory Commission).

Philipson, L.L. (1978) "Safety of LNG systems" *Energy Sources* 4: 135-55.

Reese, W.P. (1978) *Maritime Risk Assessment Applied to California LNG Import Terminals*, CAORF II Symposium, Kings Point, New York.

SAI (1975) *LNG Terminal Risk Assessment Study for Oxnard, California*, prepared for Western LNG Terminal Company, SAI-75-615-LJ (La Jolla, CA: Science Applications Inc.), Chapters 1,8, and 9.

SAI (1976) *LNG Terminal Risk Assessment for Point Conception California*, prepared for Western LNG Terminal Company (La Jolla, CA: Science Applications, Inc.).

Schneider, A.L. (1978) *Liquefied Natural Gas Safety Research Overview* Report No. CG-M-01-79 (Washington, DC: US Department of Transportation).

SES (1976) *Environmental Impact Report for the Proposed Oxnard LNG Facilities*, Draft EIR, Appendix B (Los Angeles, CA: Socio-Economic Systems, Inc.).

Slovic, P., Fischhoff, B., and Lichtenstein, S. (1980) "Facts and fears: Understanding perceived risk", in R.C. Schwing and W.A. Albers (eds) *Societal Risk Assessment: How Safe is Safe Enough?* (New York: Plenum).

TNO (1976) *Evaluatie van de gevaren verbonden aan aanvoer, overslag en opslag van vloeibaar aardgas* (Apeldoorn: TNO Bureau Explosieveiligheid).

TNO (1978) *Evaluatie van de gevaren verbonden aan aanvoer, overslag en opslag van vloeibaar aardgas met betrekking tot een Eemshaven-terminal* (Rijkwijk: TNO Bureau Explosieveiligheid).

Weinberg, A.M. (1982) "Reflections on risk assessment" *Risk Analysis* 1(1) March.

WSD (1978) *Transport gefährlicher Güter zu den geplanten DFTG/ICI Umschlagsbrücken* (Aurich: Wasser- und Schiffahrtsdirektion Nordwest).

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RELATED IIASA PUBLICATIONS

Kunreuther, H.C. (ed) (1982) *Risk: A Seminar Series.* CP-82-S2 ($19.00).

Kunreuther, H.C. and Lathrop, J.W. (1982) *Siting Hazardous Facilities: Lessons from LNG.* RR-82-36. Reprinted from *Risk Analysis* (1981) 1(4) ($1.00).

Kunreuther, H.C. and Ley, E.V. (eds) (1982) *The Risk Analysis Controversy: An Institutional Perspective* (Berlin: Springer). ISBN 3-540-12012-2.

Kunreuther, H.C., Linnerooth, J., *et al.* (1983) *Risk Analysis and Decision Processes: The Siting of Liquefied Energy Gas Facilities in Four Countries* (Berlin: Springer). ISBN 3-540-12804-2.

Kunreuther, H.C., Linnerooth, J., and Starnes, R. (eds) (1982) *Liquefied Energy Gas Facility Siting: International Comparisons.* CP-82-S6 ($19.00).