NOT FOR QUOTATION
WITHOUT PERMISSION
OF THE AUTHOR

ASSESSMENT AND COMPARISON OF LIQUEFIED ENERGY GAS TERMINAL RISK

Christoph Mandl
John Lathrop

July 1981
WP-81-98

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

CONTENTS

ASSESSMENT AND COMPARISON OF LIQUEFIED ENERGY GAS TERMINAL RISK

Christoph Mandl and John Lathrop

CHAPTER 1:
EXECUTIVE SUMMARY*

This report has two main goals:

1. To present and compare the various procedures of risk assessment as they have been applied to liquefied energy gas (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 four LEG terminal sites, namely Eemshaven (Netherlands--NL), Mossmorran (United Kingdom--UK), Point Conception (USA), and Wilhelmshaven (Federal Republic of Germany--D).

---

*The research reported in this paper is supported by the Bundesministerium fuer Forschung und Technologie, F.R.G., contract no. 321/7591/RGB 8001. While support for this work is gratefully acknowledged, the views expressed are the author's own, and are not necessarily shared by the sponsor.

The major findings of this report can be summarized as follows:

1. There is no unique concept of risk that is used throughout all the risk assessment reports examined in this study. Many of the important differences between the reports stem from the different risk concepts used. Some reports do not even define their underlying risk concepts. However, there is a concept of risk that involves several measures, each based on both probabilities of failures and consequences of failures, that is judged to be superior to other less comprehensive risk concepts.
2. The possible failures of the system, the probability of those failures and the estimation of their consequences to life and limb differ between the reports. Not all the differences can be explained by differences between the terminals and sites; some must be viewed as resulting from the limited knowledge and understanding of LEG risks. In this respect too little reference is made to remaining uncertainties in the estimation of risk in most reports.
3. Given the differences between the reports there is no relative tendency for each report individually to over- or underestimate the risk. Rather each report is more conservative on certain topics and less so on other topics as compared to the other reports. Thus no report can be singled out as producing a more conservative estimate of the risk (with respect to all parts of the total risk) than all the other reports.

4. On a relative risk scale it can be said that among the four sites Point Conception is the terminal with the lowest risk (because of very low population density), Mossmorran and Wilhelmshaven are the two terminals with the highest relative risk (because of high population density and more vessel traffic) and Eemshaven is in between. However, this does not imply anything at all about absolute risk.
5. Although risk is an important dimension of the decision to import LEG and to choose a specific site for the terminal, it should not be forgotten that other dimensions, like reliability, are important too. Any decision regarding LEG importation and terminal siting should involve comparisons with alternative options. As part of that process the risk of LEG should be compared with the risk of other options.
6. Whatever flaws the LEG risk assessments may have, they are clearly superior to less systematic ways to identify possible system weaknesses and inform the decision making process on the topic of risk.

This paper is the first part of a research report. The second part will specifically address the problem of giving guidelines to evaluate LEG terminal risk assessment reports and in particular to evaluate the risk assessment reports for the four terminal sites under study.

CHAPTER 2:
INTRODUCTION

2.1. BACKGROUND, PURPOSE AND SCOPE

In the last decade a new technology for transporting and storing natural gas has become increasingly important for the overall energy supply of industrialized countries. The central idea of this new technology is to reduce the temperature of natural gas below -162°C, at which point natural gas becomes a liquid with a six-hundreth the volume of the gas. The advantage of liquefied natural gas (LNG) is that it can be transported and stored efficiently in tanks due to its high energy per unit volume. Only in liquefied form can natural gas be transported via ships from supply points in Indonesia, Algeria, and other countries to demand points in the U.S., Europe, and elsewhere with reasonable costs.

However, due to the extreme temperatures of LNG it is necessary to build special ships, special terminals to transfer LNG to and from the ships and special tanks on land to store LNG. Cost considerations made it necessary to plan and build LNG vessels and LNG terminals of considerable size. A typical LNG vessel can contain 125,000m^3 LNG. At LNG terminals up to 60,000m^3 LNG is transferred per day (which is equivalent to an energy flow of approximately 15,000 Megawatts--the power of about 15 standard nuclear reactors) and terminal storage tanks are planned to contain up to 500,000m^3 LNG. It is therefore not surprising that this high concentration of LNG at the site of a terminal created concern that there might be potential negative effects, particularly to the environment and to the local population.

This report in fact covers a broader category of terminals than those handling LNG. One of the terminals examined is to handle liquefied propane and butane, substances which involve many of the same risk assessment features and problems as LNG involves. Since all of these substances, liquefied methane, propane, and butane, are called liquefied energy gasses (LEG), the terminals examined in this study will be referred to as LEG terminals. Although there are many aspects involved in assessing the advantages and disadvantages of an LEG terminal at a specific site, the risk to the local population turned out to be one of the crucial questions. Because of a lack of historical data on accidents at LEG terminals, the frequency of such accidents as well as their consequences to people cannot be readily estimated. Therefore, over the past 7 years attempts have been made to quantify the risk to the local population for different planned LEG terminals, using different techniques and models with different results.

It is the purpose of this report to carefully review the risk assessments undertaken for four LEG terminals in four different countries, to discuss their plausibilities, explain the differences and compare the estimated risk. Where necessary and appropriate we will also attempt to expand the risk assessment reports. Because LEG terminal risk assessment is a new technique, there is still some disagreement among experts as to how to quantify risk, which models to use, what to include in a risk assessment and what to exclude.

There are two main goals which the authors hope to achieve with this report:

1. To present and compare the various procedures of risk assessment as they have been applied to liquefied energy gas (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 four LEG terminal sites, namely Eemshaven (Netherlands--NL), Mossmorran (United Kingdom--UK), Point Conception (USA), and Wilhelmshaven (Federal Republic of Germany--D).

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

2.2. RISK, PROBABILITIES AND CONSEQUENCES

Before it is possible to quantify risk, we must define it. It will become apparent in this section that different 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 is good to admit at the outset of this discussion that risk is an essentially troublesome concept from the point of view of evaluation. Ideally, if one adopts the axioms of rational choice under uncertainty, the evaluation of any decision alternative should consider the probability distribution over the consequences which result from that alternative, which may be expressed in a space of several dimensions (see, e.g., LUCE-GEN in the acronym coded reference section). Yet the concept of risk singles out a subset of those dimensions for special analysis. The term is typically applied to particular uncertain costs, diverting attention from other costs and uncertain benefits that could be just as important for evaluation. In the case of LEG importation, for example several dimensions are of concern for site selection and facility design, as are listed in the next section. Of those, several involve uncertain costs, for example, financial losses to the applicant if anything goes wrong (delay in application approval, loss of source contract, ship accident), environmental losses due to accidents or even routine disruption, fatalities and injuries due to accidents, property losses due to accidents, and losses to consumers from natural gas supply interruption if anything goes wrong (these losses include unemployment and health effects in an extreme winter). While all of these uncertain costs could be and are referred to as risks, and all of them could be analyzed by techniques of risk assessment, in fact the term risk assessment in the context of LEG typically refers only to assessments of uncertain loss of life due to accidents. That is the scope for all risk assessments reviewed in this report.

One could try to argue that the narrow scope of application of the risk assessments reviewed here reflects a judgment that externalities involving loss of life deserve special attention. However, other LEG effects lose and save lives: a supply interruption in a severe winter can cost lives; an increased share of clean-burning natural gas in the energy supply can prevent early deaths due to air pollution. It seems, then, that the scope given to risk assessments is an implicit acknowledgment that special attention should be given to assessing the possibility of accidental and/or catastrophic loss of life. We shall 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 studying what we have called the political perspective of risk (see, e.g., SLOV-GEN). That literature identifies particular dimensions of importance in describing 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 risk to an individual compares with other risks commonly experienced. It is beyond the scope of this report to develop a comprehensive, single measure of political-perspective risk. However, in choosing a definition of risk, we should be responsive to that perspective and be sure to select as risk measures ones that capture these concerns.

With this as a background, the best way to develop a definition of risk is to start by quoting some of the definitions from the risk assessment literature (see reference section for acronym-report codes):

> *SAI- USA:* "Risk is the expected number of fatalities per year resulting from the consequences of an accidental event."
>
> *CREM- UK:* "Risk is the probability of an injurious or destructive event, generated by a hazard, over a specified period of time."
>
> *BATTE2- OTH:* The 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."
>
> *KEEN- OTH:* "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."

It is of interest to note that these quotes are the only definitions of risk found among all of the risk assessments reviewed in this study. In all assessments not mentioned above, risk is assessed without ever being explicitly defined. In addition, in one of the quoted cases, SAI-USA, other summary measures are given, including risk of multiple fatalities, that are not included in the quoted definition. The general presumption of most of the risk assessments seems to be that risk is a multi-dimensioned concept that can be adequately described to a decision maker by various sets of numbers, without an explicit definition of what risk is.

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 to the consequences these events might have (in terms of number of fatalities).

Surveying the set of risk assessments reviewed in this study, one can identify two extreme definitions of risk. One extreme, given by the risk definition of CREM-UK, considers probabilities of destructive events only and does not look at the consequences these events can have. This approach is only practical as a non-evaluative description of the risk of a facility. Such an approach only makes sense for comparison or evaluation in the very limited case when all destructive events have equally-valued consequences, and risk is defined as the probability that any one of the events would occur in a given time interval (or expected number of events in that interval). It would be clearly meaningless to label two facilities equally risky if they had equal probabilities of an accident, but the accident in one facility had much more serious consequences than the accident in the other facility.

On the other extreme, risk can and is some times viewed as the worst possible event (with the most serious consequences). Again we would argue that comparing this kind of risk is not meaningful because it omits the probability of an event and thus the relevance of such a worst possible event.

The underlying concept of this report is based on the axioms of rational choice under uncertainty referred to before, i.e., that any evaluation of the risk of a decision alternative should depend upon the probability distribution over consequences that results from selecting that alternative. While descriptions of political choice 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 as described before. We do this by adopting definitions of risk that address political perspective concerns. These definitions, used throughout this report, are the ones described by Keeney et al. (KEEN-OTH):

- *Societal Risk:* Total expected fatalities per year.
- *Individual Risk:* Probability of an cxposed 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.

As we will discuss in more detail in chapter 4.5.1., each of these definitions addresses a different aspect of the political perspective of risk. However, they are interrelated. They can all be derived from the same basic set of data: the annual probability distribution over accidents and the conditional probabilities that each exposed individual will be killed by each 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. That data can be used to calculate the probability distribution over number of fatalities, which in turn yields the risk of multiple fatalities and the societal risk, as defined above. The same data can be used to calculate the annual probability that each 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 of various groups of individuals, classified by location or occupation (e.g., LEG terminal employee), is the group risk for each group.

Two important aspects of accident risk are not included in these definitions: injuries and property damage. There is one argument to justify these omissions: the kind of accidents we are dealing with are characterized by closely interrelated fatalities, injuries and property damages. Risk measures based on fatalities can be taken as good relative indicators for all three types of risks, so long as all evaluated alternatives 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 one or universal one. Various readers from particular orientations may have other definitions that they find more suitable for their purposes. However, our definition requires the estimation of consequences and the probabilities of consequences, two activities which are topics of the bulk of this report. Any reader with almost any definition of risk will be concerned with one or both of these topics, and so will find the report relevant to assessments of risk as he defines it.

2.3. LEG TERMINAL RISK ASSESSMENT AS A DECISION AID

Given the orientation of this report, it is easy to forget that a risk assessment is not an end unto itself, but in fact is only one element of the complex process of LEG facility siting and design. More importantly, a risk assessment is supposed to be a decision aid for one or more of the decisions that must be made within that process. An understanding of where a risk assessment fits within an LEG siting and design process is essential to the understanding of the adequacy and worth of a risk assessment as a decision aid.

An LEG siting and design process can be described as part of a hierarchy of decisions. As an example, consider the hierarchy for importation of LNG. At the highest level is the decision concerning how much to expand the national energy supply. Then there is the decision concerning how much to expand the amount of natural gas within that total. Then the sources of that natural gas must be identified: domestic, foreign via pipe, foreign via LNG. If it is decided that a new LNG facility is desirable, then the site must be selected, and the detailed design of the facility developed. There are two features of such a hierarchy of particular note here. First: risk to life and limb is only one dimension of concern for the decisions listed. Other dimensions include cost, land use environmental quality, air quality benefits of natural gas, and dependence on foreign sources. There is even another important dimension involving risk:

supply interruption risk due to shortage, embargo, accident, earthquake, or weather preventing berthing.

The second notable feature of the decision hierarchy is the interdependence of the decisions. While the top-down order in which the decisions were listed may approximate the typical chronological order, in fact each decision depends on the outcomes of decisions below it. For example, the decision to select LNG as a new source of gas depends on cost and risk figures that are functions of the site and design used. In fact, if it were not for that interdependence, the top three decisions would not be relevant to this paper, which concerns itself with reports on terminal siting and design. It follows that the decisions are made in an involved order, as tentative decisions based on uncertain estimates shuffle down the hierarchy and feedback shuffles back up.

Given the several decisions in the hierarchy that must be made that involve risk dimensions, it would seem that there are several roles for risk assessment in LEG facility siting and design. Yet the processes studied in our research have narrowed that role down to a single application: on one dimension, risk to life and limb; at one level, siting or design (depending on the country). There are several effects of this narrowing. To begin with, it diverts analytic effort and political attention away from those questions not addressed by risk assessment. For example, supply interruption risk could be a significant factor in the California case, given the energy throughput (equivalent to about 15 nuclear reactors), the storage capacity, and average ship arrival rate. A supply interruption could be caused simply by weather. Yet that problem did not receive nearly the attention that accident risk to life and limb did, even though it could have been a factor in site selection. In fact, supply interruption risk (due to shortage) was the chief argument for initiating the LNG application in the first place, and so was apparently an important consideration.

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

There is a third effect of the narrow role given risk assessment that is more subtle than the ones already named, 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 the 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 the analysis results. The detection of this effect requires interpretation; it cannot be definitely documented from any evidence. It nevertheless suggests that the role given to risk assessment can affect its results.

Risk assessment does not exist in a vacuum. It is a decision aid in a much larger process. Any understanding of current assessment, and any suggestions for improvement, requires an understanding of that larger process. As this section has pointed out, that larger process controls the role and nature of risk assessment in very basic and important ways.

CHAPTER 3:
REVIEW OF THE LITERATURE

Before going into the quantitative and technical details of the different risk assessment reports (see Chapter 4) we want to compare and evaluate the literature in qualitative terms. In Chapter 3.1 we will discuss risk assessments that have been undertaken for the sites Eemshaven (Netherlands--NL), Mossmorran (United Kingdom--UK), Point Conception (USA) and Wilhelmshaven (Federal Republic of Germany--D) with some reference to risk assessments for other sites. In Chapter 3.2 we will primarily discuss papers that critically reviewed risk assessments and present their major points of criticism.

3.1. RISK ASSESSMENT REPORTS

In Table 3.1 we try to give a comprehensive overview of the most important risk assessment reports available to us including not only the reports prepared for the four sites--Eemshaven, Mossmorran, Point Conception, and Wilhemshaven--but also a few others of particular interest. Before discussing some of the aspects of Table 3.1 we want to comment on the chosen issues of this table:

a. *Parts of the system considered:* Not all reports consider all the main parts of an LEG terminal, namely vessel, transfer and storage tanks. In particular, for Wilhelmshaven there are two types of reports. One dealing only with vessel operation and LEG transfer, the other dealing only with the storage tanks. Unfortunately, the latter reports cannot be commented on here, because they are confidential.

b. *Concept of risk:* As we already discussed in Chapter 2.2, there is no unique definition of risk. Each report should therefore be quite specific on what type of risk is analyzed.

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 is solved in different reports. Two techniques can assist in performing this task. The *event tree* is a technique to develop a logical sequence of events (failures) resulting in unwanted consequences (accidents). Event tree analysis can help to avoid overlooking possible accidents. Having identified the possible events (failures), the goal of *fault tree analysis* is to determine the probability of a specific accident as the result of a sequence of basic events (failures) of the system. Fault tree analysis evolved in the aerospace industry in the early sixties and has since then become a standard technique for systems safety analysis. It was also used extensively in WASH-OTH.

d. *Estimation of consequences of events:* It is necessary that the consequences be stated in terms a decision maker is concerned with. For this reason, and because of the definitions of risk typically assumed, most reports estimate the consequences in terms of the number of fatalities a certain event can cause. However, some reports only estimate the physical consequences (e.g., size of a LEG spill as a result of a specific event or size of a LEG vapor cloud) and do not relate them to number of fatalities.

e. *Estimation of risk:* Different estimations are given depending on the definition of risk employed. In some cases no estimation is given at all.

f. *Final findings:* As we see it the ideal result of a risk assessment report should be the quantification of the risk and its comparison to risks from other sources such that the decision making process can determine whether the risk from an LEG terminal is high or low compared to other risks. The ideal comparison is between risks from alternatives actually faced in the decision making process: site A vs site B, site A vs no site, etc. That risk comparison is the risk assessment result of most direct usefulness to the decision process. In any case, it should be kept in mind that decisions concerning the acceptability of the risk from an LEG terminal involve social value tradeoffs and perhaps political considerations that go beyond the mission of the risk assessment and the legitimate authority of technical risk assessors. It follows that the final finding of a risk assessment should impart information to the decision maker for him to use as a basis for his decision without making that decision for him. If a risk assessment reports that a risk is acceptable, then the technical assessors 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 little experience with LEG accidents there remains a substantial amount of uncertainty about the accuracy of the estimations of probabilities and consequences of events. Different reports handle this problem differently: Some ignore uncertainties completely, some give conservative estimations, some perform sensitivity analysis and some give error bounds on the quantified risk.

h. *Single Event with highest risk:* If mitigating measures to reduce the risk are undertaken it is interesting to know which event bears the highest risk, as it is often the case that the highest-risk event offers the most cost-effective opportunities for mitigation.

When evaluating the reports one should keep in mind that the differences between the reports which become obvious from Table 3.1 can at least partially be explained by the fact that these reports were prepared and used for different decision processes and therefore each report was developed in a way suited to the particular decision process it was to serve.

Obviously the studies that are essentially different from all the other reports in Table 3.1 are CREM-UK, BROTZ-D, KRAPP1,2,3-D, and WSD-D. Particularly on the issues concept of risk, estimation of consequences, estimation of risk, and final findings they do not fit into the pattern of the other works. It cannot be determined whether this is due to different scientific backgrounds and standards of the analysts, limited resources available to perform the tasks, different decision processes at Mossmorran and Wilhelmshaven compared to all other sites, or some other reasons. Whatever the reasons might be we would not consider these four reports as examples of very good LEG risk assessment reports, in terms of the considerations adopted in our study.

3.2. RISK ASSESSMENT REVIEWS

A few reports have already addressed the question of evaluating the validity of risk assessment methods. The first major report, often referred to as the Lewis report (LEWIS-REV), was not concerned with LEG but with the Reactor Safety Study (WASH-0TH). The first significant paper specifically reviewing LEG vessel risk assessment was written by Fairley in 1977 and concerned probability estimation for catastrophic LNG vessel accidents (FAIRL-REV). A 1978 report by Schneider (SCHNE-REV) deals in great detail with specific questions of safety, like dispersions from LNG spills as well as vapor cloud deflagration and detonation. The most recent

Table 3.1 Comparison of reports on issues.

Issues	Reports	TNO1-NL	ACTION-UK
a.	Parts of system considered	vessel, transfer, storage tank	vessel
b.	Concept of risk	risk of multiple fatalities and group risk	group and individual risk
c.	Estimation of		
c.1	probabilities of events	yes, quantitative	yes, quantitative
c.2	event tree analysis used	yes	no
c.3	fault tree analysis used	no	no
d.	Estimation of consequences of events	yes, quantitative in terms of fatalities	yes, quantitative in terms of fatalities
e.	Estimation of risk	societal and individual risk is low compared to other man-made risks	individal risk is high compared to other man-made risks
f.	Final finding	societal and individual risk is low compared to other man-made risks	individual risk is high compared to other man-made risks
g.	Uncertainties in final findings	not mentioned	not mentioned
h.	Single event with highest risk	grounding of LNG tanks	

Table 3.1. (continued)

	CREM-UK	ADL-USA	FERC-USA	SAI-USA
a.	vessel transfer storage tank	vessel transfer storage tank	vessel	vessel transfer storage tank
b.	probability of an injurious or destructive event	multiple fatalities risk	societal, group and individual risk	risk of multiple fatalities and group
c.				
c.1	only in terms of low, very low, extremely low	yes, quantitative	yes, quantitative	yes, quantitative
c.2	no	yes	yes	yes
c.3	no	yes	no	yes
d.	yes, but only physical cons. (e.g., 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.	no estimation of expressed fatalities; estimation of probabilities of events only	yes, quantitative	yes, quantitative	yes, quantitative
f.	"No reason to doubt that the installations cannot be built and operated in such a manner as to be acceptable in terms of community safety.	Pt. Conception is a suitable site with respect to vessel traffic safety. Risk is very low	risk is comparable to risks from natural events and therefore on an acceptable level	"The risk is extremely low."
g.	not mentioned	sensitivity analysis	disagreement among experts is mentioned	sensitivity analysis
h.	not identified	not identified	not identified	not identified

Table 3.1. (continued)

	BROTZ-D	KRAPP1,2,3-D	WSD-D	BATTE-OTH
a.	vessel, transfer	vessel	vessel	vessel, transfer, storage tank
b.	not defined	not defined	not defined	multiple fatality, societal and group risk
c.				
c.1	only in terms of very low	yes, quantitative	only in terms of very low	yes, quantitative
c.2	no	no	no	yes
c.3	no	no	no	no
d.	yes, but only physical consequences (e.g., 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
e.	no estimation give	no estimation given	yes, quantitative	yes, quantitative
f.	With regard to consequences and their probabilities there is no danger, having in mind the relevant laws	no final findings	the risk is not insignificant	risk is about the same as the risk from the gas distribution network
g.	not mentioned	not mentioned	mentioned	considered and error bounds given
h.	not identified	not identified	not identified	rupture of transfer pipeline with delayed ignition

Table 3.1. (continued)

	HSC-OTH	KEEN-OTH	SES-OTH
a.	vessel, transfer storage tank	vessel, transfer, storage tank	vessel, transfer, storage tank
b.	multiple fatality and group risk	multiple fatality, societal, group and individual risk	multiple fatality risk
c.			
c.1	yes, quantitative	yes, quantitative	yes, quantitative
c.2	yes	yes	no
c.3	no	no	no
d.	yes, quantitative in terms of fatalities	yes, quantitative in terms of fatalities	yes, quantitative in terms of fatalities
e.	yes, quantitative	yes, quantitative	yes, quantitative
f.	risk is only acceptable if suggested mitigating measures are undertaken	risk is below those risks that the population near the terminal is exposed to presently	level of safety cannot be specified accurately
g.	not mentioned	sensitivity analysis was conducted to examine effects of variations of two parameters	considered and error bounds given
h.	not identified	not identified	not identified

and most comprehensive review of LNG risk assessments was done in 1980 by the National Advisory Board of the National Academy of Sciences (NMAB-REV). In the rest of this chapter we will concentrate on this latter report, because it covers the main points of criticism from the other reports and raises additional questions.

The major findings on LNG risk assessment in NMAB-REV can be summarized in 9 points:

1. Most reports seem to focus on the low-probability, high-consequence events. They tend to ignore other important events, for example of higher-probability and lower-consequence, and so underestimate the overall risk.
2. Most studies do not consider future traffic patterns (i.e., projected ship sizes and traffic density) that may affect predicted accident routes. Estimations of probabilities of LNG vessel accidents in the vicinity of LNG terminals with a lifetime of at least 20 years ought to account for expected changes of traffic patterns over the same period.
3. In reports that consider risk-reduction factors, too much credit is given to them with apparently arbitrary estimates of their effectiveness. Also, these risk-reduction factors are often treated as if they are independent of one another, with the effects of several risk-reduction factors multiplied to give the overall reduction in the accident probability. Such assumptions of independence are typically not adequately justified.

4. Human error is usually not accounted for in the reports. When it is considered, human error events are usually treated as if they are independent, while experience shows that human errors are not independent of one another.

5. Confidence limits or error bounds for the probability of an LNG spill are rarely given.

6. Differences in the various dispersion models for predicting cloud size lead to large differences in the estimation of the consequences.

7. The reports rarely discuss uncertainties of the data or the results. Instead, the elements in the analyses are presented as facts. Therefore, the reports imply greater accuracy in the results than is warranted by the current state of knowledge.

8. In many reports the risk of an LNG terminal is compared to other risks. These types of comparison with other risks (e.g., auto driving, fires) help to give a feel for the magnitude of the estimate. But such comparisons do not and should not imply that the LNG risk is acceptable.

9. Whatever flaws the LNG risk assessments may have, they are clearly superior to less systematic approaches in identifying possible system weaknesses and likely failure modes and informing the decision makers on the topic of risk, which is certainly one aspect of the whole decision problem.

These 9 points can also be taken as a brief introduction into the kind of questions we will be dealing with in chapter 4. Although all the above points are certainly very important we feel that some should be looked at in greater detail, which we will do in Chapter 4, some additional points should be raised, and taking all these points into account some general guidelines can be given as to how to produce a good risk assessment. The latter two topics will not be addressed in this report, however, but will be discussed in a research report to follow.

CHAPTER 4:
ASSESSMENT AND COMPARISON OF LEG TERMINAL RISK

In this chapter we will discuss in detail the probabilities and consequences of different events (failures). The way in which we proceed follows along the lines of the reports SAI-USA and BATTE2-OTH. After giving a technical description of the four LNG terminals we divide the rest of this chapter into three distinct parts. First we consider the estimation of probabilities of events, then the estimation of the spill size, speed and vapor cloud as a result of the failures and finally we consider the consequences to the local population by quantifying the overall risk as a result of the first two parts, population density and a few other factors. The primary purpose of this chapter is to present the results from the risk assessment reports in a comparable manner and to discuss the differences in estimates of probabilities and consequences between the reports in terms of the underlying assumptions of the models used and their plausibility.

However, as we already showed in Chapter 3.1, not all the reports are easily comparable. Some reports do not consider all the events we will be discussing. Additionally, some reports do not quantify either the probabilities or the consequences of events. Therefore, this chapter cannot and will not be a complete comparison for all events. Rather, we want to give some insight into the risk at all the terminals, to show how one should go about it if a risk assessment is to be made for Mossmorran and Wilhelmshaven, and to identify the open questions in this context.

4.1. SYSTEM DESCRIPTION OF THE LEG TERMINALS

In Table 4.1. we give a brief description of the planned terminals at the sites Eemshaven, Mossmorran, Point Conception and Wilhelmshaven. As can be seen, Mossmorran is a different type of terminal than the other ones. Not only is Mossmorran an export terminal, but the exported gases are mainly propane and butane, while LNG consists mostly (approximately 90%) of methane. As far as one can tell from the available risk assessment reports, the technical layouts of the different terminals are much the same. Not only are the LEG vessels similar (except in size) or even the same, but also the storage tanks and the transfer systems are very much the same. On a relative risk scale one can expect that the risk increases with the size of the terminal and also with the number of people living (or working) within a certain distance of the terminal. As far as size is concerned the Point Conception and Wilhelmshaven terminals are larger than the other two and Wilhelmshaven has the largest amount of total storage capacity, though Eemshaven has the largest individual tanks. Population density is particularly low at Point Conception. The amount of energy flow through the terminals is quite impressive. Considering that large new nuclear reactor units produce approximately 1000 Megawatts at full power, the energy flows at Point Conception and Wilhelmshaven are each approximately comparable to the output of 15 such nuclear reactor units.

An overall impression of the location of the terminals can be taken from the maps in Figures 4.1-4.4. For all sites except at Point Conception the vessels have to travel through a channel, with populated areas nearby. The town of Borkum, for example, is only 1.5 km away from the LNG vessel route to Eemshaven and the town of Wangerooge is 3.5 km away from the vessel route to Wilhelmshaven. As indicated in Table 4.1, other gasses are transferred at Mossmorran (mainly butane and propane) than at the three other terminals (mainly methane). Some chemical differences are shown in Table 4.2, which result in some differences in the consequences for the same spill size. We will discuss this in more detail in Chapter 4.3.2.

Overall one could say that on a relative risk scale Point Conception could be the least risky terminal, because of its low population density. However, this fact might be offset by the fact that Point Conception is at the same time the largest terminal in terms of average transfer. The Wilhelmshaven terminal, which is about the same size as the Point Conception terminal, should have a higher risk than Point Conception because of its higher population density. But the extent to which the risk at the different terminals differs can only be quantified through a detailed analysis, to be presented in the remainder of Chapter 4.

4.2. EVENTS: THEIR PROBABILITIES AND RESULTING SPILL SIZE

One of the most difficult questions of risk assessment is the identification of possible events or failures and the estimation of their frequencies or probabilities. First of all, because LEG risk assessments deal with low-probability events, by definition it is nearly impossible to get enough historical data to estimate the probabilities in a straightforward manner.

Rather, one has to build models and rely on data from other presumably similar systems. As if this were not enough, another important part of the risk assessment problem is the identification of events that have never occured before that would have serious consequences. It is certainly impossible to conceive of all possible events, as one can easily demonstrate when looking at the invention of new technologies, such as new airplanes. This problem was also acknowledged in the Lewis Report (LEWIS-REV), where it was stated that:

> "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."

We therefore do not and cannot claim that the events considered here are a complete set of possible events. However, it can be said that this set of events includes all events that were thought of in the risk assessment literature, e.g., TNO1-NL, SAI-USA, ADL2-USA and BATTE2-OTH.

As is usually done in the literature we subdivide the events into three groups: vessel accidents, failures of the transfer system and events leading to a rupture of a storage tank.

Table 4.1 Description of terminals and sites.

	Eemshaven	Mossmorran	Pt. 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, prop./but.
Average transfer per day (in m^3 liquefied or Megawatt)	18500 m^3 ≈4900 Megawatts (MW)	13400 m^3	58500m^3 ≈15500 MW	56500m^3 ≈15000 MW
Maximum capacity of ships	125000 m^3	60000 m^3 prop.but. 10000 m^3 gas.	130000m^3	125000m^3
Number of ships per year	54	80 for prop./but. 9 for gas.	190	170 ships of 125000m^3 264 ships of 10000m^3
Number of berths	2	1	1	2 for large ships 1 for small ships
Number and capacity of storage tanks	2x120000 m^3	4x60000 m^3 prop./but. 2x31000 m^3 gas.	2 later 3 with 77500m^3 each	6x80000m^3
Double hull storage tanks	yes	yes	yes	yes
Surrounding dikes to contain the contents of the storage tanks	yes, can contain 100% of tank content	yes, can contain 100% of tank content	yes, can contain 100% of tank content	yes, can contain 100% of tank content
Number of people living within 2 km of terminal	60 (12 people/km^2 land)	approx. 350 (50 people/km^2 land)	projection for 1990: 14 (2.2 people/km^2 land)	0 but recreation area within distance
Number of people living within 5 km of terminal	858 (28.9 people/km^2 land)	approx. 8000 (200 people/km^2 land)	projection for 1990: 98 (2.5 people/km^2 land)	5900 (151 people/km^2 land)
Number of people living within 10 km of terminal	9800 (85 people/km^2 land)	approx. 100000 (470 people/km^2 land)	data from year 1977: 129 (0.9 people/km^2 land)	43000 (275 people/km^2 land)

Table 4.2. Some properties of liquefied energy gases.

Property	**Methane**	**Ethane**	**Propane**	**Butane**
Boiling Point	-163°	-88°	-42°	-1°
Specific gravity at boiling point	0.466	0.546	0.585	0.601
Vapor density at 0° (Air = 1.0)	0.555	1.04	1.56	2.04
Auto-Ignition temperature	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
Content of energy of 1m^3 liquid at boiling point in kilowatt-hours	6444			

All temperatures in degrees Celsius.

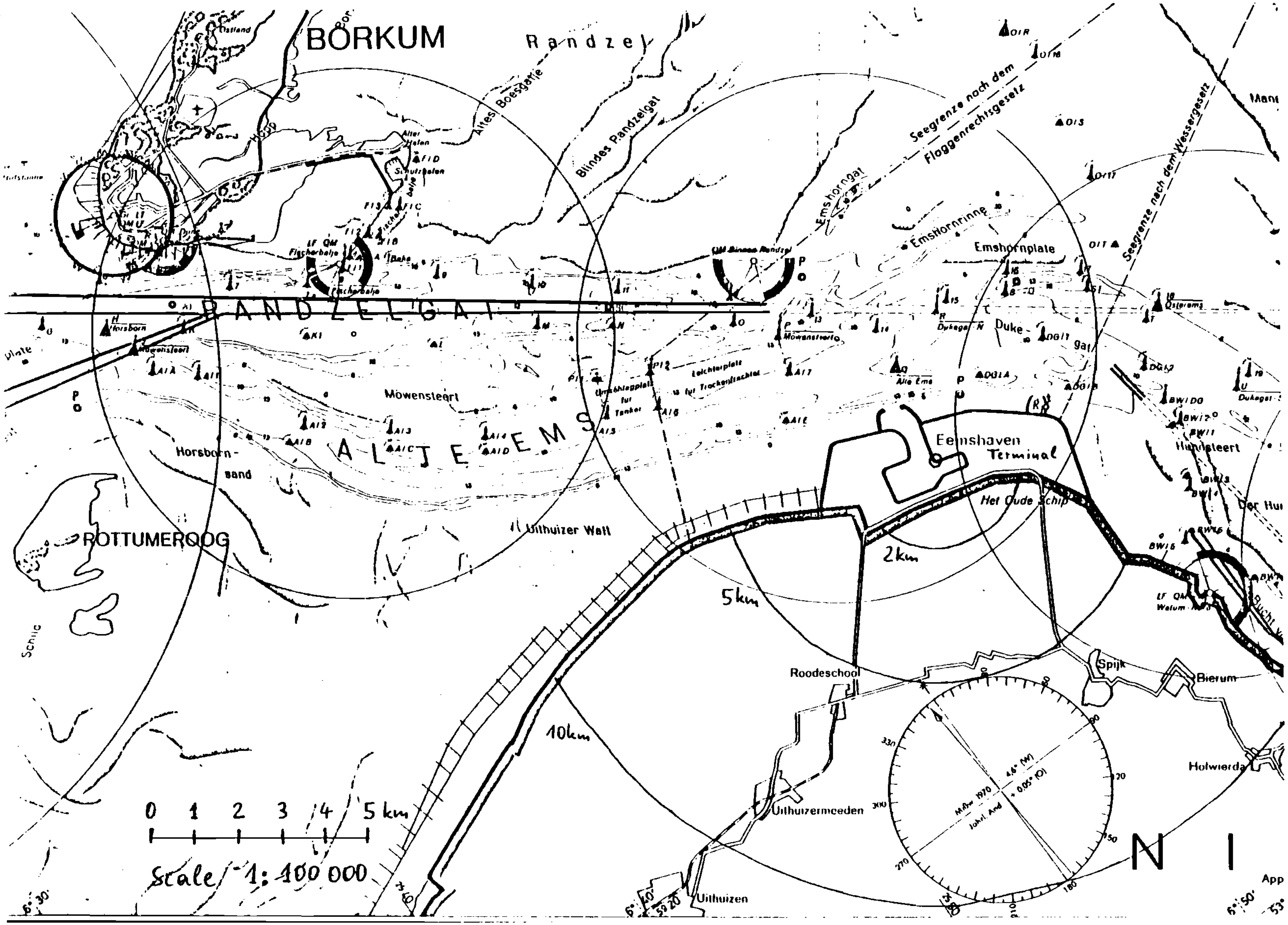
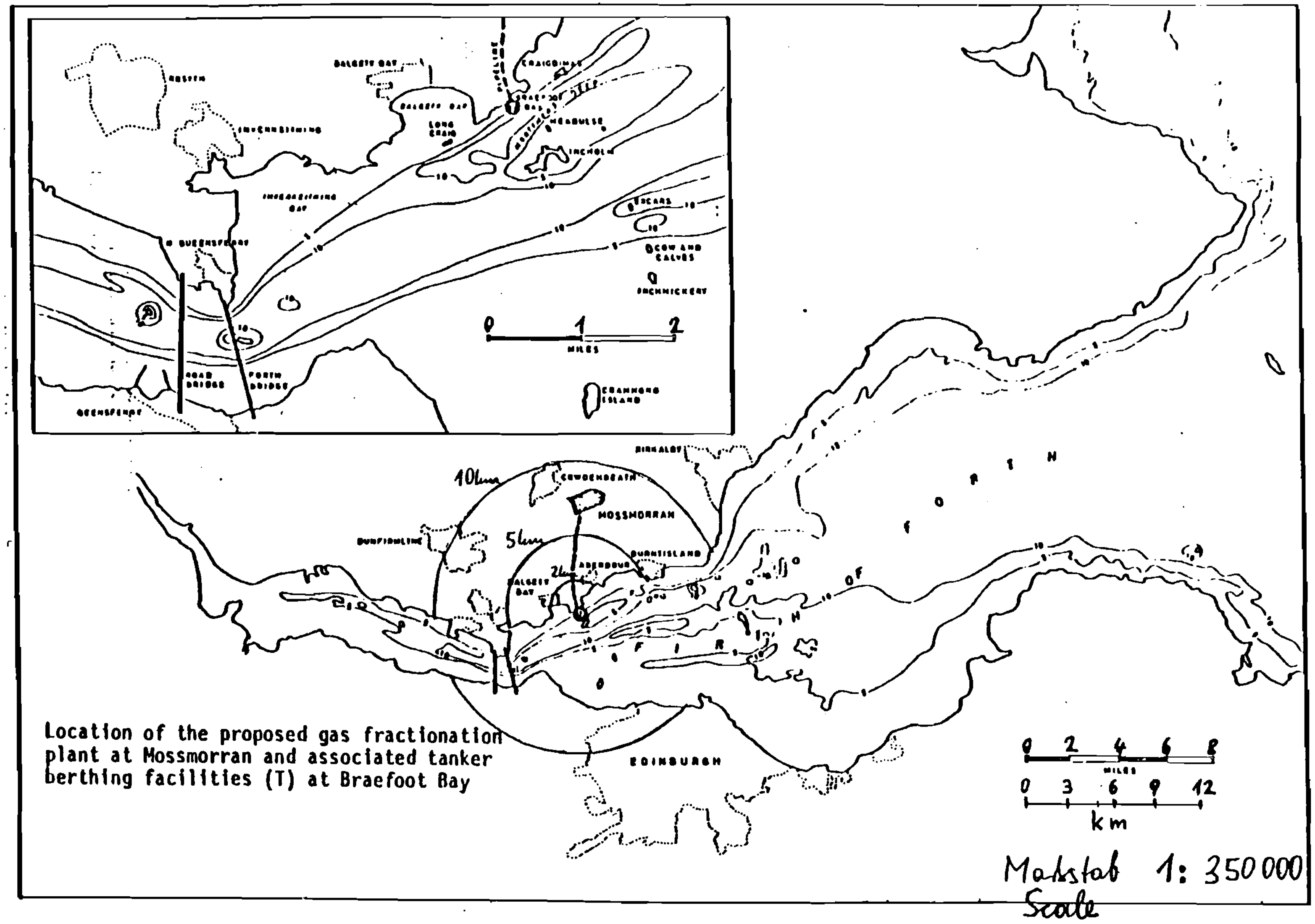
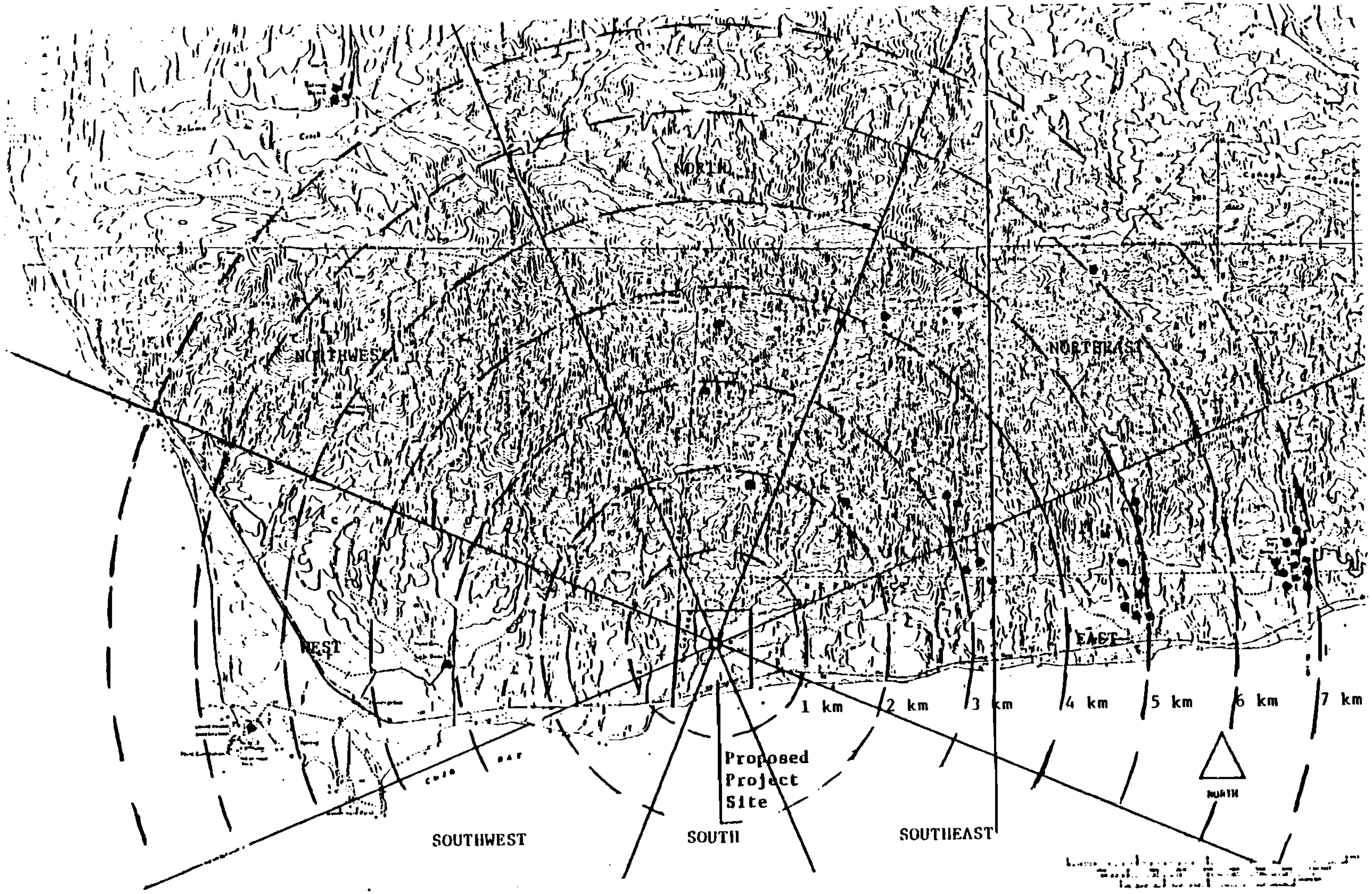


Figure 4.1. Map of Eemshaven.



Location of the proposed gas fractionation plant at Mossmorran and associated tanker berthing facilities (T) at Braefoot Bay

Figure 4.2. Map of Mossmorran.



Scale 1:57500

• Each dot represents one house

Source: Personal communication with Hollister Ranch, Cojo Ranch, Jalama Ranch, December 1977.

Figure 4.3. Housing Locations Near Proposed Terminal at Point Conception.

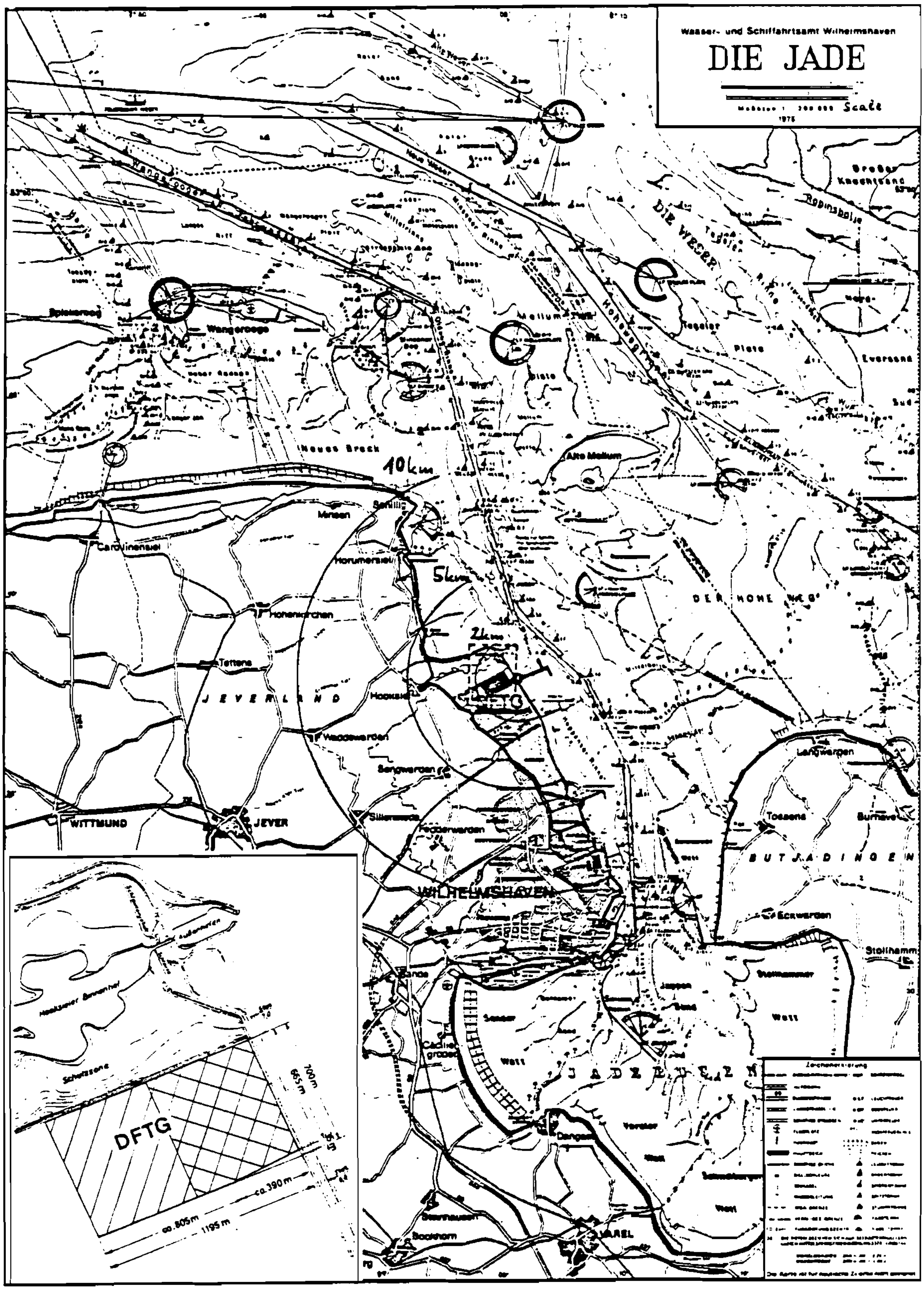


Figure 4.4. Map of Wilhelmshaven.

4.2.1. Vessel Accidents

Basically, there are two types of models used to estimate certain accident probabilities, as described by Philipson (PHIL-GEN). First, one must differentiate between two important parts of an accident—one part being the probability of an accident and the second part being the probability of an LEG spill given that an accident occurred.

To establish estimates of the probabilities of accidents two methods are used in the literature:

1. *Statistical Inference:* Estimates are computed by using historical data, first for a larger class of ships, such as oil tankers, and then modifying the estimates to account for the anticipated differences in LEG ships and their operations at the 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 capabilities of the system had been in place. Examples of this type of analysis are LIGT-ACC and FERC-USA.
2. *Kinematic Modeling:* In SAI-USA ship collisions are analyzed by assuming ship motions to be random in a zone of interest corresponding to the short interval of time preceding an accident. A kinematic model provides the expected number of collisions per year under this assumption for a harbor with specific characteristics of configuration and traffic. A calibration to the actual average conditions of seven harbors is then made by scaling the model to fit actual past collision frequencies in these harbors.

In a similar manner the probability of a spill given an accident is either estimated from data taken from other but similar tankers or computed via a model by taking the physical characteristics of the ship hull and the tanks into consideration.

Considering specifically the statistical approach, the estimates are criticized by Fairley (FAIRL-REV), who claims that due to remaining uncertainties the actual probability might be substantially higher. The types of accidents estimated by the above mentioned methods are collision, grounding and ramming. Three other types of accidents 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 4.3. We now discuss how the different reports derived their estimates:

1. *Collison, grounding and ramming:* Only SAI-USA uses a kinematic model, calibrated by statistical evidence, while in all the other reports, statistical inference alone is used. In NMAB-REV the work of LIGT-ACC and REES-ACC is qualified as outstanding compared to the other works considered in NMAB-REV. TNO1-NL relies on LIGT-ACC and ADL2-USA relies on REES-ACC. The work of KRAPP1,2,3-D again relies strongly on TNO1-NL. One can certainly not expect the probabilities of (1), (2) and (3) of Table 4.3 to be equal between the sites. However, the difference between FERC-USA and SAI-USA is certainly hard to understand. Unfortunately, CREM-UK does not give any estimate at all on the topics of Table 4.3. We therefore excluded this report from the table. The only other report, ACTION-UK, takes its estimation directly from HSC-OTH, which was confirmed by MARSH-

UK, who reviewed ACTION-UK.

2. *Other failures:* Only ACTION-UK, ADL2-USA, SAI-USA and BROTZ-D consider other hazardous events. The estimations of (4) and (5) are straightforward from historical data. Only ACTION-UK, ADL2-USA and SAI-USA consider internal system failure. ACTION-UK, using data taken from HSC-OTH, attribute their internal system failure rate to fire/explosion while the LEG vessel is at the berth. The reasons for the fire/explosion remain unclear. The systems failures in the other reports are due to metallurgical failure.

Overall, it should be mentioned that the estimates given in Table 4.3 are not always taken directly from the reports. In some cases the estimates were adjusted to take additional data into account. SAI-USA used more ships with larger tanks than currently planned, so the probabilities and spill sizes were reduced accordingly. FERC-USA only considered spill sizes of $25000 m^3$ in their report although they stated the data for smaller spill sizes as well. This was added in Table 4.3. KRAPP1,2,3-D produced a variety of different results by 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, which was used in KRAPP1-D.

Table 4.3 Estimation of LEG vessel failures.

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA	BROTZ-D	KRAPP1,2,3-D
(1) Probability of collision that can lead to a spill per ship approaching the LEG terminal	$2.8 \cdot 10^{-5}$		see (14)	$5 \cdot 10^{-4}$	$1.3 \cdot 10^{-8}$	-	$4 \cdot 10^{-5}$
(2) Probability of grounding that can lead to a spill per ship approaching the LEG terminal	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-5}$ includes (2) and (3)		$4 \cdot 10^{-4}$	0	-	$7 \cdot 10^{-5}$
(3) Probability of ramming that can lead to a spill per ship approaching the terminal	-			$3 \cdot 10^{-4}$	0	-	$3 \cdot 10^{-7}$
(4) Probability of missile or airplane crash causing a spill per year	-	-		-	$4 \cdot 10^{-7}$	$8.3 \cdot 10^{-5}$	-
(5) Probability per year of a meteorite falling on a specific area of one square meter	-	-		-	$3.3 \cdot 10^{-13}$	-	-
(6) Probability of internal system failure	-	$3.2 \cdot 10^{-3}$		-	$1.0 \cdot 10^{-11}$	-	-
(7) Number of ships per year	54	80	190	190	190	432	432
(8) Deck-size of ship in m^2 (maximum)	12000	6600	12000	12000	12000	12000	12000
(9) Length of stay of loaded ship in the vicinity of the terminal (in years)	-	-	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
(10) Size of one tank (maximum) in m^3	25000	12000	25000	25000	25000	25000	25000

Table 4.3 Estimation of LEG vessel failures (continued).

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA	BROTZ-D	KRAPP1,2,3-D
(11) Probability of different spill sizes given (1)			See (14)			-	0.05 spill size not defined
0< ≤ 1000m^3	0	0		0.02	0		
1000< ≤10000m^3	0	0		0.026	0		
10000< ≤25000m^3	0.56	0.25		$2.3 \cdot 10^{-2}$	0.22		
25000< ≤50000m^3	0.44	0		0	0.025		
50000< ≤75000m^3	0	0		0	0		
(12) Probability of different spill sizes given (2)						-	0.009 spill size not defined
0< ≤ 1000m^3	0	-		0.0024	-		
1000< ≤10000m^3	0.33	-		0.0057	-		
10000< ≤25000m^3	0	-		$3.9 \cdot 10^{-3}$	-		
25000< ≤50000m^3	0	-		0	-		
50000< ≤75000m^3	0	-		0	-		
(13) Probability of different spill sizes given (3)			See (14)			-	0.1 spill size not defined
0< ≤ 1000m^3	-	-		0.0034	-		
1000< ≤10000m^3	-	-		0.0065	-		
10000< ≤25000m^3	-	-		0	-		
25000< ≤50000m^3	-	-		0	-		
50000< ≤75000m^3	-	-		0	-		
(14) Total probability of different spill sizes per year*						-	$3.8 \cdot 10^{-3}$ spill size not defined
0< ≤ 1000m^3	0	0	0	$2.3 \cdot 10^{-3}$	0		
1000< ≤10000m^3	$4.5 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	0	$3.3 \cdot 10^{-3}$	0		
10000< ≤25000m^3	$8 \cdot 10^{-4}$	0	$7.4 \cdot 10^{-5}$	$2.5 \cdot 10^{-3}$	$8.9 \cdot 10^{-7}$		
25000< ≤50000m^3	$7 \cdot 10^{-4}$	0	$3.2 \cdot 10^{-6}$	0	$9.9 \cdot 10^{-8}$		
50000< ≤75000m^3	0	0	$6.5 \cdot 10^{-9}$	0	0		

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

3. *Findings:*

   a. Compared to the probability of collision, grounding and ramming, the other events are rather unlikely (except for the internal failure in ACTION-UK).

   b. The differences between the three reports for Point Conception are substantial (between 10^{-3} and 10^{-6} for 10,000 to 25,000m^3 spills) and cannot be explained.

   c. Although the traffic patterns at Eemshaven, Mossmorran and Wilhelmshaven are quite different, they all come up with a total probability of the order 10^{-3}, but the spill sizes differ and are not even defined for Wilhelmshaven.

4.2.2. LEG Transfer System Rupture

This failure is generally not considered to be very critical (compared to vessel accidents and storage tank failures), because the overall risk deriving from it is relatively low. Therefore, this failure is not even considered in many reports. Possible events that can lead to a transfer system rupture are: meteorites, earthquakes, ramming, airplane crash and internal system failures. The overall probabilities for different spill sizes are given in Table 4.4. Because the consequences of an LEG transfer system rupture are not worse than those from a spill after a vessel accident (for the same spill size), it is obvious that the risk does not add significantly to the overall risk, due to the small spill sizes.

Table 4.4. Estimation of LEG transfer systems failure.

	TNO1-NL	**CREM-UK**	**SAI-USA**	**BROTZ-D**
Probability of spill size per year				
$0 < \leq 30 m^3$	0	low	$1.6 \cdot 10^{-3}$	very low
$30 < \leq 280 m^3$	0	0	no spill	very low
$280 < \leq 460 m^3$	$1.0 \cdot 10^{-4}$	0	size given, but small	0

4.2.3. Storage Tank Rupture

Finally, we consider the events which could create the largest spill, the rupture of storage tanks. In the literature, it is assumed that one of the following events can cause a rupture: severe winds, airplane and missile crash, meteorites, earthquakes, internal system failure and accidents at other chemical plants nearby. In Table 4.5 we report the estimates of the different events for the terminals.

The estimate of TNO1-NL is taken from historical data of a peak-shaving LNG plant. CREM-UK only qualify the probability as "remote," without reference to how this qualification was produced. ADL2-USA and SAI-USA derive their estimates from historical data on weather conditions, earthquake frequencies and frequencies of airplane crashes. The probabilities for internal system failure—due to metallurgical failures--were derived through a technical analysis, considering the material and the variations of the temperature of the material causing fatigue or stress. BROTZ-D estimates the probability of an airplane hitting one of the six tanks from historical data from Germany. No other probability estimates for Wilhelmshaven are available for discussion, because parts of the reports are confidential. No spill sizes are given in BROTZ-D, but after an airplane crash into a storage tank, a complete rupture of this tank can be assumed as a conservative estimate.

All storage tanks are placed within containment basins capable of containing all the contents (in liquefied form) of the tanks. All credible failure scenarios assume that these containment basins will not break and therefore all spills remain within these basins.

Only SAI-USA considers probability of rupture of more than one tank at a time, due to a common cause. The maximum credible spill is then considered as a rupture of all three storage tanks (each consisting of 77,500m^3) at a time. SAI-USA adjust their probabilities to the fact that the tanks are empty approximately 40% of the time.

Findings:

1. The probability of a storage tank rupture is estimated for all sites (except Mossmorran and possibly Wilhelmshaven, where not all reports are available for comment) of being on the order of 10^{-5} per year.
2. As a conservative assumption the spill size is generally assumed to be at least the complete contents of one tank. CREM-UK only assume 15% of the contents of one storage tank to be spilled. BROTZ-D does not estimate the spill size.

3. TNO1-NL, ADL2-USA and SAI-USA have implicitly or explicitly considered the events given in Table 4.5. In CREM-UK it is not clear what failures have been considered. For Wilhelmshaven we cannot make a statement, because of the unavailability of some reports.
4. There are no major differences in the estimates, except for (2) between ADL2-USA and SAI-USA. The reason for this difference is unclear, because ADL2-USA claims to derive its estimate of (2) from SAI-USA.
5. Common cause failures causing more than one tank to rupture are only considered by SAI-USA.

4.3. PHYSICAL CONSEQUENCES OF LEG SPILLS

4.3.1. General Remarks

We have so far discussed the probabilities of different spill sizes that result from failures of parts of the system. Before we can quantify the number of fatalities certain spill sizes can cause, we have to discuss what happens to the spilled LEG and how it can cause fatalities.

There seems to be agreement that only ignition and consequent rapid burning or detonation of the spilled LEG can have consequences to life and limb, because of thermal radiation and blast effects.

Table 4.5 Estimation of storage tank failures.

	TNO1-NL	CREM-UK	ADL2-USA	SAI-USA	BROTZ-D
(1) Probability of different spill sizes per year due to storm and waves					
0< $\leq$ 80000m^3	-	-	$\sim 10^{-6}$	0	-
80000< $\leq$100000m^3	-	-	-	0	-
100000< $\leq$150000m^3	-	-	-	0	-
(2) Probability of different spill sizes per year due to airplane crash, missiles and meteorites					
0< $\leq$ 80000m^3	-	-	$\sim 10^{-5}$	$3.6 \cdot 10^{-7}$	$5 \cdot 10^{-5}$
80000< $\leq$100000m^3	-	-	-	0	-
100000< $\leq$150000m^3	-	-	-	0	-
(3) Probability of different spill sizes per year due to earthquakes					
0< $\leq$ 80000m^3	-	-	$\sim 10^{-6}$	$5.2 \cdot 10^{-6}$	-
80000< $\leq$100000m^3	-	-	-	0	-
100000< $\leq$150000m^3	-	-	-	$4.7 \cdot 10^{-6}$	-
150000< $\leq$230000m^3	-	-	-	$3.8 \cdot 10^{-6}$	-
(4) Probability of different spill sizes per year due to nearby chemical plants					
0< $\leq$ 80000m^3	-	very unlikely and no spill size given	0	0	-
80000< $\leq$100000m^3	-		0	0	-
100000< $\leq$150000m^3	-		0	0	-
(5) Probability of different spill sizes per year due to internal system failure					
0< $\leq$ 80000m^3	-	-	$\sim 10^{-5}$	$2.4 \cdot 10^{-6}$	0
80000< $\leq$100000m^3	-	-	-	0	0
100000< $\leq$150000m^3	-	-	-	0	0
(6) Overall probability per year					
0< $\leq$ 9000m^3	0	"remote"	0	0	$5 \cdot 10^{-5}$
9000< $\leq$ 80000m^3	0	0	$\sim 10^{-5}$	$8 \cdot 10^{-6}$	
80000< $\leq$100000m^3	0	0	-	0	0
100000< $\leq$150000m^3	$2 \cdot 10^{-5}$	0	-	$4.7 \cdot 10^{-6}$	0
150000< $\leq$230000m^3	0	0	-	$3.8 \cdot 10^{-6}$	0

Looking at Table 4.2 it is clear that LEG will immediately start to vaporize after a spill resulting in a vapor cloud. This vapor cloud will then travel downwind and disperse. If there is no ignition, eventually all parts of the cloud will reach the lower flammability limit of concentration, below which it cannot be ignited. To estimate the effects and probabilities of ignition 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 will 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 will then discuss the estimates for the ignition probabilities at different sites and for different events.

4.3.2. Vaporization and Dispersion of LEG after a Spill

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 data includes only data for spills up to $50m^3$ for an LNG spill on land and to $200m^3$ for an LNG spill on water. The prediction of behavior of large spills has therefore had to rely on theoretical models, which are not easy to validate. Predictions differ for large spills but produce good estimates of the observed spills.

Given the amount of effort undertaken in this still very active research area, we do not intend to present a complete review of the existing models. Rather we want to discuss some of the major findings of reports which have already reviewed the models, to present the predictions used in the different risk assessment reports and to give some idea of what seems to be plausible predictions.

4.3.2.1. Spills on Sea

Immediately after a spill, LEG will start 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 those questions, one assuming an instantaneous release of LEG--so-called puff models--the other assuming steady release over a certain period of time--so-called plume models. The puff models predict a vapor cloud of cylindrical shape with a radius equal to the radius of the LEG pool. For different LNG spill sizes and pool sizes, vaporization time and vapor cloud size immediately after all liquid has vaporized are given in Table 4.6, which was taken from HAV1-DP and FERC-USA.

Table 4.6. Prediction of initial LNG vapor cloud size following different spill sizes on water.

	Model	4000 m^3 spill a. Pool radius	 b. Vaporization time	 c. Vapor cloud radius	 d. Vapor cloud height
	Puff Models				
A.1	Ray/Kalelkar (used by Germeles-Drake and CHRIS)	189	2.8	189	9
A.2	J.Fay	197	2.9	197	8
A.3	Hoult	189	2.5	189	9
A.4	Ottermann	195	4	195	8
A.5	Muscari	232	3.4	232	6
	Plume models				
B.1	Burgess et al.	-	-	-	-
B.2	Feldbauer et al.	-	-	-	-
B.3	U.S. Federal Power Commission	-	-	-	-

Note: Radius and height are in meters and time is in minutes.

Model	10000 m^3 spill				25000 m^3 spill				100000 m^3 spill			
	a.	b.	c.	d.	a.	b.	c.	d.	a.	b.	c.	d.
A.1	267	3.6	267	11	377	4.5	377	13	633	6.3	633	19
A.2	288	3.9	288	9	425	5.3	425	10	753	8.4	753	14
A.3	267	3.2	267	11	372	4	372	13	630	5.7	630	19
A.4	274	5	274	10	387	6.4	387	12	651	8.9	651	18
A.5	328	4.3	328	7	462	5.4	462	9	777	7.6	777	13
B.1	-	-	-	-	540	11.9	-	-	-	-	-	-
B.2	-	-	-	-	610	15	-	-	-	-	-	-
B.3	-	-	-	-	377	4.5	-	-	-	-	-	-

For the prediction of the vaporization, meteorological data is not important. This however changes when the behavior of the vapor cloud has to be predicted. There are two parameters which are important: atmospheric stability and wind speed. The relation of atmospheric stability to weather conditions is shown in Table 4.7.

Table 4.7 Relation of Atmospheric Stability to Weather Conditions.

Surface wind speed, km/hr	Daytime Insolation			Nighttime Conditions	
	Strong	Moderate	Slight	Thin overcast or $\geq$ 4/8 cloudiness†	$\leq$ 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*
E--Slightly stable conditions
F--Moderately stable conditions

†The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

*Applicable to heavy overcast, day or night

In HAV3-DP the downwind distance of a flammable vapor cloud (above lower flammability limit) was predicted using different models. These results are shown in Table 4.8. Although the differences in the predictions of the different models in Table 4.8 seem to be great, one has to bear in mind that the predictions were made for different atmospheric stabilities.

Also, as is pointed out in ADL2-USA, these predictions are only valid on water, because specific landscapes can have different effects on the dispersion of the vapor cloud.

The overall assessment of the models in HAV3-DP was that the Germeles-Drake and the SAI models are the most plausible. Looking now at the reports, ADL2-USA used the Germeles-Drake model, SAI-USA used the SAI model, ACTION-UK used the Feldbauer et al. model, while the other reports used their own models not mentioned in Tables 4.6 or 4.8.

Table 4.8. Maximum downwind distance of a flammable vapor cloud following a 25000m^3 spill of LNG onto water, given wind speed of 8km/hr.

Model	**Atmospheric Stability**	**Distance (km) from spill point**
Germeles and Drake (Cabot Corporation)	Stable-F	18.5
CHRIS (U.S. Coast Guard)	Stable-F	26.2
J.Fay	Very Stable	28.0
Burgess et al. (U.S Bureau of Mines)	Stable	40.6-80.9*
Feldbauer et al. (American Petroleum Institute)	Slightly Unstable-C	8.4
U.S. Federal Power Commission	Neutral-D	1.2
SAI	Neutral-D	2.3

*Range presented to indicate vaporization uncertainty.

The predicted downwind distances, taken from the different reports, are listed in Table 4.9. Although the predictions depend on spill size, atmospheric stability and wind speed, not all reports give downwind distances for all combinations of these three parameters. It should also again be noted that these predictions are valid primarily over water, where the landscape does not influence vapor cloud dispersion in a specific way. One could expect that vapor cloud dispersion is faster over rough landscape, except in the case of propane and butane vapor, which could accumulate in low area due to their high density.

In discussing Table 4.9 one has to bear in mind that ACTION-UK is considering LPG, which has a lower flammable limit of approximately 2% in air, in contrast to 5% for LNG. Because ACTION-UK takes all its information from HSC-OTH, which uses the Feldbauer et al, model to predict LNG vapor cloud dispersion, the greater distances are not surprising. Atmospheric stability E in combination with a wind speed of 8 km/hr is used for ACTION-UK because that is claimed to be the worst case. CREM-UK is not considered because the report does not give any estimate of vapor cloud behavior.

Even without considering ACTION-UK, the differences between studies are substantial. While SAI-USA and BROTZ-D predict relatively short distances, ADL2-USA and FERC-USA are comparable in their prediction of large distances. It is also worth noting that the distance increases with decreasing wind speed in FERC-USA, while for SAI-USA distance decreases with decreasing wind speed. Also the results of Table 4.9, taken from the various reports do not seem to be completely consistent with Table 4.8, taken from HAV3-DP--a point we cannot explain.

Because the models of TNO1-NL, FERC-USA, ACTION-UK, and BROTZ-D were not reviewed, we cannot make a statement on their validity. In HAV2-DP the models of ADL2-USA and SAI-USA were compared. It is concluded in HAV2-DP that the predictions of the two models show agreement within the uncertainty ranges. In other words, given the present state of knowledge both models could be correct.

Findings:

1. The available reports indicate that there remains substantial uncertainty in the maximum distance reached by the flammable region of an unignited vapor cloud.
2. Although Table 4.8 indicates that there are models that predict longer distances than the model of Germeles and Drake, HAV2-DP and HAV3-DP suggest that the Germeles and Drake model is one of the most plausible models and therefore is a reasonable conservative model. This should, however, not exclude the possibility that downwind distances could be longer than those predicted by Germeles and Drake.

Table 4.9. Maximum downwind distance of a flammable vapor cloud following an instantaneous spill of LEG onto water.

Report	Spill Size in m^3 LEG	Atmospheric Stability	Wind Speed in km/hr	Downwind Distance in km
ACTION-UK	800	E	8	4.7
ADL2-USA	1000	A	25	0.4
		D	21	2
		E	19.8	3
		F	10.8	5
ACTION-UK	20000	E	8	19
BROTZ-D	20000	during night only	all wind speeds	3.5
		A-F	all wind speeds	2.3
TNO1-NL	25000	D	–	3.3
		E,F	--	10
ADL2-USA	25000	A	25	1
		D	21	7
		E	19.8	10
		F	10.8	20
FERC-USA	30000	A	25	0.5
			16	0.5
			9	0.6
		D	25	4.2
			16	4.9
			9	5.9
		E	25	7.8
			16	9.2
			9	11.3
		F	25	18.1
			16	21.6
			9	27.1
SAI-USA	37500	A,D,F	0	1
		A,D,F	11	2
		A,D,F	25	3.5
		A,D,F	54	6

Report	Spill Size in m^3 LEG	Atmospheric Stability	Wind Speed in km/hr	Downwind Distance in km
ADL2-USA	50000	A	25	1
		D	21	9
		E	19.8	15
		F	10.8	25
ACTION-UK	64000	E	8	32
SAI-USA	88000	A,D,F	11	2.5
ADL2-USA	125000	A	25	1.5
		D	21	11
		E	19.8	20
		F	10.8	35

4.3.2.2. Spill on Land

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

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

where t is the time after spill and F is a parameter characteristic of the substrate contacting the LEG. Only TNO1-NL, ADL2-USA and SAI-USA consider vapor cloud behavior after a spill on land. In Table 4.10 we list their estimates. Again the differences between ADL2-USA and SAI-USA are substantial.

The small vaporization rate given in TNO1-NL is due to the fact that the dikes surround the storage tanks at a small distance (some meters) from the outer wall of the tank. For that reason NMAB-REV suggests further research to examine more carefully the results expected from a large spill on land, especially for the case of low dikes some distance from the tank, and to compare the effectiveness of such dikes with the effectiveness of high, close-in dikes. Point Conception is planned to have low dikes, while the plans for Eemshaven are for high, close-in dikes. Wilhelmshaven and Mossmorran are planning dikes similar to those at Point Conception.

Table 4.10. Downwind distance of a flammable vapor cloud following an instantaneous spill of LNG onto land.

Report	Spill size in m^3 LNG	Atmospheric stability	Wind speed in km/h	Downwind distance in km
TNO1-NL	150000	-	-	-
	Only 330 m^3 will vaporate during first 10 minutes after spill, slowing down after this time			
ADL2-USA	87500	A	25	0.5
		D	21	2.7
		E	19.8	4.6
		F	10.8	15.0
SAI-USA	88000	A,D,F	25	0.6
			10.8	0.6
			0	0.4
	352000	A,D,F	54	1.5
			25	1.4
			10.8	1.1
			0	0.6

4.3.3. Ignition of Vapor Clouds

Although the vapor cloud is not toxic it can have some effects even if not ignited. These effects on people are mainly skin irritation (because the vapor cloud is very cold) and suffocation problems, because if the concentration of natural gas is high there might not be enough air for breathing. However, compared to the hazard of an ignited vapor cloud these other hazards are considered negligible.

Ignition probability is composed of two parts. The first part is the direct ignition by the event that caused the spill. As can be seen from Table 4.11 these probabilities, depending on the different events, are generally high. This is because it is assumed that an event that causes a tank to rupture, also creates enough frictional heat to ignite the resulting vapor cloud.

The second part of the ignition probability is the probability that the vapor cloud is ignited by some other source given that it is not ignited immediately. Obviously this latter part depends on the availability of ignition sources within the flammable bounds of the vapor cloud.

The probabilities given in Table 4.11 are all derived from expert judgment, though expertise for this particular judgment task is admittedly difficult to characterize. Delayed ignition will in general have larger consequences, because the vapor cloud increases in size and travels downwind. Therefore a high immediate ignition probability will reduce the overall risk. In this respect TNO1-NL and ACTION-UK are more conservative in their estimates than the other reports. Certainly, the ignition probability can be site dependent. For example, KEEN-OTH points out that the immediate ignition probability is estimated at a high value because collisions at the specific site studied would generally involve larger vessels carrying dangerous cargoes (such as chlorine). Because historical data on LNG spills is lacking, the estimated ignition probabilities can hardly be validated.

The reports not listed in Table 4.11 do not state the ignition probabilities. While CREM-UK and BROTZ-D do not mention ignition probability at all, ADL2-USA does mention it but does not state the estimates used.

Table 4.11. Probabilities of immediate ignition following different events.

Event causing the ignition	TNO1-NL	ACTION-UK	FERC-USA	SAI-USA	BATTE2-OTH	KEEN-OTH
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 systems 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	-	-

FERC-USA, SAI-USA, BATTE2-OTH and KEEN-OTH use the same model for delayed ignition probability. They assume that each source of ignition has the same probability p of igniting the vapor cloud. Thus the probability 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 assume that each person is a source of ignition, because (s)he will use facilities (e.g., car, oven, light) that are actual sources of ignition. The differences between the reports are the judgmental estimates of the probability p. Table 4.12 gives these different estimates.

Table 4.12. Ignition probabilities per source in case of delayed ignition.

	FERC-USA	**SAI-USA**	**BATTE2-OTH**	**KEEN-OTH**
Probability p that each person within the vapor cloud ignites the cloud	0.0025	0.1	0.01	0.01-0.1

We present P_n for different p and n in Table 4.13. As it becomes clear from Table 4.13 all assumptions on p can be either conservative or non-conservative depending on the number of people (and thus ignition sources) within the reach of the vapor cloud. The estimate of FERC-USA, for example, is less conservative for Point Conception than the estimate of SAI-USA because there are not more than 130 people living within 10 km distance from the LNG facility. Thus the FERC-USA estimate implies that there is a substantial probability that the vapor cloud will not be ignited at all, while the estimate of SAI-USA implies that the vapor cloud will be ignited with very high probability. On the other hand using the model for Wilhelmshaven with 43,000 people living within 10 km of the LNG site (see Table 4.2), the FERC-USA estimate implies that the vapor cloud will be ignited, but only after covering more populated area than that predicted using the SAI-USA estimate.

Table 4.13. Probability that a vapor cloud will have been ignited within n sources for different values of p.

	p = 0.0025	p = 0.01	p = 0.1
n = 10	0.02	0.09	0.65
n = 50	0.12	0.39	0.99
n = 100	0.22	0.63	0.9999
n = 200	0.39	0.86	–
n = 500	0.71	0.99	–
n = 1000	0.92	0.9999	–
n = 2000	0.99	--	–
n = 4000	0.999	--	–

The TNO1-NL approach is different. It is assumed that a vapor cloud is immediately ignited when it arrives at a populated area, in particular the coast, after a vessel accident, or it is ignited at sea by another ship with probability 0.5 or it is not ignited at all. The estimated probabilities for Eemshaven are given in Table 4.14. Table 4.14 is computed by considering that another ship is not necessarily near the vessel accident site thus reducing the probability. The probability of delayed ignition at the coast is computed by considering the fact that not all vapor clouds travel to the coast due to different wind directions.

Table 4.14. Delayed ignition probabilities in TNO1-NL.

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 TNO1-NL estimates with the estimates from the other reports, only the estimate range of p =0.01−0.1 in Table 4.13 can explain the immediate ignition at 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 from the other reports.

4.3.4. Fatalities Caused by Ignited Vapor Clouds

Effects from ignited vapor clouds can be twofold: thermal effects and blast effects. There is no doubt that thermal effects exist. However, it is an open question if blast effects due to a deflagration or detonation can occur at all with methane and if so, if the the peak overpressure created by a deflagration or detonation is significant enough to cause damage. TNO1-NL considers the blast effects as the only serious danger and thermal effects are considered as being of comparatively minor importance. CREM-UK considers both thermal and blast effect, as is logical since the Mossmorran terminal handles materials--butane, propane and ethylene--which are known to explode in certain mixtures with air. ADL2-USA only considers thermal effects, because an explosion (both deflagration or detonation) of methane is considered very unlikely. FERC-USA and SAI-USA again only consider thermal effects. BROTZ-D considers both thermal and blast effects. In NMAB-REV it is concluded that the possibility of explosions of LNG vapor clouds cannot be ruled out completely, although there does not exist empirical evidence for such a possibility.

One first step to estimate the percentage of fatalities within certain distances from the vapor cloud is to state the level of thermal radiation and peak overpressure above which fatalities can be expected. Here one has to distinguish primary and secondary effects. Primary effects are fatalities directly caused by thermal radiation and peak overpressure. Secondary effects are fatalities caused by fires created from thermal radiation and fatalities caused by collapsing buildings as a result of peak overpressure. NMAB-REV concludes that thermal radiation at large 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 available to us consider only primary thermal effects and secondary blast effects. BROTZ-D maintains that primary blast effects can be ruled out, because the required peak overpressure has never been observed. Secondary thermal effects however are a possibility for people sheltered from direct radiation, but are very difficult to estimate. One way to include secondary thermal effects is to assume a low radiation level as a threshold level for fatalities.

The only report relating blast effects to fatalities is TNO1-NL. BROTZ-D does not consider secondary blast effects. Table 4.15 presents the percentage of people killed from secondary blast effects estimated in TNO1-NL. It is assumed that the probability of a detonation is 0.01, while the probability for deflagration is 0.99.

Table 4.15. Estimated proportion of fatalities, according to TNO1-NL.

	Detonation (Probability 0.01)	Deflagration (Probability 0.99)
Percentage of people killed after ignition at coast after 25000-50000 m^3 LNG spill on sea	within 3.3km of ignition source: 7% within 1.2km of ignition source: 65%	within 1.2km of ignition source: 1%
Percentage of people killed after ignition at coast after 10000 m^3 LNG spill on sea	within 2.5km of ignition source: 7% within 0.7km of ignition source: 65%	within 0.7km of ignition source: 1%
Percentage of people killed after ignition at spill site after transfer systems or storage tank rupture resulting in 460 m^3 vaporated LNG	within 2km of ignition source: 7% within 0.8km of ignition source: 65%	within 0.8km of ignition source 1%

Table 4.16 Effects of different radiation levels.

Radiation level	CREM-UK	ADL2-USA Exposure time: 30 sec.	FERC-USA Exposure time: 10 sec.	SAI-USA Exposure time: 5 sec.
4.7 kW/m^2	lower level of pain on skin	lower fatality level	-	-
16.5 kW/m^2	-	-	lower fatality level	-
17.7 kW/m^2	-	-	-	lower fatality level

The estimated effects of different radiation levels are stated in Table 4.16. Given that the radiation level can be described by the function (see ADL2-USA)

$$I = F \left[\frac{1}{X^2} \right]$$

where I is the radiation level and X is the distance from the center of the fire, Table 4.16 implies that the distance from the center of the fire to the lower fatality level is about twice as large in ADL2-USA than in FERC-USA and SAI-USA. CREM-UK and BROTZ-D do not give a lower fatality level.

ADL2-USA and FERC-USA consider only the case when ignition of the vapor cloud occurs shortly after the beginning of the spill, when the vapor cloud can still be considered cylindrical in shape. In Table 4.17 the distance from the center of the fire to the lower fatality level is given for different spill sizes on sea, taken from ADL2-USA and FERC-USA. It is clear that the distances given in Table 4.17 only apply to people not sheltered. Moreover, a conservative assumption is that all people within the distances are unsheltered and thus fatalities.

Table 4.17. Distance from point of spill to lower fatality level in case of ignition at the spill site on sea for different spill sizes.

LNG spill volume in m^3	Distance in km to lower fatality level of radiation from the point of spill	
	ADL2-USA	FERC-USA
1000	0.8	-
25000	2.9	1.0
37500	3.5	1.3
50000	3.9	1.4
125000	5.5	1.9

ADL2-USA also considers a fire resulting from a spill of the storage tank into the surrounding dikes and concludes that the distance to the lower fatality level from the center of the fire, the storage tank, is 550m.

SAI-USA uses a complex model to compute radiation levels including the case of delayed ignition.

Findings:

1. The reports differ greatly on the major cause of fatalities. While TNO1-NL assumes all fatalities to be caused by secondary effects of vapor cloud explosions, ADL2-USA, FERC-USA and SAI-USA assume all fatalities to be caused by thermal radiation. CREM-UK and BROTZ-D do not consider fatalities as a result of ignited vapor clouds.
2. There is also some difference as to the radiation level above which there will be fatalities. ADL2-USA adopts the most conservative assumption on this topic among the reports.
3. Of the studies performed on the four sites considered in this report, only TNO1-NL and SAI-USA include effects of delayed ignition, in their risk calculations. While ADL2-USA and FERC-USA consider delayed

ignition, they include only immediate ignition at the spill site in their calculations.

4. The effects of LNG and LPG vapor clouds can be different, because it is known that LPG vapor clouds explode more easily than LNG vapor clouds. Because the thermal radiation is in both cases about the same, the potential hazard of an LPG vapor cloud is greater than that of an LNG vapor cloud of the same size.

4.3.5. Effects on Nearby Plants

The ignition of an LNG vapor cloud can have effects on nearby plants with possibly high secondary effects on the people living or working near the plants. Except at Point Conception there are chemical plants near all other LEG terminals. CREM-UK and BROTZ-D considered this point and concluded that effects on the chemical plants nearby do not increase the overall risk significantly.

In TNO1-NL it is pointed out that in case of a detonation a nearby NH_3-storage tank could collapse with inadmissible consequences (the lethal dose of NH_3 would reach tens of kilometers).

4.4. DEMOGRAPHIC AND METEOROLOGICAL DATA

In addition to the information presented in the previous sections, it is necessary to consider meteorological and demographic data for the different sites. The reason is that wind speed and atmospheric stability play an important role in deciding how far a an unignited vapor cloud can travel as discussed before. The wind direction and the population density data are necessary to determine how many people are at risk from any given accident. In Table 4.18 we present the relevant data for the different sites.

In addition to the populated areas in the vicinity of the LEG terminals there is one island, Borkum, in the vicinity of the vessel route to and from Eemshaven and another island, Wangerooge, in the vicinity of the vessel route to and from Wilhelmshaven. The shortest distance between Borkum and the vessel route is 1.5 km, and the shortest distance between Wangerooge and the vessel route is 3 km. Two thousand people live in Wangerooge with a substantial number of tourists added in summer. For Borkum the number of inhabitants is not known to us, but the risk to the people of Borkum is considered in TNO1-NL.

4.5. ASSESSMENT OF RISK TO THE PEOPLE

4.5.1. Implications of the Definitions of Risk

Each of the definitions of risk adopted in Section 2.2 addresses a different aspect of risk from a political and social perspective. The first two definitions, probability of exceeding specific numbers of fatalities per year and expected fatalities per year, fall in the general category of societal risk, involving impacts that fall on society as a whole: those directly affected and those observing the effects. The last two definitions, probability of an individual in a specific group becoming a fatality per

Table 4.18 Meteorological and demographic data.

	Eemshaven	Mossmorran	Pt. Conception	Wilhelmshaven
Percentage of different atmospheric stabilities	not known, but probably similar to Wilhelmshaven			
A,B,C		23.6	16.9	11
D		61.1	28.2	61
E		5.4	41.5	12
F,G		9.9	13.4	7 (the remaining 9% are not given)
Percentage of different average wind speeds				
≤ 5.5 km/hr		15.4	6	not given
5.5< ≤ 8.8 km/hr		18.7	14	
8.8< ≤16.1 km/hr		27.3	26	"dominant"
16.1< ≤24.9 km/hr		24.5	54	not given
24.9< ≤34.6 km/hr		10		
34.6< ≤45.1 km/hr		3.4		
45.1 km/hr<		0.7		
Percentage of time wind is blowing from LEG terminal to populated area (land)	34 (estimated from data for Wilhelmshaven)	71	34	54
Population density within a given distance of LEG terminal per km^2 of land:				
≤ 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%)

year and probability of an exposed individual becoming a fatality per year, fall in the general category of individual risk, concerning the impacts felt directly.

Risk by the first definition, risk of multiple fatalities, is typically displayed as a complementary cumulative probability distribution: probability per year that the number of fatalities will exceed x, vs. x. Such a curve is often called a Rasmussen curve, after the director of the Reactor Safety Study (WASH-OTH), where it was prominently used. Such a curve contains information not available in the individual probabilities: the effect of correlations between those probabilites. A Rasmussen curve addresses the sensitivity to catastrophe found in the political perspective of risk. Consider two facilities that cause equal numbers of expected fatalities per year. In one facility those are bunched into very rare catastrophes, and in the other they are spread over common small accidents. The former facility may encounter greater political opposition due to sensitivity to catastrophe. The Rasmussen curve is the only format used to present risk by our adopted definitions that addresses sensitivity to catastrophe.

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 number of lives lost.

The third definition, 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 neighbors, campers, boaters, etc. This definition also allows separate determinations of occupational and non-occupational risks, two risks often treated quite differently in political and social processes.

Risk as defined by the fourth definition, probability of an exposed individual becoming a fatality per year, is simply an average over the group risks measured by the third definition. This measure is somewhat troublesome because it is dependent on the definition of exposed population. If "exposed" is defined as having an individual probability of fatality of greater than 10^{-12} per year, the individual risk will be averaged over a region extending not too far from the facility. If on the other hand "exposed" is defined with a cutoff 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: risk due to 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 scaling the risk of the facility.

The following section presents methods of computation and results for each of the four risk measures discussed here.

4.5.2. Quantification of Risks

In section 2.2 we defined the four different concepts of risk. Before presenting the estimated risks from the different reports we want to show how these concepts of risk are interrelated and what information is needed to compute the different risks. Here we follow closely KEEN-OTH.

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

$$Pr(x) = \sum_i Pr\ (x \mid S_i) \cdot Pr(S_i) \tag{1}$$

where $Pr(x \mid S_i)$ is the probability of exactly x fatalities resulting from 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

$$F(S_i) = \sum_x x\ Pr(x \mid S_i).$$

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

Societal risk is indicated by the expected number of fatalites F per year. This is calculated from

$$F = \sum_i Pr(S_i) F(S_i)$$

where the contributions of all possible events are summed together.

Individual risk is measured by the annual risk level R to an individual in the population exposed to possible risks from LEG. This is found by dividing the expected number of annual fatalities by the total number N of people exposed, yielding

$$R = \frac{F}{N}.$$

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 fatalities $F_G(S_i)$ to individuals in group G is tabulated, the overall expected fatalities F_G per year to group G is found to be

$$F_G = \sum_i Pr(S_i) F_G(S_i).$$

The *individual risk* R_G *in a particular group* G is

$$R_G = \frac{F_G}{N_G}$$

where N_G is the number of people in the group G.

The risk of multiple fatalites 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 (1). It is simply the sum of the probability of y fatalities, $y + 1$ fatalities and so on. Hence

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

In section 4.2. the different events S_i as well as their probabilities $Pr(S_i)$ were considered. In section 4.3 the probabilities $Pr(x \mid S_i)$ were discussed.

The resulting estimates of the societal risk, the individual risk and the risk of multiple fatalities are given in Table 4.19. No estimates of the risks were given in CREM-UK and BROTZ-D.

Not surprisingly, Point Conception has the lowest risk among the three sites. However, as we discussed in the preceeding chapters, different reports considered quite different events S_i. The probabilities $Pr(x \mid S_i)$ and $Pr(S_i)$ also varied for the same event S_i and the same site between different reports.

It should also be noted that the estimate of SAI-USA was given for an LNG terminal with more storage tanks and larger ships. Although we adjusted the estimates in earlier chapters accordingly to make them comparable with ADL2-USA and FERC-USA, this was not done in Table 4.19. Therefore, the risk of the smaller LNG terminal currently planned, as it would be estimated by the SAI-USA analysis, would be lower than that stated in Table 4.19.

The individual risk depends on the total number *N* of people exposed. That number 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 differ between assessments even when the societal risk is the same.

Table 4.19. Estimates of Risks for the Different Sites.

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA
Societal Risk (fatalities per year)	$4 \cdot 10^{-2}$	--	$7 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	$1.2 \cdot 10^{-6}$
Individual Risk (probability of fatality per year)	$\leq 7 \cdot 10^{-6}$	$7 \cdot 10^{-4}$	$\leq 9\ 10^{-8}$	$7.8 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$
Number of people at risk	≥ 5000	?	≥ 80	15	90
Risk of multiple Fatalities: Probability that number of fatalities is equal to or greather than					
1	$3 \cdot 10^{-3}$	--	$1 \cdot 10^{-6}$	--	$6.4 \cdot 10^{-7}$
10	$1 \cdot 10^{-3}$	--	$1 \cdot 10^{-8}$ - $6 \cdot 10^{-7}$	--	$3.4 \cdot 10^{-11}$
100	$5 \cdot 10^{-6}$	--	0	--	0
1000	$5 \cdot 10^{-6}$	--	0	--	0
5000	$3 \cdot 10^{-7}$	--	0	--	0
per year					

REFERENCES

Risk Assessment Reports for Eemshaven (NL)

TNO1-NL: "Evaluatie va de gevaren verbonden aan aanvoer, overslag en opslag van vloeibaar aardgas met betrekking tot een Eemshaven-terminal." H. van Amerongen, J.W.J. Bouma, and G. Snellink, TNO Bureau Industriele Veiligheid, Feb. 1978, Rijswijk-NL.

TNO2-NL: "Evaluatie van de gevaren verbonden aan aanover, overslag en opslag van vloeibaar aardgas." J.G.A. de Graaf. TNO bureau, Explosieveiligheid, Dec. 1976, Rijswijk-NL.

Risk Assessment Reports for Mossmorran (UK)

ACTION-UK: "Mossmorran - Braefoot Bay: Shipping Hazards." Aberdour and Dalgety Bay Joint Action Group, January 1979, Aberdour-UK.

CREM-UK: "The Hazard and Environmental Impact of the Proposed Shell NGL Plant and Esso Ethylene Plant at Mossmorran, and Export Facilities at Braefoot Bay," Volumes I and II. A Report prepared for Fife Regional Council, Dunfermline District Council and Kirkcaldy District Council by Cremer & Warner, May 1977, London.

HSC-UK: "A safety evaluation of the proposed St Fergus to Moss Morran natural gas liquids and St Fergus to Boddam gas pipelines." Health & Safety Executive, July 1978, London.

MARSH-UK: "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,' J.G. Marshall, Burgoyne and Partners, January 1979, London.

Risk Assessment Reports for Point Conception (USA)

ADL1-USA: "Draft Environmental Impact Report for Proposed Point Conception LNG Project," compiled by Arthur D. Little, Inc., for State of California Public Utilities Commission, February 1978.

ADL2-USA: "LNG Safety," Technical Report 16 of Draft Environmental Impact Report for Proposed Point Conception LNG Project, Arthur D. Little Inc., February 1978, Cambridge, Mass.

FEIR-USA: "Final Environmental Impact Report for the Point Conception LNG Terminal Project," Volume I, Summary of Revisions to Draft EIR, California Public Utilities Commission, July 1978.

FERC-USA: "Final Environmental Impact Statement," Volume III, Comments and Appendices. Western LNG Project, Federal Energy Regulatory Commission FERC/EIS-0002F, October 1978, Washington, D.C.

SAI-USA: "LNG Terminal Risk Assessment Study for Point Conception, California," Science Applications, Inc., La Jolla, California, January 1976. (Prepared for Western LNG Terminal Company).

Risk Assessment Reports for Wilhelmshaven (D)

BROTZ-D: "Sicherheitstechnisches Gutachten zum Planfeststellungverfahren eines Schiffsanlegers vor dem noerdlichen Teil des Voslapper Grodens im Norden von Wilhelmshaven." W. Broetz, Instituts fuer Technische Chemie der Universitaet Stuttgart, December 1978, Stuttgart.

EAI-D: "Eine kritische Betrachtung der geplanten Uebergabe- und Transportbrueckeneinrichtungen fuer den DFTG-LNG-Terminal in Wilhelmshaven, Deutschland." ausgearbeitet fuer Mobil Oil A.G. in Deutschland von Energy Analysts, Inc. June 1978.

GEN-D: "Genehmigungsvorbescheid: Errichtung eines Erdgas - Terminals in Wilhelmshaven der Deutschen Fluessigerdgas Terminal Gesellschaft DFTG." Bezirksregierung Weser-Ems 204-40211 N9-1, July 1979, Oldenburg.

JOHA-D: "Gefaehrdung der Umwelt durch gefaehrliche Stoffe bei Kollisionsfaellen von Gas- und Chemikalientankern," G. Johannsohn, Bremen.

KRAPP1-D: "Abschaetzung des Risikos, dass Tanker mit gefaehrlicher

Ladung im Jadefahrwasser mit anderen Schiffen kollidieren oder auf Grund laufen." O. Krappinger Hamburgische Schiffbau-Versuchsanstalt GmbH, June 1978, Hamburg

KRAPP 2-D: "Risikoanalyse: Ueber die Gefaehrdung der an den Umschlagsbruecken der DFTG und ICI liegenden Schiffe durch den die Anlage passierenden Verkehr auf dem Fahrwasser der Jade." O. Krappinger, Hamburgische Schiffbau-Versuchsanstalt GmbH, June 1978, Hamburg.

KRAPP3-D: "Ergaenzung der Risikoanalyse: Ueber die Gefaehrdung der an den Umschlagsbruecken der DFTG und ICI liegenden Schiffe durch den die Anlage passierenden Verkehr auf dem Fahrwasser der Jade." O. Krappinger, Hamburgische Schiffbau-Versuchsanstalt GmbH, October 1978, Hamburg.

LLOYD-D: "Gutachten: Zur Sicherheit von LNG-Tanken." Germanischer Lloyd, Hamburg, March 1978.

WSD-D: "Bericht 'Transport gefaehrlicher Gueter zu den geplanten DFTG-/ICI-Umschlagbruecken'." Wasser- und Schiffahrtsdirektion Nordwest, Aurich, October 1978.

Other Risk Assessment Reports (OTH)

BATTE1-OTH: "Risk Assessment Study for the Harbor of Gothenburg," prepared for the Swedish Energy Commission, Stockholm, Sweden, Battelle-Institute, E.V., Frankfurt, FRG, January 1978.

BATTE2-OTH: "Risk Assessment Study for an Assumed LNG Terminal in the

Lysekil Area," prepared for the Swedish Energy Commission, Stockholm, Sweden, Battelle-Institute, E.V., Frankfurt, FRG, February 1978.

HSC-OTH: "Canvey--An investigation of potential hazards from operations in the Canvey Island/Thurrock area," Health and Safety Executive, June 1978, London.

KEEN-OTH: "A Risk Analysis of an LNG Terminal." Ralph Keeney, Ram Kulkarni, and Keshavan Nair, *Omega* 7 (1979), 191-205.

SAI-OTH: "LNG Terminal Risk Assessment Study for Oxnard, California." Science Applications, Inc., La Jolla, California, Prepared for Western LNG Terminal Company, December 1975.

SES-OTH: "Environmental Impact Report for the proposed Oxnard LNG Facilities." Draft EIR Appendix B, Socio-Economic Systems, Inc., Los Angeles, CA.

WASH-OTH: "Reactor Safety Study: an Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Report WASH-1400, October 1975, Washington, D.C.

Reviews of Risk Assessments (REV)

FAIRL-REV: "Evaluating the 'Small' Probability of a Catastrophic Accident from the Marine Transportation of Liquefied Natural Gas," William B. Fairley, in *Statistics and Public Policy, by W.B. Fairley, and Frederick Mosteller* (eds.), London: Addison-Wesley Publishing Company, 1977.

LEWIS-REV: "Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission." H.W. Lewis, Chairman. Prepared for the U.S. Nuclear Regulatory Commission, Washington, DC, September 1978. NUREG/CR-0400.

NMAB-REV: "Safety Aspects of Liquefied Natural Gas in the Marine Environment." National Materials Advisory Board. Publication NMAB 354, National Academy of Sciences, June 1980, Washington, D.C.

SCHNE-REV: "Liquefied Natural Gas Safety Research Overview." Alan L. Schneider. US Department of Transportation, Report No. CG-M-01-79, December 1978, Washington, D.C.

Marine Accidents Analysis (ACC)

LIGT-ACC: "Determination of Probability of Marine Accidents with Respect to Carriers Proceeding in Dutch Coastal and Inland Waters." V.H.M. Ligthart, *Journal of Hazardous Materials*, 3 (1980), 233-247.

REES-ACC: "Maritime Risk Assessment applied to California LNG Import Terminals," W.P. Reese, CAORF II Symposium, Kings Point, NY, September 1978.

SAI-ACC: "Risk Analysis for Marine Transportation," Eugene Chen, SAI, La Jolla, CA., 1978.

LNG Vapor Dispersion (DP)

BATTE-DP: "Heavy Gas and Risk Assessment," Proceedings of a Symposium on Heavy Gas, Reidel Publishing Company, Dordrecht, 1980.

HAV1-DP: "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment," Jerry A. Havens, U.S. Coast Guard, April 1977, Washington, D.C.

HAV2-DP: "A Description and Assessment of the Sigmet LNG Vapor Dispersion Model." Jerry A. Havens, Report No. CG-M-3-79, prepared for US Coast Guard, February 1979, Washington, D.C.

HAV3-DP: "Assessment of Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water." J.A. Havens, *Journal of Hazardous Materials*, 3 (1980), 267-278.

DOE-DP: "An Approach to Liquefied Natural Gas (LNG) Safety and Environmental Control Research." US Department of Energy, DOE/EV-0002, February 1978, Washington, D.C.

General Papers (GEN)

ADA-GEN: "Decision Analysis of California LNG," Applied Decision Analysis, Inc., December 1977, Menlo Park, California.

DRAKE-GEN: "The Importation of Liquefied Natural Gas," Elisabeth Drake and Robert C. Reid, *Scientific American*, 236 (1977), No. 4, 22-29.

FAY-GEN: "Risks of LNG and LPG." J.A. Fay, Annual Review of Energy, MIT, Cambridge, 1980.

HORN-GEN: "The potential risks of liquefied natural gas," A. Van Horn and R. Wilson, Energy 2 (1977), 375-389.

KALE-GEN: "Handle with Care: Using Risk Analysis for Hazardous Materials Facilities," E. Drake and A. Kalelkar, *Risk Management*, March

1981, pp.44-50.

LIND-GEN: *Making Decisions*. Dennis Lindley, London, Wiley, 1973.

LUCE-GEN: *Games and Decisions*. R.D. Luce and H. Raiffa, New York, Wiley, 1957.

MARTI-GEN: "LNG Risk Management," Paul Martino, The Aerospace Corporation, *Envionmental Science & Technology*, American Chemical Society, 1980, 1446-1454.

OTA-GEN: "Transportation of Liquefied Natural Gas," Office of Technology Assessment, Washington, DC: Congress of the United States, September 1977.

PHIL-GEN: "Safety of LNG Systems," L.L. Philipson, , *Energy Sources*, 4 (1978), 135-155.

PTI-GEN: "LNG/LPG Terminal Safety." J.J. Closner, H.J. Kuss, J.L. Lott, and J.D. Porricelli, Preload Technol Inc., Garden City, NY, 1980.

SES-GEN: "Survey of LNG Risk Assessment," Prepared for California Public Utilities Commission, Contract SA 31, Socio-Economic Systems, Inc., August 1977.

SLOV-GEN: "Facts and Fears: Understanding Perceived Risk," P. Slovic, B. Fischhoff, and S. Lichtenstein, in R.C. Schwing and W.A. Albers, Jr. (eds.), *Societal Risk Assessment: How Safe is Safe Enough*?, New York: Plenum Press, 1980.

WEIN-GEN: "Reflections on Risk Assessment," Alvin M. Weinberg, to appear in Risk Analysis.

WILS-GEN: "Risk-Benefit Analysis," R. Wilson and A. Van Horn, 1978.

VES-GEN: "Fault Tree Handbook," W. Vesely, F. Goldberg, N. Roberts, and D. Haasl, U.S. Nuclear Regulatory Commission, Report NUREG-0492, Washington, D.C., January 1981.