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LIQUEFIED NATURAL GAS: SAFETY ISSUES, PUBLIC CONCERNS, AND DECISION MAKING

Andrew J. Van Horn and Richard Wilson

ENERGY AND ENVIRONMENTAL POLICY CENTER
JEFFERSON PHYSICAL LABORATORY
HARVARD UNIVERSITY

NOVEMBER 1976

INFORMAL REPORT

BIOMEDICAL AND ENVIRONMENTAL ASSESSMENT DIVISION
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

under contract no. EY-76-C-02-0016 with the

UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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BNL 22284
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Energy and Environmental Policy Center
Jefferson Physical Laboratory
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Prepared under Contract No. 33-542-9018-2 for Brookhaven National Laboratory, Upton, New York as part of the Biomedical and Environmental Assessment Division Program sponsored by the Division of Biomedical and Environmental Research, U.S. Energy Research and Development Administration under Contract No. EY-76-C-02-0016.

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BROOKHAVEN NATIONAL LABORATORY
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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Printed Copy $6.00 Microfiche $3.00

Acknowledgments

This work forms a portion of an assessment of risk/benefit decision making by the authors which is being carried out as part of the Biomedical and Environmental Assessment Division program under Dr. Leonard Hamilton of the Brookhaven National Laboratory.

We wish to thank Elizabeth Clark, Mabel Liang and Diane Rolinski for their efforts in the preparation of this paper. We further wish to thank those who have commented on a draft version of this work, particularly Dr. Elizabeth Drake for many detailed and helpful comments.

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I. Introduction

Natural gas is an important, widely used fossil fuel which is convenient and relatively non-polluting. Because U.S. domestic supplies have been declining since 1972, suppliers have sought to import additional gas in the form of liquefied natural gas (LNG), which is 1/600 the volume of natural gas and is therefore convenient for transportation and storage. If present plans and proposals pending approval are implemented, there will be a rapid increase in the use of liquefied natural gas in the United States. The facilities required include liquefaction plants, large ocean-going tankers, import-receiving terminals, storage depots, and gas transmission pipelines. These have high capital costs and like other industrial operations have associated socio-economic and environmental impacts.

LNG is stored at -260°F and is a flammable fuel, which when spilled spreads and evaporates. If not quickly ignited, the flammable vapors generated tend to spread laterally, since they are heavier than air when cold. Thus they can move downwind as a vapor cloud. For a large spill of LNG on water (such as the contents of a ship's tank), an LNG vapor cloud may drift several miles from the site of a spill under stable atmospheric conditions, if it encounters no ignition sources en route. Hence an LNG vapor cloud is potentially more dangerous than natural gas at normal temperatures which will rise and disperse much more readily in air. In a tanker accident an LNG spill on water will not be contained. The liquid will quickly spread on the water surface until it evaporates within a few minutes, depending on the volume of the spill. In an accident on land a dike around the storage tank can contain the liquid, and the evaporation rate is limited by the surface area covered by the liquid. The vapor cloud may disperse harmlessly, or if ignited, a significant and serious fire may result.

Since LNG facilities are often sited in or near densely populated areas, the results of a very large spill could be catastrophic. Accidents involving LNG facilities have occurred, most notably in Cleveland in 1944 when 128 people were killed by the conflagration after an LNG tank collapsed. The liquid flowed into the surrounding neighborhood and ignited. Since that time considerable improvements have been made in LNG technology (including the addition of dikes around storage tanks).

Several studies have tried to estimate the small likelihood of large LNG accidents, and a number of tests have been performed to understand the behavior of LNG when it is spilled. (Despite this attention to engineering safety details, the threat of sabotage may well represent the largest risks to the public from LNG facilities.) The intent of this report is to present a description of the risks and impacts presented by LNG operations in the near future, summarize the safety issues, examine the origins of public concern in two LNG facilities siting disputes, and to suggest some of the important criteria which need to be evaluated for responsible decision making. On balance the overall risks of LNG supply systems are probably less than those of some energy systems now in use. Nevertheless, continued attention to the potential risks is needed to ensure that this remains true.

II. Recommendations

Because LNG has the potential for large accidents, it is imperative that current risk estimates be verified independently and that disagreements among model calculations be understood. Recommendations on the siting of LNG facilities are now being made by the Federal Power Commission and other regulatory bodies, and a significant decision on natural gas transportation systems from Alaska will be made by the President by September 1977. Since the basis for past decisions has not been adequately presented, future decisions should be made openly with the best information and methods. LNG can prove to be a desirable fuel source, but its use will require responsible siting policies as well as continued attention to safety. Better information and improved methods of presenting this information to decision makers is required.

The principal recommendations resulting from our studies of LNG risks and of the public participation in facilities' siting disputes may be summarized as follows:

- The number of agencies concerned with LNG terminal siting is large. Because of overlapping jurisdictions, the lack of national guidelines for siting, and the unresolved safety issues the process of approval has been lengthy. For each LNG import terminal at least eleven federal agencies and twice as many state and local bodies are involved in the approval process. These jurisdictions and the regulatory responsibilities should be clarified and a clear national policy on LNG importation established.

- National LNG terminal siting guidelines should be established, not to preempt any of the regulatory agencies, but to provide them with the information they need. These guidelines should distinguish whether they are intended to protect against fatalities, injury, or inconvenience in the event of "design basis" accidents. The guidelines should be developed in a manner such that they can be implemented by state or local agencies, who should retain the right of ultimate site approval in order to ensure that specific local conditions are taken into account.

• Our case studies have indicated that the public has encountered difficulties in obtaining reliable information about proposed facilities and that public groups, including state and local governments, often lack the financial resources and organization to obtain knowledgeable and impartial technical advice. Federal guidelines would help provide information but these difficulties will, nevertheless, persist under the current regulatory framework.

• The early presentation of feasible alternative sites and open public discussion of the costs, risks, and benefits of these alternatives prior to the gas company's selection of a "best" site would both increase the decision options and lead to greater public confidence in the selection process. The extra costs incurred in publicly presenting feasible alternatives would probably have already been repaid by speedier approval and by enhanced public acceptance of this technology.

• Roughly 10 or fewer major LNG import/receiving terminals will be required to import the volumes expected by 1985 (2 trillion cubic feet of natural gas per year). Because these are basically regional facilities an effort should be made to publicly select an inventory of suitable alternative sites within each coastal region. The risks, costs, and benefits of the best of these alternative sites should then be publicly presented, so that all relevant concerns, including safety and land use planning, may then be taken into account.

• The unresolved safety issues have been widely discussed, and it is doubtful that more safety hearings can resolve them. An accelerated research program is needed to ascertain the range of sensitivity of risk estimates to:

1. differences in vapor cloud dispersion models and choices of atmospheric stability conditions;

2. differences in selection of "peak to average" methane/air concentration ratios to define the "safe" lower flammable limit within a vapor cloud;

3. differences in ignition source distribution and in assumptions of their effectiveness in igniting a vapor cloud at different locations;

4. differences in population density surrounding tanker routes and terminal sites;

5. variations in physical phenomena such as the gravity spreading of LNG, boiling rates, and spill rates.

- Burning tests and vapor dispersion tests on large spills (up to $25{,}000 m^3$) should be used to resolve discrepancies in existing models and to investigate vapor cloud dispersion, flame shapes, and thermal radiation characteristics under different site and weather conditions. Many tests have already been performed on smaller spills.

- The structural integrity of LNG tankers under spill conditions generated by an accident or sabotage, and the resulting spill characteristics should be better determined.

- Experimental verification is needed for physical theories of superheat-limited explosions which may result from LNG spills injected into or onto water. The effects of LNG composition and mode of LNG spill in accident conditions on possible explosions need to be understood. LNG-water interactions are just one area where liquid-liquid superheat explosions are being investigated and coordination of these studies with other fields is worthwhile.

- A thorough comparison of risk estimates should be made and published.

- Transforming LNG into a semi-solid gel for use in shipping and storage might significantly reduce spill and vaporization rates. Additional research on the properties of such a gel and the engineering economics of semi-solid transportation should be pursued.

• The possibility of sabotage must be introduced into any risk assessment and considered in siting of facilities. So far, this has been largely omitted.

• Detailed contingency plans, training, testing, and review procedures, and criteria for decisions under accident conditions need to be developed and scrutinized.

• Research results should be published in the scientific literature and disseminated widely to the public before they are used to justify safety decisions. Clear discussions of the technical issues are needed.

• The risks of LNG facilities fall primarily on those nearest the facilities, yet the benefits are received by society as a whole. No one wants to live near a power plant, yet everyone wants to use the power. Siting LNG terminals in less densely populated areas would ensure that the uncertain risks are reduced and in addition would result in the costs being borne by those who use the gas. The proportional increase in already expensive LNG costs due to remote siting may be worth the enhanced public safety and may also be desirable because of its more equitable internalization of costs to those who benefit.

• Finally, and perhaps most importantly, procedures acceptable to the public for evaluating risks and benefits must be found. These should include local comparisons as well as societal comparisons with other energy and industrial facilities.

III. Summary

Background

The use of liquefied natural gas (LNG) is expected to increase rapidly in the next five years. At the moment it is primarily used as a means of storage and about 100 storage facilities exist in the U.S. Increasingly LNG will be used for transportation of imported natural gas. A number of large receiving facilities are planned or under construction on both the east and west coasts. LNG will be transported from foreign countries or from Alaska in large, specially built tankers up to 165,000m^3 in capacity to these terminals, where it is stored, vaporized, and supplied to gas transmission pipelines. It may also be stored in smaller sites as back-up gas supply for use during peak periods or when pipeline gas is curtailed.

LNG is stored at $-260^{o}F$ and is approximately 1/600 the volume of the original natural gas. It is volatile and if spilled it will quickly evaporate. An LNG vapor cloud is denser than air and can move downwind and stay flammable until it ignites or disperses harmlessly. In 1944 in Cleveland 4250 cubic meters of LNG were spilled, allowed to spread, and ignited, killing 128 persons and causing extensive property damage. Other more recent smaller accidents, particularly an empty LNG tank fire on Staten Island in 1973 in which 40 workmen perished, have aroused public concern for LNG safety. This concern is important since most large LNG facilities have been sited within or near densely populated areas, where the demand for gas exists.

Safety Issues

If LNG is spilled on land it will spread until contained by a dike. On water there is no containment. As the cold liquid evaporates it will lie close to the ground. As it is heated it will rise a few feet to form a neutrally buoyant vapor cloud thermally isolated from the ground, which can extend for several miles depending on the size of the spill and the atmospheric conditions. The cloud will be flammable when mixed with air in gas concentrations between 5 and 15%. Although the likelihood of major accidental spills is estimated to be small, the results of ignition could be catastrophic should an LNG vapor cloud drift into a populated area. Estimates of the potential fatalities from a large, accidental LNG spill near presently designed import terminals range from about 40 to 2000 lives with a likelihood of occurrence of such an accident estimated at less than one in a million per year. These estimates have been made by the Federal Power Commission and by Science Applications, Inc., among others, and depend on many assumptions because of the limited operating experience of these large facilities. Such estimates depend on the characteristics of the site and the population density around the site. Their uncertainty, coupled with the known properties of LNG, has led to concern about LNG safety.

Accidents may be caused by ship collisions on water, tank failure, perhaps due to earthquake or aircraft impact, worker carelessness, sabotage, or from other initiating events. For proposed plants at Pt. Conception, Oxnard, and Los Angeles Harbor, processing the equivalent of one billion cubic feet of natural gas per day (1 bcfd) the fatality estimates of the F.P.C., excluding sabotage, are roughly 0.005, 0.1 and 0.5 deaths per year, indicating the variability of risk estimates associated with these different terminal sites. Such risk estimates may be compared with those of alternative energy technologies with equivalent energy throughputs, although the uncertainties make this comparison difficult. For example, the energy output of 1 bcfd from an LNG vaporization plant is equivalent to about nineteen 1000MW electric power stations operating at 65% capacity factor.

Risk Estimation

Quantification of risk estimates involves first the identification and then the estimation of the probability of a sequence of events which must be calculated from existing data or from models. Since our experience with actual LNG systems is limited, most of the estimates depend on models. The calculation starts with an estimate of the likelihood of an event leading to a spill from the tanker, the LNG transfer system, the storage tank, or the vaporizing system. Then model caclulations are made of the spread and evaporation of the liquid, the atmospheric drift and dispersion of the vapor cloud, the ignition probability, radiated heat intensity, and the potential fatalities and damage resulting from this sequence of events. The final risk estimate thus comes from a multiplication of the accident probabilities and of the accident consequences. These must be reliably assessed and scrutinized. However, the effects of sabotage on risk estimates, a potentially important factor, have not been quantified in any of the existing studies. Indeed, it will be difficult to do so. Since an act of sabotage can be generated deliberately in the most unfavorable meteorological conditions, it should be considered in future siting decisions.

There are disagreements in the assumptions and results of present LNG risk assessments. Several areas need clarification and further research:

1. Calculations of the downwind distance a flammable vapor cloud may travel if not ignited. Estimates by responsible people vary from 300,000 feet to 37,000 feet under stable atmospheric conditions for a 25,000m^3 spill on water. These differences largely result from variations in the assumed "safe" methane/air concentrations within the vapor cloud. Pockets of flammable mixtures may persist in parts of the cloud where the average concentration has fallen below the lower flammable limit of 5%. The choice of a statistically safe concentration depends on the probability level taken for any remaining flammable pockets.

2. Calculations of the likelihood of an LNG detonation. It is generally

agreed that in small quantities LNG vapor is unlikely to explode in the open. It has not been demonstrated that large methane vapor clouds can propagate a detonation, even if initiated by an explosive charge. Tests at China Lake, California have been conducted in 20m diameter hemispherical balloons in so far unsuccessful attempts to detonate gas and air premixed at stoichiometric concentrations. It is thought that the finite thickness of a methane-air cloud may limit the scale of any explosion. In addition, a detonation wave may be quenched by turbulent inhomogeneities in an unconfined cloud. Further research is warranted and would be applicable to other hydrocarbon gases such as propane, butane, and gasoline.

3. Rapid, homogeneous nucleation of a film of LNG in contact with water may lead to LNG vapor explosions. It should be determined whether under some conditions occurring during a large spill from an LNG tanker, LNG-water vapor explosions might be large enough to escalate the size of the accident. (These conditions are discussed in more detail in the text.)

4. Thermal radiation estimates from large LNG fires. These estimates have been experimentally tested for confined LNG pool fires less than 80 feet in diameter, and theory and experiment are in quite good agreement over the range of the present data. Apart from the smaller uncertainties of extrapolation to larger spills, there is subjective disagreement over the numerical value of the radiated heat flux to be considered "safe" at a given distance from an LNG pool fire. 1500 Btu/hr-ft^2, which will cause extreme pain after 20 seconds to exposed skin and blistering after about one minute, is often selected as a "safe" heat intensity, since anyone exposed to this heat flux or less is assumed to be able to retreat safely.

Still others argue that 500 Btu/hr-ft^2 would be more reasonable, since it is near the threshold at which no unbearable warmth will be felt for any length of exposure and would not require retreat. This is a subjective value judgment which should be considered in determining safe separation distances for LNG facilities.

5. In order for the LNG vapor cloud to cause severe damage it must be ignited. Usually a density of probable ignition sources is assumed and a fixed likelihood for each source of igniting the vapor cloud at that distance is used to estimate the risk. The actual density and effectiveness of potential ignition sources need to be more accurately assessed.

6. Since the scale of planned facilities is greater than existing plants, it is not evident that failure rates of equipment and operational reliability will be as high as claimed, especially during the first years. Attention should be given to updating risk assessments and to understanding how the risk will change over the life of the facility.

7. Semi-solidification of LNG. If LNG could be made economically into a semi-solid gel for use in LNG tankers, the spill and vaporization rates in the event of an accident might be significantly reduced. Research into the fundamental properties of an LNG gel which is a semi-solid containing small amounts of methyl alcohol or water at -260^{o}F is being carried out at the LNG research center at MIT. Studies of the engineering and economic feasibility of using such gels in transportation or storage should now be investigated.

Because of the potentially large accidents associated with LNG facilities and the unresolved safety issues, siting in less densely populated areas should be considered. Urban siting near densely populated areas seems less desirable when alternative sites are available. Since large LNG import facilities are serving regional energy markets it should be possible to obtain sites outside of highly urbanized areas.

Public Concerns and Siting Disputes

We have discussed public concerns with a number of intervenors, regulatory officials, and attended public hearings. Public concern about general situations involving risk arises from three sources:

1. known measured risks which have occured in the past and might occur in the future;
2. potential risks of a catastrophic nature;
3. risks which conflict with strongly held values such as aesthetic, ecological, or life-style beliefs.

Any of these can serve to arouse and sustain public attention. Once this concern has been stimulated, a number of judgmental factors will determine the response, and public attention may become focused on details which otherwise might seem to be trivial in comparison to other issues.

The protracted nature of disputes on siting of energy facilities is very much related to the manner in which approval for these facilities was sought. Public confidence is greatly diminished by the difficulty in obtaining reliable information and by the seeming reluctance to let the public participate in decision making. Once they have perceived a possible change in the quality of their lives due to potential LNG risks, some of the intervenor's protests were against a decision process which didn't appear fair or seemed to violate their right to determine their presumed "best interests". When experts couldn't give definitive answers there seemed no good reason for them to approve of proposed LNG projects which apparently had substantial risks to them without corresponding benefits.

We have examined in detail the LNG facilities siting disputes in

Cumberland, Rhode Island and in Providence, Rhode Island. In Cumberland, Valley Gas Co. sought permission to build a 300,000 barrel (47,700m^3) LNG tank on its site in January 1973. The Concerned Citizens of Cumberland were worried about the hazard to the local grammar school located 1022 feet from the proposed tank. Some homes are even closer. Zoning board hearings were held August 6 and 7, 1973 after a public relations campaign was conducted by Valley Gas. Witnesses for the intervenors cited difficulty in obtaining information not yet published and questioned the safety judgments of the consultants to Valley Gas Company, who judged the facility to be safe. Details of the hearings demonstrated the nature of public concerns about LNG. The 4-1 zoning board approval was appealed to the Public Utilities Commission which held a further hearing to judge whether the facility was needed, whether it was appropriately located, and whether it would be safe. As of November 1976 no decision has been rendered.

In 1973 Algonquin LNG Inc. asked for permission to build two additional 600,000 barrel (95,400m^3) LNG tanks at Field's Point, an industrial complex 1.5 miles from downtown Providence surrounded by Washington Park, a densely populated area. The nearest home is 1800 feet from the proposed tanks. The City Council and the fire department became apprehensive about LNG risks and commissioned a study of the entire LNG import-receiving-storage terminal at Field's Point. The Federal Power Commission also performed an environmental impact review which did not consider alternative sites or make any cost-benefit analyses of the proposal. The risk estimates were only ranked qualitatively and the quantification of the risk was minimal. In 1975 F.P.C. hearings were held at which it became evident that the original approval had been given by the city before the F.P.C. environmental review without recognizing the potential risks. More stringent engineering features were recommended, and in April 1976 a new Building Board of Review voted 4-0 to let the project proceed. The City Council then voted to block the permit. The issue is still not resolved and neither the Public Utilities Commission nor the Federal Power Commission has yet ruled on the case.

These siting disputes may be repeated elsewhere as LNG operations expand. Although alternative sites were considered by the applicants in the early stages of these projects they were not then revealed to the public. In the Providence case no alternatives were revealed until after the draft environmental impact statement. These were presented publically only in written testimony at a hearing in Washington, D.C. The initial presentation of information regarding these facilities was not carried out in a manner which enhanced public confidence in either the technical judgments or the decision process.

LNG Decision Making

Because of the significant expansion anticipated for LNG operations on both the east and west coasts, decision makers need to utilize more detailed information and make use of better methods for assessing the trade-offs among the risks, costs, and benefits of the alternative options. Uncertainties in our present knowledge of LNG accident risks, in the future cost and availability of alternative fuels, in the costs of switching to other fuels, in the effects of gas curtailments on employment and productivity, in the environmental impacts and costs of LNG facilities, in the risks of unavailability of foreign LNG supplies, and in the public acceptability of LNG should be reflected in forthcoming decisions. Since the time scale of these projects is twenty to thirty years and the present costs of LNG are high, these uncertainties may be important for determining the scale of our commitment to LNG. Also, the health and low pollution benefits of natural gas in comparison to alternatives may well outweigh the high economic cost of LNG. In view of these uncertainties, some decisions for future expansion could possibly wait until some of them are resolved.

In this section factors affecting the need for LNG are discussed and evaluation criteria for siting LNG facilities are presented. It is evident from our study that state and local agencies often lack the technical expertise and finances to determine appropriate criteria for LNG facilities. The development of federal siting guidelines and of alternative regional sites for import terminals would assist this process.

A simplified analytical methodology is suggested for resolving LNG siting disputes like that of Cumberland, Rhode Island. The proposed methodology would use multi-attribute preference theory to examine the trade-offs between the reliability of the gas supply, the safety of the facility, and the overall cost. Simplified, hypothetical preferences are suggested to indicate the possible applicability of the methodology. Applying these techniques might be instructive insofar as it forces the concerned parties to focus on their most important concerns and includes public preferences in the decision process.

Finally, we discuss in this paper the natural gas supply options confronting California and national planners. The scale of California's commitment to LNG will clearly depend on the Alaska-Canada-Midwest gas pipeline decision to be made by the President before September 1, 1977, based on a recommendation by the F.P.C. Significant variables include the forecast cost of oil and alternative gas supplies, pipeline transmission costs, and the safety and reliability record of east coast LNG import terminals now beginning to come on stream. A possible decision sequence for California LNG options is suggested. Because of the magnitude and implications of these decisions, it is recommended that a detailed study incorporating the techniques of decision analysis be carried out. At the very least a better framework for quantitatively evaluating and presenting to decision-makers the costs, risks, and benefits of the possible options is required.

The environmental impacts, costs, risks, and the benefits of LNG must be considered together. Natural gas is clean and relatively non-polluting. Through improved decision-making, LNG may prove to be an acceptable source of this premium fuel.

IV. Background

The Logistics of Liquefied Natural Gas

Because domestic supplies of natural gas are diminshing, LNG, which is approximately 1/600 the volume of the original gas, provides an attractive means for transportation and storage of this fuel. There are two main functions for LNG: first, to supply natural gas for base-load use in places where there would otherwise be a shortage; second, to meet peak demands and provide security of supply. Because it is stored at temperatures of -260°F (-162°C), it requires careful handling using cryogenic technology. When spilled it vaporizes rapidly. Since its vapors are flammable and possibly explosive, and since LNG facilities contain large amounts of stored energy, there are potential risks to society in return for the benefits of this increased gas supply.

Since 1960 the liquefied natural gas industry has undergone rapid growth. LNG use for peak-shaving accounted for the initial growth of the industry, but a number of base-load facilities are planned or under construction on the west and east coasts. There are now about 57 peak-shaving plants (49 in operation), and 49 satellite storage facilities in the U.S. with storage capacities of greater than 1.9 million cubic meters of LNG. Three base-load plants are planned for Alaska (one is operational now), and 13 import-receiving terminals are proposed, with two operational, one mothballed, three under construction, and seven in the planning and approval stages [1].

Liquefied natural gas has become a significant item of international commerce. It is transported in specially constructed tankers ranging in cargo capacity up to 160,000m^3 of LNG. Large terminals for base-load storage of imported LNG have been built on the East Coast and similar facilities are planned for the West and Gulf Coasts (See Table 1). Major shipping routes exist between Algeria and the U.S. East Coast, Alaska and Japan, Borneo and

Table 1

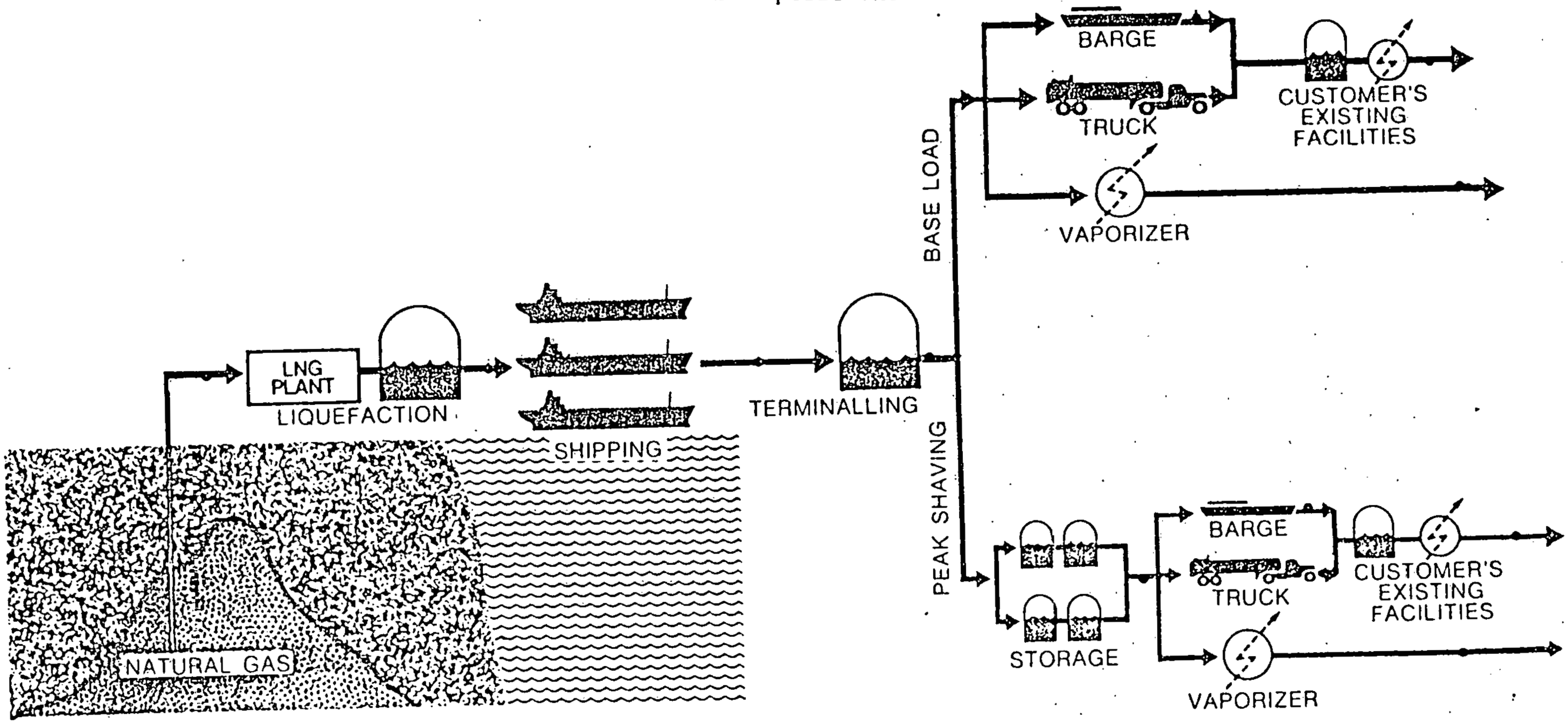
LNG IMPORT/RECEIVING TERMINALS IN THE U.S.†*

Company and Plant Site	Storage Capacity MMcf	MBbl	Liquefaction-Vaporization Capacity (MMcf/day)	Year of Operation
DISTRIGAS CORP, Everett, MA	3250	974 (1 x 374 + 1 x 600)	135	1971
PUBLIC SERVICE ELEC & GAS OF NEW JERSEY Staten Is., NY	6000	1800 (2 x 900)	360	1973-1975
COLUMBIA LNG CORP & CONSOLIDATED SYSTEM LNG CO, Cove Pt., MD	5000	1500 (4 x 375)	1000 200	1976-Base Load Plant
ALGONQUIN LNG INC. (EASCOGAS LNG, INC.) Providence, RI	6000	1800 (3 x 600)	300 375	1973-1st tank 2 add'l pending
NATURAL GAS PIPELINE CO. OF AMERICA (Peoples Gas) Ingleside, TX	5500	1600 (2 x 800)	400	1977-planned
TRUNKLINE LNG CO. Lake Charles, LA	6000	1800 (3 x 600)	---	1977-planned
NORTHWEST NATURAL GAS CO., Newport, OR	1200	348	100	1976-under construction
WESTERN LNG CO. Terminal Is., Los Angeles Harbor, CA	7700	2200 (4 x 550)	400 (5000)	48 mos. after approval
SOUTHERN ENERGY CO. Elba Island, GA	4000	1200 (3 x 400)	540	1976-under construction
TRANSCO TERMINAL CO. Racoon Is., NJ	6000	1800 (3 x 600)	---	1977-planned
WESTERN LNG CO. Oxnard, CA	3850	1100 (2 x 550)	520 (2300)	48 mos. after approval
WESTERN LNG CO. Pt. Conception, CA	7700	2200 (4 x 550)	3300	48 mos. after approval
PHILLIPS-MARATHON* Kenai, AK	2300	675 (3 x 225)	90	1969
EL PASO ALASKA Pt. Gravina, AK	6000	2200 (4 x 550)	3375	1980-planned
PACIFIC ALASKA LNG* CO., Cook Inlet, AK	3000	1100 (2 x 550)	400	1978-planned

*includes three liquefaction plants and storage for export in Alaska.
†Pipeline and Gas Journal, Annual LNG Issue, June 1976, p. 21.

FIGURE 1.

LNG Operations



FROM: D.L. Katz, and H.H. West, "The Overall Problem--Risk/Benefit for LNG Shipping and Storage." Presented at the Engineering Foundation Conference on Risk/Benefit Methodology and Application, Sept. 21-26, 1975 , [19].

Japan, Algeria and England and France, Libya and Spain and Italy. Proposed trade routes are from the Persian Gulf to India and Japan, Nigeria to the U.S., Europe and Brazil, Alaska to the U.S. West Coast, the Caribbean via Venezuela to the U.S., Ecuador and Chile to the U.S. West Coast, and New Guinea to the U.S. West Coast and Japan. By 1980 LNG trade internationally is expected to account for 6% of the world's natural gas consumption and by 1990 the U.S., Japan, and Europe will be importing about 20 billion cubic feet per day (20 bcfd=$0.57 \times 10^9 m^3$/day) of natural gas in the form of LNG. By 1980 3.2 bcfd or $90.6 \times 10^6 m^3$/day may be imported from Algeria into east coast ports. This would entail about one large tanker arrival each day. Proposals to transport 3.7 bcfd into Southern California (0.55 bcfd from Indonesia and 3.2 bcfd from Alaska) are presently under consideration. The Energy Resources Council has suggested an upper limit of 2 trillion cubic feet per year for U.S. imports of LNG, about 10% of the total expected gas demand by 1985. However, the LNG industry would like to supply more than this amount and projects to import over 3 trillion cubic feet per year are pending or in the planning stage [61].

Bringing LNG to market is highly capital intensive and involves a number of operations (Figure 1):

1. Exploration, exploitation, and collection of the natural gas;
2. Purification, liquefaction, storage, loading, and shipping;
3. Ocean transport in LNG tankers;
4. Receiving at terminals near deep water ports, storage or transport by barge or truck to other storage facilities, revaporization and transmission via the gas pipeline system.

Operations in the first two categories listed above usually take place overseas (with the notable exception of Alaska) and are, therefore, less subject to public concern in this country. The average price of an LNG tanker of

Table 2. System Description and Economic Costs and Benefits of the LNG Receiving and Vaporization Plant at Oxnard, CA. (Ref. 21)

I. System Description

A. Natural Gas Output

1. Baseload - .55 billion cubic feet per day (4 bcfd ultimate)
   5 Seawater Vaporization Units (36 ultimate)

2. Peaking - .45 billion cubic feet per day (1 bcfd ultimate)
   4 Peaking Vaporizers (10 ultimate)

3. Total peak output - 1.00 billion cubic feet per day (5 bcfd ultimate)

B. Storage Tank Capacity - 2 @ 550,000 barrels of LNG = 3.85 billion cubic feet of Natural Gas.

C. Gas Transmission Pipeline

1. Length - 12.2 miles (53.3 ultimate)

2. Diameter - 42 inches

D. LNG Tankers

1. Ship capacity - 130,000 cubic meters of liquefied natural gas ≅ 2.84 billion cubic feet of natural gas.

2. Fleet size - 9 (21 ultimate)

3. Annual tanker arrivals - 75 (443 ultimate)

E. Land Requirements

1. Receiving terminal and plant - 38 acres (55 ultimate)

2. Pipeline - 37 acres (485 ultimate)

II. Costs

A. Initial Capital Outlay for Construction

1. Plant - $200 million

2. Pipeline - $14 million

3. Tankers - 9 @ $167 million ≅ $1.5 billion

B. Operation

1. Operating staff salary (annual) - $545,000

2. Taxes (annual) - $7 million

III. Benefits

A. Employment

1. Construction

a. Labor Force - 1260

b. Payroll - $50 million

2. Operation

a. Labor Force - 29 for present proposed operation (90 ultimate)

b. Payroll - $545,000

B. Increase in Local Tax Revenues - $7 million/year

C. Disposable income over 20 year lifespan of facility > $8.3 million ($27 million if ultimate capacity of 4 bcfd is reached)

125,000m^3 capacity is over $100 million, and by 1985 the cumulative investment in LNG has been forecast as about $18 billion [2]. Table 2 gives typical economic costs and benefits for the proposed import facility at Oxnard, California.

LNG Accidents

Because LNG is volatile, very cold, and its vapors are flammable and potentially explosive, it presents risks to those who must handle it and to the general public as well. These risks have gained public attention largely through four principal accidents. The largest LNG accident occurred on October 20, 1944 in Cleveland, Ohio, when one of four storage tanks failed and rapidly released 4250 cubic meters of LNG. Because there was no dike or berm surrounding the tank to contain the spilled LNG (as is now required) it flowed into the streets and sewers. The LNG was ignited and where confined in pipes or buildings, it exploded. Flames burned half a mile high. Altogether, 128 people died, 300 were injured, 80 houses and 10 industrial plants were seriously damaged. Because of the destruction the exact cause of the accident was never discovered, but it is generally agreed that inadequate diking, poor tank location, and the wrong choice of metal for the tank were major contributors. The most probable direct cause was the use of a 3% nickel steel alloy for the tank construction. The metal became brittle at low temperatures and collapsed [3,4]. Today a 9% nickel steel alloy, which was developed for fusion welding, is used in order to provide the necessary fracture toughness down to liquid nitrogen temperatures (-320^{o}F). The LNG industry believes that a disaster of the magnitude of the Cleveland accident could not be repeated today because of improvements in technology and design. There is no question that today's facilities are safer. But how safe?

Three more recent accidents involving LNG facilities were: (1) The explosion and fire in Texas Eastern's LNG storage tank on Staten Island in

February 1973; the accident occurred during repair of the aluminized mylar lining which had developed leaks during two years of service. The tank had been emptied of LNG for one year, and the tank lining was under internal repair. The supposedly non-flammable insulation material caught fire, hot combustion gasses overpressurized the tank and lifted the roof, and forty workers who were trapped in the tank perished [5]. (2) The tank explosion at the Northwest Natural Gas Facilities in Oregon, during construction of the tank, before LNG was introduced, which caused four deaths. This incident was probably due to careless work practice and was not directly related to LNG [6]. (3) In 1972 a conflagration took place in the control room of an LNG plant in Montreal, Canada. The fire was initiated by the entry of leaking natural gas through an air line. Since the control room is an important part of the plant safety system, the fire was potentially more serious than if it had occurred in another building [7].

These accidents are a reminder of the risks of accidents associated with LNG. The LNG industry feels "that the Staten Island and Northwest incidents should be discounted because LNG was not directly involved" [8]. Although the Northwest accident was due to carelessness in construction, the selection of a flammable tank lining for the Staten Island tank raised doubts about the safety standards of the industry.

The accidents mentioned above, in addition to minor incidents, which are not always reported, clearly indicate that safety should be a foremost consideration for LNG facilities. Indeed, the LNG industry has long recognized the need for conscientious implementation of the latest safety measures, and in comparison to some other industries its safety record is good.

Experience in handling other cryogenic liquids has led to increased LNG safety, and considerable research has been undertaken to determine the properties of LNG. However, when it comes to building or operating any specific

LNG facility, economics, politics, current practices and regulations, existing plants, worker competence, siting policies, and numerous other factors all influence the actual risks and benefits. In the following sections of this report we shall examine some of the issues surrounding the impacts of LNG facilities.

Environmental Impacts of LNG Operations

LNG facilities and their associated pipelines can have substantial environmental impacts, particularly related to their construction effects and land use during the facility lifetime. These have been enumerated, usually qualitatively, in the massive volumes which compose environmental impact statements. Unfortunately there exists in most of these reports no succinct summary of these effects or even of the proposed parameters. These reports are typically very badly organized, so that any useful data is buried. Table 3 is our attempt to list the major environmental impacts of the proposed Alaska-California LNG transport system and an import terminal as given in References 21, 57, and 58. Where possible we have tried to scale the impacts to a throughput of 1 bcfd of natural gas. Many of these effects can be considered representative of other LNG facilities, although the impacts are obviously site specific. Despite the massive volume of the several environmental impact statements, this summary indicates that not all pertinent information is given.

Table 3. Major Environmental Impacts of LNG Facilities Proposed for Alaska and California (Ref. 21, 57, 58)

I. Effects on Water Bodies

A. Construction

1. Dredging for Port or Docks

a. Reduces concentration of dissolved oxygen in the water.

b. Increases amount of suspended contaminants (especially hydrocarbons and heavy metals) which have been released from the sediment.

c. Temporarily reduces photosynthetic activity.

2. Salinity - may be altered slightly during construction.

3. Effects on Marine Biota

a. Temporary elimination of plants and animals from dredged area.

b. Habitat changed.

c. Zooplankton and other organisms killed.

B. Operation

1. Heating and Cooling of Discharge Water

a. ΔT - Temperature change
1. liquefaction +21°F
2. revaporization - 5°F to -9°F

b. Effects on Marine Biota - lethal or sublethal effects on plankton, larvae and juvenile forms of fish and shell fish.

2. Waste Discharge into Water

a. Acrolein (used within cooling system to prevent fouling by marine animals, detoxified) - .57 to 1.57 ppm/bcf NG processed.

b. BOD_5 - 0.001 tons/bcf NG processed.

c. Phosphate (PO_4^{-2}) - 0.004 tons/bcfNG processed.

d. Chloride (Cl^-) - 0.030 tons/bcf NG processed.

e. Oil - 0.003 tons/bcf NG processed.

f. Suspended solids - 0.013 tons/bcf NG processed.

g. Total dissolved solids - 0.130 tons/bcf NG processed.

3. Consumptive Use of Water

a. Liquefaction - 306 million gallons/bcf NG

b. Revaporization - 450 million gallons/bcf NG, 170,000 gal/min.

c. Sanitary and domestic uses - 3100 gal/day.

d. Dust control during construction - 20,000 gal/day.

e. Hydrostatic test water - 11.5×10^6 gal/tank.

II. Effects on Ground Water

A. Construction Traffic - deeper thawing of Alaskan permafrost with significant impact on ground water drainage

B. Frostbulb formation around pipeline - blocks subsurface drainage (AK)

C. Site dewatering for plant may dry up adjacent salt water marsh (CA)

III. Effects on Air Quality (partial list only from indicated references)

A. Emissions from pipeline compressor stations

1. SO_2 - .11 tons/bcf NG
2. NO_x - 7.3 tons/bcf NG
3. CO - .42 tons/bcf NG
4. Excess heat - 1.05×10^{11} Btu/bcf NG

B. Vaporization Facility Emissions

1. NO_2 (worst concentration 0.04 ppm, annual average less than 0.001 ppm)

C. Emissions from ship's boilers

1. SO_2 annual average for continuously moored tanker $-8 \mu g/m^3$.

D. Specific Ramifications - e.g. even small amounts of SO_2 reduce lichen growth on trees thereby having a detrimental effect on indigenous caribou and other lichen eating animals.

IV. Electric Power Consumption

A. Average 12 to 25,000 kilowatts/bcfd. About 100×10^6 kWh/(yr - bcfd).

V. Effects on Land

A. Topological Alterations

1. Alaska - permafrost degradation and removal of granular borrow for pipeline base may result in erosion, soil subsidence, change in drainage patterns, slope failures.
2. California - site grading may have significant topological effects.

B. Roadways and Increased Traffic

1. Alaska - degrades permafrost.
2. California - impaction of fragile desert vegetation. Also, increase in use of 4 wheel drive recreational vehicles from improved access roads.

C. Disruption of Local Plant Life

1. Alaska
   a. Forest and woodland vegetation would not be allowed to grow over pipeline.
   b. Increased danger of forest fires.
2. California
   a. Impaction of grasslands, cultivated lands, orchards.
   b. Elimination of vegetation from plant site and pipeline route.
   c. Saltmarsh drainage and destruction.

D. Disruption of Local Animal Life

1. Disruption of life cycles for all animal species within plant and pipeline area.
2. Added risk to endangered species (e.g., San Joaquin kit fox and California least tern in CA).
3. Increased access of hunters to caribou, deer, etc.

E. Disruption of Archeological and Historical Sites - Without comprehensive field surveys this cannot be known with certainty but areas under consideration potentially contain Indian artifacts and so present the possibility of vandalism and artifact removal.

F. Erosion - Improper release of hydrostatic testing water could result in severe erosion which could lead to ground shifting and pipeline rupture.

G. Noise Effects

1. Noise from compressor stations audible within 6000-7000 ft. radius.
2. Added noise levels may further disrupt life cycles of animals especially in the hitherto undisturbed Chugach National Forest.

VI. Gas Throughput Efficiency of LNG Operations

	Gas Throughput Efficiency (%)
LNG Liquefaction	83.0
Volume of LNG delivered from shore facilities to tanker (% of vessel capacity)	99.0
Gas loss during loading operations	1.0
Volume of LNG loaded	98.0
LNG boil-off during voyage (at 0.2-0.3% of vessel capacity per day)	~2.0
LNG heel retained for return voyage	3.0
	95.0
LNG tank storage (less than 0.1% per day loss)	99.7
LNG re-vaporization (gas-fired)	98.0+
Overall Gas Throughput Efficiency to Pipeline	~76.0+

V. Safety Issue Summary

Properties of LNG

Liquefied natural gas consists primarily of methane (95%), with smaller amounts of ethane (3%), propane (1%), nitrogen (0.5%), and heavier hydrocarbons (0.2%). The exact composition depends on that of the original natural gas. Although most contaminants are removed prior to liquefaction, traces of sulphur compounds, carbon dioxide and water may remain when the gas is liquefied to 1/610 of its original volume at $-259^{o}F$. A typical peak-shaving LNG (Table 4) has a molecular weight of 16.8 amu, a density of 27.2 lb/ft^3, a heating value of 1020 Btu/SCF and a specific gravity of 0.4. It is insoluble in water. LNG differs from liquefied petroleum gas (LPG) primarily in the constituents of the mixture. LPG consists mostly of heavier hydrocarbons (usually propane and butane) and has similar safety problems. Because it is stored under pressure at ambient temperatures and the vapor is explosive even in open spaces, LPG is probably more dangerous than LNG, which is stored at at atmospheric pressure [9].

LNG, LPG, and other hydrocarbons such as gasoline and kerosene all burn rapidly with an intense fire, and these fires are similar. At first sight, it would seem that LNG and LPG are no more dangerous than gasoline (which is dangerous enough). Table 5 lists the physical properties of LNG and gasoline. If contained in a confined space natural gas vapors from LNG can react explosively. In the proper mixture of LNG vapor and air, the vapor can burn, releasing large amounts of heat. LNG can also cause asphyxiation and freeze burns to those in the immediate vicinity, but these are relatively minor risks. In comparison with gasoline, the additional danger of LNG and LPG arises from their rapid evaporation and the spreading over large distances of the combustible vapor, which can occur in minutes, depending on the size of the spill.

TABLE 4

Physical Properties and Constituents of LNG*

	Methane CH_4	Ethane C_2H_6	Propane C_3H_8	Iso-Butane C_4H_{10}	Normal Butane C_4H_{10}
Composition of typical peak shaving LNG (mole %)	95.9	2.5	0.9	0.12	0.15
Composition of typical Algerian LNG (mole %)	87.4	8.4	2.4	0.5	0.7
Molecular weight	16.04	30.07	44.09	58.12	58.12
Melting point °C (1 atm)	-182.5	-188.3	-187.7	-159.6	-138.3
Boiling point °C (1 atm)	-161.5	-88.6	-42.2	-11.7	-0.6
Liquid specific gravity (at boiling point)	0.425	0.550	0.580	0.562 (normal	0.581 temperature)
Gas specific gravity (air = 1)	0.554	1.038	1.522	2.006	2.006
Critical temperature °C	-82.1	32.4	96.8	135.0	152.0
Critical pressure (atm)	45.8	48.3	42.0	36.0	37.5
Evaporation latent heat (Kcal/Kg)	121.9	116.0	101.7	87.5	92.1
Total calorific value	9,520	16,820	24,320	31,530	32,010
Natural ignition temperature °C	537	--	466	--	405
Heated gas ignition temperature °C	1,325	--	990	--	990
Combustion range in air %	5.0-15.0	3.0-12.5	2.1-9.4	1.8-8.4	1.9-8.4

$1 m^3$ of LNG @ BP ≃ 22.35 x 10^6 B.t.u. of natural gas at STP (1020 Btu/ft^3); 1 barrel (1 bbl) = .159m^3 ≃ 3.57 x 10^6 B.t.u. = 42 U.S. gallons. The B.t.u. equivalent will vary somewhat with the composition of the gas.

*National Academy of Science, Proceedings of Conference on LNG Importation and Terminal Safety, Boston, June 1972, p. 262 (Washington, D.C.: The Academy, 1972)

TABLE 5

Physical Properties of LNG vs. Gasoline
(Ref. 13)

	LNG	Gasoline
Boiling Point (1 atm)	-258°F	100-300°F
Ratio Gas Volume (STP)/Liquid Volume	615	220
Heat Content (BTU/ft^3) gas at STP	1020	4400
Heat Content (BTU/m^3) liquid	22.4×10^6	35.3×10^6
Flame propagation velocity (ft/sec)	1.28	1.25
Combustion heat radiated during pool fire(%)	~15-30	~30
Ignition temperature (°F)	999	495
Flammable limit in air (upper %)	14	7.6
Flammable limit in air (lower %)	4.8	1.4
Liquid Density (H_2O=1)	0.42	0.70

A contributor to the likelihood of LNG spills is its very cold temperature. At very low temperatures some metals become brittle and should LNG come in contact with materials not specifically designed for low temperature service, fracture failure may result. This was what occurred in the Cleveland accident, and this is one of the chief concerns in a collision involving an LNG tanker. "Because of the brittle behavior of steel [of the type used in ship hulls] when cooled to LNG temperature, the puncturing of one tank in a vessel by collision or grounding could lead to the cooling and the fracture of adjacent tanks, propagating the failure to both ends of the vessel" [10]. The tanks themselves will not suffer brittle failure since they are already cold and made of special metal alloys, but it is possible that the structural members of the hull which are under stress may be subject to fracture failure under accident conditions. A more thorough analysis of the behavior of LNG tankers under accident stresses is needed. Self supporting (free standing) tanks for LNG tankers may be less easily damaged than the cheaper membrane containment used in some tankers.

A spill of 25,000m^3 or only one of five tanks is considered more likely than larger spills. However, for a spill of 100,000m^3 on water, most of a large tanker's contents, "a vapor cloud 1km in radius and 6m deep would be formed in less than 15 minutes." [12]. The possible consequences of such an LNG spill are potentially disasterous if the vapor cloud were to drift into an inhabited area and ignite. Since major LNG facilities are in or near large cities, such an accident is conceivable. There has been considerable contention over the probability of such a sequence of events.

If there is an LNG spill on water or land, the liquid will evaporate as fast as heat transfer from the substrate allows. If the spill is contained, such as by a dike or berm, then the land beneath will freeze and evaporation will be slowed. If, on the other hand, the spill is on the sea, it cannot be easily contained. The LNG will chill the water immediately below, and will spread laterally on the surface. The cold gas is denser than air and when methane and dry air are mixed adiabatically, the vapor will lift from the water and drift as a negatively buoyant cloud until dispersed by diffusion and wind. The gas will be flammable at the edges of the cloud, where the LNG/air concentration is between 5 and 15%. There may be pockets of inflammable gas distributed for miles depending on the size of spill, siting and atmospheric conditions. These general characteristics have been outlined by a number of authors [11-17]. These papers seem to be in general agreement, but there are nonetheless widely differing estimates about the distance an LNG vapor cloud will travel and remain flammable.

A cloud of LNG vapor "could have dimensions of a few miles long by a few miles wide. For an extended vapor cloud to form, it is necessary that no ignition source be present in the cloud. Most of the postulated large releases are due to collisions with the ship or barge transporting the LNG. Almost inevitably such a collision provides sparks enough to ignite the clouds at the source and thus prevent its spreading. If this failed to happen, once the cloud reached a populated region, it would surely be ignited for there is a high density of ignition sources in populated areas. Thus, if unignited at the source, the cloud could spread over water, but would not be expected to penetrate into populated areas without ignition. Once ignited, the forward progress of the cloud would stop, and it would burn back towards the source. Although the possibility of a large cloud formation is very small, it represents the hazard capable of producing the most damage to life and property." [18].

Research on LNG Safety

Considerable research on liquefied natural gas safety has been carried out [19]. Some rudimentary quantitative risk assessments have been attempted for east coast LNG terminals. However, a comprehensive risk assessment did not exist until a December, 1975 study of the risks of a proposed LNG terminal in Los Angeles Harbor was performed by Science Applications Inc., for Western LNG Terminal Company [20]. This assessment represents the first thorough effort to quantify failure probabilities and examine the likely consequences of LNG accidents, but it still contains important shortcomings. Each major spill system was subjected to fault tree analysis: the tanker, the LNG transfer system, the storage tank, and the vaporizing system. A number of initiating events including ship collisions, natural events such as earthquakes, operational and material failures, aircraft hazards and other sources of failure were considered. For each possible spill, model calculations were made to quantify the LNG spread and evaporation, the atmospheric dispersion of the vapor cloud, the ignition probability, radiated heat intensity, and potential fatalities and damage. A probability for each accident sequence and the resulting consequence was then obtained.

The reliability of risk estimates of this type depends both on the experimental data base and the accuracy of the models used. There are a number of places where this detailed study might be criticized, but on the whole it represents a large step towards understanding overall LNG risks. Some of the results of this study for the L.A. Harbor estimate failure probabilities per year for the ship's sidewall as 1.2×10^{-6} caused by craft or missile impact when moored on site and 4.9×10^{-3} from ship transit collisions in Los Angeles Harbor. The probability of an LNG storage tank and dike being breached is calculated as 1.2×10^{-6} per year from aircraft impact. According to this report the earthquake risk is 10^{-14} per year, which implies that a quake of sufficient magnitude to destroy the tank and dike would occur only once in one hundred trillion years. For California this seems low. (Certainly it is difficult to have confidence in any estimates of this size. The age of the earth is on the order of 5 x 10^9 years.) When these failure probabilities are multiplied by probabilistic estimages of spill consequences, the likelihood of fatalities per year has been estimated. The S.A.I. estimates for L.A. Harbor are given in Table 6. Other estimates of risk probabilities from various sources are presented in Table 7. These examples may exclude certain sources of risk, such as the effect of secondary fires or the risks due to sabotage. In general, probability estimates of 10^{-9} and below are not to be taken literally. It is unfortunate that S.A.I. chose to present their calculations to this degree of accuracy. Small factors need to be examined in detail, since common mode failures, other accident sequences, or design failures are more likely than 10^{-10} per year. No estimates of the probability of sabotage were included, and in these days saboteurs with explosives cannot be so easily dismissed. More thorough attention should be paid to the risks of sabotage since these are probably greater than the foreseeable engineering risks.

Significant sources of uncertainty among various LNG risk estimates arise from different scenarios involving LNG spills. Varying spill rates and the characteristics of the surface (including soil type, density, porosity, and moisture content) lead to different conditions for the spreading and evaporation of an LNG pool. Weather conditions, details of the vapor cloud dispersion model, and the criteria for statistically safe concentrations of residual flammable gas pockets will influence the downwind travel distance estimated. If the population at risk is not distant from the spill location, the risk will be primarily related to the width of the hazard zone, the probability of ignition, and the intensity of the resulting pool or vapor fire.

Mathematical models have been developed to describe these characteristics. Extrapolations are involved for estimates of large spill behavior, since the experimental tests have been much smaller than the potential spill size for an entire storage tank. There is disagreement among the models as

TABLE 6

Science Applications, Inc. Fatality Estimates for L.A. Harbor LNG Terminal (Ref. 20)

Probability of Occurrence of Calculated Fatality Levels, for the 400 Million ft^3 Per Day South Alaska Project.

Fatalities	Probability of Occurrence Per Year, All Cases
1 - 100	1.2×10^{-7}
100 - 1,000	8.7×10^{-8}
1,000 - 2,000	7.3×10^{-8}
2,000 - 10,000	1.7×10^{-8}
10,000 - 20,000	4.9×10^{-12}
20,000 - 30,000	7.0×10^{-16}
30,000 - 40,000	8.2×10^{-25}
40,000 - 50,000	5.9×10^{-33}
Maximum 42,000	6.9×10^{-37}

Table 7. Examples of LNG Risk Estimates
(Ref. 20, 21, 57)

I. Accident Description

A. Spill on water--LNG rapidly spreads and evaporates. If ignited, a pool fire may result, or the vapor may move downwind to the land and be ignited, or it may disperse harmlessly before ignition. For those caught outdoors within the burning cloud, fatality is approximately 100%. In daytime 20% of the population is assumed to be outdoors. Property damage will occur.

B. Spill on land--should be confined within dike surrounding tank. Danger from radiated heat from fire if ignited.

II. Sources of Spills With Varying Consequences

A. Internal causes (this list is not intended to be complete--pipe failures will have limited spills; tank failures can be much larger.)

1. Valve rupture probability $\sim 10^{-8}$/hour

2. Tank rupture probability $\sim 10^{-6}$/year

3. Automated valve failure 1×10^{-3}/demand

4. Automatic shutdown failure 1×10^{-4}/demand

B. External causes (dependent on the site)

1. Natural Hazards

a. Earthquakes--Although all plants proposed in California are at most 2 miles from a major fault, and their pipelines often cross faults over 20 times, the S.A.I. probability for a major accident due to earthquake activity is 10^{-14} per year.

b. Hurricanes and high winds--Plants are structured to eliminate severe stress due to wind loading. Early storm warnings will allow for the evacuation of tankers and the emptying of ship-to-tank transfer lines which might be affected by the storm.

c. Tidal waves (tsunamis)--LNG plants are built in protected harbor areas. While tsunamis are a possibility in southern California, they present no major risk to the LNG plant.

2. Man-made

a. Airplane crash into plant: annual probabilities--LNG storage tanks 2.5×10^{-4}, major pipelines 5.2×10^{-4}, LNG tankers 1.5×10^{-4}/year.

b. Tanker collision--estimated accident of any kind 0.331 per year or 0.00165 per bcfNG. Rupture probability 0.005/year.

c. Sabotage (Potentially important, but not quantified).

III. General Risk Probability (strongly dependent on the site and surrounding population density, and are subject to disagreement)

A. Probability of plume reaching land unignited--1.2 x 10^{-4}/year or 5.9 x 10^{-7} per bcfNG

B. Estimated human fatalities--0.013 to 0.20 per year or about 20 x 10^{-5} per bcfNG

C. Expected frequency of one fatality--about 1 per 25 years or 1 per 5 x 10^{3} bcfNG

D. Maximum fatalities in large accident--40-2000 [$\approx 10^{-7}$ per year] to the distance to the lower flammable limit (LFL) of the vapor cloud. Under the most stable atmospheric conditions the distances to LFL for a 25,000m^3 spill of LNG, about 1 tankful on an LNG tanker with five tanks, vary from 300,000 feet (Fay, M.I.T.), to 200,000 (Burgess, Bureau of Mines), to 37,000 feet (American Petroleum Institute) [21]. These differences arise principally from the use of different peak to average concentration ratios in setting a criterion for safe dispersal, from the use of neutral atmospheric weather conditions rather than very stable conditions, and from lesser factors including different assumptions about the buoyancy of the vapor cloud and different physical models for LNG evaporation, spreading, and dispersal. Until a thorough comparison is made and published, it is difficult to establish the correctness of a particular model, especially when the experimental data are for much smaller spills.

The distance to the lower flammable limit of the vapor cloud should be set to take account of localized flammable pockets in parts of the cloud where the average concentration is below the nominal flammable limit (5%). S.A.I. concludes that for large vapor clouds the peak concentration will exceed the mean value by factors of 1.1 to 1 and 1.2 to 1, not by 2 to 1, or 10 to 1, or 20 to 1 as hypothesized from some experimental tests. A plausible explanation is offered for the differences between the experimental interpretation and their model calculations, but this should be independently verified. Even if the different models agreed, stochastic variations in concentration can still occur and the choice of the LFL designated as "safe" depends on the confidence level presumed for the existence of a flammable pocket within that portion of the cloud.

Other topics of importance for further research on LNG safety include:

1) Detonations in unconfined vapor clouds. Detonations of gas clouds are potentially more dangerous than simple ignition of a vapor

cloud, as evidenced by accidental liquid propane explosions [9]. For confined methane vapor clouds explosions are possible, but for unconfined methane large explosions have not been observed [23]. The U.S. Coast Guard has sponsored tests at China Lake in an attempt to detonate stoichiometric mixtures of methane and air in 60 foot diameter balloon hemispheres. High explosive initiators as large as 2kg were used, but no detonations were observed. The effects of stratification and inhomogeneities and possible effects of scale in LNG vapor clouds need to be determined by further research.

2) Liquid-liquid vapor explosions. When a hot liquid is poured onto a cold liquid there is the possibility of a rapid transfer of heat (thermal energy) to mechanical energy. The question arises, do real situations occur when the mechanical work approaches the thermodynamic maximum and can this work be performed so rapidly that the forces are large or so that a chemical explosion is initiated, thus magnifying the effect? It seems that the answer to these questions is no, but not with the certainty we would like to have.

There have been a number of examples of vapor explosions as one hot liquid falls on a colder liquid and in several instances these have been destructive. Vapor explosions have been observed for molten aluminum on water, molten steel on moist ground, molten lava upon water, sodium on molten uranium oxide, freon R22 on mineral oil or water, and LNG on water. This field of research was reviewed in 1971 by Witte [22], and the potential explosion hazards have been discussed in references 24-29. The most recent review of hydrocarbon vapor explosions by Porteus and Reid states that "new experiments have shown that, under the proper conditions, explosions may be obtained in cases where previous investigation reported that none were possible"[29d]. The likelihood of LNG-water explosions changes with the composition of the LNG and with the manner in which the LNG and water are brought into contact. Although the energy release itself may not be damaging, at the least, LNG vaporization rates would probably increase substantially should vapor explosions occur.

To obtain a rapid enough energy release to cause major damage by an LNG-water explosion, there must be a mechanism for the rapid formation of vapor, and the LNG must be finely fragmented into droplets. Vapor explosions are now thought to arise from the creation of a superheated film of the LNG upon the contact of water and LNG. As the temperature rises, the spontaneous homogeneous nucleation of this superheated film may occur, followed by a rapid flashing into vapor. An initial small explosion might cause fragmentation of the LNG, and create a large surface area; subsequently a larger volume of superheated film might explode.

The conditions described by Henry [27a] and by Reid [29c] for a superheat explosion on the mixing of two liquids can be graded in order of importance and certainty:

a. the two liquids must be in close contact and not have an intervening solid or vapor phase.

b. the temperature at the interface between the two liquids must be greater than the temperature at which homogeneous nucleation takes place in the bulk of the liquid without a nucleation site. The process of homogeneous nucleation defines the <u>superheat limit</u> (T_{SL})--the highest temperature at which the superheated liquid can exist. Only at this temperature or above can nucleation occur rapidly enough to form an explosion.

c. if the temperature of the hot liquid is below the homogeneous nucleation temperature, T_{SL}, no explosion seems to occur under any circumstances in agreement with item b. The interface temperature when one liquid is poured onto another seems well calculated by assuming contact of two infinite plane slabs. Then the interface temperature (T_i) is given by

$$\frac{T_H - T_i}{T_i - T_c} = \psi = \sqrt{\frac{k_c \rho_c C_c}{k_H \rho_H C_H}}$$

where T, k, ρ, C are the temperature, thermal conductivity, density, and heat capacity, and subscripts c and H signify the cold and hot liquids. For water poured on LNG T_i is only 5^oK to 20^oK below the temperature of the water.

d. if $T_i < T_{SL}$ there will be no explosion on pouring one liquid onto another. However, if $T_H > T_{SL} > T_i$ some droplets of the cold liquid may warm up until the interface temperature reaches T_{SL}. Then a delayed explosion can occur. (This is not relevant for the LNG case, because T_i and T_H are both greater than T_{SL}.)

e. if $T_i >> T_{SL}$, vapor bubbles can suppress explosions. This is not a rigid condition, since it depends critically upon the method of bringing the two liquids into contact. Pure methane has not been observed to explode when poured upon water, but when impacted upon the surface at high velocity it can explode. LNG compositions which are not normally considered explosive might explode if impacted. For LNG-water vapor explosions: $T_H = 293^oK$; $T_{SL} = 166^oK$; $T_H/T_{SL} = 1.76$; $T_i/T_{SL} \simeq 1.68$.

In most discussions of vapor explosions in industry, it is the first condition that is relied upon to prevent an explosion. Thus, in a hypothetical core disruption accident of a liquid metal fast breeder, T_{SL} for sodium is about 2100°K; T_H = 3500°K is the temperature of molten mixed oxide fuel, but the interface temperature for the bulk of the uranium oxide/sodium interface is less than 2000°K because of the high thermal conductivity and heat capacity of the sodium. Explosions could only occur with small amounts of trapped sodium. Even so, LMFBR safety is questioned on this ground, and intensive international research continues.

However, for liquid hydrocarbon spills upon water the last criterion is the only one which stops an explosion. If an LNG ship were to collide, and a tank were broken open, we can with our present limited knowledge imagine entry of water into a tank followed by boiling and pressure buildup. The pressure might then impel LNG into the sea, causing a vapor explosion. This course of events was not deemed possible in 1972, but the experiments of Porteous and Reid bring it into the realm of small but non-zero probabilities [29d].

It is not clear how much energy would be released in such a vapor explosion or whether it would be damaging. Nevertheless, the pressure buildup within one of the ship's LNG tanks followed by LNG-water vapor explosions would substantially increase the vaporization rates of LNG. It is possible to envision a scenario where the vapor buildup and expulsion of LNG into the water oscillates with the process of sea water flowing into the emptying tank. Even if the LNG-water explosion itself did not cause damage, the more rapid formation of vapor could lead to a much more intense fire if ignition were to occur. Further research is clearly needed, both on liquid-liquid vapor explosions under these conditions and on the potential behavior of LNG in the event of a ship's tank rupturing.

3) Phase change pressurization due to stratification and "rollover" [30]. Since LNG is a mixture of several hydrocarbons, stable layers of different composition can form. As the two layers absorb heat differently and approach the same density, a sudden release of vapors may occur, leading to a pressure pulse. Storage tanks are now designed to withstand this. Relief values and adequate mixing can also deal with this problem. For this reason it is important to know the precise composition and age of LNG shipments.

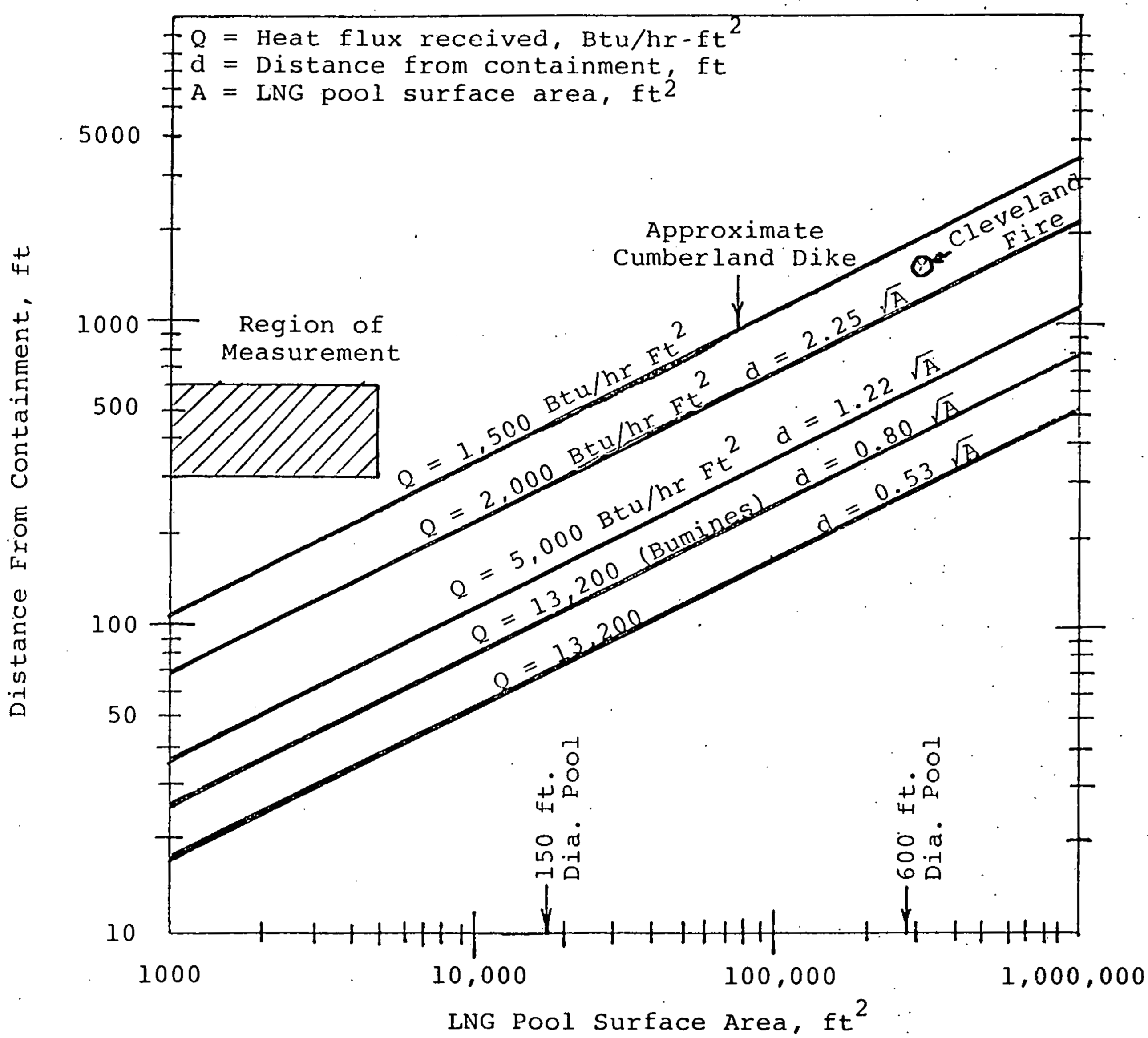
4) Thermal radiation from fires. The resulting heat from a burning but contained spill of LNG can be damaging to people and property. The effects of wind are important for tilting flames and for predicting the radiated heat flux. Safe separation distances from LNG tanks are an essential part of the site plan, and determining the "safe" distance from an LNG fire has led to many tests of small amounts of LNG burning in open pools up to 80 feet in diameter. Most thermal radiation estimates are in agreement with the experiments which have been performed [31,32].

Figure 2 represents an extrapolation of thermal radiation data obtained by May and McQueen [35]. The region of experimental data is indicated. (It has also been reported that the Cleveland LNG pool fire, which was about 600 feet in diameter, was safely observed from one quarter mile distance.) At large distances from an LNG fire there may be thermal absorption effects to lessen the intensity or even a filtering out of the easily absorbed spectral lines. Differences in absorption of the CO_2 and H_2O emission lines may lead to deviations from the simple exponential absorption usually assumed in air. The relative humidity of the air is also an important factor, and specific site characteristics will affect the

Figure 2

RADIATED HEAT FROM AN LNG POOL FIRE

(From W.G. May and W. McQueen [Ref. 35])



thermal radiation flux.

No one has yet burnt a shipload. This leaves open the question of extrapolation from the smaller test pool to the larger pool which would be created if an entire tank of LNG were to fail and the LNG were trapped in the dike surrounding the tank. Much of the safety argument centers on the criteria used to define a "safe" thermal radiation exposure level. For example, in Cumberland, R.I., the Valley Gas Company planned to place a 300,000 barrel tank 1,022 feet from the 585 pupil Ashton Elementary School. Several people thought that 2,000 feet would be a more appropriate distance for siting similar tanks [33, 34].

There has been dispute over the appropriate heat flux radiated from a fire to choose as the safe limit: 10,000 Btu/hr-ft^2 will ignite wooden structures, 5700 Btu/hr-ft^2 will blister exposed skin in 7 seconds and has been taken as the fatality limit by S.A.I. 1500 Btu/hr-ft^2 is often taken as the "safe" limit. Heat at this "safe" intensity will cause extreme pain after 20 seconds of exposure and blistering after about one minute. It is assumed that anyone experiencing this heat intensity would safely retreat from the area. Some critics feel that a lower value like 465 Btu/hr-ft^2 (1.5kW/m^2) is more reasonable, since it is the threshold below which no unbearable pain is felt for any exposure duration. Of course, the adoption of a lower figure of merit would require greater distances surrounding potential fire sources.

5) Control methods for LNG fires. Small LNG fires can be fought with dry chemicals. The rate of burning might be controlled by high-expansion foam, although foam cannot extinguish the fire. However, controlled burning may be preferable if reignition is likely. It

is difficult to fight LNG fires, and water sprays, while useful to cool exposed objects, may actually intensify the fire by increasing LNG evaporation rates if they fall on the LNG pool. It is still a matter of some discussion, whether to try to burn a spill before it disperses or to disperse it quickly before ignition. If, for example, there were small gas flames surrounding a dike, escaping gas would be burnt before a dangerous concentration could arise. However, this method has its drawbacks since it might escalate a minor accident and has not been adopted [36].

6) Engineering design and materials used in LNG facilities. Because of the extreme temperature ramges which must be endured during spill and fire conditions, selection of the metals, concrete, and other materials of significance. New insulating concretes (35 lbs/ft^3 vs 140 lbs/ft^3) proposed for use in dikes to reduce vaporization rates need to be throughly tested for thermal shock characteristics. Concretes used in high dikes must be able to withstand the intense heat from a pool fire. More cautious engineering design incorporating multiple diking, insulated concretes, vapor containment barriers, and tanks designed to withstand higher seismic loads can all reduce the hazard from spills, but at a price. Industry codes such as National Fire Protection Association 59A and the regulations of the U.S. Coast Guard and the Office of Pipeline Safety Operations should continue to be updated to accommodate advances in engineering design and the use of new materials. The experiences in Cleveland in 1944 where an inadequate metal alloy was used for the tank, and in Staten Island in 1973 where the supposedly non-flammable tank insulation burned disastrously demonstrate the necessity for rigid design and testing criteria.

7) Semi-solidification of LNG. The use of a semi-solid gel form of LNG in shipping or storage might significantly reduce spill and evaporation rates in the event of accident. An extra energy expenditure of about 66 Btu/lb will drop the temperature of LNG to -300°F, making it into a solid. However, this may not be practical for a number of engineering and economic reasons. It is possible to make a semi-solid LNG gel by rapidly condensing and freezing methyl alcohol or water in the LNG. Only one-third of a percent by weight of alcohol or water is retained in the gel, which remains semi-solid at -260°F. Research into the properties of this gel is being carried out at the LNG research center at M.I.T. Studies of the scientific, engineering, and economic feasibility of using such gels in transportation or storage should be pursued.

To ensure the safety of LNG facilities several steps should be taken:

1. Endeavor to prevent any spill;
2. Contain any spill, if possible (although this is unlikely on the sea);
3. Disperse the vapor, or ignite the spill intentionally;
4. Ensure that any habitation is far enough from the facility to be safe.

The safety of an LNG facility can be protected at any one of these stages. Clearly it is to industry's advantage to prevent a spill, for once there is a spill, the facility could be damaged. However, tanks in an LNG ocean tanker might give way in a ship-to-ship collision, workers might be careless, or despite all engineering measures, a saboteur could break open either an LNG tank or ship under the most unfavorable meteorological conditions. It is not possible to be absolutely certain that there will be no spill, so we must take precautions at the other stages as well. Large separation distances may well be the most reliable method of achieving the desired safety.

Despite the arguments over safety, LNG has been used since 1960 without serious accidents to the public. Although costly ($3 per million Btu delivered), it has distinct benefits over switching to alternative sources of energy. The combustion of natural gas is cleaner and leaves fewer effluents than either coal or oil. Other fossil fuels also present hazards in their storage, transportation, and use. In addition, there are potentially large costs to convert from gas to these fuels, and the present gas pipeline network is in place and operates efficiently. Nevertheless, as we have indicated, careful attention to the public safety and further research related to the risks of LNG are needed if we are to utilize this supplemental energy source.

Recommendations

The principal recommendations from our studies of potential LNG risks are as follows:

- The unresolved safety issues have been widely discussed, and it is doubtful that more safety hearings can resolve them. An accelerated research program is needed to ascertain the range of sensitivity of risk estimates to:

  1. differences in vapor cloud dispersion models and choices of atmosperhic stability conditions;
  2. differences in selection of "peak to average" methane/air concentration ratios to define the "safe" lower flammable limit within a vapor cloud;
  3. differences in ignition source distribution and in assumptions of their effectiveness in igniting a vapor cloud at different locations;
  4. differences in population density surrounding tanker routes and terminal sites;
  5. variations in physical phenomena such as the gravity spreading of LNG, boiling rates, and spill rates.

• Burning tests and vapor dispersion tests on large spills (up to 25,000m^3) should be used to resolve discrepancies in existing models and to investigate vapor cloud dispersion, flame shapes, and thermal radiation characteristics under different site and weather conditions. Many tests have already been performed on smaller spills.

• The structural integrity of of LNG tankers under spill conditions generated by an accident or sabotage, and the resulting spill characteristics should be better determined.

• Experimental verification is needed for physical theories of superheat-limited explosions which may result from LNG spills injected into or onto water. The effects of LNG composition and mode of LNG spill in accident conditions on possible explosions need to be understood. LNG-water interactions are just one area where liquid-liquid superheat explosions are being investigated and coordination of these studies with other fields is worthwhile.

• A thorough comparison of risk estimates should be made and published.

• Transforming LNG into a semi-solid gel for use in shipping and storage might significantly reduce spill and vaporization rates. Additional research on the properties of such a gel and the engineering economics of semi-solid transportation should be pursued.

• The possibility of sabotage must be introduced into any risk assessment and considered in siting of facilities. So far this has been largely omitted.

• Research results should be published in the scientific literature and disseminated widely to the public before they are used to justify safety decisions.

VI. LNG Facilities Siting Disputes

The Cumberland, R.I. LNG Tank

Cumberland is a small town on the Blackstone River, 20 miles north of Providence, on the ring road U.S. Route 295. About 1954, Ashton, a part of Cumberland, was selected as a headquarters site for the Valley Gas Co. The land was zoned agriculturally and according to Valley Gas President, Mr. C. G. McCaffrey, "Valley Gas sought a change to industrial zoning and said then that no tanks were envisaged" [37]. The Ashton Elementary School was built in 1964, about 1000 feet northwest of the Valley Gas Co. headquarters. A tank for storage of 1 million gallons (3780m^3) of LNG was constructed with no prior hearing in 1970, although by this time there were propane storage tanks on the site. This LNG was supplied by truck from Massachusetts and was primarily used for peak shaving. Again the Valley Gas Co. stated that they had no further expansion plans. In January 1973, Valley Gas Co. petitioned the Town Council for permission to build a 12,600,000 gallon (300,000 barrel or 47,700m^3) LNG tank 155 feet in diameter and 145 feet high at their Ashton site. The Town Administrator ruled that the matter should be heard by the Zoning Board and Valley Gas requested a zoning board variance to allow the construction of the tank. The variance was necessary because the Valley Gas property was now zoned for industrial "A" use which does not permit storage tanks, and the proposed tank would have been 70 feet higher than the local ordinance which limits building height.

Actions of Opponents and Proponents

The Providence Journal had written about the Staten Island fire, and a number of local citizens became concerned about a large tank in Cumberland because of the proximity of their homes and the Ashton school. A meeting was called, out of which evolved the Concerned Citizens of Cumberland. A steering committee was chosen which included three immediate neighbors of Valley Gas; the others lived one or more miles away. Time was short, because the zoning board hearing was scheduled for March 8, and external advice was hard to get. The Providence Journal had mentioned the names of Prof. James Fay from the Department of Mechanical Engineering at M.I.T., and one of us, Richard Wilson of the Department of Physics at Harvard as being technical experts previously concerned about LNG safety.

On behalf of the intervening group, Prof. Wilson asked for details of the proposed tank and its site. Some of these were made available orally. A map of the tank site, which according to its date had not been drawn until after the initially planned board meeting, was later made available to the remonstrants. Because of the public opposition, the Valley Gas Company requested postponement of the hearing, so that they could prepare a better case. Due to further postponements, the actual zoning board hearing did not take place until August 6 and 7, 1973. In the interim, the Valley Gas Company had hired Arthur D. Little, Inc. as consultants. In addition, Valley Gas conducted a public relations campaign which included newspaper advertisements and three letters to Cumberland residents. In his letter of June 29, 1973, C.G. McCaffrey, President of Valley Gas said:

"1. There is a shortage of all forms of energy.

2. By having LNG on hand, Valley Gas will be able to lessen the impact on customers in the likely event that our pipeline supplier further curtails natural gas shipments to us.

3. The tank would be on our headquarters' property so that our technical and mechanical people can daily observe its functioning.

4. We would take all necessary precautions to insure everyone's safety during its construction and operation, and we detailed the construction plans and safety procedures.

5. View the tank as a reservior to draw on during fuel shortage.

LNG storage facilities have established a perfect safety record since the development of national codes, dependable methods and cryogenic materials used today (such as nine percent nickel steel and the building of dikes).

I want to restate what I said in my first letter. 'If I thought for one minute that there was the slightest possibility of the tank causing an accident, it wouldn't be built.'"

Valley Gas also held an informational public forum on July 2, which provided much sought after information to local residents. At this meeting, Dr. Elizabeth Drake of Arthur D. Little, who had been a principal investigator in some LNG burning tests conducted by the American Gas Association, gave her opinion that under the worst accident circumstances for the proposed tank, "at 950 feet a person could have his skin exposed to a fire for 30 seconds before experiencing pain" [37].

The Zoning Board Hearings

At the first session of the hearings, held August 6 and 7, 1973, about 500 persons were present, more people than at the annual town meeting in June. Professor James Fay of M.I.T., chairman of the Massachusetts Port Authority and author of several papers on LNG and related topics, and Professor George Seidel of Brown University, an expert in cryogenics, testified on behalf of the opponents of the tank. Professor Fay concentrated his testimony on the dispersion of LNG after a spill. Professor Seidel questioned the advisability of the tank location so close to the Ashton School and suggested that an underground tank, while more expensive, would avoid the problem of spills. Both mentioned the unexpected nature of earlier LNG accidents and incidents and said that prudent safety judgments should assume the occurrence of a large spill.

Dr. Fay stated that a spill of 5000 barrels of LNG, less than 2% of the capacity of the tank, could form a vapor cloud 700 feet in diameter which could blow downwind and be flammable for nearly two miles. He felt that the 1972 National Fire Protection Association Code 59A, the principal standard to which the tank would be designed, did "not fully reflect the considerations of possibility of flammable clouds drifting downwind from spills, and that distances between storage tanks and public buildings or other areas where people might congregate in that code are in fact too small for safe design and operation" [38]. He noted the rapid development of LNG technology and the recent nature of tests done on LNG. He cited the Staten Island accident as evidence that "we are not completely and fully aware of all the dangers assiciated with this kind of technology. I believe very serious consideration should be given to proper siting of facilities in such locations that should there be an accident there would be absolutely no chance of harm to any human person" [39]. He did not specify what level of risk, if any, would be "absolutely" safe.

Dr. Elizabeth Drake was the principal safety witness for the Gas Company. She stated: "In essence, LNG technology is far from new. It is built upon decades of experience with liquid fuels and cryogenic liquids and is based on well-established codes and standards developed specifically for LNG" [40]. The following quotation taken from a later report co-authored by Dr. Drake elaborates briefly on LNG standards:

> "Changes in several codes and standards, including NFPA 59A, are presently being considered. If changes are made, they may or may not be of major significance but, based on past experience will generally be more restrictive than their predecessors. Any changes are necessarily made in slow and deliberate manner, so that there tends to be a time lag altering the standards to reflect new knowledge and improved technology.
>
> It would appear that the details of the standards have been largely influenced by the gas industry, since industry employees or contractors generally have most of the expertise that is necessary to deal with the subtleties of design and performance requirements. The overall objectivity

and intent of the standards, however, may have been influenced by a more balanced interest in safety, since many contributors to the codes were not sponsored by the gas industry.

The codes in general, do not explicitly describe the extent to which they may control or limit the hazards presented by accidental failures. That is, for example, given a rate and quantity of release of LNG due to a specific failure, the code does not provide a method of estimating the extent of the resulting fire hazard, although this could be done using presently available knowledge and methods. Instead the codes present exclusion distance requirements which infer some assumed maximum accident and allowable fire exposure at the property line, though neither is specifically described" [41].

Dr. Drake further testified at the hearing:

"The primary hazard associated with an LNG spill is, of course, fire. Heat from a large LNG fire is intense just as in the case with any large fire and liquid fuels. The safe distances can be estimated for various LNG fire shapes and sizes. To achieve safe facilities, one needs to identify potential causes of spills, determine their likely locations and sizes, and then estimate zones which may be affected by an accident of the type considered. Depending on the results, appropriate adjustments may have to be made in plant layout to minimize risk or injury to people and property" [42].

It was not made clear whether such a detailed estimate of safety zones had been carried out for Valley Gas, but the implication was later made that such estimates had been carried out. Dr. Drake concluded from her use of mathematical models developed in experimental LNG tests conducted in California that "the safe distance for people estimated using these methods is about 950 feet from the tank area" [43]. It was not specified under what conditions, if any, the 950 foot distance might be invalid. She added that her model did not include any effects of the terrain, although she felt this would make the 950 feet a conservative estimate since the school was on higher ground. She finished her testimony by saying "In my opinion, there is no hazard to the children at the Ashton school either from a major fire or from vapor dispersion, and I believe this is a safe siting" [44].

Dr. Drake, since she appeared after Dr. Fay, was able to rebut his testimony. She believed "Professor Fay may not be fully aware of the differences between spills on water and spills on land.", since Fay's published work was primarily for spills at sea. The lawyer for the Valley Gas Company also took great pains to establish the credibility of Dr. Drake over Dr. Fay by pointing out that Dr. Drake has been a discussion leader at an LNG conference in Boston in June 1972, where Arthur D. Little Co. and Chicago Bridge and Iron representatives had been present, and that Dr. Fay had not been invited to this conference. Although attendence at this particular conference had no bearing on Dr. Fay's reputation in the field, and should have been irrelevant, this establishment of credibility was a factor in the later decision of the zoning board.

The Zoning Board Decision

On November 7, 1973 the Cumberland Zoning Board released their 4-1 decision approving the petition of the Valley Gas Company. Eight conditions were set regarding:

1) Fire protection equipment;
2) Training of fire department and Valley personnel;
3) Construction and maintenance of the dike;
4) Design, engineering and construction of the tank;
5) 24 hour supervision and fire protection;
6) Jurisdiction over installation, operation, and modification;
7) Jurisdiction over fire safety;
8) Expenses of outside opinion to be borne by Valley Gas.

The findings of fact and conclusions of the board were:

"1) This Board has weighed and evaluated the evidence presented by Valley's witnesses and the witnesses for the Remonstrants and concludes that the evidence presented by the witnesses for Valley is more credible and believable than that presented by the witnesses for the Remonstrants. The detailed background and practical day-to-day knowledge of Valley's witnesses is in sharp contrast to the theoretical 'book' knowledge of the witnesses for the Remonstrants. The Board, therefore, finds that Valley has sustained its burden of proof on the issues presented to this board.

2) There is a serious public need for the storage tank proposed by the Valley. The construction of the storage tank will enable Valley to provide adequate winter fuel supplies for homes, institutions, businesses and northern Rhode Island areas. The need has been clearly demonstrated by the evidence and has been conceded by the Remonstrants.

3) The construction of the proposed tank will have no adverse effect on property values in the neighborhood, will not alter the character of the neighborhood, and will be consistent with the development of the area. In view of Valley's existing plant at the proposed location and the mixed uses of the area, the Board finds that the proposed facility will not substantially or permanently injure neighboring property.

4) The traditional traffic which may result from Valley's operation of the proposed facility will be limited to a very short stretch of Mendon Road and will not create any additional traffic or any appreciable traffic hazard.

5) Based on its own experience and the expert testimony of the witnesses presented by Valley, the proposed facility will not result in any change in the use of Valley's property, but will merely be an increase in the density of an existing use and so will be in harmony with the existing character of the neighborhood which already includes Valley's present facilities.

6) The facility proposed by Valley, with the safety features described in the evidence, is generally accepted, widely used and enjoys a proven safety record. Accordingly, we find that the proposed facility will not be hazardous to the public or adjoining property owners.

7) The design and construction of the tank will be in strict accordance with the most modern LNG technology and will exceed in many instances nationally accepted standards.

8) The site proposed by Valley has been examined by this Board which has also considered the testimony presented with respect to that site. We find that the site is entirely suitable and safe and that neighboring porperties will not be adversely affected.

9) In our judgment, the public convenience and welfare will be substantially served by the construction of the proposed storage tank.

10) In our judgment, the appropriate use of neighboring property will not be substantially or permanently injured by the construction of the proposed tank.

11) The proposed tank will be in harmony with the character of the neighborhood, appropriate to the use of buildings permitted in such district, and possessive of a reasonable tendency towards promoting the public convenience, the public welfare, and the public health.

12) The proposed use is reasonably necessary for the convenience or welfare of the public.

The dissenting opinion was given by Mr. McGill, who said:

"It wouldn't be right to give a 'Yes or No' vote on an issue where so much time, effort, and money has been spent or so much controversy has been brought about without giving good reasons for doing so. Here are my reasons:

The Town fathers who initially planned the zoning of the town saw fit to zone this area where they wish to build the tank--Industrial A.

People built homes nearby and the town built an elementary school about 1000 feet away, having in mind I'm sure, that a storage facility of this kind would not be allowed because it is not allowed in 'Industrial A'.

During the hearings there were many conflicting opinions on the safety of the tank (especially in regard to distances that were safe for the school and surrounding area) by people who were well qualified to give an opinion. The safety factor was important because of the fact that one volume of LNG (liquid natural gas) is equal to 600 volumes of Natural Gas which makes this a terrific source of energy. From what I get out of it, seems to me, 1,022 ft. is cutting things a little too close on the distance away from the school. There are no Federal or State Laws on the books spelling out distances to go by so to use my own judgment I think it's just common sense not to put it there.

I don't want Cumberland to go on record as having the closest school on record abutting an LNG tank. I'd rather go the other way and be the furthest.

The children, teachers, as well as residents should not have to look out the window and see this tank and live in constant fear of an accident that could cause an explosion when there's no absolute necessity for it. I know the tank is needed but there must be alternate sites"[45].

The decision was appealed to the R.I. Public Utilities Commission which conducted a further hearing on January 29, 1974.

It is clear that the media played a significant role in providing information and arousing public concern. The LNG tank fire in Staten Island was much reported in the press, and at first it was unclear that it was not a tank full of LNG which had exploded. In the Cumberland tank proposal the first involvement of the media was to announce the news as given by the gas companies. The Cumberland newspapers carried articles which quoted Charles McCaffrey, President of Valley Gas Co., about his enthusiasm for safety.

Smaller items quoted the concern of the tank opponents. There was no lead article about the issues involved and articles generally reported statements rather than providing background information, particularly with respect to technical safety issues. The zoning board hearing was well and fairly covered by local papers. However, there was no coverage which showed real understanding of the issues until after the zoning board hearing. The appeal hearing was covered by several local newspapers and the local T.V. station in considerable detail. In addition a local monthly newspaper the "Advocate" devoted its February 1974 issue entirely to LNG issues and the LNG safety debate.

Post Hearing Actions

At the appeal hearing of the Public Utilities Commission Richard Wilson was the principal witness for opponents. His written testimony noted the difficulty he encountered in obtaining technical details of the tank and of obtaining research papers by Dr. Drake cited at the August hearing as being "published very shortly." Some of this research had been used to justify the safety of the proposed tank. Dr. Wilson also wrote that Dr. Fay's published work indicated that he was as qualified an expert on LNG as Dr. Drake and should have been so considered by the zoning board of review. (Judging from the transcripts, the testimony of the expert witnesses for Valley Gas, who were paid by Valley Gas, was more explicitly and carefully prepared than the testimony of the unpaid expert witnesses for the intervenors. This, as always in such cases, was a disadvantage for the intervenors, which hearing boards should, and usually do, take into account.)

The consideration of alternatives to the Valley Gas proposal was also raised. No comparison of alternative sites or alternative tank-dike configurations was placed on the public record. Although Valley Gas had conducted an aerial survey of their general region, this was not revealed or discussed. It appeared that the site already owned by Valley Gas was the only site evaluated for safety of the LNG tank because of convenience and expense. In oral testimony the issues of sabotage by terrorists and the acceptability of the risk were discussed. Professor Wilson suggested that flying in an airplane was a voluntary risk which he could decide to accept or reject whereas attending school near an LNG tank was an involuntary and continuous risk, about which presumably the school children and prior homeowners had no choice. He felt that regulatory bodies should be particularly conservative in placing such tanks in populated areas.

According to the Chairman of the Public Utilities Commission, the appeal "board decision would revolve around three questions regarding the tank:

1) Is the facility needed?

2) Is this the proper location for such a facility?

3) If the facility were placed there, would it be safe?" [45b].

As of November, 1976, the Public Utilities Commission had not ruled on the appeal.

Providence, R.I. LNG Import and Storage Terminal

Providence sits at the head of Narragansett Bay, a large bay extending 30 miles in from the ocean. It is a natural location for port facilities. Fields Point, an industrial complex containing petroleum storage tanks and located 1.5 miles from downtown Providence, seemed to the gas companies an obvious place to expand and to construct a large marine terminal for LNG. This would include the docks for LNG tankers, revaporization and storage facilities. Washington Park, a heavily populated area adjacent to Fields Point, is comprised of middle and lower income people who have not usually objected to industrial facilities in an effective way. The proposed LNG import terminal would be located about 1800 feet from the nearest home and is surrounded by the existing oil and gas tanks. The project initially won the approval of the Mayor of Providence and the City Council. Algonquin LNG Inc. completed construction on a 600,000 barrel ($95,400m^3$) tank at Fields Point in 1973 and then requested permission to build two additional tanks of the same size.

However, some local citizens, members of the Washington Park Citizens Association, had become aware of the opposition to the Cumberland tank and were concerned by the Staten Island incident. Despite the fact that the first tank had already been built and the building review board had held its hearing on the other two, the City Council became apprehensive about LNG and the fire department worried whether it could contain a large fire. The city then sought to have a safety study funded by Algonquin Gas. Factory Mutual Research Corporation of Norwood, Massachusetts was selected by the fire department. Some of those opposing the tanks questioned whether this study could be objective and whether industry codes designed to guard against frequent small accidents in which engineering experience is helpful could adequately prevent rare, large accidents.

The concern over the Algonquin siting dispute was greater than that over the Cumberland LNG tank for two reasons. Technically, an LNG ship terminal is a more serious risk than one storage tank. A dike can contain a spill on land; a spill on sea cannot be contained. Moreover, the plan was to engage in interstate commerce which made this a federal matter, subject to the National Environmental Policy Act and in particular section 102, so that the power of the opposition was correspondingly greater. In March, 1972, the Federal Power Commission had declined to take jurisdiction over construction and operation of the Everett and Staten Island facilities. In May 1973 this decision was reversed. The deciding factor is unclear, but the Staten Island tank fire certainly led to increased public concern, and the F.P.C. cited the fact that interstate commerce was intended. The initial refusal of the F.P.C. had raised the possibility that tanks could be built for intrastate commerce without the need for F.P.C. approval. Then when interstate commerce was needed, the benefit of using an existing site might have outweighed the additional risk.

The application for the expansion of the LNG terminal at Providence was then consolidated by the Federal Power Commission with the applications for importation of LNG into the existing terminals at Everett, Mass., and Staten Island, N.Y., because many of the issues were the same. Easco Gas, a firm organized by Algonquin Gas and Public Service Electric and Gas Co. of New Jersey, planned to import LNG to sell to both the Staten Island distributor, Distrigas, and to Algonquin in Providence. Later the cases were separated by the F.P.C.

The Federal Power Commission environmental impact review of the Algonquin expansion proposal stated that the largest risk, while "remote", would arise in the event of a spill on water. "Under the worst wind conditions (5-10 mile per hour stable wind from the north) the flammable cloud three miles in extent could cover the homes of about 10,000 people located generally south of the Providence tank" [46]. Although the likelihood is small, the resulting loss of life and property from such an occurrence would be great. The highest likelihood for smaller accidents was in the confined harbor area. "There is, as yet, not much direct experience with the extent of hazards to the public from the type of LNG import terminal similar to the proposed Providence facility. However, there is a reasonable base of experiments with LNG spills, well-founded analytical techniques, and considerable experience with the transport and storage of other flammable fluids" [47]. Rather than quantify the risks, the F.P.C. included risk and severity indices, on a linear scale from one to ten which represented their judgment about a number of risk factors. These indices were not easily interpreted nor were they particularly informative.

In the application and the draft E.I.S., no attempt was made to compare the proposed terminal site with possible alternatives or to make a cost/benefit analysis as is required by section 102 of NEPA. Therefore it seemed to the opposition that all they had to do was to find a better site and point it out th the authorities. One alternative site at Rome Point, 20 miles south of Providence was suggested. It is a site approved for nuclear power safety by the Advisory Committee on Reactor Safeguards of the AEC, but it was not acceptable to the Environmental Protection Agency for hot water discharge. It is near a deep water channel and seemed a suitable remote site for an LNG terminal. Moreover, it is not far from the east coast main gas pipeline. After this was pointed out and possibly for other reasons as well, the Mayor of Providence, Joseph Doorley, reversed his stand and opposed expansion of the Fields Point oil/gas tank complex.

The F.P.C. Hearings

Formal Federal Power Commission hearings were held in Washington in winter 1975 to review the F.P.C.'s environmental impact statement. At these hearings a number of alternative sites were publicly discussied for the first time. However, the written testimony of W.F. Coates did not contain even rough benefit-cost estimates for comparison of the alternative sites. Rome Point was not listed as a potential site, and two otherwise good sites at Jamestown and Tiverton, R.I. were rejected by Algonquin Gas because of anticipated resistance from local residents. (This was an example of the now familiar conflict between environmental preservation and public safety. In the remote siting of the LNG terminal at Cove Point, Maryland, this conflict was resolved when another intervenor recognized the superior claim of public safety. Had Algonquin anticipated the public resistance in Providence, they might well have opted for a site in a less populated area.)

A two day local hearing was then held in Providence on May 15 and 16, 1975. At this hearing the Providence Gas Company stated that it needed the storage facility to provide secure supplies of gas, which it required to make up 19 percent of its estimated annual volume that it could not obtain through national pipelines. About 7.4 million m^3 of gas each day were needed, about half of which could be supplied by LNG (6,000m^3/day LNG), the rest from SNG (synthetic natural gas) or propane. The proposed terminal would additionally provide "more jobs for construction workers and employees of expanding businesses, tax revenue for the city and encouragement for the economy" [48].

At the same hearings Frances Darigan, Jr., former city councilman, said "the City Council did not become knowledgeable about potential hazards of liquefied natural gas (LNG) storage until after it gave assent to Algonquin's first tank." Councilman Harry A. Johnson said "Washington Park neighbors would derive no benefit from the added tank to offset the risks to them." The chief of the Providence fire department testified that a major fire at the terminal would be "a situation beyond the capabilities of the Providence Fire Department." Although his men have foam equipment and training for fighting LNG fires, "the city does not own a fireboat and might have to commandeer tugs to battle a fire from the Providence River." Fire Chief Michael Moise testified on behalf of himself and as a representative of the current Mayor, Vincent A. Cianci, Jr. His views were "based on a safety evaluation prepared for the city, but paid for by Algonquin by Factory Research Corporation" [49].

These events typify some of the recurring issues in such disputes. There is no question that the potential risks of LNG facilities are borne principally by those closest to the facility, while the benefits are derived by the larger community. Hence nearby residents would usually prefer to site them in some other neighborhood. Public officials may desire to obtain such facilities for the benefits they provide, but adopting a conservative position with repsect to risk may be politically desirable. The self-interest of proponents is often evident, but there can also be self-interest on the part of adversaries, who may gain reputation and publicity as guardians of the public safety. These factors demonstrate the need for thorough risk-benefit analyses and acknowledge the inherently political nature of such disputes in the face of uncertain risks.

Post Hearing Actions

The Factory Mutual report concluded that with stringent safety requirements the facility would be safe. They described the maximum consequence accident, which has only a remote possibility of occurring, in the following way :

> "Ignition of a spill covering the entire surface area of the dike could result in dangerous heat flux levels to people 1300 feet away and insulated tanks 700 feet away if left to burn uncontrolled. If the high expansion foam system could not control such a fire, the other LNG tanks would be seriously exposed, particularly if the fire originated at the proposed middle tank. It is doubtful that manual fire fighting could be effectively used to keep the other LNG storage tanks cool. Consequently, if these tanks did fail from exposure, a fire involving all three diked areas simultaneously could eventually occur. If so, we estimate the safe distance for people would be approximately 3000 feet from the diked area. Piloted ignition of wood (i.e., ignition source needed) would occur at a distance of approximately 1500 feet from a diked area and unpiloted (i.e., spontaneous) ignition at a distance of 700 feet. Under such conditions, we believe a major conflagration involving areas outside the LNG terminal could result (e.g., Providence Gas Company, Texaco Inc., New England Bituminous Terminal Corporation, Sun Oil Company, McLaughlin-Moran, Inc. and British Petroleum Corp.).
>
> To put the above in proper perspective, we believe there is only a remote possibility that such a spill could occur. Also, it is possible that the high expansion foam protection would be effective in controlling an LNG pool fire.
>
> It is not anticipated that any credible LNG spill and subsequent fire during LNG transfer operations would pose a thermal radiation hazard outside the terminal" [50].

Presumably, the lack of a precise quantitative estimate of "remote possibility" did not enhance the confidence of the residents of Fields Point about the safety of the facility, particularly since it is obvious that sabotage might achieve this situation.

Because of these risks, additional safety features including pre-stressed concrete impounding walls surrounding each tank, extending to the full height of the tank, automatic foam generators, and reserve water supplies were added to the design. Fire Chief Moise in a letter of December 15, 1975 to Mayor Cianci stated that the level of risk presented by the Algonquin terminal was now acceptable to the fire department. These safety precautions would reduce the risk of spills on land, but again no quantitative estimates of the magnitude of risk reduction achieved was given. Additionally, none of these meausres would appreciably affect the risk of spills on water, which posed the greatest hazard to the citizens of Providence.

After 3 years, on Friday, April 23, 1976, the Providence Building board of review voted 4-0 to let the project proceed. The Washington Park Citizens Association immediately sought an injunction to bar the city from giving a permit [51]. The City Council on April 26 voted to block any permit on the grounds that the members of the Building board were new. In the summer of 1976 the Rhode Island legislature passed a law signed by Governer Noel which required the Public Utilities Commission and the State Fire Marshall's office to hold hearings and give approval before any more LNG facilities are built. Other events, including a large chemical fire on July 21, 1976 at J.F. Donovan Inc. chemical supply near the existing LNG tank, have kept this issue in the public eye. The dispute is not resolved and neither the F.P.C. nor the P.U.C. has ruled on this case.

VII. Public Concern for LNG Facilities Siting

As we have seen, public concerns significantly influence and define the decision-making process. In liquefied natural gas facilities siting disputes both the proponents and the opponents are partially representative of the public interest. The risks associated with LNG facilities are greater for those in proximity to the facilities, while the benefits are shared by a larger segment of society. Is the risk reasonable for the benefit accrued? To whom? Can the risk be reduced and is it worth the cost? Again, to whom? These are but two questions of public policy which must be addressed.

The foregoing sections of this report have outlined some of the principal issues involved in siting disputes. This section will re-examine the public concerns and is based on discussions and correspondence with twelve principals involved in three different LNG disputes, on public hearings, and on discussions with state and local officials.

Origins of Public Concern

Personal proximity or the proximity of friends or relatives to LNG facilities was a primary initiator for curiosity about LNG. The Staten Island accident led to the realization that LNG and to some extent LPG have differences from more familiar petroleum products. Media accounts of this accident created great concern in those who were close to planned facilities. The question was raised, although it is not strictly technically relevant, "if an empty tank can kill 30 people, what can a full one do?" The catastrophic nature of the maximum possible accident could not be ignored despite assurances from gas companies that the likelihood of a major accident was very small and despite assurances that the facilities had been judged "safe" by gas company experts.

Probabilities which indicated only a "remote possibility" of a major accident were not reassuring in the face of known smaller accidents. Disagreement among experts about the likelihood of an LNG disaster also contributed substantially to public anxiety. Although a great deal was known about LNG, no definitive overall risk analysis had been carried out at the time of these disputes. Even now such analyses are not agreed upon, although they can focus the debate on the important questions. Nevertheless, the public does not generally distinguish between the comparatively larger likelihoods of accidents with small consequences and the very low probabilities of more severe accidents when there is uncertainty about large accidents.

Those who had to bear the risk did not perceive a tradeoff between risk and benefit in a situation where the risk was not precisely known and where they seemingly had no choice but to bear the risk, unless they were willing to move their homes. Since the facilities are located near populated areas, the number of people continously at risk is large. Even if the need for such facilities was accepted, a more prudent siting policy, away from densely habited areas, appeared to the public to be the best approach and the approach which was most easily understood to be infallible. The siting of LNG facilities therefore became a focus for public concern.

Technical Credibility

The primary technical issues have been previously outlined. The judgment of relative safety was obviously at issue; the proponents said the facility is "safe", and the opponents believed that the "risk is too great".

As with other public policy issues which include scientific and technological components, there was confusion and overlap among several distinguishable questions:

1. What are the scientific and technological bases for estimating the expected risks and benefits?

2. What is the probability of an accident with particular consequences? Is the estimate reliable?
3. Can the risk be reduced and what will it cost?
4. Is this risk acceptable?
5. Is the distribution of risks and benefits fair?

Answering the first three questions can require scientific and technological expertise. They should be answered as well as possible with the limitations, assumptions, and uncertainties indicated. The last questions are almost entirely questions of individual preference and of public policy. However, until the first three questions are distinguished, the overlap between all of them can be so great that attempts to answer them simultaneously may mean that none are adequately answered.

Part of the reason that these questions are confused is due to the industry belief that the public only cares about "safety" in a yes/no manner. This is suggested by the following quotation from an Office of Pipeline Safety Report: "The AGA (American Gas Association) has not taken an active role in informing the public about LNG. Probably this is because the public is not interested in the technological aspects but primarily in 'Is it safe?' Industry recognizes that the public, with a general suspicion of 'big business' might well become more concerned and suspicious if industry undertook a major public relations effort on the safety of LNG operations" [52]. The public clearly does care to understand how the safety judgment is made. In the Cumberland case the President of Valley Gas didn't admit to the slightest possibility of an accident, thus undermining public confidence in his statements.

When the judgment of "safety" is in doubt, as it certainly seems to be for LNG siting, the public is very interested in having answers to technical questions. They are not just interested in being told "It is safe". Although they are not technical experts, the public intervenors were capable of understanding the technical issues and appreciative of the areas where greater technical knowledge was required. It is undoubtedly true that the public might well become suspicious if subjected to a "major public relations effort". What is needed are not public relations campaigns but the presentation of facts and background on the issues.

Where possible the public should participate in the decisions as early as feasible, in this case prior to site selection. The development of national siting guidelines for major import terminals would be helpful, but local or state interests should still have control in siting judgments. Perhaps the governor should have final authority in siting LNG import facilities, in a manner analagous to approving large airports or ports. Although the early presentation of alternative sites may have higher costs for the gas companies, the public interest would best be served and the approval process speeded by allowing early discussion of potential sites. (This obviously raises the age-old question of local versus central decision making, which is only partially addressed here.)

Precisely because the acceptability of a risk is a judgment, it appeared to the remonstrants that LNG proponents either had different factual information than that available to them or that biases of the proponents led them to their "safe" interpretation. The intervenors thus felt that the technical issues and the decision-making process had to be subjected to public scrutiny.

Some of the issues mentioned during discussion with intervenors and expressed at public hearings may be paraphrased as follows:

[If one LNG tank fails, and we know of examples of accidents, then why won't the tank near me also fail?] Details of tank construction and design are not usually pointed out in the press releases about accidents. The result is that all LNG tanks become suspect, even if the failed tank might have been unique in design or in materials which contributed to the failure. By the same token it doesn't follow that all tanks with similar characteristics will be safe. The limited statistics available for LNG facilities don't necessarily characterize a new facility. Previous accidents are, at least, indicative of the uncertainties in our knowledge and of the general safety associated with LNG facilities.

[The British practice has been to site LNG storage tanks the same size as that proposed a minimum distance of 2000 ft between the nearest occupied building and the LNG storage tank. Why did the expert from a private consulting company appearing on behalf of the gas company pick 950 ft for the Cumberland tank?] Differences in siting codes and criteria applied in specific situations are not always recognized. The result and interpretation of this safety calculation was subject to disagreement by several other expert witnesses. The disagreement among experts was in the criteria to be applied in judging a "safe" level of thermal radiation outside the site boundary should a large pool fire occur. However, this was never clearly stated in reports or testimony. To the public and to at least one member of the zoning board it seemed that the scientific disagreement was over the veracity of the 950 foot "safe" distance and over the factor of safety which should apply to that calculation. In the background was the feeling of the experts for the intervenors that it would cost little to be cautious in the Cumberland case. The gas company never put a figure on the cost of having the tank on another site. Residents between 950 and 2000 feet were obviously interested in the "safe" distance and felt that the gas company should have indicated possible uncertainties in their quoted number.

[The deaths which occured in the Apollo space project are an example that mistakes can always happen no matter how safe the project. Something can always be overlooked and we all know that safety precautions are not always taken.] For example, at the Providence, R.I. LPG terminal, a ship was observed unloading scrap metal adjacent to a ship unloading LPG. There was no apparent site security, nor was fire fighting apparatus visible, although it may have been present. Such observations do not enhance public confidence in a safety judgment which may be based on such precautions being taken. (It is true, however, that risk assessments should allow for human error, and this raises an interesting dilemma: the best safety precautions are often invisible and harder therefore to sabotage. Yet public visibility of safety procedures enhances confidence and perhaps reduces the likelihood of sabotage.)

Further concern with the thoroughness of precautions was mentioned. [Should there be an accident, could we cope with it?] There was doubt that fire departments are equipped to handle LNG fires, although training and proper equipment certainly can improve the situation. The following quotations reflect this concern: "A determination as to whether the local Fire Department would be effective in fighting a LNG fire has not been able to be made at this time. The New York Fire Department admits that it does not have the firefighting experience involving large tanks such as the ones projected for this project" [53]. In Cumberland, R.I. the Ashton Fire District Wardens said: "The Ashton Fire District is not equipped to cope with any LNG fire" [54]. In the port at Providence, where there is an LNG import facility, there was no fire boat or plan for dealing with an LNG spill on water. As quoted previously the Chief of the Fire Department had testified that a major fire at an expanded LNG terminal would be "a situation beyond the capabilities of the Providence Fire Department" [49].

There was general concern for the rigor of safety evaluations which had been performed. On February 12, 1974 the Providence Journal editorialized:

"The safety aspects of the LNG tank construction permit should come

> under more exacting requirements and informed challenge. Since the wind direction is such a crucial factor in an LNG accident, should not the Fields Point LNG tank site be subject to as exhaustive a meteorological study as is the Charlestown site for a proposed nuclear plant in a rural area? If all life and property is lost wherever a lethal LNG vapor cloud drifts and ignites, then the application for construction should include public safety and health requirements all as rigorous as those demanded in nuclear plant construction" [55].

Some intervenors have interpreted the potential accident risk from LNG facilities to be greater than those of nuclear power or have suggested that since both involve potentially large accidents, and nuclear plants are sited remotely that LNG plants should also be sited remotely. In this case the concerned citizen may have been comparing consequence estimates without considering their likelihood. Present LNG terminal siting criteria are based on a "maximum dike fire scenario" and nuclear power plants are designed to prevent "a maximum credible accident". We are not sure whether these are comparable. But it does seem certain that LNG can be made much safer than nuclear power plants. A nuclear power plant in a remote site may be safer than an LNG terminal in a city, but if both are in a remote site, LNG can clearly be safer. (Again, if both are very safe, the small difference seems academic).

[What about accidents which are never reported? How can we judge safety or believe the gas companies when we are told 'it is safe' and then find out about accidents? We are capable of separating minor accidents from major ones, but we won't believe it when they tell us their safety record is perfect.] This is an important question which is basic to the credibility of any industry. "The LNG industry, however, has not been without its minor incidents, many of which may have gone unreported to local authorities or regulatory bodies either because no injury or serious damage resulted, or because the magnitude of tbe incident was relatively small and it was handled internally without recourse to outside response personnel. The industry had mixed feelings about an incident reporting system, however. It appears that the industry would be receptive to a 'minor incident' annual reporting system if 'minor incidents' were well defined so that no misunderstandings and differences in interpretation could arise among LNG operators. On the other hand, the industry felt that 'serious incidents' should be reported and investigated in detail in the manner that major gas distribution pipeline fires and explosions are. Again a very precise definition of a 'serious incident' should be developed. Industry generally did not appear to be aware of the fact that LNG leaks are presently reportable under CFR 192 Amendment 192-12; Docket No. OPS-14" [8].

It should be noted that a probabilistic risk analysis incorporating fault tree and event tree analysis techniques cannot be improved unless "minor incidents" are consistently recorded. Incidents which occur during construction, start-up, maintenance, or close-down must also receive more attention and likewise be reported. If this had been done, the public would find the safety record of the LNG industry much more believable.

The difficulty of obtaining facts from local sources and the difficulty of obtaining reports on LNG safety are cited several times. Intervenors found it difficult to obtain information and even their expert witnesses seemed to have considerable difficulty in obtaining reports which were used by the proponents to justify facility safety. Part of the reason for this was the fact that the data on which the safety claims were based was unpublished at the time, and the analytical models had not been subjected to peer review in refereed journals. In the case of the Valley Gas Company in Cumberland, R.I., a "somewhat intensive public relations campaign" was conducted which included several letters to local residents and newspaper advertisements. One month before the zoning board of review Valley Gas held an informational seminar at which some of their expert consultants were present. According to local residents who were present, this meeting was the first time they could obtain much of the factual information they desired, and this meeting alone was far more effective than Valley Gas' public relations and advertising campaign.

A Matter of Trust

Trying to obtain information and understand the bureaucracy in an LNG facility siting dispute can be time consuming, frustrating, and costly. Obtaining information from gas companies or copies of unpublished papers presented at conferences can be difficult. Finding expert witnesses and organizing legal cases (for either the proponents or opponents) can be expensive and exhausting. Figuring out the regulations and the jurisdictions of the Federal Power Commission, Office of Pipeline Safety Operations, Environmental Protection Agency, Corps of Engineers, U.S. Coast Guard, Occupational Safety and Health Administration, and of state and local agencies can be nearly impossible. The lists given in Table 8 and 9 apply to Oxnard, California.

A gas company considers many factors in selecting a site for a facility. The site must be capable of containing the tank, its dike, and associated plants. It needs to be accessible to roads if LNG is to be shipped by truck, or to a deep water port if it is an import terminal. It should be near to a pipeline, the land must be available at a reasonable price, and the environmental impact of the facility must not be too detrimental. Safety is only one of the many elements in the gas company's site determination. It is concerned with its responsibilities to consumers, workers, stockholders, the general public and its neighbors, as well as with its public image.

The gas consumer wants a secure and low-cost supply of gas. The person who resides near to an LNG facility is interested in all of the above considerations but does not wish to bear an unacceptable level of risk or see his property values and quality of life deteriorate without just compensation. If he disagrees with the judgment of the gas company, he faces a formidable task. In the worst case it can appear to him that:

Table 8

AGENCIES AND THEIR JURISDICTIONS
LNG TERMINAL, SHIPPING AND PIPELINE *
(Oxnard, California)

Agency Federal	Jurisdiction, Statutes, Codes
Army Corps of Engineers	Construction of dock facilities, dredging, and pipeline crossings of navigable waters - River and Harbor Act of 1899, Section 10. Certification from state required to insure compliance with state plans for land and water use programs for coastal waters and shorelines - 33 CFR, Section 209.120
Environmental Protection Agency	Issues permits for wastewater discharges - Federal Water Pollution Control Act. Reviews air water and noise impact on environment - NEPA 1969, Clean Air Act, Noise Control Act.
Department of Transportation U.S. Coast Guard	Approves design and operations of dock facilities; approves vessel operations, regulates safe shipping practices - Dangerous Cargo Act; Ports and Waterways Safety Act.
Department of Agriculture (Mineral Lands Leasing Act)	Permits for right-of-way through National Forest and for road construction. Control of construction practices.
Department of Defense U.S. Naval Construction Battalion Center, City of Port Hueneme	Determination as to whether marine facilities would interfere with military operations at Port Hueneme.
Department of Interior	Reviews impacts on environment.

*Taken from Reference 21, p. 369.

Federal Communications Commission	Certifies all communication equipment. Permits for radio towers.
Federal Aviation Administration	Reviews terminal designs to determine if hazard to aviation would be created.
Federal Power Commission	Approval for construction or operation of any pipeline or related facility for the transport of natural gas in interstate commerce - Section 7(c), Natural Gas Act, Title 18 CFR.
Occupational Safety and Health Administration Department of Labor	Approval of facility if in compliance with OSHA regulations.
U.S. Public Health Service	Issues certificates after reviewing design plans which relate to sanitation features and construction prevention of communicable diseases, and deratization of the ship.

<u>State of California</u>

California Coastal Zone Conservation Commission	Permits for soil test borings, plant siting, and construction.
California Regional Water Quality Control Board	Discharge permit for dewatering and hydrostatic test water from LNG site and pipeline and cooled discharge from vaporization.
California Public Utilities Commission	Certificate of Public Convenience and Compliance with Construction Standards.
Department of Fish and Wildlife	Permits for changing, obstructing, or diverting any river or stream.
Division of Industrial Safety	Industrial Safety Permits (for excavation and buildings) and State of California OSHA compliance permits.

Division of Highways	Permits for road access, road arrangement, and entrance.
Oxnard Harbor District	Port Warden approval of fire and safety equipment and design of dock.
The Resources Agency	Permits and easements for electric, gas, water, sewer, telephone, and utility lines on state land.
State Land Division	Approval to purchase/lease state lands, if necessary
State Lands Commission	Permits of geological and geophysical surveys.
Local	
Building and Safety Department, City of Oxnard	Building permits - LNG transfer and seawater exchange lines.
Fire Department, City of Oxnard	Approval of LNG Transfer Line Leak Detection System.
Planning Department, City of Oxnard	Use Permit Pipeline excation permit and permission to obstruct traffic.
Ventura County Air Pollution Control District	Permits for construction and operation of LNG storage tanks, gas-fired vaporizers, and other plant equipment.
Ventura County Building and Safety Department	Building and grading permits.
Ventura County Fire Department	Construction permits for all tanks. Approval of Fire Protection Systems.
Ventura County Flood Control District	Approval of storm and flood control measures.
Ventura County Planning Department	Zoning Change and Special Use Permits
Ventura County, Los Angeles County, City of Oxnard, City of Camarillo, City of Port Hueneme	Pipeline construction excavation permits and permission to obstruct traffic.
Los Angeles County	Compliance with local air quality standards.

Table 9

STANDARDS APPLICABLE TO THE CONSTRUCTION AND OPERATION
OF THE PROPOSED LNG PLANT AND MARINE TERMINAL *
(Oxnard, California)

1) Title 49 CFR, Part 192 - Amendment 192-10, Liquefied Natural Gas Systems and Part 192 Safety Standards for Transport of Natural Gas by Pipeline.

2) American Association of State Highway Officials (AASHO).

3) American Society of Mechanical Engineers - Pressure Vessels.

4) American Society of Civil Engineers - Wind Forces.

5) American National Standards Institute; various standards in the areas of Civil Engineering, Lighting, Instrumentation, Mechanical Engineering, Noise, Sanitation, Materials Handling.

6) American Concrete Institute (AGI) Specifications for Structural and Reinforced Concrete Construction.

7) American Institute of Steel Construction (AISC).

8) American Petroleum Institute (API); API std. 620, Appendix Q, 1973 and API std 2510A.

9) American Waterworks Association.

10) American Society for Testing and Materials ASTM: Concrete and Structural Steel Standards.

11) Diesel Engine Manufacturers Association.

12) Hydraulic Institute Standards (HIS); Pump Standards 1969.

13) American Gas Association; AGA Gas Engineers Handbook-Purging.

14) American Welding Society - Structural Welding Code.

15) USCG Regulation - CFR Title 33 Security of Vessels and Waterfront Facilities.

16) National Board of Firefighting Underwriters.

17) National Fire Protection Association (NFPA); NFPA No. 10 (1972), Installation of Portable Fire Extinguishers.

* Taken from Reference 21, p. 373.

18) NFPA No. 30 - Flammable and Combustible Liquids Code.

19) NFPA No. 59A-1972; Storage and Handling of LNG.

20) NFPA No. 70-1971; National Electrical Code.

21) NFPA No. 77-1972; Static Electricity.

22) NFPA No. 78-Lightning Protection Code.

23) NFPA No. 87-1971; Piers and Wharves.

24) NFPA No. 90A-1972; Air Conditioning and Ventilating Systems.

25) NFPA No. 194-1968; Screw Threads for Fire Hose Couplings.

26) NFPA No. 196-1972; Fire Hose.

27) Occupational Safety and Health Act - Title 29 CFR, Parts 1910, 1910.23 and 1926.

28) Uniform Building Code - Zone 3.

A decision has been made by the gas company and then experts are hired to justify that decision. Few alternatives, if any, are considered.

Business interests support the gas company because it is a matter of economics and future gas supplies; jobs count for more than the safety of unknown individuals; economics supersede ethics.

Gas company officials don't live near the facilities, so they are not really in the position of nearby residents. Employees are paid to accept this risk while residents are not compensated for it.

Government officials don't wish to offend business interests. Perhaps they are not competent to judge the risks or they are not cognizant of the real risks or they are corrupt.

Furthermore, it is not clear who would be held liable in the event of an accident, since the owners of port terminal facilities and LNG tankers may be holding companies with no real assets other than the facilities themselves.

Finally, experts who work for consulting companies are reluctant to publish or make controversial statements about safety issues, since if they do, their firms will not get contracts from industry.

For the public concerned about LNG safety and for those who bear the risk, the ultimate judgment of a facility's safety becomes largely a matter of trust.

Equity Issues

In more than one case LNG facilities have been sited in areas surrounded by lower income residential neighborhoods and other industrial facilities which also impose risks and inconvenience on those living nearby. These groups feel that they should not be required to bear any additional risks. As the public becomes increasingly aware of its rights, the LNG industry is likely to find itself in the position of those who wish to build large airports or highways near cities. How then can we ensure that this energy source will be made available and that the risks, costs, and benefits of LNG facilities are fairly distributed?

As we have indicated, open public discussion of the safety issues would increase public confidence in the decision process. The development of national safety standards and facility siting guidelines would greatly assist those state and local agencies which do not have the staff, expertise, or finances to determine the risks and appropriate guidelines independently. Additional engineering safety measures will help, but siting LNG terminals in less densely populated areas would ensure that the risks are reduced and would result in the costs being borne by those who use the gas. The proportional increase in already expensive LNG costs due to more remote siting may well be worth the enhanced public safety and may be desirable because of its more equitable internalization of costs to those who benefit. Those who wish to site LNG terminals in more populated areas should demonstrate its advantages or disadvantages via a risk-cost-benefit comparison among the feasible alternatives. Then we may see more clearly the tradeoffs involved and present them to the public process.

Public Perceptions of Risk

From our case studies of LNG facility siting disputes and from our knowledge of other societal decisions involving risk, we can construct a set of more general questions which reflect public concerns over risk situations. These questions are of importance in the formulation of public policy and indicate some of the diverse concerns which are likely to arise when risks are considered. Public concerns over risks arise from three sources:

1. known, measured risks which have occurred in the past and might occur in the future;
2. risks of a potentially catastrophic nature;
3. risks which conflict with strongly held values such as aesthetic, ecological, or life-style beliefs.

Any of these can serve to arouse and sustain public attention. Once this concern has been stimulated, a number of judgmental factors will determine the response, and public attention may become focused on details which otherwise might seem to be trivial in comparison to other issues. A list of questions which seem generic to many societal risks, including LNG, may be paraphrased as follows:

1. What are the scientific and technological bases for estimating the expected risks and benefits?

    a. What is the range of disagreement over these basic facts?

    b. What is the experimental basis for these facts?

    c. What is the theoretical basis for these facts?

    d. What direct experience do we have with the same or similar systems?

    e. How do these facts apply to the specific design or situation being assessed?

    f. Have these facts been subjected to scrutiny by other experts in the open literature?

2. What is the probability of an accident with particular consequences?

    a. Is the maximum accident of a catastrophic nature? Can its probability of occurrence be reliably determined? [To most people the magnitude is more important than the likelihood. In other words, "it's not the odds, it's the stakes!"]

    b. Is the risk properly calculated? Have the appropriate quantitative methodologies been applied?

    c. What is the uncertainty in the risk estimates? [Any uncertainty leads to anxiety about vulnerability, particularly for high consequence risks.]

    d. Will the safety precautions be taken? What happens if they are not? Have all important common mode failures been considered in the risk analysis?

    e. What are the latent or delayed consequences?

    f. How will the likelihood of an accident change with time or with prior planning?

    g. What provisions are there for updating the accident data base and re-evaluating the risks based on further experience?

    h. For how long a time period is the risk calculation valid?

    i. Are there any circumstances under which the risk analysis would would not apply? Have sabotage or deliberate acts been considered?

3. Can the risk be reduced and what will it cost?

a. Does the risk level depend on physical safety precautions or on people? Which precautions are more failsafe than others?

b. Are the consequences irreversible? Could we cope with an accident or mitigate the results of an accident?

c. Is there any experience or accepted prevailing practice for standard setting? What agencies, jurisdictions, and safety codes apply? Are they adequate?

d. What groups will obtain the benefits? Can the benefits be reduced to lessen the risks?

e. What groups are most likely to bear the consequences? How do the consequences vary for different groups?

f. Can affected groups be appropriately compensated for bearing an increased risk?

g. What options are open to those who do not wish to enjoy the benefits or assume the risks?

4. Is this risk acceptable? Is the distribution of risks and benefits fair?

a. Has a clear statement of both the benefits and risks been made?

b. Is the risk to each group worth the benefit gained? What are the specific risks and benefits to each group?

c. Is there a choice among alternatives? Were alternatives seriously considered? What are the risks and benefits of the alternatives? How do they compare to the original proposal? Apart from related alternatives, might there be completely different ways to achieve similar benefits without these risks?

d. Do the affected groups have any control over the risk situation? Over the design process?

e. Is the risk voluntarily assumed?

f. Is the risk visible? Is it continuous or intermittent? Will I be aware of it?

g. Is the risk familiar?

h. Is the consequence immediate or latent? How is the future to be "discounted", if at all? [Latent risks seem to more acceptable since the benefits are enjoyed today. Smoking is a prime example.] Is discounting possibly large future risks (or benefits) a wise policy?

i. What are the project's future implications? Will other future options be foreclosed?

j. How do the potential risks and benefits compare to similar risks and benefits present in today's society?

k. Who is responsible in the event of an accident? Will his assets and insurance cover potential liabilities?

l. Is the decision process fair?

m. Has the public been able to participate in an effective manner?

In practice, the answers to many of these questions will not be accurately known. However, for situations in which we are inevitably dealing with uncertainty, knowing the appropriate questions and defining the limits of our knowledge can by itself provide significant information and constraints for decision-making.

Recommendations

A previous section has discussed the potential risks of LNG and has recommended further research on LNG safety. The principal recommendations from our studies of the public participation in facilities siting disputes may be summarized as follows:

- The number of agencies concerned with LNG terminal siting is large. Because of overlapping jurisdictions, the lack of national guidelines for siting, and the unresolved safety issues the process of approval has been lengthy. For each LNG import terminal at least eleven federal agencies and twice as many state and local bodies are involved in the approval process. These jurisdictions and the regulatory responsibilities should be clarified and a clear national policy on LNG importation established.

- National LNG terminal siting guidelines should be established, not to preempt any of the regulatory agencies, but to provide them with the information they need. These guidelines should distinguish whether they are intended to protect against fatalities, injury, or inconvenience in the event of "design basis" accidents. The guidelines should be developed in a manner such that they can be implemented by state or local agencies, who should retain the right of ultimate site approval in order to ensure that specific local conditions are taken into account.

• Our case studies have indicated that the public has encountered difficulties in obtaining reliable information about proposed facilities and that public groups, including state and local governments, often lack the financial resources and organization to obtain knowledgeable and impartial technical advice. Federal guidelines would help provide information but these difficulties will, nevertheless, persist under the current regulatory framework.

• The early presentation of feasible alternative sites and open public discussion of the costs, risks, and benefits of these alternatives prior to the gas company's selection of a "best" site would both increase the decision options and lead to greater public confidence in the selection process. The extra costs incurred in publicly presenting feasible alternatives would probably have already been repaid by speedier approval and by enhanced public acceptance of this technology.

• The possibility of sabotage must be introduced into any risk assessment and considered in siting of facilities. So far, this has been largely omitted.

• Detailed contingency plans, training, testing and review procedures, and criteria for decisions under accident conditions need to be developed and scrutinized.

• Research results should be published in the scientific literature and disseminated widely to the public before they are used to justify safety decisions. Clear discussions of the technical issues are needed.

• Roughly 10 or fewer major LNG import/receiving terminals will be required to import the volumes expected by 1985 (2 trillion cubic feet of natural gas per year). Because these are basically regional facilities an effort should be made to publicly select an inventory of suitable alternative sites within each coastal region. The risks, costs, and benefits of the best of these alternative sites should then be publicly presented, so that all relevant concerns, including safety and land use planning, may then be taken into account.

- Finally, and perhaps most importantly, procedures acceptable to the public for evaluating risks and benefits must be found. These should include local comparisons as well as societal comparisons with other energy and industrial facilities.

VIII. LNG Decision Making

Decisions regarding the use of liquefied natural gas and the siting of LNG facilities must consider a number of factors relevant to diverse interest groups. The basis for previous decisions appears to have been inadequately presented to the public, and the decisions may not have achieved the most satisfactory compromises among the parties concerned. Situations in which the decision process has lacked clarity may have been acceptable when the scope of LNG operations were small, but there is significant expansion underway or planned on both the east and west coasts. Because LNG facilities will occupy large areas and provide a small but non-negligible fraction of the U.S. total energy supply, more detailed information and better methods for decision making are required.

The most recent environmental impact statements and reports issued by the Federal Power Commission [21, 57] and California agencies [58] for the proposed California import terminals at Los Angeles, Oxnard, and Point Conception represent large advances over their counterpart reports issued for east coast LNG facilities. These themselves represent advances on the absence of reports as recently as four years ago. Even so, none of the existing reports we have read, which comprise thousands of pages of documentation, attempts to structure the information into a format which could be assimilated by a decision maker. Neither has the material been presented in a manner such that the recommended tradeoffs are clearly substantiated by the information given.

It is well known that there are uncertainties in our present knowledge of LNG accident risks, in the future cost and availability of alternate fuels, in the costs and risks of switching to other fuels, in the effects of energy conservation on demand, in the effects of gas curtailments on employment and productivity, in the environmental impacts and costs of LNG facilities, in the risks of cut-offs or unavailability of foreign LNG supplies, and in the public acceptability of this fuel source. Since the time scale of these projects is twenty-to-thirty years and the present costs of LNG are high, these uncertainties may be important for determining our scale of commitment to LNG. Further, it may be that some decisions for future expansion could wait until some of the uncertainties are resolved.

In this chapter it is our aim to provide a review of some of the questions which need to be answered and to suggest decision analysis frameworks for considering two LNG decisions: the siting of an LNG tank in Cumberland, Rhode Island, and the development of large-scale Alaska-California LNG operations comprising pipeline, tankers, and terminals. Before doing so we will review the context in which LNG decisions are taken.

The Scope of the Problem

Any decision to use LNG requires establishing the need for supplemental supplies of natural gas. On a local basis the relevant information is presented by the local gas company. It is probably outside the scope of zoning boards to go beyond verifying local gas needs. However, for import/receiving terminals expected to supply a wider area detailed projections are important. Once an initial need is established, the projected demands over the life of the facility should be accounted for. This is where uncertainties will arise. Environmental and socio-economic impacts of the proposed facilities are then considered, and cost and benefit streams are derived over the lifetime of the operation. These data enable the cost, risk and benefit tradeoffs to be made explicit and the net benefits or a matrix of costs and benefits to be evaluated. For an LNG facility siting is the chief determinant of these impacts. It is the siting decision which has caused most of the public disputes, since most interest groups have generally conceded the immediate need for the gas.

The primary objective of LNG systems is to provide a reliable supply of natural gas which otherwise might not be available. In order to judge whether the costly capital investment in LNG systems is justified, the extent of the need must be well established. For a local decision, as in Cumberland, the data presented by the local gas company has usually been accepted without much question, but for decisions affecting regional or national supplies, as in California, the information on supply and distribution needs to be well-developed and regionally disaggregated. The effects of uncertainties in regional supplies and in costs of alternative fuels must be estimated over the life of the facility. It has been assumed that existing gas pipelines and distribution networks will be utilized where possible and that the amount of new pipeline should be minimized. However, for certain siting disputes it may be desirable to build additional or longer pipelines in order to lessen local risks or to minimize specific environmental impacts by siting the facility farther from gas markets. For this reason the costs and impacts of alternative pipeline routes and alternative sites need to be spelled out in each case where a facility is proposed.

Although gathering information and developing cost-benefit estimates for alternatives may be difficult, it should be done in order to arrive at the solution with the greatest net benefits to society. If alternatives are not publicly proposed for a specific project, there are always the implicit alternatives which may be overlooked. Often these are arguably outside the scope of decision making, but they should be examined if only to demonstrate that LNG is the preferred energy option. Proposers of LNG facilities imply that other options are less desirable or less feasible. For example, they assume that switching to other fuels not distributed by the gas company (e.g., oil or electricity) would be more costly to society than building LNG facilities and that the adverse effects of conserving gas by cutting back on its wasteful use would be more costly than paying for higher-priced LNG. It may not be the obligation of the gas company whose job is to provide for our gas needs to justify these assumptions, but information of this nature should be considered by any decision maker.

More importantly, new supplies of gas might become available within the lifetime of the proposed LNG facilities, thus reducing their net benefit to society. If natural gas prices are deregulated, it is possible that domestic production will rise to higher levels ten years hence. In the future, substitute or synthetic natural gas from petroleum or coal may also be developed successfully or the costs of methanol production may drop. Since we are considering large-scale LNG systems lasting for thirty years, it is sensible to suggest that these options might affect the future costs and benefits streams. These possibilities should not be neglected. From the immediate perspective, all too prevalent in decision making, the need for LNG has been established, and judging from 1975-76 and suggested 1977 curtailments, additional natural gas supplies are indeed desirable. Nevertheless, the scale and timing for development of LNG facilities may depend on answers to some of these questions which will only be known in the future.

The reason for understanding the necessity for additional gas supplies becomes important when lead times for developing LNG facilities are considered and compared to the lead times for supplying alternate fuels. The planning and approval process can take several years itself, followed by three-to-four years to construct an LNG terminal and bring it into production. In the short term LNG may in fact be easier to implement than other fuel supply options, since the technology is known and gas supplies are available, whereas other options have even longer lead times and greater technological uncertainties. From this point of view LNG is desirable, but can we supply the required amounts?

One possible limitation on LNG imports might be the ability to construct enough LNG tankers to meet the worldwide demand. However, present estimates indicate that there is adequate LNG shipbuilding capacity to provide the necessary tanker fleet to ship all the supply. Whether or not the supply will be adequate is an open question. Japan and Western Europe are expected to be large consumers of worldwide LNG supplies, and it is possible that combined demands may exceed the foreign production capacity after 1985. Moreover, a number of LNG contracts have been renegotiated to account for rising prices, and it is expected that the price of foreign LNG will be closely tied to that of oil, affecting the price to the U.S. consumer. For foreign supplies the possibility of an embargo, sabotage, or other shutdown of the liquefaction plant is also present, although it must be noted that during the Arab oil embargo of 1973 Algeria, an Arab country, kept its contractual commitments to supply LNG as far as the state of repair of its facilities allowed. The operational reliability and financial status of foreign suppliers may be outside of U.S. control. Thus, competition, national security, foreign policy, and the balance of payments may well limit the quantity of our LNG imports.

In August, 1976, the Energy Resources Council asked for an upper limit of two trillion cubic feet per year of gas from total foreign LNG imports by 1985 (i.e., about 92.9 million m^3 of LNG) [61]. About 0.4 Tcf/yr. are already approved and current applications could exhaust the remainder. Further, for security reasons the imports from any one country would be limited to 1 Tcf/yr. Import projections for the East Coast in 1985 are .87 Tcf/yr. (trillion cubic feet per year) and for the West Coast at least 0.2 Tcf/yr. [21, 62]. The gas industry would like the U.S. to import up to 3 Tcf/yr.

to supplement domestic gas production which has been declining since 1973 when 22.6 trillion cubic feet were produced. By 1990 over half the production must come from reserves yet to be discovered. In 1985 the total U.S. gas supply is expected to be about 20 trillion cubic feet per year, including imported LNG.

Future decisions on how LNG is to be priced may affect the desirability of large-scale LNG systems. The price of LNG is now "rolled in" to the existing price on a percentage basis. Since LNG represents only a small fraction of existing supply, the price to the consumer using gas supplies supplemented by LNG has not escalated dramatically. It is likely that future LNG prices will continue to be "rolled in". However, the actual price may be politically regulated both in this country and at the well head, so calculations of costs and benefits should incorporate a range of possible prices to judge the sensitivity of these assumptions. The expected demand will also be correlated with the price to the consumer. Therefore, fair pricing of LNG will pose interesting problems to the regulator as well as to the analyst trying to calculate the costs and benefits of LNG and alternate fuel options. Regional variations in pipeline transmission costs and in availability of other fuels may significantly influence the distribution of costs and benefits.

In light of high capital costs and concern for LNG risks, the marginal cost of increased safety precautions, including remote siting, may prove to be small in comparison to total costs. Decision makers will have to judge carefully whether the risks and benefits are fairly distributed, especially among those who reside nearest to LNG sites. It should be determined if those bearing the increased risks are entitled to compensation in the form of reduced taxes, rebates on fuel costs, or by having a proportion of their property and accident insurance paid by the gas company. Of course, we see no reason why LNG facilities should be singled out in this way and these considerations could apply in the future to all hazardous or environmentally objectionable facilities. For LNG facilities, such compensation could be determined by a simple formula related to distance from the facility. If alternative sites are proposed, the compensatory costs may suggest that sites with lower risk to the surrounding population would be cheaper and thus preferred. These "compensatory costs" are of significance even if compensation procedures are not actually implemented because such schemes may be too difficult to implement.

Of course, considering future compensation schemes raises the question of compensating those who live near other hazardous facilities as well. The remote siting of LNG terminals avoids this issue and ensures that the costs are paid by those who benefit from the use of the gas.

Evaluation Criteria

The most important environmental impacts (apart from accidental fire risks) result from the effects of construction and operation on the land itself [see Table 3]. The routing of pipelines and siting of the terminal and storage facilities are the major determinants of these impacts. In this respect, the potentially adverse effects of LNG are less than the corresponding risks of similarly sized oil pipelines and refineries which can produce greater air pollution and longer-term damage to the biosphere in the event of oil spillage.

A number of evaluation criteria have been developed to assess LNG sites. For LNG terminals the following categories have been used:

1. topographic conditions including the size of the site, access to transport, pipelines, markets, and site elevation and slope;
2. foundational stability including soil and seismicity conditions;

3. meteorological and atmospheric conditions;
4. oceanographic conditions;
5. deep water port capability including the amount of dredging needed;
6. navigational suitability including year-round ice conditions, fog, wind, squalls, and snow;
7. anchorage suitability;
8. land use conflicts including existing zoning laws, present land use, the status of surrounding areas, purchase availability, impact on parks and forests, recreational, historical and archeological sites;
9. terrestrial and marine biological impacts;
10. potential risk to employees, the surrounding population and to existing property and facilities;
11. socio-economic impacts including disruption during construction and operation, increased employment, tax revenues, and future development of the community;
12. regional energy needs.

For routing pipelines the Federal Power Commission considers the following as factors to be minimized [63]:

"1. total pipeline distance;
2. routing in areas requiring substantial grading for right-of-way preparation;
3. number of streams, highway and pipeline crossings;
4. routing in areas with special hazards such as avalanche or slope instability;
5. routing in areas where construction and operation of the pipeline would conflict with other established land uses.

Factors to be maximized are:

1. routing in areas having favorable pipe supporting and excavation characteristics;
2. availability of granular borrow;
3. use of existing transportation facilities for construction material supply and maintenance access."

Apart from these considerations, the flexibility of LNG systems to expand to meet increasing demand or to provide reliable supplies in the event of operational malfunctions should be factors, particularly for decisions choosing among gas transmission pipeline-only options, LNG proposals, and alternative energy sources. It may be less costly to add additional compressors on an Alaskan pipeline to increase pipeline throughput than to build additional LNG tankers and liquefaction or regasification units. However, in the eastern U.S. some pipelines are operating near their maximum pressures.

It is clear that any decision making process would like to consider all the foregoing information and factors as input. However, depending on jurisdictional boundaries and the ground rules for the specific decision, certain categories will dominate, and some factors will be prescribed within specified limits. Several methodologies suggest themselves as relevant to the decision problems posed in the previous pages. In the remainder of this report we shall try to suggest how the techniques of decision analysis might be applied [64]. Although we discuss simplified situations, these techniques might be applied to help interest groups evaluate a set of national siting guidelines for LNG facilities or to determine the expansion sequence for regional LNG facilities.

The methods of decision analysis have been applied previously to situations involving conflicts similar to that in Cumberland, Rhode Island.

The applicable techniques are called "multi-attribute utility theory" or "multi-attribute decision analysis" [65]. Other techniques of decision analysis may prove useful for California decision makers in determining the scale and sequence of California's future LNG operations.

The Cumberland Case Revisited

In the Cumberland case the first step is to identify the interest groups of importance to the decision. Defining interest groups may be subject to dispute, but the principal interest groups have already identified themselves. In the general case, these are:

1. the utilities who will build, maintain, and operate the facilities;
2. the regulatory agencies who must license and oversee the operations. These range from local zoning boards and fire departments to agencies like the California State Energy Resources and Development Commission, the Federal Power Commission and the U.S. Coast Guard [see Table 8];
3. the environmentalists plus impacted groups who live nearest to LNG facilities and thus bear more risk and possibly reduced property values;
4. local interests who will enjoy employment, taxes, and increased commerce;
5. the consumers who will use the gas.

For the purposes of our simplified discussion we will assume that the interests of the consumers are represented by the four other interest groups, and we shall consider the first four groups as spanning the most important points of view.

Although the present request to build an LNG tank at the site of the Valley Gas Company in Cumberland is still in abeyance, evaluation of the preferences of the four primary interest groups might lead to a satisfactory alternative. The limited details presented by the Valley Gas Company suggest that their existing site represents the least cost alternative to them. This has led the present decision to be either yes or no--to build or not to build--and after nearly four years no tank has been built. Perhaps an approach considering both alternative sites and possible changes in the tank-dike size or design, resulting in increased safety, could lead to a resolution of the current dispute.

In requesting permission to build the tank, no alternative sites were proposed although some were suggested by intervenors. The need for the supplemental gas supply was conceded (20,000,000 ft^3/day) after a brief discussion of the future demands for gas in the Blackstone Valley, and the size of the tank proposed was 300,000 barrels equaling 47,700 m^3 or about 50 days supplemental supply [38]. Although a smaller-sized tank might present a smaller risk there were no negotiations regarding the size of the tank. The possibility of a high concrete wall dike around the tank (15 feet away from the 155-foot diameter tank) rather than or in addition to a lower dike enclosing a greater surface area (about 310 feet by 310 feet) was not considered, presumably because of cost, nor was the effect of an LNG fire upon the existing propane storage tanks considered in estimating the maximum potential accident. These possibilities are suggested here to broaden the scope of discussion and to suggest that higher dikes with smaller pool area or multiple dikes or dikes with vapor containment barriers should be considered.

The testimony presented before the Cumberland Zoning Board of Review and the Providence Public Utilities Commission qualitatively indicated the most important attributes to the four primary interest groups:

1. reliability of the gas supply;
2. availability of a suitable tank site within Cumberland with access to roads for LNG delivery by truck. The gas company does not have the right of eminent domain and local interests would prefer having the tax revenues;
3. minimum overall cost, including factors such as the pipeline distance to the present Valley Gas sendout facility;
4. safety of the facility and the truck delivery routes.

Other attributes provide constraints on the decision, but appear to be less important to the decision. This would have to be verified by further discussion with the interest groups. Using these attributes, we shall suggest a methodology for arriving at a design for the Cumberland LNG storage tank which might be acceptable to the four interest groups. This methodology has proved useful in dealing with problems of comparable complexity. Some examples are given in reference 65.

If alternative sites could be identified in proximity to Valley Gas's existing facility, differences in the costs and benefits could be evaluated to determine whether any of the alternatives would be acceptable to the concerned groups in terms of costs, risks, and benefits. If no suitable alternative sites can be found, it may still be possible to reduce the risk by design changes or to enhance the acceptability by compensation procedures. Presumably, the reliability of the gas supply would be the same for any site, unless the size of the proposed tank were substantially reduced. The distance to the send-out facilities is fixed by the chosen site location and as long as alternative sites were not prohibitively far away, any additional costs would represent the costs of reducing the risk to an acceptable level.

Achieving tradeoffs among attributes 1, 3 and 4 necessitates adopting a measure for safety which can be simply understood. Safety is related to: a) the distance from the tank-dike to the nearest populated area; b) the size of the LNG storage tank and its surrounding dike as measured by the surface area enclosed by the dike and the tank capacity; c) other design criteria like seismic levels, wind loading, site security, etc. These parameters indicate a number of ways in which an LNG storage tank might be made acceptable:

1. Find a suitable site in which the distance to the nearest populated area is large enough to be acceptable to those surrounding the site.
2. If suitable alternative sites do not exist, design a safer storage tank or a higher dike near to the tank as in recent LNG tank designs. A higher dike nearer to the tank reduces the area of any pool fire and thus the heat radiated. If an acceptable "safe" distance had been determined in advance by querying potential intervenors such as local residents, a tank and dike could have been designed which had the appropriate "safe" distance. This would largely be determined by relative preferences for a particular heat flux as a function of distance from a pool fire, which is the accident most likely to cause damage. Such a tank might be smaller or, if higher dikes are used, more costly. Some capacity could be traded for decreased risk or the risk could be reduced by paying for the higher dike or for multiple dikes with vapor barriers.

A number of alternatives might be developed by Valley Gas; hopefully, several would have feasible costs and be satisfactory to all interest groups.

However, it is possible that the tank with an acceptable "safe" distance (to the intervenors) would always be too small to provide the reliable supply or too costly to build. The multi-attribute approach offers a convenient framework for compromise. In this case it would seem reasonable to adopt the technique of "utility maximization" or "preference maximization" in order to arrive at a satisfactory tank size and siting [64, 65].

The process of "preference maximization" would be carried out for each alternate site and would involve at least one representative of the four interest groups. Dollar costs would be determined for several tank and dike sizes, so that they could be added to the fixed costs of site preparation and construction to estimate a cost for each alternative. We assume the benefits of each alternative are the same, apart from the effects tank size might have on reliability, although we suspect that the reliability will not suffer appreciably from safer designs. Hypothetical preference functions for the interest groups are illustrated below in order to suggest how the different interest groups might view the project. It is assumed that the pipeline distance is fixed for each site, so that facility safety, cost, and reliability of the gas supply are the variables to be traded off against one another. The example is intended to be a simplification, but the method is capable of accommodating more complex tradeoffs and a greater number of attributes.

Multi-Attributed Preferences for Cumberland

One method to assess safety is by asking each interest group to assign a relative preference value to having the nearest residence "x" feet from the edge of the dike. The techniques for obtaining such preference curves will not be discussed here, but are given in the literature [64, 65]. We assume that large distances will have a preference rating of 1, while nearby distances would have decreasing preference values determined from maximum thermal radiation estimates. Here the interest groups would have to decide their relative preferences for protecting against fatalities, burns, or discomfort as a function of distance from the dike. This simple model implies that all sites have the same exposed population (population density) outside the site boundary. Suitable scale factors could later account for differing population densities surrounding alternate sites. For the proposed Cumberland tank a "safe" distance with a heat flux of 1,300 Btu/hr-ft^2 was estimated by consultants from Arthur D. Little to be 950 feet. Present federal regulation would require only about 250 feet. The following curves might be obtained, with preferences being rated on a scale between 0 and 1 (Figures 3-5). These curves indicate that a gas company official probably has greater preference for the estimates of the experts than does someone who lives nearby. The shape of the two preference functions are entirely different. The regulatory agency might like to assign a 100-foot margin to the experts' estimates and then assume that all distances beyond 1,050 feet are equally "safe" from their point of view. The local businessman is not quite so risk averse as the nearby resident, but still prefers to be farther away than the deemed minimum "safe" heat flux at a specified distance. For any proposed tank and dike size, the preference value would be assigned to the heat flux, as a function of distance from the dike and from a design-basis pool fire. These preferences will undoubtedly depend on the nature of the surrounding neighborhood. For example, the Cumberland Elementary School is located 1,050 feet from the dike. The relative preferences for site safety may then be represented by these preference values. Assume the gas company official has assigned a preference of 1.0 to the safety of this location for the tank design, which an expert deemed safe at 950 feet (i.e., a radiated heat

Figure 3

HYPOTHETICAL SINGLE-ATTRIBUTE
PREFERENCE FUNCTIONS FOR SAFETY

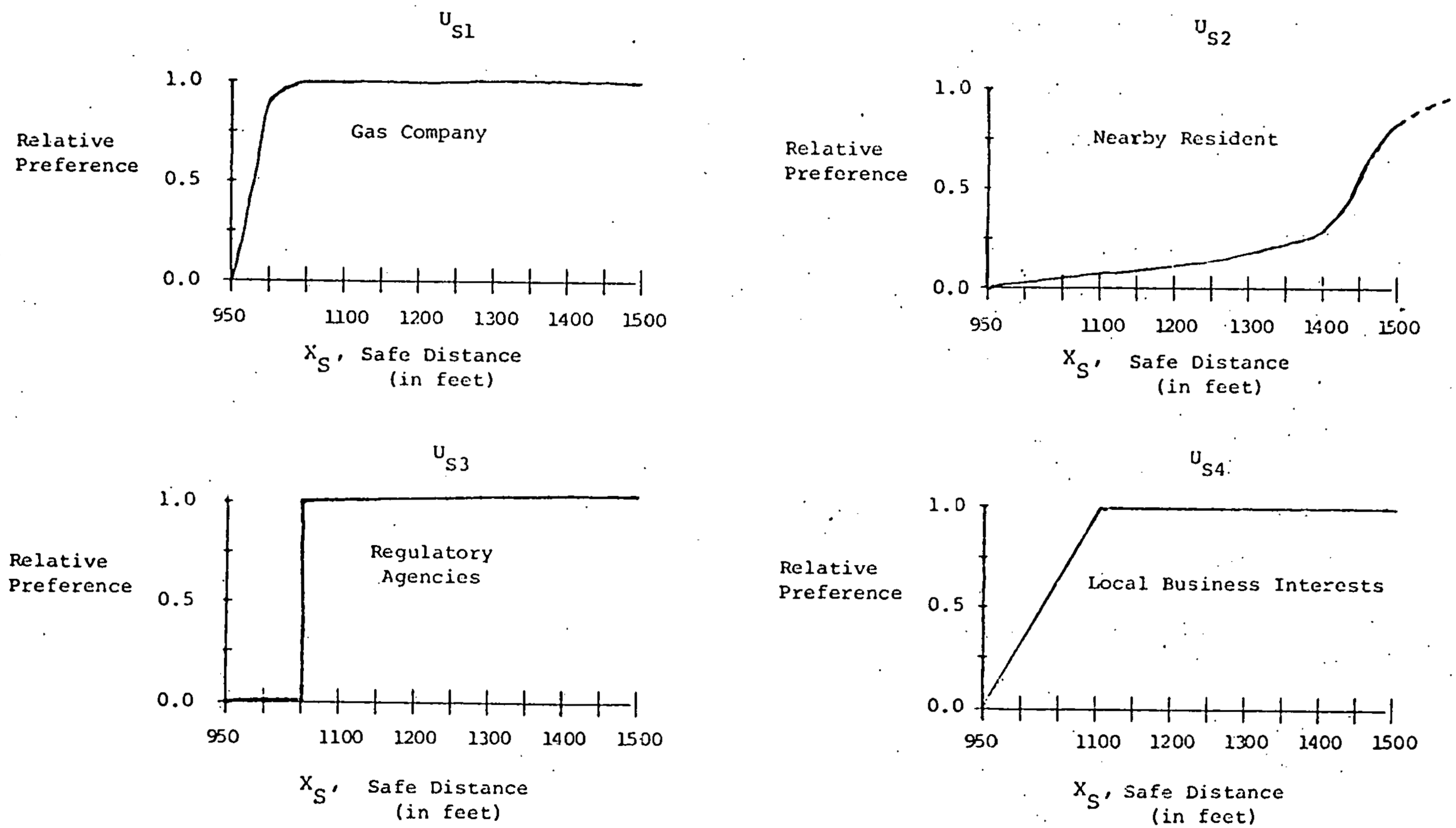


Figure 4

HYPOTHETICAL SINGLE-ATTRIBUTE PREFERENCE FUNCTIONS FOR RELIABILITY OF GAS SUPPLY

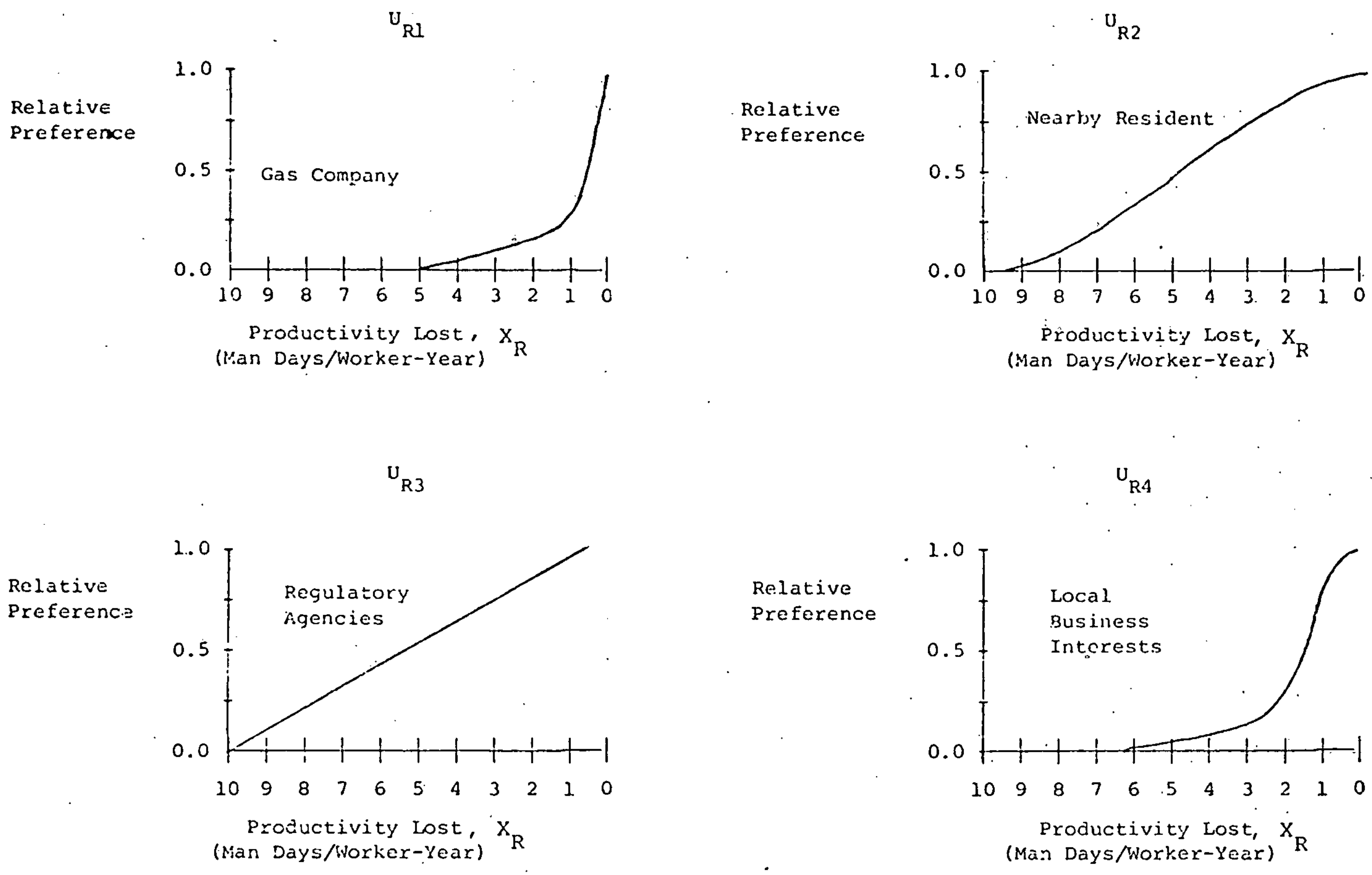
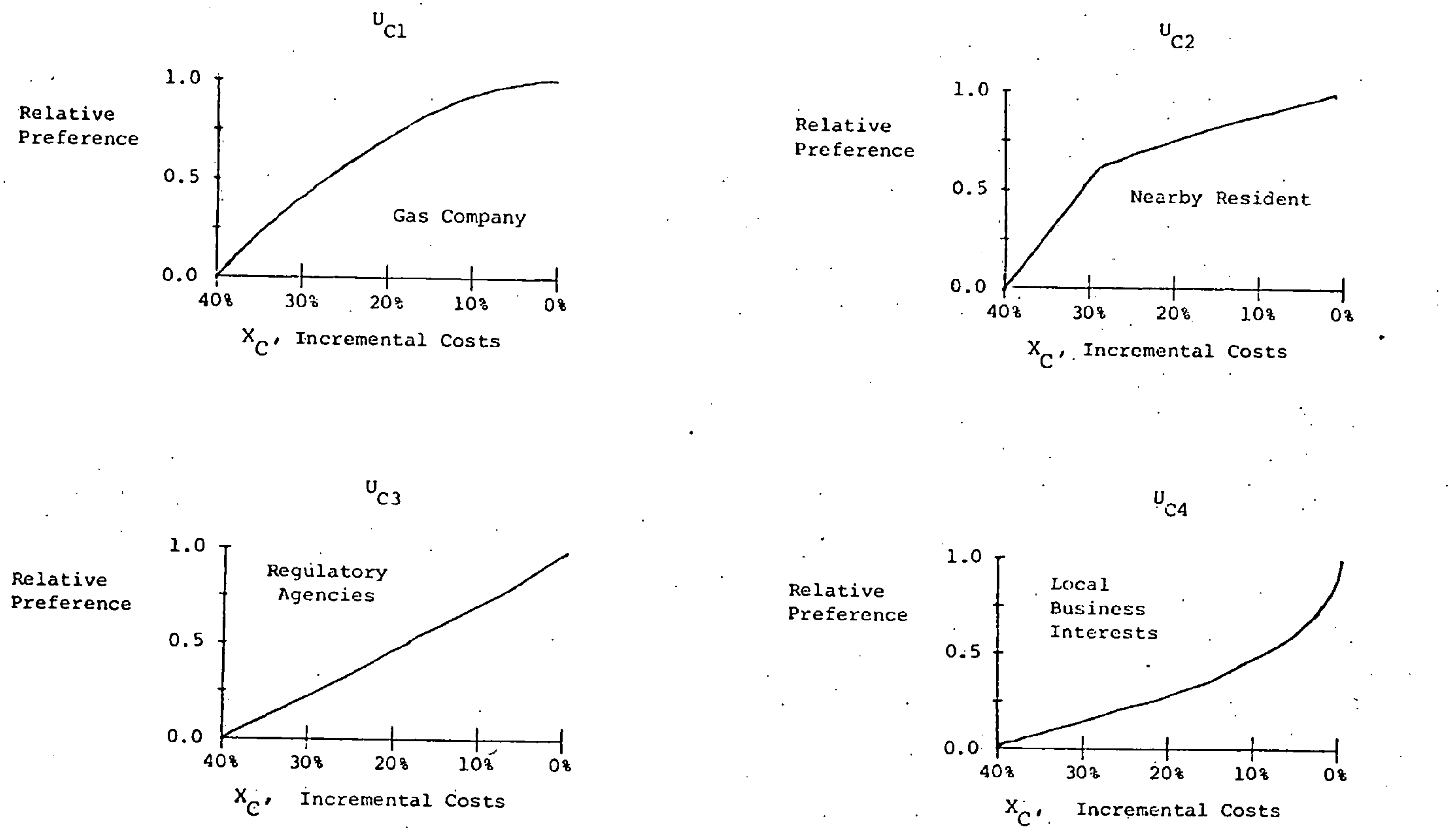


Figure 5

HYPOTHETICAL SINGLE-ATTRIBUTE PREFERENCE FUNCTIONS FOR INCREMENTAL COSTS



flux of less than 1300 Btu/hr-ft^2 for any pool fire contained within the dike). He obviously feels the school is safe. The nearby resident has assigned a utility of 0.05, which describes his preference value for this distance. Likewise the regulator believes the school is just safe--but safe nevertheless. The local businessman thinks it's pretty safe (preference value = 0.75).

Similarly the gas supply reliability preference function can be determined for each group, but in order to be meaningful in terms of tank design the reliability must be related to tank capacity. It is not necessary to know this functional relationship to assess peoples' preferences, but presumably the Gas Company has used it to decide on the proposed capacity. If an LNG tank of too small capacity were designed, all demands would be satisfied until near the end of a very severe winter (a design winter) in which large pipeline curtailments occurred. We might assume for the sake of argument that over some range of tank capacities the number of work days lost by customers of Valley Gas can be simply related to the tank diameter. Four hypothetical preference curves are illustrated below. For the gas company official, expected to supply gas at all times, the preference value drops rapidly since any productivity lost due to gas supply failure is his responsibility. The local resident, initially opposed to any tank, is willing to trade some productivity loss in order to reduce his continuous risk. The regulatory agency has a civic conscience, but realizes also that a tank of large capacity means more risk and greater regulatory responsibility. The businessman might actually feel that one or two days lost in a severe winter would not be a great disaster, but a large number would be. Interestingly, he may be more willing to endure a brief shortfall in supplies than the hypothetical gas company official. We expect that the reliability attribute is dominated by safety and cost, once a decision to build a tank is reached. The third important attribute is the incremental cost of construction, maintenance, and operation of a safer tank and dike configuration. We express this as a percentage of the cost of the proposed tank.

We will briefly suggest how these preference functions might be used to arrive at acceptable trade-offs and to illuminate the most important attributes of the decision to the decision maker. For development of the methodology and earlier applications the reader is referred to the literature [64, 65]. Once the preference functions are known the relative preferences corresponding to a particular site tank location, dike arrangement, and capacity can be used to calculate the overall preference for that alternative for each interest group. Each group's composite preference function for the three attributes may be expressed as

$$U_i(X_S,\ X_R,\ X_C) = f[U_{Si},\ U_{Ri},\ U_{Ci}]$$

where f is a scalar function, and i is the interest group. Two possible forms which have been derived for U_i are the additive form:

$$U_i(X_S,\ X_R,\ X_C) = \lambda_{Si}U_{Si}(X_S) + \lambda_{Ri}U_{Ri}(X_R) + \lambda_{Ci}U_{Ci}(X_C),$$

where $\lambda_{Si} + \lambda_{Ri} + \lambda_{Ci}=1$, X_S is the distance, X_R the number of workdays lost, X_C the percentage increment in cost, and U represents the preference functions in Figs. 3-5; or the multiplicative form:

$$k\ U_i(X_S,X_R,X_C) + 1 = [k\ k_{Si}U_{Si}(X_S)+1]\cdot[k\ k_{Ri}U_{Ri}(X_R)+1]\cdot[k\ k_{Ci}U_{Ci}(X_C)+1]$$

where k is a scaling constant chosen so that U_i will be between 0 and 1, and the k_{Xi} are also scaling constants between 0 and 1 chosen such that $k + 1 = (k\ k_{Si}+ 1)(k\ k_{Ri}+ 1)(k\ k_{Ci}+ 1)$. Either the additive or multiplicative form of U_i might be correct, depending on the risk aversion of the interest groups. The assumptions of preferential and utility independence also need to be verified. If they are, the constants required in the composite function may be determined using methods similar to those for determining the individual preference functions.

Once the overall preference functions are determined for each group, the objective is to combine them in a meaningful way in order to find the designs or level of safety on each site which maximize the combined preferences for all four interest groups. This process is called Pareto-optimization and has been applied in Reference 65c. This combination should be additive for Pareto-optimization. Here the relative weights for each group must be varied to examine the potential trade-off options. For descriptive purposes, let us assume the composite preference function is additive and is given by $P(X_R, X_S, X_C)$. Let subscripts 1, 2, 3, and 4 correspond to the gas company, the local residents, the zoning board, and the local businessmen, respectively. The combined preference functions for each group are U_1, U_2, U_3, and U_4 and the respective political weights are W_1, W_2, W_3, and W_4. The overall composite preference function, relating to a particular alternative might be:

$$P(X_S, X_R, X_C) = \sum_{i=1}^{4} W_i U_i(X_S, X_R, X_C)$$

After these representative preference functions are determined, the gas company should, in principle, be able to design a tank-dike configuration and size for each site to maximize the preferences indicated. For example, if the company wished to consider only its views it would assign $W_1 = 1.0$ and the rest equal to 0.0. Another choice might be $W_1 = .4$, $W_2 = .25$, $W_3 = .1$, $W_4 = .25$. The resulting design might be quite different if relative weights $W_1 = .2$, $W_2 = .6$, $W_3 = .1$, $W_4 = .1$ were chosen. In this manner a set of options could be developed and compared for each specific site.

Even with a greater number of attributes, multi-attribute preference theory could be applied to this decision problem. However, any preference functions and political weighting factors represent simplifications of the problem and can never wholly represent the entire decision problem. Nevertheless, applying the methods suggested here can illuminate the trade-offs between cost, safety, and reliability. Once the preferred design parameters are chosen at each site to maximize the composite preferences, the gas company would be in a position to seek approval for the best alternative. The resultant trade-offs among cost, safety, and reliability would be more explicit and the concerned parties would have participated in the decision process.

In the absence of such methods, it should be remembered that, as yet, common sense arguments have been used in this case without an agreeable conclusion. Even if the specific design options were not fully developed there is value in using the procedure to focus on the important trade-offs from different points of view. It may be advisable to use such techniques in the development of state or federal siting guidelines to assist local decision makers.

California Natural Gas Options

We shall now suggest a framework for evaluating the larger problem of California's future commitment to liquefied natural gas. In order to do this we shall incorporate a methodology for dealing with decisions involving uncertainty called decision analysis. First, however, we shall sketch a simplified version of the possible scenarios confronting California's natural gas planners today.

California and national planners are faced with several alternative proposals to supply natural gas to California and the Midwest. The California options are closely tied to the alternate decision to construct a gas pipeline from Prudhoe Bay across Alaska and Canada into the U.S., continuing to an eastern terminus near Chicago. Independent proposals involving LNG require a gas pipeline from Prudhoe Bay to liquefaction plants in Southern Alaska, LNG being transported by tanker to one or more of three proposed Southern California import/receiving terminals, where it would be vaporized and put into transmission pipelines [see Table 10 and References 57 and 58]. In the event of no Alaska-Canada gas pipeline it is possible that California will become a gas supplier to the Rocky Mountain States and the Midwest, at a higher gas cost to those consumers than for a more direct pipeline. In the event of limited LNG shipments to California it is likely that a branch of the Alaska-Canada pipeline would be built to a site in northern California near San Francisco [Figure 6]. California now receives much of its gas, 1.63 trillion cubic feet per year, from Western Texas, New Mexico and Canada. Varying projections indicate that between 20 and 65 percent of California's natural gas supply will come from LNG by 1990 [66].

Clearly the effects of each alternative will depend on whether the pipeline proposal is approved. The risks, costs, and benefits of each are dependent on many factors such as the availability, location, and cost of other fuel supplies, the scale of development of the LNG option, contractual agreements between western and midwestern gas suppliers, system reliability, delays in regulatory approvals, escalations in construction costs, flexibility and cost of future expansion, and public acceptability. The pipeline for the LNG option from Prudhoe Bay will have associated environmental impacts and will cross a seismically active area. The longer Alaska-Canada pipeline will also have substantial environmental impacts.

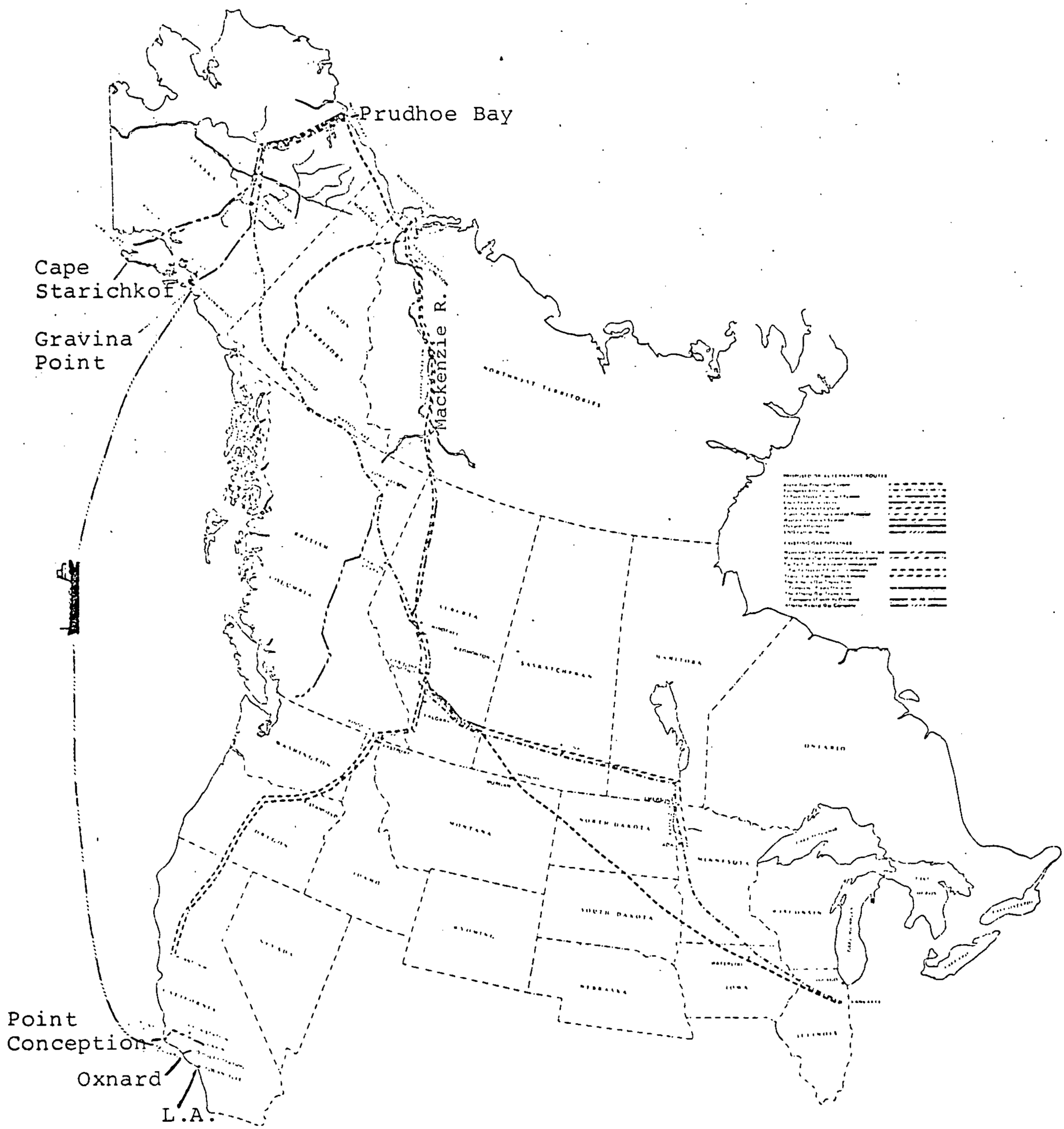
Because of present uncertainties it may be desirable to first develop only one LNG import terminal in California and then expand it or develop additional sites after new information indicates the most desirable option. When the output exceeds 4 bcfd (4 billion cubic feet per day) in Southern California, two sites will be needed anyway because of volume limitations.

Table 10

WEST COAST NATURAL GAS SUPPLY PROPOSALS

PROPOSER	ALASKA (Prudhoe Bay Field)		CALIFORNIA	
	LNG Liquefaction and Shipping Facilities, plus Required Pipelines	Natural Gas Pipelines Only	LNG Vaporization and Receiving Facilities, plus Required Pipelines	Natural Gas Pipelines Only
El Paso-Alaska -Western LNG	Pipeline from Prudhoe Bay to Point Gravina Prince William Sound (809 miles, 3.1 bcfd) LNG to Pt. Conception via tanker (1900 nautical miles)		Pt. Conception (2.8 bcfd + 0.3 bcfd peaking) (2.1 bcfd alternative); pipeline to Arvin and Cajon (142 and 109 miles respectively)	
Pacific-Alaska -Western LNG	Pipeline to Cook Inlet, Nikiski (0.2 to 0.4 bcfd) LNG via tanker to Los Angeles		LA Harbor, 16,000 ft. pipeline (0.2 to 0.4 bcfd, ultimately 4 bcfd)	
Pacific-Indonesia-Western LNG			Oxnard: Pipeline to La Vista (12.2 miles) [ultimately to include 53.3 miles to Quigley Canyon] (0.52 bcfd from Borneo)	
Arctic Gas		Prudhoe Bay to Yukon Border (195 miles, 2.25 bcfd) connecting with: Mackenzie Delta pipeline to Alberta, forking into Idaho and Montana (2297 miles, ultimate 4.5 bcfd) including possible extensions to Northern California (917 miles) and Illinois (1138 miles, 1.5 bcfd)		Idaho, Washington, Oregon extension to Antioch, California (874 miles, 0.85 bcfd)
Federal Power Commission Alternatives	Pipeline to Cape Starichkof, LNG via tanker to Oxnard	Prudhoe Bay via Fairbanks and Alberta to Illinois (3711 miles) plus possible Mackenzie Delta connection.	Combined 4.0 bcfd base-load plus 1.0 bcfd peaking terminal at Oxnard to use Alaskan supplies, including 224 miles transmission pipeline	Fairbanks alternative with no California pipeline extension (California to obtain gas supplies from Southwestern U.S.)

Figure 6



Alternative Pipeline routes to supply natural gas to California and the Midwest (from Federal Power Commission Staff, Final Environmental Impact Statement for the Alaska Natural Gas Transportation Systems, April 1976, p. I-A5.)

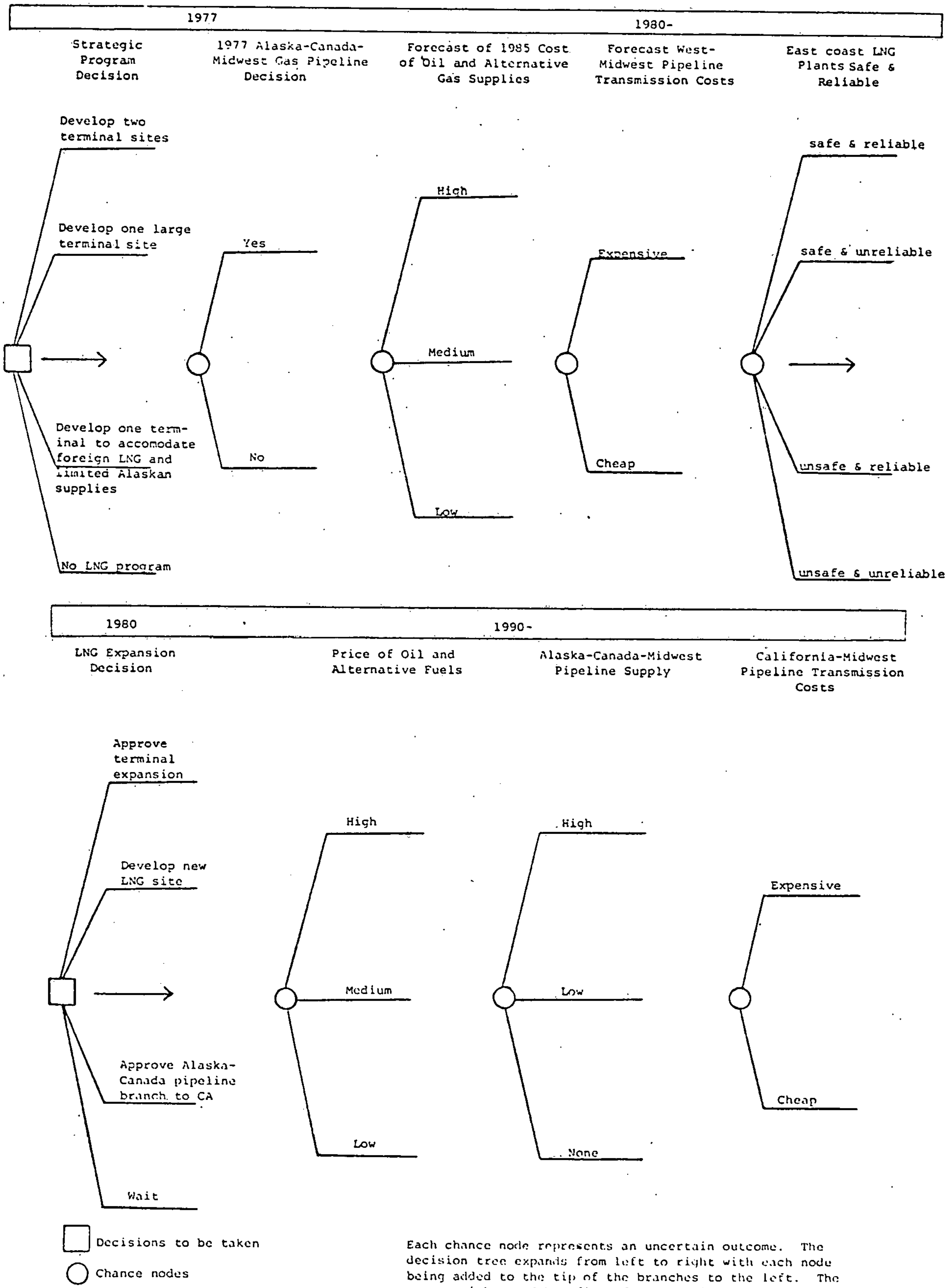
Even when deliveries exceed 1 bcfd, an LNG terminal shutdown due to accident or mechanical failure could cause disruption in gas supplies. These trade-offs are important to the initial decision to develop one or more sites. Moreover, all of these factors need to be presented in a framework which can be assimilated by decision makers and the public.

Regulatory approval has not yet been given and the decisions are clearly complex. Thus far, however, a clear and concise statement of the problems, the alternatives, and the important costs and benefits has not been provided. Because of uncertainties in our present knowledge, and the 20 years or longer lifetime of these facilities, it might be prudent to adopt a sequential approach for developing the possible options. Figure 7 suggests a timetable for LNG decision-making in California. Two recent studies have incorporated similar decision analysis methods to evaluate potential alternatives for synthetic fuels commercialization and for the U.S. breeder reactor program [67, 68].

The impacts of each of the potential uncertainties needs to be evaluated in order to make the best decisions in 1977, and in the future, here indicated as 1980. Between now and 1980 new information will become available: the gas supply picture will be clearer, the issue of deregulation will be decided, negotiations for LNG pricing and compensatory supply agreements among the states may be resolved, leading to more reliable estimates of gas transmission costs and long term supply information. Importantly, LNG operations on the east coast should have indicated their safety and operational reliability after several years of actual operation. This information will help determine the scale of California's commitment to LNG and whether a branch of the Alaska-Canada gas pipeline should be extended to California if the pipeline to the Midwest is, in fact, approved. California will almost certainly decide to

Figure 7

POSSIBLE DECISION SEQUENCE FOR CALIFORNIA LNG OPTIONS



Each chance node represents an uncertain outcome. The decision tree expands from left to right with each node being added to the tip of the branches to the left. The costs, risks, and benefits of each option need to be evaluated. Probabilities can be assigned to be possible outcomes.

develop at least one LNG terminal site in 1977 because of her pressing need for gas, but decision analysis can suggest the costs and benefits of potential expansion scenarios.

On July 1, 1976 the United States Senate approved a bill directing the Federal Power Commission to recommend a route for delivery of natural gas from the North Slope of Alaska by March 1, 1977. The President would then select the final route with limited judicial review by July 1, 1977 [69]. This choice will decide among either of two routes for the pipeline-only option across Alaska and Canada to the Midwest or the Alaska-California LNG proposals discussed here. Because of the magnitude and implications of this decision for California and the nation, a comprehensive and comprehensible framework is urgently required to evaluate the trade-offs, risks, and benefits of these options. Even if the methods of decision analysis are not formally applied, an explicit and concise presentation of the issues and impacts is sorely needed.

IX. References

1. Pipeline and Gas Journal (Annual LNG Issue), June 1976.

2. Hardy, Edwin, Chem. Eng. Prog., 70 (August 1974), pp. 21.

3. National Fire Protection Association, Gas Explosion and Fire (Report UNF-7). Boston: NFPA, 1944.

4. Elliot, M.A., C.W. Seibel, F.W. Brown, R.T. Artz, and L.B. Berger. Report on the Investigation of the Fire at the Liquefaction, Storage, and Regasification Plant of the East Ohio Gas Co., Cleveland, Ohio, October 20, 1944 (R.I. 3867). Pittsburgh: U.S. Bureau of Mines, February 1946.

5. U.S. House of Representatives, Committee on Interstate and Foreign Commerce, Special Subcommittee on Investigations (7/10-12/73), 93rd Congress, 1st Session. Staten Island Explosion: Safety Issues Concerning LNG Storage Facilities. Washington, D.C.: U.S.G.P.O. (#93-42), 1973. (Also: Special Subcommitte on Investigations, 2nd Session, Legislative Issues Relating to the Safety of LNG Storage. Washington, D.C.: U.S.G.P.O., March, 1974.

6. "Explosion Rips Largest Gas Tank, Killing Four," Eng. News Record, 31 (4/4/68), and "Explosion Inquiry Blames Open Valve, Missing Cutoff," Eng. News Record, 29 (5/16/68).

7. "LNG Plant Explosion," Fire Journal, 66:4 (July 1972), pp. 38.

8. Office of Pipeline Safety. Technology and Current Practices for Processing, Transferring and Storing Liquefied Natural Gas (Report No. C-76971), prepared by D. Allan, et. al. Cambridge: Arthur D. Little, Inc., December 1974, pp. 94.

9a. Simmons, John A. Risk Assessment of Storage and Transport of Liquefied Natural Gas and LP-Gas. Science Applications, Inc., November 25, 1974.

9b. Burgess, D.S., and M.G. Zabetakis. Detonation of a Flammable Cloud Following a Propane Line Break: The December 9, 1970 Explosion in Port Hudson, Missouri (R.I. 7752). Pittsburgh: U.S. Bureau of Mines, 1973.

10. Fay, J., and J. MacKenzie, "Cold Cargo." Environment Magazine, November 1972.

11. Hoult, D.P. "The Fire Hazard of LNG Spilled on Water," in Prooceedings on Conference on LNG Importation and Terminal Safety, Boston, June 1972. Washington, D.C.: The National Academy of Sciences, 1972.

12. Fay, J., "Unusual Fire Hazard of LNG Tanker Spills." Journal of Combustion Science and Technology, 7 (1973), pp. 47.

13. Burgess, D., and M.G. Zabetakis. Fire and Explosion Hazards Associated with Liquefied Natural Gas (R.I. 6099). Pittsburgh: U.S. Bureau of Mines, 1962.

14. Burgess, D., J. Birodi, J. Murphy. Hazards of Spillage of LNG into Water (PMSRC Report No. 4177, MIPR, No. Z-70099-9-12395). Pittsburgh: U.S. Bureau of Mines, September 1972.

15. Lind, C.D. Unconfined Vapor Cloud Explosion Study (Paper 67E). Houston: AICHE 79th National Meeting, 3/16-20/75.

16. American Gas Association LNG Safety Program. Consequences of LNG Spills on Land, November 1973.

17. May, W.G., W. McQueen, and R.H. Whipp. Spills of LNG on Water. Paper presented at API Conference, Philadelphia, May 17, 1973.

18. Summary Report on the DISTRIGAS Everett Marine LNG Terminal. Prepared by the Cabot Safety Committee, Distrigas Corp., September 1973.

19. Katz, Donald L., and Harry West. "The Overall Problem-Risk/Benefit for LNG Shipping and Storage, in Risk-Benefit Methodology and Application (UCLA-ENG-7598), David Okrent, ed., Deceober, 1975.

20. Science Applications, Inc. LNG Terminal Risk Assessment Study for Los Angeles, California (Report SAI-75-6140LJ), December 1975.

21. Federal Power Commission, Bureau of Natural Gas. Pacific-Indonesia Project (Draft Environmental Impact Statement, Docket Nos. CP 74-160, CP 74-207, CP 75-83-3). Washington, D.C.: F.P.C., May 1976.

22. Witte. L.C., and J.E. Cox. Non-Chemical Explosive Interaction of LNG and Water (Report 71-WA/HT-31). New York: ASME, 1972.

23a. Lind, C.D. Explosion Hazards Associated With Large Spills of Hazardous Materials (Phase I Report, CG-D-30-75 on Contract DOT-CG-34, 095-B), October 1974.

23b. Lind, C.D., and R.A. Strehlow. Unconfined Vapor Cloud Explosion Study. Jacksonville, Florida: The Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, October 26-30, 1975.

24. Katz, D.L., and C.M. Sliepcevich, "LNG/H_2O Explosions: Cause and Effect." Hydrocarbon Proc., 50:11 (1971), pp. 240.

25. Enger, T., and D.E. Hartman. Mechanics of the LNG-Water Interaction (AGA Conference, May 1972). Houston: Shell Pipeline Corp., 1972.

26. Colgate, S. Fluid-Fluid Explosive Self-Mixing. Socorro: New Mexico Institute of Mining and Technology, July 1975.

27a. Henry, R.E., and H. Fauske. Energetics of Vapor Explosions (Paper ASME 75-HT-66). California: American Society of Mechanical Engineers Heat Transfer Conference, August 1975.

27b. Fauske, H., "The Role of Nucleation in Vapor Explosions." Trans. Am. Nucl. Soc., 15 (1972), pp. 813.

28. Carslaw, H.S., and J.C. Jaeger. Conduction of Heat in Solids. London: Clarendon Press, 1959.

29a. Nakanishi, E., and R.C. Reid, "Liquid Natural Gas-Water Reactions." Chem. Eng. Prog., 67 (1971), pp. 36.

29b. Wakeshima, H., and K. Takata, "On the Limit of Superheat." J. Phys. Soc. Japan, 13 (1958), pp. 1398.

29c. Reid, R., "Superheated Liquids." American Scientist, 64 (1976), pp. 146.

29d. Porteus, W.M., and R.C. Reid, "Light Hydrocarbon Vapor Explosions." Chem. Eng. Prog., May 1976.

30. Sarsten, J.A. "LNG Stratification and Rollover," in Conference Proceedings on LNG Importation and Terminal Safety, National Academy of Sciences, Boston, June 1972.

31. American Gas Association, LNG Safety Program (Phase II). Consequences of LNG Spills on Land, November 1973; Interim Report on Phase II Work, July 1, 1974.

32. Liquid Natural Gas: Characteristics and Burning Behavior. Report by Conch Methane Services, Ltd., 1962.

33. R. Wilson, written testimony on Valley Gas Company Application, pp. 9-11.

34. Walters, W.J., "Thirteen Years Safe Handling of LNG in the U.K." Conference Proceedings on LNG Importation and Terminal Safety, NAS, Boston, 1972.

35. May, W., and W. McQueen. "Radiation From Large LNG Fires," Conference Proceedings on LNG Importation and Terminal Safety, NAS, Boston, 1972.

36. Welker, J.R., H.R. Wesson, and C.M. Sliepcevich. To Burn or Not to Burn! American Gas Association Conference, Philadeplhia, May 1969.

37. Pawtucket Times, July 3, 1973.

38. Official Transcript, Town of Cumberland Zoning Board of Review, August 6-7, 1973, pp. 104.

39. Ibid., pp. 106.

40. Ibid., pp. 139.

41. Reference 8, op. cit., pp. v.

42. Reference 38, op. cit., pp. 140.

43. Ibid., pp. 147.

44. Ibid., pp. 153.

45a. Woonsocket Call, "Valley Gas Get Green Light for LNG Tank," November 8, 1973; Cumberland Lincoln News Leader, "Conditions Set for LNG Approval."

45b. "Gas Tank Appeal Being Heard," The Evening Bulletin, January 28, 1974.

46. Federal Power Commission. Draft Environmental Impact Statement For the Construction and Operation of An LNG Import Terminal at Providence, Rhode Island (Docket Nos. CP 74-47, 73-88, 73-139, 73-197, 73-199), October 1973, pp. 3-63.

47. Ibid., pp. 3-27.

48. Kaull, J.T., "Seeking 2 More LNG Terminal Tanks is 'Folly'." Providence Journal, May 16, 1975.

49. Kaull, J.T. "Fire Chief Testifies His Department Could Not Control LNG Fire," Providence Journal, May 16, 1975; "Darigan Hits at Plan for 2nd LNG Tank," Providence Journal, May 17, 1975.

50. Merritt, Robert C. A Hazards Analysis of A Proposed Addition to the LNG Storage Terminal at Providence, R.I. (FMRC 22340). Factory Mutual Research, May 1974, pp. 20.

51. The Evening Bulletin, April 26, 1976.

52. Reference 8, op. cit., pp. 101.

53. Federal Power Commission, Bureau of Natural Gas. Final Environmental Impact Statement for the Construction and Operation of an LNG Import Terminal at Staten Island, New York (Docket Nos. CP 73-47, 73-88, 73-132, 73-148, 73-230, 74-122), July 1974.

54. Letter from Arthur Hawkins, Ashton Fire District, to Edward Hayden, Town Administrator, March 8, 1973.

55. Editorial, Providence Journal, February 12, 1974.

56. Lowrance, W.W. Of Acceptable Risk. Los Altos: Kaufmann, Inc., 1976.

57. Federal Power Commission. Final Environmental Impact Statement for the Alaska Natural Gas Transportation Systems, Vols. I-IV, El Paso Alaska Company (Docket No. CP 75-96, et. al.), April 1976.

58. Harbor Environmental Staff, Port of Los Angeles. Final Environmental Impact Report, Western LNG Terminal Co., L.A. Harbor. Los Angeles: February 1976.

59. Science and Public Policy Program, University of Oklahoma at Norman. Energy Alternatives: A Comparative Analysis (prepared for CEQ, ERDA, EPA, FEA, FPC, DOI, NSF). Washington, D.C.: U.S.G.P.O. (041-011-00025-4), May 1975.

60. Federal Power Commission. National Gas Survey, Vol. II, Supply Technical Advisory Task Force Report: Liquefied Natural Gas. Washington, D.C.: U.S.G.P.O., 1973.

61. Energy Resources Council, Federal Energy Administration. Policy Statement on LNG Imports, August 1976.

62. Bray, G.R., S.K. Julin, and J.A. Simmons. Supply of Liquefied Natural Gas to the Northeast Region. Science Applicaitons, Inc. (Draft Report), October 1975.

63. Reference 57, op. cit., Vol. II, pp. 376.

64a. Raiffa, Howard. Decision Analysis. Reading: Addison-Wesley, 1965.

64b. Keeney, R.L., and H. Raiffa. Decision Analysis with Multiple Conflicting Objectives. New York: John Wiley and Sons, 1976 (forthcoming).

64c. Decision Analysis Group. Readings in Decision Analysis. Menlo Park: Stanford Research Institute, 1976.

65a. Keeney, Ralph L. Energy Policy and Value Trade-Offs (Research Memorandum RM-75-76). Laxenburg: International Institute for Applied Systems Analysis, December 1975.

65b. Keeney, R.L., and K. Nair, "Decision Analysis for the Siting of Nuclear Power Plants--the Relevance of Multi-Attribute Utility Theory." Proceedings of the IEEE, 63 (1975), pp. 494.

65c. Gros, J. A Paretian Environmental Approach to Power Plant Siting in New England (Ph.D. Thesis). Cambridge: D.E.A.P., Harvard University, May 1974.

66. Ahern, W., R. Doctor, W. Harris, A. Lopson, D. Morris, R. Nehring. Energy Alternatives for California: Paths to the Future (Rand Report R-1793-CSA/RF), December 1975.

67. Synfuels Interagency Task Force. Recommendations for Synthetic Fuels Commercialization Program. Washington, D.C.: U.S.G.P.O. (041-001-00111-3), November 1975.

68. Richels, Richard. R & D Under Uncertainty: A Study of the U.S. Breeder Reactor Program (Ph.D. Thesis). Cambridge: Energy and Environmental Policy Center, Harvard University, June 1976.

69. "Bill Directs President to Pick Route for Gas." New York Times, July 2, 1976.

70. Federal Power Commission, Bureau of Natural Gas. Draft Environmental Impact Statement For the Construction and Operation of an LNG Import Terminal at Everett, Massachusetts (Docket Nos. CP 73-135, CP 74-137, CP 74-227, CP 76-9), February 1976.

Additional References

1. "Accidental Explosions: Can Research Make Damage Patterns Predictable?" Cryog. Ind. Gases, 11:2 (April, 1976).

2. Alia, B.L., M.F. Wheatcroft, "Structural Materials for Marine Application." Marine Techn., 13:2 (April, 1976), pp. 176-183.

3. Allan, D.S., A.A. Brown, and P. Athens, "Risks Associated With an LNG Shipping Operation." 4th Intl. Symposium on Transport of Hazardous Cargoes, Florida, October, 1975.

4. American Gas Association. LNG Safety Program - Phase III: Consequences of LNG Spills on Land (Project IS-3-1, Section G), 1973.

5. Anderson, P.J., E.J. Daniels, "LNG Terminals: Existing and Proposed Systems Compared." Pipeline Gas J., 202:11 (September, 1975), pp. 44-66.

6. Anderson, R.P., and D.R. Armstrong. Experimental Study of Vapor Explosions (LNG-3, Session VI, Paper 3). Washington, D.C.: 1972.

7. Andrews, G.E., and D. Bradley, "The Burning Velocity of Methane-Air Mixtures." Comb. & Flame, 19 (1972), pp. 275-288.

8. Atallah, S., and D.S. Allan, "Safe Separation Distances from Liquid Fuel Fires." Fire Technology, 7:1 (1971), pp. 47-56.

9. Berger, E., P. DeBris, D. Meyer, "Offshore Natural Gas Production by Liquefaction, Storage and Unloading on A Semi-Submersible Platform." Pet. Times, 80:2023 (March, 1976), pp. 29-32.

10. Blander, M., D. Hengstenberg, and J.L. Katz, "Bubble Nucleation in n-Pentane, n-Hexane, n-Pentane + Hexadecane Mixtures, and Water." J. Phys. Chem., Vol. 75 (1971), pp. 3513-3619.

11. Blander, M., J.L. Katz, "Bubble Nucleation in Liquids." A. I. Che. J., 21:5 (September, 1975), pp. 833-848.

12. Board, S.J., C.L. Farmer, and D.H. Poole, "Fragmentation in Thermal Explosions." Int. J. Heat Mass Trans., 17 (1974), pp. 331-339.

13. Board, S.J., R.W. Hall, and G.E. Brown. The Role of Spontaneous Nucleation in Thermal Explosions: Freon/Water Experiment. United Kingdom: Berkeley Nuclear Laboratories (RD/B/N-3007), 1974.

14. Burgess, D., and M. Hertzberg, "Radiation From Pool Flames." Heat Transfer in Flames, N.H. Afgan and J.N. Beer, eds. New York: John Wiley and Sons, 1974, Chapter 27, pp. 413.

15. Burgess, D.S., J. Biordi, and J. Murphy. Hazards of Spillage of LNG Into Water (PMSRC Rpt. No. 4177). Pittsburgh: U.S. Bureau of Mines, 1972.

16. California State Assembly. Transcript of California Hearings on Liquefied Natural Gas, July, 1976. Sacramento: California State Assembly Publishing Office, 1976.

17. Colgate, S.A., and T. Sigurgeirsson, "Dynamic Mixing of Water and Lava." Nature, 244 (1973), pp. 552-555.

18. Devanna, A.L., G. Doulames, "Planning is the Key to LNG Tank Purging, Entry, and Inspection." Oil & Gas J., 73 (September, 1975), pp. 74-82.

19. Dilatush, E., "LNG Carrier Ships Rely Heavily on Instrumentation." EDN/EEE Mag., 21:4 (February, 1976), pp. 25.

20. "Distrigas vs. the F.P.C. - The Case Concerns All Regulated Enterprise." Barron's, December 31, 1973.

21. Drake, E.M., "LNG Rollover - Updated." Hydro. Proc., January, 1976.

22. Drake, E.M., A. Jeje, and R.C. Reid, "Transient Boiling of Liquefied Cryogens on a Water Surface: I. Nitrogen, Methane, and Ethane; II. Light Hydrocarbon Mixtures." Intl. J. Ht. and Mass Trans., 18 (1975), pp. 1361-1375.

23. Drake, E.M., and H. Wesson, "Review of LNG Spill Vapor Dispersion and Fire Hazard Estimation and Control Methods." Proc. AGA Transmission Conf., Las Vegas, May, 1976.

24. Drake, E.M., and R.C. Reid, "How LNG Boils on Soils." Hydro. Proc., May, 1975.

25. DuBarry, T.W., "Whither the LNG Ship?" Nav. Archit., No. 3 (July, 1975), pp. 121-146.

26. EcoSystems, Inc. A Methodological Procedure for Risk Analysis of LNG Operations (Report for C.E.Q.), 1974.

27. Enger, T., and D.E. Hartman, "Mechanics of the LNG-Water Interaction." Am. Gas Association Distribution Conf., Atlanta, Ga., May 8, 1972.

28. Essais D'Ependage de Gaz Naturel Liquefie Sur du Sol. Report on the Experiments Conducted by Gaz de France, September, 1972.

29. "An Experimental Investigation of Atmospheric Diffusion and Ignition of Boiloff Associated with a Spillage of LNG." T.R.W Report No. 08072-7 for AGA, Inc., November, 1968 (Film Section of the Report).

30. Fauske, H.K., "On the Mechanism of Uranium dioxide-Sodium Explosive Interactions." Nucl. Sci. Eng., 51 (1973), pp. 95-101.

31. Fay, J.A., and D. Lewis, "The Inflammability and Dispersion of LNG Vapor Clouds." 4th Intl. Symposium on Transport of Hazardous Cargoes, Florida, October, 1975.

32. Federal Energy Administration. Proceedings of Public Hearings of October 26, 1976 On Federal Policy on LNG Imports, Washington, D.C.: F.E.A., 1976.

33. Federal Power Commission, Bureau of Natural Gas. Draft E.I.S. for the Cook Inlet-California Project, Pacific Alaska LNG Co. (Docket No. CP 75-140). Washington, D.C.: F.P.C., September, 1976.

34. Garland, F., and G. Atkinson. The Interactions of Liquid Hydrocarbons with Water. Washington, D.C.: U.S. Dept. of Transp., U.S. Coast Guard (AD 753561), October, 1971.

35. Germeles, A., and E. Drake, "Gravity Spreading and Atmospheric Dispersion of LNG Vapor Clouds." 4th Intl. Symposium on Transport of Hazardous Cargoes, Florida, October, 1975.

36. Gideon, D.N., Putnam, A.A., A.R. Duffy. Review of LNG Safety Research. Cryogenic Engineering Conf. and International Cryogenic Materials Conf., Queens University, Kingston, Ontario, Canada, July, 1975.

37. Guise, A.B., "How to Fight Natural Gas Fires." Hydro. Proc., 54:8 (August, 1975), pp. 76-79.

38. Henry, R.E., J.D. Gabor, I.O. Winsch, E.A. Spleha, D.J. Quinn, E.G. Erickson, J.J. Heiberger, and G.T. Goldfuss, "Large-Scale Vapor Explosions." Proc. Fast Reactor Safety Meeting (Conf.-740401-P2, 922), Beverly Hills, California, April 2-4, 1974.

39. Holt, R.J., amd A.H. Muenker. Flameless Vapor Explosions in LNG/Hydrocarbon Spills (Report No. GRU. 2GPR. 72). Linden, N.J.: Exxon Research and Eng. Co., 1972.

40. Hottel, H.C., and A.F. Sarofim. Radiative Transfer. New York: McGraw-Hill, 1967, pp. 203.

41. Ijams, T.E., and B.A. Wolfee. Planning for Safety. Cryogenics Conf., Queens University, Kingston, Ontario, Canada, July, 1975.

42. Javelle, B., and J. Raynand, "Structural Problems in Methane Carriers." Shipp. World Shipbuild., 168:3909 (September, 1975), pp. 831-833.

43. Katz, D.L., "Superheat-Limit Explosions." Chem. Eng. Prog., 68:5 (1972), pp. 68-69.

44. Kime, J.W., R.E. Johnson, W.D. Rabe, "Damage Stability Requirements for Tankships, Chemical Ships, and Gas Ships." Marine Techn., 13:2 (April, 1976), pp. 121-151.

45. Lewis, B., and von Elbe. Combustion, Flames and Explosions of Gases. New York: Academic Press, Inc., 1961, Table 1, Appendix C, pp. 706.

46. Lind, C.D., and R.A. Strehlow, "Unconfined Vapor Cloud Explosion Study." 4th Intl. Syposium on Transport of Hazardous Cargoes, Florida, October, 1975.

47. "LNG and LPC - Safety in Storage." Gas World 181:4689 (April, 1976), pp. 205-210.

48. Lobbam, J., and J. MacKay, "Satellite LNG Installations." Gas Eng. Manag., 16:5 (May, 1976), pp. 165-172.

49. Long, G., "Explosions of Molten Aluminum in Water: Cause and Prevention." Metal Progress, 71:5 (1957), pp. 107-112.

50. Matsumoto, J., I. Kato, "Repair Welding of Aluminum Welding Pipes for LNG Tanks." Keikinzoku Yosetsu, 12:5 (1974), pp. 214-223.

51. Modermott, J., "LNG Technology." Chem. Technology Review No. 10. Park Ridge, New Jersey: Noyes Data Corp., 1973, 357 pp.

52. Monfore, G.E., A.E. Lentz, "Physical Properties of Concrete at Very Low Temperatures." J. PCA Res. Dev. Lab., 4:2 (1962), pp. 33-39.

53. Murray, F.W., D.L. Jaquette, W.S. King. Hazards Associated With the Importation of Liquefied Natural Gas (Rand Report R-1845-RC), June, 1976.

54. Otterman, B., "Analysis of Large LNG Spills on Water, Part 1: Liquid Spread and Evaporation." Cryogenics, 15:8 (August, 1975), pp. 455-460.

55. Porteous, W. Superheating and Cryogenic Vapor Explosions (Ph. D. thesis). Cambridge, Massachusetts: Mass. Inst. of Tech., 1975.

56. Raj, P.K., and S. Atallah. "Thermal Radiation from LNG Spill Fires," to be published in Advances in Cryogenic Engineering, Vol. 20, K.D. Timmerhaus, ed.

57. Raj, P.K.P., and A.S. Kalelkar. Fire Hazard Presented by a Spreading Burning Pool of LNG on Water. West Sect., Combustion Inst., Fall, 1973.

58. Raj, P.K.P., and H.W. Emmons. On the Burning of a Large Flammable Vapor Cloud. West and Central Sect., Combustion Inst., Texas, 1975.

59. Rapid Phase Transformation During LNG Spillage on Water (Paper 2, Session VI, LNG-3). Washington, D.C.: September 24-28, 1972.

60. Rausch, A.H., amd A.D. Levine, "Rapid Phase Transition Caused by Thermodynamic Instability in Cryogens." Cryogenics, 13:4 (1973), pp. 224-229.

61. Reid, R.C., "Superheated Liquids." American Scientist, 64:2 (March-April, 1976).

62. Scmitt, I.W., "The Trans-Alaska Gas Project Site Selection and System Optimization." Marine Tech., 13:1 (January, 1976), pp. 1-13.

63. Stevens, J.W., and L.C. Witte, "Transient Vapor Film Behavior During Quenching." Trans. Am. Nucl. Soc., 15 (1972), pp. 418-420.

64. Steward, F.R., "Linear Flame Heights for Various Fuels." Comb. & Flame, 8 (1964), pp. 171-178.

65. Steward, F.F., "Prediction of the Height Turbulent-Diffusion Buoyant Flames." Comb. Sci. Tech., 2 (1970), pp. 203-212.

66. Strehlow, R.A. Fundamentals of Combustion. Scranton, Pa.: International Text Book Co., 1968, pp. 197.

67. Tenge, P., O. Solli, O. Foerli, "Significance of Defects in LNG Tanks in Ships" (Proc. Symp. Boston, May, 1974), in ASTM Special Technical Publication No. 579, J.B. Wheeler, et. al., eds. Philadelphia: ASTM, 1975, pp. 10-43.

68. Thomas, P.E., "The Size of Flames from Natural Fires," 9th Symp. (Int'l) on Combustion. New York: Academic Press, 1963, pp. 844-859.

69. U.S. Coast Guard. Liquefied Natural Gas, Views and Practices, Policy and Safety (CG-478). Washington, D.C.: U.S.C.G., February, 1976.

70. West, H., L.E. Brown, and J.R. Welker, "Vapor Dispersion, Fire Control and Fire Extinguishment for LNG Spills." 4th Intl. Symposium on Transport of Hazardous Cargoes, Florida, October, 1975.

71. Witte, L.C., J.E. Cox, and J.E. Bouvier, "The Vapor Explosion." J. Metals, 22:2 (1970), pp. 39-44.

72. Witte, L.C., T.J. Vyas, and A.A. Gelabert, "Heat Transfer and Fragmentation During Molten Metal/Water Interactions." J. Heat Trans., 95 (1973), pp. 521-527.

73. Wolfe, R.J., H.H.J. Vanderveldt, A.E. Henn, "Some Considerations of Fracture Mechanics Applications in Ship's Design, Construction, and Operation." Eng. Fract. Mech., 7:3 (September, 1975), pp. 565-581.

74. Wooler, R.G. Marine Transportation of LNG and Related Products. Cambridge, Massachusetts: Cormell Maritime Press, 1975, 359 pp.

75. Wright, R.W., and G.H. Humberstone, "Dispersal and Pressure Generation by Water Impact Upon Molten Aluminum." Trans. Am. Nucl. Soc., 9 (1966), pp. 305-306.