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Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: Second Status Report

October 1980

U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Environment
Environmental and Safety Engineering Division

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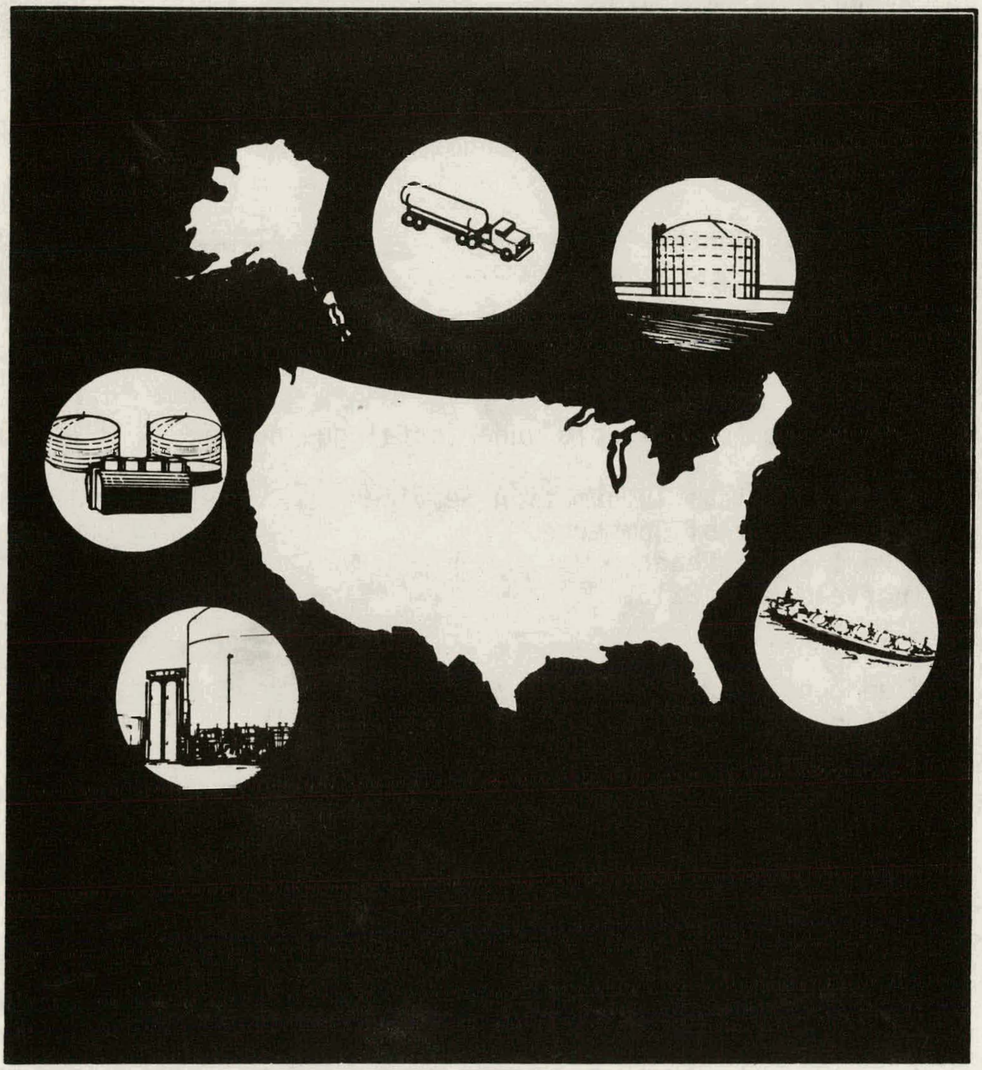

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U.S. Department of Commerce
- Maritime Administration
- National Bureau of Standards

U.S. Department of Transportation
- Coast Guard
- Federal Railroad Administration
- Office of Pipeline Safety Regulations

National Aeronautics and Space Administration

National Science Foundation

The Fertilizer Institute

The Gas Research Institute

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FOREWORD

The Assistant Secretary for Environment has responsibility for identifying, characterizing, and ameliorating the environmental, health, and safety issues and public concerns associated with commercial operation of specific energy systems. The need for developing a safety and environmental control assessment for liquefied gaseous fuels was identified by the Environmental and Safety Engineering Division[a] as a result of discussions with various governmental, industry, and academic persons having expertise with respect to the particular materials involved: liquefied natural gas, liquefied petroleum gas, hydrogen, and anhydrous ammonia.

This document is arranged in three volumes and reports on progress in the Liquefied Gaseous Fuels (LGF) Safety and Environmental Control Assessment Program made in Fiscal Year (FY)-1979 and early FY-1980. Volume 1 (Executive Summary) describes the background, purpose and organization of the LGF Program and contains summaries of the 25 reports presented in Volumes 2 and 3. Annotated bibliographies on Liquefied Natural Gas (LNG) Safety and Environmental Control Research and on Fire Safety and Hazards of Liquefied Petroleum Gas (LPG) are included in Volume 1.

Volume 2 consists of 19 reports describing technical effort performed by Government Contractors in the area of LNG Safety and Environmental Control. Volume 3 is a similar compilation and contains 6 contractor reports on LPG, anhydrous ammonia and hydrogen energy systems.

(a) Effective June 1980, the Environmental Control Technology Division was augmented by acquiring additional functions: the new name of the organization is the Environmental and Safety Engineering Division. Throughout the text, where the old name is used, is should now refer, in all cases, to the Environmental and Safety Engineering Division, Office of the Assistant Secretary for Environment. Future publications will reflect this change completely.

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ANNOTATED BIBLIOGRAPHIES

SECTION I

EXECUTIVE SUMMARY

SECTION I

EXECUTIVE SUMMARY

Liquefied gaseous fuels are an integral part of our energy system. They are compact, clean burning and have the potential for reducing some of the impacts on energy supply, transportation and storage that may be caused by shortages of other fuels. For example, the volume reduction of about 600, obtained by liquefying natural gas, has important transportation and storage implications. The storage of liquefied natural gas (LNG) at critical regional locations (peakshaving and satellite facilities) within the United States can supply natural gas during seasonal periods of high demand and during emergencies when other sources of energy are disrupted. Liquid and liquefied energy materials are essential in many industrial systems and processes and the availability of these materials is important to both the economy and security of the nation.

The Department of Energy (DOE) has responsibilities to develop a National Energy Plan and to implement comprehensive research, development and demonstration (RD&D) programs designed to achieve solutions to short- and long-term energy supply and management problems (PL 95-91). A portion of the National Plan (ERDA 77-1, page 32) has the objective of identifying and characterizing environmental, health, and safety issues and public concerns associated with the commercial operation of specific energy systems. The Environmental and Safety Engineering Division (ESED), Office of the Assistant Secretary for Environment, has responsibility for preparing assessments in some of these areas, including liquefied gaseous fuels.

To fulfill this responsibility the ESED is sponsoring a broad spectrum of research on safety and environmental control aspects of liquefied gaseous fuels. The objective of this effort is to gather, analyze and disseminate technical information that will aid future decisions made by industry, regulatory agencies and the general public on facility siting, system operations, and accident prevention and mitigation. This research addresses a definable need for additional information and complements related programs supported by other government agencies and industry.

Two previous documents in this series[a] describe the DOE approach to LNG safety and environmental research and the status of effort in the Liquefied Gaseous Fuels (LGF) Safety and Environmental Control Assessment Program at the end of Fiscal Year (FY)-1978. This status report summarizes the progress and accomplishments of efforts sponsored or cosponsored by the ESED in the LGF Assessment Program during FY-1979 and early FY-1980.

I.1 PURPOSE AND EMPHASIS OF LGF ASSESSMENT PROGRAM

The need for a comprehensive integrated RD&D program to resolve liquefied gaseous fuel issues has been identified by the ESED as a result of discussions with many experts from government, industry and academia. The development of a program specifically addressing LNG issues began in late fall 1976, building on information developed in a cooperative program with the U.S. Coast Guard and the American Gas Association. Further input came from an ERDA sponsored LNG Safety and Control Workshop (December 1976) which was attended by over 40 persons selected to represent a cross section of cognizant experts from industry, government, and academia. Many of the safety and environmental issues identified for LNG appear to apply to the handling of other liquefied gaseous fuels and energy materials.

The purpose of the LGF Assessment Program is, therefore, to develop additional safety and environmental control information on LNG and other significant liquefied gaseous fuels and energy materials. The emphasis of this effort is on information needed by industry, regulatory bodies and the general public for making decisions relating to the handling, transportation and storage of these materials.

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[a] An Approach to Liquefied Natural Gas (LNG) Safety and Environmental Control Research, DOE/EV-0002, February 1978.

Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: A Status Report, DOE/EV-0036, May 1979.

An outline of the DOE LGF Assessment Program Plan describing the major research elements needed to achieve the program objectives can be found in Section II of the first LGF Program Status Report (DOE/EV-0036). Three distinct objectives are identified to meet the goals of the integrated program:

1. Verify Predictive Capability

   Develop and validate analytical modeling capability to provide firm technical foundation for the promulgation of regulations and to adequately support the development of prevention and control strategies, techniques and procedures. Wherever possible, theory and predictive capability will be based on laboratory experiments.

2. Verify Prevention Methods

   Investigate and validate methods to prevent the release to the environment of liquefied gaseous fuels. The focus is on materials, techniques, and strategies which are intended to prevent a release. These are, by nature, essentially "passive" systems.

3. Verify Control Methods

   Investigate and validate methods to control the release to the environment of liquefied gaseous fuels should a release occur. The emphasis is on materials, techniques, and strategies which are intended to reduce the impact of a release. By nature, these will tend to be "active" systems.

The LGF Program is coordinated with the efforts of other agencies. Program and subprogram research activities are being conducted at national laboratories and technical institutions with the involvement and support of industrial research contractors.

I.2 SUMMARY OF REPORTS

Summaries of the 25 reports contained in Volumes 2 and 3 are presented in this volume as an overview of current activities in the LGF Assessment Program. The summaries are grouped according to their primary technical emphasis. The LNG reports (Reports A through S) are categorized according to the relevant technical area in the LNG Assessment Program. Reports on the other liquefied gases (Reports T through Y) are grouped by energy form.

I.2.1 LNG Reports

The work described in Volume 2 (Reports A through S) addresses research goals in seven technical areas of the program: Vapor Generation and Dispersion, Fire and Radiation Hazards, Flame Propagation, Release Prevention, Release Control, Instrumentation and Technique Development, and Scale Effects Experiments. Release Prevention and Release Control are combined for the purpose of summarizing Reports I, J and K because these reports relate to both areas.

VAPOR GENERATION AND DISPERSION

Three reports in Volume 2 describe research on LNG vapor generation and dispersion.

Report A - Simulation of LNG Vapor Spread and Dispersion by Finite Element Methods

Two finite element models, developed under previous work and adapted by Lawrence Livermore Laboratory (LLL), are described in Report A. The models have been used to investigate the feasibility of using the finite element method (FEM) to simulate LNG vapor spread and dispersion.

The motivation for this work is the continuing need to develop models that accurately predict consequences of large LNG spills. The predictive capabilities of existing models that simulate LNG vapor dispersion processes are considered to be still less than satisfactory.

A primary objective of this study was to compare the adequacy of a hydrostatic model with that of a more complete nonhydrostatic model applied to typical LNG spill scenarios. Both models solve time-dependent, two-dimensional conservation equations of mass, momentum and energy. Buoyancy effects are included in both models using the Boussinesq approximation. An additional assumption in the hydrostatic model is that the vertical pressure gradient is balanced entirely by the buoyancy force. This hydrostatic assumption allows easier computation of the flow field, but its range of applicability is also greatly reduced.

The applicability of these models was investigated in numerical experiments representing a range of LNG spill scenarios and atmospheric conditions. Results of these tests demonstrate clearly that the FEM is a versatile numerical tool for predicting LNG vapor dispersion phenomena.

The comparison of the hydrostatic and nonhydrostatic models showed good agreement in all field variables (temperature, pressure, and velocity) for cases of high diffusivity ($V = K = 10\ m^2/sec$) with and without a pre-existing wind. With moderate diffusivity ($V = K = 1\ m^2/sec$) the models yielded similar results for the temperature and pressure fields. However, the hydrostatic model failed to produce the correct recirculation flow and indicated unreasonably large vertical velocity components near the top boundary. The hydrostatic model does not appear to be applicable to cases of low diffusivity ($V = K = 0.1\ m^2/sec$). With low diffusivity, the non-hydrostatic model yielded reasonable results only for the case without wind. The model's failure in the pre-existing wind case was attributed to the mesh being too coarse for the flow field under consideration.

The simulated cases in this study lead to the conclusions that a hydrostatic model cannot be applied to the worst LNG spill cases and that further model development should be based on the nonhydrostatic formulation. Report A outlines several refinements that are to be applied to the non-hydrostatic model as part of the next phase of model development at LLL.

Report B - Modeling of Negatively Buoyant Vapor Cloud Dispersion

Report B summarizes progress at Massachusetts Institute of Technology in the development of new analytical methods for modeling negatively buoyant vapor cloud motion and dispersion. A principal purpose of this effort is to provide a common basis for comparing results from earlier negatively buoyant models, and to determine whether the differences results from different assumptions or the nature of the mathematical analysis. The new model is of intermediate complexity, falling between the SIGMET three-dimensional, unsteady flow model and the modified classical models of Fay & Lewis and of Germeles & Drake.

This report describes the assumptions and simplifications used in constructing the new model. Considerations are presented that justify treating flow within the vapor cloud as flow within a viscous boundary layer. Because the flow within the cloud is primarily in the horizontal direction, a hydrostatic pressure distribution is assumed. An entrainment relationship is proposed to account for vertical mixing. The rate of entrainment consists of two independently additive terms, the first due to horizontal shear and the second due to free-stream turbulence.

The equations developed (conservation of mass, lateral components of momentum and energy, entrainment relation and caloric equation of state) are hyperbolic in character. Effort has concentrated on developing asymptotic analytical solutions. The classical Boussinesq approximation and a uniform vertical distribution of dependent variables are used to simplify the integration.

Report B identifies some quasi one- and two-dimensional steady and unsteady flows for which solutions were investigated. The results indicate the relative importance of the different physical phenomena that affect the motion of negatively buoyant vapor clouds. The development of asymptotic solutions in analytic form is particularly relevant to the practical need for gaining knowledge of flow conditions where dilution is great enough to preclude further hazard.

Report C - Effect of Humidity on the Energy Budget of a Liquefied Natural Gas (LNG) Vapor Cloud

The dispersion characteristics of the vapor cloud above an LNG spill will be strongly influenced by its buoyancy. Methane, the principal component of LNG, has a vapor density greater or less than that of air depending on temperature. Compared with air at 293K, methane vapor has a relative density of 1.45 at its normal boiling point (112K) and 0.55 at 293K. The buoyancy of an LNG/air mixture may depend, therefore, on the heat added to the cloud by external sources. Report C describes a study performed at LLL that evaluates the effect of humidity as one such source of heat.

The effect of humidity on the buoyancy of the cloud was calculated using a relationship based on temperature, density and methane concentration for mixtures of air, methane and water vapor. The theoretical results were compared to data from experiments performed at the Naval Weapons Center, China Lake, California. In these experiments, LNG was spilled at the center of a square pond 50 m on a side. Simultaneous measurements were made of methane concentration and temperature to test the theoretical assumptions of adiabatic isothermal mixing of methane and humid air.

In comparing the theoretical change of temperature versus methane concentration with experimental data, the measured results, in general, show higher temperatures than expected. Low wind conditions give poorer agreement than that of the high wind case. This report considers possible explanations but concludes that there are insufficient data to decide the cause of the disagreement. Further work is planned in this area.

FIRE AND RADIATION HAZARDS

Report D provides an assessment of research needs relating to the analysis and control of LNG fire and radiation hazards. This assessment includes deflagration and detonation phenomena and is, therefore, also relevant to the research scope of the LNG Program Element devoted to Flame Propagation.

Report D - LNG Fire and Explosion Phenomena Research Evaluation

Four types of combustion phenomena are considered: ignition, vapor cloud burnup, pool fires and detonation. This report discusses the range of current knowledge that permits the magnitude of LNG combustion characteristics to be estimated, the areas where such estimates cannot be made with confidence and the scope and priority of needed future research.

This study was part of the LNG Safety Studies Project (see also Reports I and P) conducted by Pacific Northwest Laboratory (PNL). The work was subcontracted to the University of Washington so that the recognized knowledge and insight of the author could be made available to the Project and, in turn, to the LGF Program. The purpose of this work is to recommend further research on LNG fire and radiation phenomena that are important considerations in hazard analysis and management. This information adds to the perspective and data used in planning and updating the research objectives of the LGF Program.

General assumptions are made to establish representative ranges of the parameters that control combustion. Each of four types of combustion phenomena is discussed in separate sections of the report. These sections include a discussion of the information considered most important for hazard management purposes, a review of the existing technical understanding in these areas and, finally, salient conclusions and recommendations for additional research. The following recommendations are presented.

The most important class of phenomena requiring research is vapor cloud burnup. Because of uncertainties related to the transition from deflagration to detonation, areas which merit further investigation are flame spread in turbulent layered gases, the interaction of gravity and flame spread, and non-detonative pressure wave characteristics. Each of these areas, especially the first-mentioned, may be amenable, to a significant degree, to scale-modeling.

Based upon results of previous research, work aimed at detonation phenomena is of lower priority. To provide better understanding of detonation probability, three research activities are recommended. The most important is to ascertain a quenching thickness. The second is to improve understanding of the confinement needed for transition from deflagration to detonation. The third need is better knowledge of direct initiation requirements. The first two are amenable to scale-down. The third can be assisted markedly through aquisition of improved chemical kinetic data that will enable reliable theoretical calculations.

The thermal radiation incident on targets outside the fire area is a characteristic of practical importance. Information on fire geometry and the thermal radiation flux at flame boundaries is available in approximate form. Hazard characteristics are only moderately sensitive to flame geometry parameters and emission flux. Thus, although much work remains to be done to better understand pool fire phenomena, this research is not considered a high priority in terms of hazard management needs.

Conditions for ignition by hot surface or hot gases are reasonably well understood. If more precise data are required, for example, the probable time to ignition after a flammable cloud accumulates, then the distribution and nature of ignition sources is the most important information not immediately available. No new research on ignition phenomena is needed for LNG hazard analysis.

FLAME PROPAGATION

Four reports are included in this section. The topics include: laminar flames in mixtures of vaporized LNG and air; chemical kinetics in LNG detonations; effects of cellular structure on the behavior of gaseous detonation waves; and computer simulation of combustion and fluid dynamics in two and three dimensions.

Report E - Modeling of Laminar Flames in Mixtures of Vaporized Liquefied Natural Gas (LNG) and Air

The combustion of fuel-air mixtures resulting from possible LNG spills is a central problem in the LLL Liquefied Gaseous Fuel Spill Effects Program. Combustion depends on a variety of factors including local fuel-air equivalence ratio, turbulence levels, humidity, and characteristics of the ignition source. As in other portions of the LLL program, combustion is being analyzed using numerical models to predict the evolution and characteristics of LNG spills. The combustion and fluid dynamic codes under development (See Report H) require chemical kinetic submodels to describe the fuel-air burning that may occur in a large LNG spill. Recent work on the development of these chemical kinetics submodels is described in this report.

Flame propagation studies have been carried out using a one-dimensional model, incorporating fluid mechanics and chemical kinetics equations. In some of the computations, a detailed chemical kinetics mechanism was used while simplified kinetics mechanisms were considered in the remainder of the computations. The chemical kinetics of combustion is theoretically well understood for laminar conditions, whereas the flow field in an LNG spill will inevitably be turbulent. The approach selected for modeling the propagation of the flame through a turbulent fuel-air mixture is to separate the problems of turbulence modeling from those of chemical kinetics, although the two are coupled to some extent. A detailed chemical kinetics reaction mechanism was used to model flame properties for methane-air mixtures at atmospheric pressures. It was possible to reproduce accurately all available laboratory experimental data on laminar flame speed and flame structure. In addition, the detailed kinetics model was used to examine the effects of adding minor constituents to the unburned fuel. It was found that the addition of water vapor has virtually no effect on the computed flame speed or flammability limit. This finding is important because it shows that data taken at test sites such as China Lake can be applied to the typically humid coastal locations of current and proposed LNG terminals. A second minor constituent examined with the detailed reaction mechanism was ethane. While the presence of ethane has been found to increase the detonability of LNG, (See Report F) the results of this study show ethane has very little effect on flame properties. As a result, it is possible to use available flame data for methane-air to represent flame properties of vaporized LNG in air with very reasonable accuracy.

Equations describing chemical kinetics of LNG combustion are complex. Detailed kinetics models require too much computer time to permit their use in the two- and three-dimensional codes being used to model the vapor cloud dispersion and combustion (See Report H). Simplified kinetics models that require much less computer time have been developed for these codes. The balance of report E describes the calibration of a simplified kinetics model. The approach was to use experimental data as a guide for the initial parameter selection, then to compare the results of the simplified submodel to those of the detailed model. Four parameters of the reaction rate equation are used for curve fitting to match available experimental data. The calibration process consisted of finding a set of these four parameters that gave the best agreement between the detailed and the simplified models. Within the limitations inherent in using a single-step reaction mechanism, a rate expression was determined that creditably reproduces flame speed data and flammability limits for methane-air flames in the atmosphere.

Report F - Chemical Kinetics in LNG Detonations

The possibility of an atmospheric gaseous detonation may be the most dangerous hazard which can result from an LNG spill. This report describes the use of a characteristic time analysis by LLL to study the detonability of vaporized LNG and air mixtures. Separate numerical models are used to treat the evolution of the blast-wave produced by a charge of high explosive and chemical ignition delay of the fuel-air mixture. The type of modeling described is intended to be used in conjunction with experimental programs. The models are validated by experimental data after which they can be used to assist the analysis of experiments and in extrapolations to conditions which are difficult or expensive to achieve experimentally. The modeling effort, therefore, provides additional diagnostic tools to aid the interpretation of experimental results and to substantially reduce the cost and time requirements of the research program.

Detonations can be produced either by transition from deflagration or by direct initiation from a blast-wave. In either case, there are quite restrictive conditions which must be satisfied if a detonation is to propagate. The shockwave associated with a detonation compresses and heats a mixture of unreacted gases very rapidly. If the shocked gas is reactive, chemical reactions will begin once the shockwave has compressed and heated the gas. At the end of a chemical ignition delay period, rapid energy releases again heat the mixture and further raise its pressure. A useful measure of the stability of a detonation wave can be derived by comparing the characteristics of shockwave delay time with the chemical induction time. If the chemical time scale is longer than the shock decay time, the detonation will weaken and decay into a sound-wave preceding a conventional deflagration. On the other hand, if the chemical time scale is shorter or comparable to the shockwave time scale, the detonation will be stable and continue to propagate. The detonation stability and direct initiation processes may thus be split conceptually into a fluid-mechanical model dealing with the blast-wave, and the chemical-kinetic model dealing with the induction times. These two submodels are described and used to analyze certain detonation phenomena.

A detailed reaction mechanism describing the chemical-kinetic evolution of methane and ethane mixtures was presented in Report E in the first Status Report (DOE/EV-0036). The model was used to investigate methane-ethane mixtures combined with stoichiometric amounts of oxygen. The addition of ethane in the compositional range of normally-occurring LNG promptly reduced the induction time of the composite fuel relative to pure methane. The detonability of LNG appears to be dominated by minor constituents such as ethane. There is both experimental and theoretical evidence to suggest that as far as kinetic sensitization and induction delay are concerned, propane and ethane behave similarly. Water vapor, on the other hand, was found to have a negligible effect on induction delay times. It was shown that the same degree of kinetic sensitization occurs for fuel-air mixtures which are not stoichiometric. This conclusion is significant because wide ranges of local fuel-air equivalents ratio would be expected in an actual LNG spill.

This work was able to determine the detailed mechanism for the fuel sensitization process. The CH_4 molecule is unusually stable. When a hydrogen atom is abstracted, the resulting methyl radical (CH_3) is even more difficult to consume. Rather than being oxidized directly, methyl radicals combine together to form ethane which is the pathway for much of the methane consumption. When ethane is present initially, more hydrogen atoms are available to initiate chain branching reactions which rapidly consume the available fuel. The kinetic process by which small amounts of ethane can dominate the consumption of methane and dramatically reduce induction times not only explains all experimental data, but also demonstrates conclusively the inadequacy of so-called thermal sensitization mechanisms.

Report F also describes comparisons made between model calculations and experimental studies of fuel detonability carried out under nearly unconfined atmospheric conditions. For each mixture selected, a one-dimensional finite difference hydrodynamic numerical model was used to calculate the evolution of the time-dependent shockwave produced by spherical charges of high explosive. The shock decay time was defined somewhat arbitrarily as the time required for the shock to decay from 20 to 10 bars. The minimum amount of high explosive required to initiate a steady detonation was determined. The shock decay time was found to vary as the cube root of the charge mass, as would be expected from analytical treatment of spherical shock front decay. By equating the chemical induction time with the shock decay time, a correlation was established between the critical mass of high explosive and the initial post-shock temperature of the reactive gas mixture. The characteristic temperature correlations were extrapolated to estimate the relevant induction time for methane-air. The models predicted critical explosive charge masses of 24 to 106 kg for pure methane in air. The range of these estimates corresponds to the range of uncertainty in the extrapolations that are made.

The kinetic modeling presented in this report suggests that several types of fuel modification might be used to increase the chemical induction time of LNG-air mixtures thereby reducing the detonability of these mixtures. An additive that could serve as a means for capturing hydrogen atoms would sharply reduce the chain branching of these systems. Similarly, if amounts of the minor constituents such as ethane or propane were removed or at least significantly reduced, the results of this study indicate that the induction time would again be sharply increased. In addition, chemically inert diluent species could be added to the LNG. Any of these processes could significantly enhance the safety of handling and using LNG if their addition were otherwise compatible with the end use of the fuel.

Report G - Effects of Cellular Structure on the Behavior of Gaseous Detonation Waves Under Transient Conditions

Increased concern about the detonability of gaseous mixtures in unconfined clouds has increased interest in the behavior of the detonation process under various transient conditions such as non-uniform distributions of pressure, temperature, and composition. The object of this LLL effort was to study the effect of cellular wave structure on the transition of the detonation process into expanding geometries. In readjusting itself during a transition state, the process may survive and continue as a detonation wave or may weaken so fast that it transforms into a simple deflagration wave. The transition from a one-dimensional expansion to a spherical expansion, such as that of a detonation wave exiting a tube, was selected for study.

Much information about the detonation process and its cellular structure have been gained during the past decades. Not only has this cellular structure been proven to exist, its existence is essential to the process. Cellular size and regularity are characteristic of a particular combination of initial conditions such as composition, pressure and temperature. Variation of these conditions causes the cell size to change and attain a new size that is characteristic of a new set of conditions. Differences in confinement, or the lack of any confinement, if kept constant during the process, will have no effect on the characteristic cell size. If the detonation wave enters an area change, the cell size will be immediately affected. As a result, the detonative process may be enhanced or weakened with the possibility of complete extinction.

The effect of the cellular structure was demonstrated by showing that there must be an inner core of the wave consisting of a critical number of cells unaffected by side rarefactions to insure the transition of the detonation process. Work done on the outer gas by the inner core was compared with the critical energy for spherical initiation. A remarkably good agreement was achieved. Extrapolation of data on a log/log plot of critical energy versus critical diameter led to a prediction of the critical energy needed to initiate detonation in a pure methane-air mixture. The plotting of characteristic cell size versus critical cell number needed for transition also led to quantitative estimates of these values for methane-air mixtures. Comparison of results on the critical energy of initiation with previously published values lead to a somewhat different view on the physical significance of the detonation kernel and its correspondence to the length of the detonation cell. The size of the kernel is unique in that the chemical energy contained is comparable to the source energy released by the initiator charge. However, the size of the kernel is not the same as the characteristic length of the detonation cell. The results show further that neither the tube diameter nor the initial pressure of the medium control the survival of the wave. The detonation process is controlled: 1) by the number of cells available to endure losses from flow effects generated by transient conditions; and 2) by the number of cells remaining to regenerate new cells that revive the detonation process.

Report H - Computer Simulation of Combustion and Fluid Dynamics in Two and Three Dimensions

This report gives a brief overview of computer codes developed by LLL to simulate unsteady gaseous combustion and fluid dynamic processes. Areas of application include pool fires, fireball formation and burn, and dispersion of fuel vapors both with and without wind.

Two codes are under development; the TDC (two-dimensional code) which models combustion and fluid dynamics in an axisymmetric or a two-dimensional Cartesian coordinate system, and the COM3 code, which uses a three-dimensional Cartesian coordinate system. Both codes use state-of-the-art finite differencing methods to solve the viscous hydrodynamic conservation equations. Although it is, in principle, feasible to obtain an accurate solution to these equations, in practice, the number of zones required is too great for even the largest computers. Thus coarse grids are used with subgrid-scale gas motions being simulated by a turbulence model. Because turbulence models are inherently empirical, the computer models must be chosen carefully and validated against experimental data. By determining that the model correctly accounts for turbulence on several different scale sizes and under different initial conditions, the code may be used to extrapolate to large-scale spills for which no experimental data exist.

Preliminary studies have shown that wind dispersion of LNG vapors is inherently three-dimensional; therefore, most effort in this area will involve the COM3 code. However, the gravity spread of vapors under calm conditions is one aspect that can be studied with the TDC. In addition to the basic conservation equations, models are needed for phenomena that affect the dispersion of fuel vapors. These include pool spread and vaporization, humidity, heat addition due to radiation from the ground and sun, and convective heat transfer from the ground or water. The kinetics equations for the chemical reaction of fuel and oxidizer must also be solved to simulate combustion processes.

The chemical kinetics for even the simplest hydrocarbons are extremely complex and would require the simultaneous solution of a large set of differential equations. An impractically large amount of computer time would be needed to solve the kinetics equations in two and three dimensions. A simplified scheme is now used whereby parameters are adjusted until the results agree either with experiments or with more accurate calculations using complex nondimensional or one-dimensional chemical kinetic models. This approach is computationally efficient but results in some loss of generality.

The TDC has the capability for using a one-step reaction scheme in which the fuel plus oxidizer goes to products (See Report E) and a more sophisticated kinetics model that accounts for the intermediate radicals formed during combustion. The initial use of the COM3 code will involve only the simple one-step scheme. Most practical combustion problems involve the propagation of a turbulent flame. At present there is no adequate model to predict turbulent flame velocities, so these must be determined experimentally. The approach used is to modify the parameters in the chemical kinetics and turbulence models used in the TDC and COM3 codes to produce the observed flame velocity. The codes can then be used to study the fluid dynamic motions resulting from that flame velocity.

Preliminary computations have been made of pool fires and fireball formation using the TDC code; however, these calculations cannot yet be considered predictive. The primary application of the COM3 code will be plume combustion.

RELEASE PREVENTION AND CONTROL

Three reports in this Section (Reports I, J, and K) describe, respectively, further research on LNG release prevention and release control, systems for reducing LNG tanker hazards, and the safety of gelled LNG. These reports document the continuation of effort summarized by Reports F, G, and H in the first LGF Program Status Report (DOE/EV-0036).

Report I - LNG Release Prevention and Control

The LNG industry employs a variety of release prevention and control mechanisms to prevent, detect, control and contain accidental LNG releases. This report summarizes progress in the PNL study to identify possible weak links, knowledge gaps and research needs that may aid the future development of release prevention and control systems.

The basic approach in this research includes progressively more detailed analysis to develop an adequate understanding of release prevention and release control systems and the factors which may nullify their usefulness. The study began by defining reference descriptions for the basic types of LNG facilities. The facilities considered include the import terminal, export terminal, marine vessel, peakshaving plant and satellite facility. Scoping assessments were performed as the next phase of the study to identify areas that may merit subsequent and more detailed analysis. These assessments contain a reference system description, a preliminary hazards analysis (PHA) and a list of representative LNG release scenarios. The final stage in the analysis is to assess the effectiveness of the release prevention and control systems identified as warranting further considerations in the scoping assessments.

Scoping assessments for each of the basic LNG facilities have been completed and are summarized in this report. The import terminal and peak-shaving plant are described in moderate detail. Assessments of the export terminal, marine vessel and satellite facility are more briefly summarized.

The assessments indicate that the storage and unloading sections of the import terminal have the potential for the largest LNG releases. Key storage section components include the inner and outer tank structure, the pressure control system, and the liquid level indicators and alarms. Important unloading section components include the transfer line, the loading arms and coupling mechanisms, and the loading emergency shutdown system. General areas which merit detailed analysis include human factors in LNG operations, LNG storage tank operations, and data gathering. Further study has been initiated in these areas.

Report I also describes briefly the initial effort undertaken in the detailed analyses of the import terminal and peakshaving plant. The basic objective of these analyses is to quantify representative release scenarios in terms of release frequency and release quantity. Work performed to date has concentrated on LNG release prevention. Future work will address engineering aspects of vapor control, fire prevention and fire control.

Report J - The Feasibility of Methods and Systems for Reducing LNG Tanker Fire Hazards

A major accident involving an LNG tanker could result in a large LNG spill and fire. Report J summarizes a recently completed study by Arthur D. Little, Incorporated, that identifies and evaluates new and novel methods for reducing LNG tanker fire hazards. These methods include reducing the release rate and quantity, altering the physical or chemical state of the cargo, protecting the tanker and crew from thermal effects and disposing of the cargo.

The basic accident event was assumed to be a 25,000 m^3 spill resulting from a collision between a large ship and an LNG tanker. This corresponds to spilling the contents of one cargo tank of a tanker with an LNG capacity of 125,000 m^3. With this spill volume, little value can be expected from fire fighting or inerting the flammable vapor after the spill occurs. The principal focus of this study is on modifications to the ship and cargo that reduce the magnitude of the potential fire.

To reduce the spill rate and/or quantity, the following methods are considered: (1) partitioning existing tank designs, (2) multi-tank ship designs, (3) inserting open cell filler material to restrict the flow of LNG, and (4) combining cellular filler material with compartmentalization. With certain limitations, all of these methods appear to be of practical value. The efficacy and perceived problems of each method are discussed.

Transforming LNG to a gel, converting LNG to methanol, mixing flame suppressants with LNG and solidifying rather than liquefying natural gas are considered as ways of changing the chemical or physical state of LNG. The transport of gelled LNG and methanol converted from methane are basically practical. However, additional development of the gel manufacturing process is considered necessary and system level cost/benefit analyses are required to establish the economic feasibility of these approaches. While the use of flame suppressants, such as halons, mixed with LNG is considered impractical, the transport of solid natural gas may have merit.

A preliminary evaluation of system costs was made considering the above concepts. Based on the transport of a billion standard cubic feet per day with LNG shipped from Algeria to Texas, the expanded-metal, hanging-wall type of flow restrictor might increase gas energy costs by less than 0.5%. In contrast, the transport of gelled or solid LNG could add 15% and conversion to methanol might increase the unit cost of delivered energy 10% or more.

Most critical locations in existing tankers may be exposed to the thermal effects of an accidental fire. Thermal insulation can greatly reduce fire damage, but water deluge systems may not be reliable under post-collision conditions. Currently, no satisfactory method exists for emergency off-loading LNG other than at terminals. This study considers the transfer of cargo to other ships, disposal by ship flares or combustors and disposal after transfer to a location remote from the vessel. The merits of these approaches and innovative solutions are discussed.

The mechanisms causing ignition at the time of impact are also examined. Statistics of past accidents show about 30% of collisions involving spilled cargo resulted in immediate ignition. A more detailed analysis of pertinent conditions is necessary, however, to predict with reasonable certainty that ignition will occur at the time of impact.

Report K - Safety Assessment of Gelled LNG

Report K summarizes the continued efforts of the Aerojet Energy Conversion Company to characterize the process, flow, and use properties of gelled LNG (GELNG) and to examine potential safety advantages resulting from gelation. The gelling of LNG reduces the spread area and rate of evaporation from an accidental spill. This could reduce the magnitude of a potential pool fire or an unignited vapor cloud.

Gels are characterized according to six properties: (1) yield stress, (2) rheological behavior, (3) flow characteristics under stress, (4) expulsion behavior, (5) gel aging characteristics, and (6) boil-off rates under simulated storage conditions. The variation of these physical characteristics with gelant content, composition, type and method of preparation are discussed. Using the minimum gellant required to obtain a given gel structure, water as a gelling agent is shown to be superior to methanol. For gels of similar composition, yield stresses were found to increase with increasing gelant content. Gels flowed easily through coiled tubes under isothermal conditions and showed shear-thinning without evidence of gel structure degradation. Gel expulsion from tanks was found to be dependent on tank surface area and compared favorably with the expulsion efficiency of LNG. Simulated storage under low to moderate heat flux conditions showed little difference between boiloff rates of LNG and GELNG. Gellation significantly increased total spill vaporization times and decreased maximum spill spread areas in unconfined spills. Vaporization rates also were lower for gels than for LNG in confined spills on sand, concrete and water. After the cessation of a small initial flow, 2 weight % gel under a 20 psi pressure showed no detectable leakage through a simulated pipe crack approximately 3.8 mm x 0.6 mm. In contrast, the LNG flow rate through this crack was 964 g/min under 10.5 psi driving pressure.

Industrial scale production (11,000 gallons of gel delivered in two hours) was studied to obtain a preliminary assessment of technical feasibility and cost. The concept considered involves direct injection of a gaseous gelant into the LNG as it is transferred to a truck or storage tank. The incremental cost of gelation is estimated as $\$0.23/10^6$ Btu. Compared with a basic cost of $\$4.25/10^6$ Btu, gelation would increase the cost of natural gas approximately 5% at the distribution point. This estimate contrasts with that of the previous report (Report J) where the incremental cost of gelation is estimated as high as 15%.

Results of this study support the conclusion that gelation provides a practical means to enhance LNG safety. Larger scale tests, detailed design effort and economic studies appear justified to confirm these results and develop practical systems.

INSTRUMENTATION AND TECHNIQUE DEVELOPMENT

Four reports are included that describe the development of instrumentation and the data acquisition system to be used in upcoming LNG dispersion tests at the Naval Weapons Center, China Lake, California.

Report L - A Four Band Differential Radiometer for Monitoring LNG Vapors

The Jet Propulsion Laboratory (JPL) developed a Two Band Differential Radiometer (TBDR) for monitoring methane that was described in Report J in the first Status Report (DOE/EV-0036). The TBDR was successfully tested during spill tests held in the fall of 1978. Following the 1978 tests, it was recognized that a capability for differentiating methane from ethane and propane is desirable. The TBDR design was modified to measure absorption at four wavelengths allowing the determination of four parameters of the LNG cloud. The Four Band Differential Radiometer (FBDR) is described in this Status Report. Report L provides details of the FBDR design and estimated performance together with a summary of recent development, testing and design verification activities.

The baseline FBDR design measures methane, ethane and propane in the spectral region 2.0 to 2.5 μm. The fourth channel is used to correct for variations of source intensity or broadband extinction in the optical path. Important design considerations include weight, power requirement, volume, signal to noise ratio, number of detectors and ambient temperature. The performance requirements include a measurement threshold of 0.4% volume of any of the three vapors, a range of threshold to 50% volume and an accuracy of 0.2% or 10% of concentration, whichever is greater.

Fabrication and assembly of the FBDR engineering model was completed in January 1980. Routine operation of the instrument has been achieved at approximately the design signal-to-noise ratio of 10^4. The thermal control servo system has been demonstrated successfully and absorption data for methane, ethane and propane have been collected with gas-to-air ratios of about 5, 15 and 30% at six wavelengths. Final analysis of these results will be the basis for selecting the four wavelengths to be used in the field units. Data analysis algorithms and supporting software have been written and analog-to-digital conversion, multiplexing and interface circuits are integrated into the system. Design verification is proceeding and preliminary test results indicate acceptable performance. System level testing of the enginnering model instrument began the week of April 7, 1980.

A production prototype will be built and used for final system integration testing. The detailed opto-mechanical design of the prototype sensor is complete and fabrication of optical and mechanical components has begun. The final electronic packaging design has also been started. Final assembly and acceptance testing of the production prototype unit is scheduled for early June 1980. System integration testing with the LLL data acquisition system (See Report O) will be undertaken in mid-June at China Lake.

After verification that system integration and overall design compatibility meet performance requirements, the production of ten field instrument systems will begin. The integration of the ten field units into the China Lake System is currently scheduled for early September 1980.

Report M - A Battery-Powered Differential Infrared Absorption Sensor for Methane, Ethane and Other Hydrocarbons

This report presents the performance goals, design considerations, and physical details of a miniature differential infrared absorption sensor being developed by LLL. The purpose of this effort is to develop a small, portable, accurate gas sensor for array deployment during LNG spill dispersion tests. The sensor is lightweight, battery-powered, self-contained, and capable of operating over the full range of expected gas concentrations and in dense fogs created when liquid methane at -164°C contacts humid air and water. Development goals include meeting all technical requirements with a sensor that can be produced inexpensively and adapted easily to other purposes, such as monitoring other gases with middle infrared absorption bands.

The sensor is a direct evolution of a miniature, portable CO_2 sensor. A prototype CO_2 sensor modified to measure methane was successfully demonstrated in the 1978 LNG spill tests at China Lake (see Report K in the first Status Report, DOE/EV-0036). The present design allows it to measure two components, but it can be modified to measure additional components at reduced sampling frequency. To minimize temperature effects and power consumption, a single source, single detector design is employed which includes a rotating chopper-filter wheel. A complementary metal-oxide semiconductor (CMOS) microprocessor interfaced with a fast arithmetic chip is used to linearize sensor output and correct for component interference. Specific operational design goals include a battery power requirement of less than 15W, less than 5 minutes warm-up time, multigas sensing capability (0.1-100% methane, 0.1-25% ethane-propane) and a sampling rate of 5/second per channel. Additional goals are an optical unit weight less than 1 kg and sensor head volume less than 500 cm^3.

From an optics standpoint, an instrument operating on the 2.4 μm band is cheaper to build because it can use readily available glass lenses and an incandescent source (see also Report L in this Status Report). However, the long paths demanded at this wavelength are incompatible with the requirement for operating in a fog. For this reason, the LLL instrument was designed to operate in the 3.4 μm absorption band. The sensor is designed in two packages: a small, lightweight optical head assembly and the electronic control and processing unit. The optical head is about the size of a 12-oz soft drink can. The physical layout of the electronic control and processing unit is not yet settled pending completion of the tower data acquisition system design. Two way communication with the tower data station processor is expected to start, stop, and possibly change the averaging time of the LNG sensor.

Two interchangeable optical absorption cells have been designed for the sensor with absorption path lengths of 2.5 and 25 cm respectively. The optical head contains a black body radiation source and an optical system of lenses and mirrors that focuses the source radiation on a detector situated behind the rotating chopper-filter wheel. Where significant fog concentrations are expected, the long path cell is replaced by the short 2.5 cm cell that contains a prism instead of mirrors to complete the optical path in the instrument. Report M includes a summary of the electrical design, with details of the optical head electronics, detector, amplifier-filter section, peak detecting A/D converter and filter synchronization circuit. The motor speed controller, source controller, electronic control and processing package, microprocessor, arithmetic processor and display components are also briefly described.

Calibration of the LNG prototype has been completed using standard gases. The sensor has been operated in a fog chamber with both the long and short path absorption cells installed. Final performance figures are not yet available because the filters used in these tests were not optimized for the device. The sensor has verified that methane and ethane signals and the mutual interference of these gases show a power-law dependence variation in absorption coefficient versus concentration. Separation and linearization algorithms using these relationships are now being prepared.

The biggest problem with the LNG prototype continues to be operation in a fog. When operated in the fog chamber for a long period, the whole sensor becomes coated with a heavy water layer which eventually absorbs or scatters all radiation from the source. Rearranging the sensor components into a modified two-ended design is expected to alleviate this problem. A drawback of the modified design, however, is that the longer path lengths needed for accurate measurements of low gas concentrations are longer than the small high-frequency eddies for which studies have been proposed. This limits the frequency response of the sensor at the lower concentrations.

Report N - Remote Sensing for Diagnosing Vapor Dispersion in Spills of Liquid Energy Fuels

As a means of determining the effects of large-scale LNG spills, LLL is developing numerical models to determine how the liquid spreads, vaporizes, and disperses under varying weather conditions (See Reports A and H). In order to experimentally verify the accuracy of these models, it will probably be necessary to conduct and diagnose future test spills in the 200m^3 or larger range. Diagnosing planned experimental spills of 40 m^3, and subsequent spills of 200 m^3 or more, will require an extensive array of in situ instruments that may cost several million dollars (see Report O). Remote sensing is a means of potentially reducing the cost, and/or providing better coverage than that of a more extensive in situ array. This report contains a comparison between a "fence" of in situ instruments proposed for 40-m^3 spills at China Lake and a Raman LIDAR system of similar cost designed to cover the same area of the cloud.

The measurement of gas concentrations in liquid energy fuel dispersion clouds by remote LIDAR[a] sensing is an attractive alternative to the use of in situ instruments in regions where the gas concentration level is low. LIDAR offers substantially higher spatial resolution and coverage that better allows for wind variations. A comparison is made between Raman[b] and DIAL[c] LIDAR and shows that Raman LIDAR is better suited to measure the concentration levels of interest. The LIDAR systems are limited primarily by the opaque fog produced by the evaporation of a cryogenic liquid fuel. The limitation is most severe for methane, for which LIDAR is not useful at concentrations above the flammability range. However, the spatial extent of the cloud is large in low concentration regions and is not easily covered with an array.

The feasibility of using Raman LIDAR on LNG spills was evaluated in a 5-m^3 spill at China Lake in September 1978. The expected performance of instrumentation supplied by Computer Genetics Corporation was verified, and the observed relationship between hydrocarbon concentration and fog was consistent with calculations. These results are described in this report.

Based on theoretical and experimental evidence, LLL proposes that a Raman LIDAR system be built to diagnose the large volume, low concentration region of 40-m^3 spills. Details of the proposed system are described including the laser and optical systems. Summary descriptions of the receiver components include the telescope, analyzer, detectors and transmission system. Data storage, analysis and display are also briefly reviewed. An estimated system cost of $400,000 is derived from a detailed analysis of commercial component costs using proven state-of-the-art technology. Manpower estimates of $70,000 per year are projected.

For 40-m^3 spills LIDAR is estimated to be competitive in cost, and superior in performance to alternative in situ instruments. When larger spills are conducted, a LIDAR system could result in a significant reduction in total diagnostic cost.

(a) LIDAR is a laser ranging technique named by analogy to RADAR.
(b) Raman LIDAR is based on emission spectroscopy.
(c) DIAL uses differential infrared absorption.

Report O - The LLL Data Acquisition System for Liquefied Gaseous Fuels Program

Dispersion tests involving LNG spills in quantities up to 40-m^3 are scheduled to begin in May 1980 at the Naval Weapons Center, China Lake, California. A data acquisition system is being developed for use during these tests by E.G.&G., Incorporated, and the Electronics Engineering Department of LLL. This system will employ 51 battery-powered complementary metal-oxide semiconductor (CMOS) data acquisition units to measure gas concentration, wind direction and speed, temperature, humidity and heat flux. Stations will be located in an area approximately 500 meters wide by 2000 meters long. Data acquired by the CMOS acquisition units will be telemetered by UHF radio links to a trailer-based microcomputer command, control, and data recording system (CCDRS).

The basic requirements of the data acquisition system are to (1) display and record wind data from 20 weather stations and 6 turbulence stations before, during and after the spill tests; (2) receive a starting signal for timing the gas sensor data acquisition system; and (3) to record data from 25 gas sensor stations during the spill tests. Gas concentration and temperature will be measured at three different heights at each of the gas sensor stations. Some of the stations will also have humidity sensors, heat flux sensors, or radiometers. Measurements will be made once per second and the data recorded in the trailer for subsequent analysis. All together, approximately 700 channels of data will be recorded for periods of one-half hour or more. Previous dispersion tests indicated that portability is a necessary requirement because of the variability of wind direction. A large area covered by the array precludes the use of power cables and commercial power. Battery-powered units are therefore required and made necessary the use of low power consuming components.

This report describes the basic requirements and components of the data acquisition stations and the CCDRS. Commercially available microcomputers will be used in the data acquisition, data recording and display.

Analog signals from instruments such as thermocouples, three-axis anemometers and humidity sensors will be digitized by the 16 channel multiplexed analog-to-digital converter. Power will be provided by gelled electrolite 12-volt storage batteries with solar cell rechargers and dc converters will generate the 5 volts ± 15 volts and other dc voltages required by micro-processors. The UHF command and data telemetry system will operate in the 406-420 MHz band. A three-level binary interface has been designed at LLL to connect the microprocessors to the radio units.

The CMOS microprocessors will be commanded to begin acquiring data by the CCDRS. All timing and sequencing will be controlled through the CCDRS microcomputers. Each major subsystem (the weather stations, the gas sensor stations, and the turbulent stations) will communicate data to Digital Equipment Corporation LSI-11 front end processors. Data will be stored on 10-M byte disc memory units attached to these processors. Following each test, data will be retrieved from the disks and rerecorded on magnetic tape to be read on the Livermore time-sharing data processing system. A graphics terminal will allow early review of the recorded data following each test.

The overall system design and detailed designs are complete. Much of the necessary electrical and electronic components have been ordered.

SCALE EFFECTS EXPERIMENTS

Three reports in this category describe the results of 5-m^3 LNG spill tests and the experimental plan and facilities of 40-m^3 spill tests at China Lake, California. The fourth report presents an environmental analysis of the proposed site for a scale-effects test facility at Frenchman Flat, Nevada.

Report P - Data and Calculations of Dispersion on 5-m^3 LNG Spill Tests

A series of liquefied LNG spill and dispersion experiments was carried out in the fall of 1978 at the Naval Weapons Center, China Lake, California. Nominally 5-m^3 LNG were spilled onto a water pond under wind conditions varying from 3 to 10 m/s. The principal reason for LLL participation was to evaluate gas concentration measuring devices which may be used in future larger scale spill experiments. This instrument evaluation effort was described in the first LGF Program Status Report (Report K, DOE/EV-0036). This report presents dispersion data taken during the experiments and compares these data with calculations made using the ATMAS computer model.

Each of four experiments involved the release of LNG through an 8-inch pipe onto a pond of water at a rate of approximately 5-m^3/min. A typical experiment lasted from 2 to 3 minutes from the beginning of the LNG release until the trailing edge of the vapor cloud passed the last sensor. Data were collected for about 5 minutes in each experiment. Comparison of the measured concentration data with model predictions was significantly hindered by fluctuations of the wind speed and direction during the experiment. Most transport models assume a constant wind velocity. Wind speed varied by as much as a factor of 3 and direction shifted up to 60° during a single test. To overcome this difficulty, plume dispersion was simulated using the ATMAS computer model. This atmospheric transport model generates a three-dimensional time-varying wind field from the wind velocity data taken during the experiments. Although the ATMAS model has significant deficiencies when applied to LNG vapor cloud dispersion, the simulations were generally quite good and provided a useful tool for interpreting field data and understanding the effects of wind variations on the vapor plume.

Experimental results are presented for each of the four spill tests. Comparisons are made between the different instruments at each station and between the experimental data and the predictions of the ATMAS code. The very sparse array of gas sensors used in the test series did not allow the generation of experimental concentration contours but required point-by-point comparisons at specific stations. Steep gradients in the vicinity of some of the measurement stations may have exaggerated the differences between calculations and experiment. Where comparisons were possible, the predictions of the ATMAS code were often in reasonable agreement with the experimental data, although exceptions did occur.

These experiments were successful in their primary purpose of evaluating the gas sensors and showed clearly the need for a large array of instruments to measure both gas concentration and the wind field. The array being built for the 1980 40-m^3 spill experiments (see Report O) is based on this knowledge.

Data from the 5-m^3 spill tests also provided information about the dispersion process. Estimates of the dispersion coefficients were obtained by comparison with data from stations at the edge of the plume. The horizontal dispersion coefficient was found to correspond to stable atmospheric conditions as defined by the Pasquill-Gifford dispersion categories. The vertical dispersion coefficient was determined from gas concentration data and was also found to correspond to stable conditions. The vertical dispersion coefficient was found to be nearly the same in all four experiments despite considerable change in wind speed.

Wind speed variations have a significant effect on source parameters. The LNG pool size was found sensitive to wind velocity. A significant result of these experiments was the first field verification of differential boiloff. The data indicate that, under certain wind conditions, part of the gas enriched in ethane and propane can propagate some distance downwind. Overall, these experiments indicate that a good description of the vapor source as a function of time will be necessary in order to reproduce the downwind behavior of the vapor plume. This will require better measurements of liquid spread and boiloff rate and an improved computer model.

Report Q - Experimental Plan for 40-m^3 Liquefied Natural Gas (LNG) Dispersion Tests

This report describes the LNG vapor generation and dispersion experiments to be conducted by LLL in 1980-1981 at China Lake. These experiments together with a series of pool fires and vapor burns (see Report R) are a joint effort between LLL and the Naval Weapons Center (NWC). The experiments will be intensively instrumented so that sufficient quantitative data are gathered to gain an understanding of the physical phenomena involved and to make detailed comparisons with computer and wind tunnel models. The anticipated result of this effort is the experimental verification of computer models applicable to full-size spills. The 40-m^3 spills planned in this test series are the minimum size in which the dispersing LNG vapor cloud is expected to influence the atmospheric boundary layer in a manner similar to that of a large spill. Data requirements for the measurement of gas concentration, temperature, heat flux, pool spread, vaporization rate, wind field, and humidity are presented.

The major goal of the experimental program is to measure gas concentrations downwind of the spill point for a series of wind speed and stability conditions, spill sizes and spill rates. Early in the program the vapor source will be characterized by the measurement of gas concentrations close to the spill point; later, direct measurements of the pool itself will be made. Concentration fluctuations will be examined as a function of downwind distance and atmospheric conditions, including the significance of these fluctuations on cloud flammability. The inhibited vertical mixing that results from the high-density of the cold cloud is an important effect that will be investigated further. Measurements of heat flux, temperature, and water content will be used to determine the energy balance in the cloud and its effects on cloud dispersal. The persistance of the downwind region enriched in heavy hydrocarbons will also be investigated. In addition to the dispersion and vapor generation data needs, there are operation data requirements. The NWC team, as operators of the spill facility, will record the spill volume, spill duration, LNG composition, and meteorological tower data. The NWC will also provide photographic coverage of the experiments.

Report Q provides details of instrument capabilities, station requirements and the data acquisition system. These sections in this report together with the data acquisition system description in Report O provide a comprehensive summary description of LLL experimental capabilities at China Lake.

The experimental program will consist of several test series each with a number of experiments and different objectives. The first two series will consist of about thirty dispersion experiments. The most important experiments will attempt to determine gas concentration contours within the gas cloud with varying spill rates, spill volumes and wind and stability conditions. The second series will address source definition and near-field dispersion. Direct measurements will be made of LNG pool spread and vaporization rate at the water surface. This will allow the estimation of source parameters such as boiloff rate, rate of vapor movement up the hill, and rate of air entrainment for the gas emerging from this area. It will be desirable to make both near and far-field dispersion measurements during each experiment. Consequently, ten gas sensors and three anemometer stations will be left in the far-field configuration to provide a correlation between the two series of experiments.

Six stations will be used for fast response measurements to provide information on turbulence. The turbulence stations will be scattered throughout the cloud. Later in the experimental series, it may be desirable to make correlations between turbulence and gas mixing at various specific locations within the dispersing cloud. It is expected that turbulence will be investigated when more fast response stations are added to the array, making it possible to densely instrument a small portion of the cloud. This dense array of instruments can then be moved to other parts of the cloud in a series of experiments designed to investigate turbulent mixing as a function of downwind distance. Measurements of the time dependence of the pool radius and evaporation rate will be attempted when appropriate instrumentation and techniques are available. Finally, a series of experiments similar to those performed in water will be performed for spills on land. This series of experiments will be less extensive and use knowledge gained from the previous experiments.

Report Q provides a detailed summary of the measurements to be made and the instruments to be used including their number, location, and performance characteristics. A schedule for the 1980 experimental series is also provided. These experiments are expected to begin in early May and continue through September at China Lake.

Report R - China Lake 40-m^3 LNG Spill Facility

This report describes the LNG spill facility at the Naval Weapons Center (NWC), China Lake, California which has been expanded to carry out 40-m^3 LNG spill tests and outlines the proposed spill tests planned for this facility.

The ultimate purpose of the LNG spill studies is to be able to model the effects of spills up to 25,000 m^3 such as that resulting from the possible rupture of one compartment of an LNG tanker. The approach is to conduct LNG spill tests of progressively increasing size from 5 m^3 up to several hundred m^3. Spill tests of 5 m^3 have been conducted at the NWC facility with LNG, liquefied petroleum gas, gasoline and liquid nitrogen. These tests have been used to develop models and scaling laws. The next series of tests will be in the 40 to 100 m^3 range. Their purpose is to verify the scaling laws developed to date and to provide design and safety criteria for a larger scale-effects test facility.

Operation of the 40-m^3 facility will be similar to that of the 5-m^3 facility. The 5-m^3 test facility has been modified by addition of larger tanks to give it a 40-m^3 spill capability. The LNG will be forced out of a vacuum-jacketed tank by pressurized nitrogen. Heat shields will protect both the 5.3 and the 40-m^3 tanks. The tests will be conducted remotely from the control van located 250 m northwest of the tank. The pond was modified slightly to be more circular in shape, and the slopes of all but the south bank were smoothed to provide less turbulent wind flow over the basin. Initial check-out of the pressurization-vent system will be done with gaseous nitrogen. This will be followed by three 5-m^3 liquid nitrogen spill tests to check out facility operation.

Three types of LNG on water spill tests will be conducted. An initial series of two 5-, one 20- and one 40-m^3 spills will be undertaken to check out the facility and instrumentation and to make radiometric measurements of pool fires. The second series will consist of six 20- and six 40-m^3 spills conducted by LLL to determine dispersion characteristics under different atmospheric stability conditions. The final test series is planned with one 5-, 15- and 20-m^3 spill and four 40-m^3 spills to make radiometric measurements and determine premixed flame characteristics of LNG vapor fires.

Report S - Technical Information for Environmental Analysis of 1000-m^3 LNG Spill Test Effects at Frenchman Flat, Nevada

The environmental effects of LNG spill tests at the proposed national LNG test site have been analyzed by LLL. A total of 69 Federally-owned facilities were evaluated as sites for this LNG field test facility. A detailed environmental effects analysis was conducted for the most likely candidate location, the Frenchman Flat basin. A cursory examination of potential environmental impacts was done for the other eight final candidate sites as described in Appendix A of Report S. The estimated environmental impact of tests at Frenchman Flat was compared to that for each of the other final eight candidate sites. A comparison was also made to determine whether impacts similar in nature and magnitude to those estimated for LNG tests were accounted for in existing environmental impact statements for Frenchman Flat. The EIS's for both the Nevada Test Site and Nellis Air Force Range were considered because the LNG tests would impact both sites.

The initial screening of 69 potential sites for the LNG field test facility included facilities having areas greater than 64 km^2 owned by the DOE and the military. This screening eliminated all but nine sites on the basis of unfavorable safety, cost, atmospheric conditions and other external constraints. When one strong reason was found for rejecting a given site, its suitability with regard to other criteria was often not examined. Therefore, there may be other reasons besides those shown for rejecting some of the sites. The nine sites remaining after this initial screening were examined further using available information. Four of the remaining sites were eliminated because they were judged to be environmentally more sensitive than Frenchman Flat to proposed energy tests. Four sites (White Sands Missile Range, Hill Air Force Range, Wendover Air Force Range, and China Lake Naval Weapons Center) were judged to entail similar environmental impacts to those expected at Frenchman Flat. More detailed studies would have to be made of these four sites to confirm this judgment. However, because other factors such as cost and logistics were judged to be less satisfactory for these four sites, it is recommended that the Frenchman Flat be selected for the location of the larger scale-effects test facility. In order that a more quantitative analysis could be made, this study selected a spill size of 1000 m^3. This is believed to bound the spill size ultimately deemed necessary in the scale-effects study.

I.2.2 Other Liquefied Gaseous Fuels

The large effort devoted to LNG research in the LGF Assessment Program has been motivated by the identification of a need for this research to understand LNG behavior in the event of an accidental release. Many insights gained and techniques developed in this research are applicable to other liquefied fuels and energy materials. The balance of the LGF Assessment Program includes research activities that complement the knowledge derived from the LNG studies and address specific safety and environmental concerns associated with liquefied petroleum gas (LPG), ammonia and hydrogen energy systems. Reports T through Y in Volume 3 describe this effort. Summaries of these reports, grouped according to energy material are presented below.

LIQUEFIED PETROLEUM GAS

Report T - Simultaneous Boiling and Spreading of Liquefied Petroleum Gas (LPG) on Water

The objectives of this project, performed by the Massachusetts Institute of Technology, are to experimentally measure boiling and spreading rates of LPG on water and to develop an analytical model to describe the phenomena involved. A discussion of existing boiling/spreading models and the related literature was reported in the first Status Report (See Report S in DOE/EV-0036). This report describes the effort of the past year which has been devoted primarily to the design, fabrication, testing and modification of the experimental components. The project is currently in the final phase of apparatus construction.

One-dimensional boiling and spreading tests are to be conducted by spilling LPG or a similar liquid into a long, narrow water trough built from Plexiglas tubing. The hydrocarbon vapor generated is ducted to a hood. The water, spilled liquid and vapor temperatures are monitored by a set of chromel-constantan thermocouples. A high-speed camera will be used to record the movement of the LPG. If the cryogen is spilled directly onto the water surface, the impact would cause undesirable wave motion and wave reflection from the far end. A distributor has been designed to minimize this disturbance, and a packing of stainless steel wool is placed at the end of the trough to prevent wave reflection. Eight vapor sampling stations are positioned along the trough. Each of these stations has the capacity to collect six separate vapor samples in an array of glass sampling bulbs. Local boil-off rates of the LPG will be monitored using an inert tracer gas and a temperature programmable gas chromatograph to analyze vapor samples. The temperatures and compositions of the vapor will provide necessary information to determine the mass boiled off as a function of time and position along the trough.

The spreading of LPG on water is analogous to a large extent to the spreading of an oil slick on water. The major difference between the two processes is the associated mass loss due to the evaporation of LPG. Several pentane spills were made to study the spreading of a non-volatile liquid on water. The experiment showed that the early spreading of pentane on water agrees well with the predictions of one-dimensional spreading developed in a theoretical model by Fannelop and Waldman. Data collected show that the dimensionless spreading distance is proportional to the dimensionless time raised to the 2/3 power.

Several liquid nitrogen spills were performed to study the effect of boiling on the spreading process. The general shape of a liquid nitrogen spill on water is a thick spreading front followed by a thinner tail as observed in the pentane spills. Report T compares the spreading time/distance data of liquid nitrogen and pentane spills with the same initial volume. Theory would predict that liquid nitrogen spreads much slower than pentane. However, bubbles of evaporated nitrogen alter the density effect of the liquid nitrogen layer. This may explain the larger than expected liquid nitrogen spreading rate. The experimental data from liquid nitrogen spills were compared with the prediction of Raj's model. The model appears to underestimate the spreading distance. However, it is limited by the assumption of a constant boiling rate.

Plans for future work include completing the fabrication of the spill apparatus and conducting further nitrogen spills to thoroughly test and check-out the experimental equipment. Both instantaneous and continuous spills of liquid propane and LPG will be carried out in the volume range from 0.5 to 3 liters. A goal of this effort is to use the experimental data to develop an analytical model which will be the basis of estimating potential hazards resulting from larger LPG accidental spills.

Report U - LPG Safety Research

The goals of LPG Safety Research being conducted by the Applied Technology Corporation (ATC) include the analysis of LPG transportation hazards and the evaluation of fire fighting agent effectiveness. Other objectives are to measure radiant fluxes from LPG fires, to determine boil-off rates for LPG spills on solid surfaces and to measure vapor concentrations downwind of small to medium scale spills. The LPG Annotated Bibliography included in Volume 1 of this Status Report was also prepared as part of this effort. Report U describes the marine hazard analysis, the fire fighting agent effectiveness evaluation, and some of the small scale boiloff tests.

This report contains a summary description of LPG vessel design, operations and fire protection systems. The fire protection philosophy for LPG ships includes fire prevention, control and extinguishment and damage potential reduction. If a fire occurs, it may be controlled, extinguished or allowed to burn out. Only small fires can be extinguished reliably, a dry chemical being the best agent for most situations. Fires may be controlled using high-expansion foams. Generally, LPG fires should be extinguished only after the spill is finished and the flow of products stopped to avoid the possibility of reignition. Water sprays may be used for cooling as a damage control measure; however, water cannot be used on LPG fires directly because it increases the fire size by increasing boiloff rates.

Fault-tree analysis was used to estimate the probability of LPG releases. The goal of this analysis was to estimate the probability of events that either directly, or as the initiation of a larger event, might endanger the public or operators. The highest risk appears to be when the vessel is in port or transversing an inland waterway. The major emphasis of this analysis is on dockside operation when a tankship is unloaded. Results of the fault-tree analysis, showing spill probability per transfer versus spill size in gallons are presented for both tanker and barge transfer operations. The spill probabilities for tankers and barges are about the same, a conclusion which is generally supported by other estimates found in the literature. Even when the spill probability is large, it does not necessarily follow that the operation is especially dangerous. Small spills, less than 10 gallons in size, which occur in more than half of all transfers appear to have very low ignition probabilities. Spills involving more than 100,000 gallons of LPG are essentially certain to be ignited. Ignition probabilities versus spill size are calculated in the absence of collision events. The ship collision contribution is omitted because it makes the fire probability estimates appear higher than they really are at the terminal.

Fire damage and personnel injuries are related to fire size. Fires resulting from spills of less than 10 gallons are unlikely to cause substantial damage or result in fatalities. Fires involving thousands of gallons are nearly certain to cause substantial damage and are quite likely to result in fatalities and serious injuries. The overall probability of a operator fatality is estimated to be in the range of 10^{-6} to 10^{-5} per transfer operation. A fatality probability for the general public is much lower because of the great separation from the transfer area. The "boiling liquid expanding vapor explosion" (BLEVE) has occurred following LPG railcar derailments. This phenomenon could possibly occur in barge operations because the cargo is pressurized. However, no fires at barge transfer facilities that resulted in BLEVES have been recorded. BLEVES cannot occur during operations with fully refrigerated LPG cargoes because all operations involve using liquids that are saturated near atmospheric pressure.

Two tests were run to measure the boiloff rate of LPG following a rapid spill onto concrete, polyurethane foam, and a sand-soil mix. The predicted boiloff rate and quantity remaining was based on a film coefficient-limited model of heat transfer by conduction through the concrete with additional terms representing atmospheric convection, solar radiation, and sensible heat from the cooling of the LPG. Agreement between the experimental results and theoretical predictions was obtained. Burning rates were found to vary with fire size and to a lesser extent with wind speed. Not enough data were obtained to provide quantitative relationships. However, maximum burning rate indicated is about 0.45 inch per minute and is reached with fires larger than 20 feet wide. If the fuel is ignited before the ground is well frozen, the burning rate can be substantially higher because of more rapid boil-off.

As part of the experimental effort conducted by ATC, about 100 tests were run on free-burning LPG fires to determine the quantities of fire fighting agent that is required to control or extinguish a fire. Tests using high expansion foam were run on fires in 5-, 10-, 20-, and 40-foot square pits. Fires were allowed to burn freely for at least a minute after ignition so that the burning rate could reach a steady rate before extinguishment was attempted. It was found that LPG fires can be controlled but not extinguished by the application of high expansion foam. To provide control within a few minutes, application rates in the range of 0.1 to 0.15 gal/min-ft^2 at an expansion ratio of 500 to 1 were required. The wide variability experience with LNG fires in the effectiveness of various types of foam was demonstrated with LPG.

Three types of dry chemical were used: sodium bicarbonate, potassium bicarbonate, and urea-potassium bicarbonate. The chemicals were applied from fixed nozzles located along the sides of the test pits. All the dry chemical agents were found effective in extinguishing LPG fires, the sodium bicarbonate being less effective than the other two agents. However, the sodium bicarbonate is an attractive choice on the basis of cost and range for large fixed systems discharging at high rates.

There is a minimum application rate below which fires cannot be extinguished by dry chemicals. Part of the extinguishment mechanism is absorption of free radicals of the combustion chain. Minimum application rate is apparently related to the average free radical concentration in the flame. There is also a minimum application time below which the fire will not be extinguished even for very high powder application rates. This minimum application is apparently related to the time required to mix powder and flame. Minimum extinguishment time for all powders was about the same, between 2 and 3 seconds. Higher powder application rates are required for LNG fires than LPG fires. Practical extinguishment systems can be designed for LPG providing care is taken so that reignition is prevented.

Report V - State-of-the-Art of Release Prevention and Control Technology in the LPG Industry

Pacific Northwest Laboratory (PNL) is conducting a study to identify possible knowledge gaps in the safety and environmental control of processing, storage and transporting LPG. The objectives of this assessment include the identification of areas where additional work may be needed and the recommendation of specific research and development strategies. Release prevention is the primary activity for avoiding uncontrolled LPG spills and the attendant potential hazards. Release control encompasses activities which limit the effects of a potential spill if release prevention methods fail. An understanding of current release prevention and release control capabilities is an important basis for the PNL assessment.

This report presents a state-of-the-art summary of release prevention and control technology in the LPG industry performed by Battelle Columbus Laboratories in support of the PNL assessment effort. A summary of release prevention and control methods and regulations is provided for pipeline, railroad and truck transportation and consumer storage. The accident record for each of these elements is discussed, together with design and construction practices, operations and maintenance and research development activities.

In pipeline transportation, most developments which contribute to release prevention are grouped in three categories: the improvement of materials, understanding accidental release causes, and the development of better operating practices. The analysis of previous pipeline accident history has been used by the Department of Transportation to include several new release prevention requirements in recent rulemaking. These include requirements for improved quality control of materials, system pressure testing, review of shutdown and emergency response procedures and cooperative notification plans.

Accidents involving the railroad transportation of LPG often result in boiling liquid expanding vapor explosions (BLEVE's). Following a number of tankcar ruptures in 1969, a research project was initiated known as the "Railroad Tankcar Safety Research and Test Project". This project, consisting of 15 phases, provided a basis for recent regulatory actions requiring thermal shields, shelf couplers and head shields on LPG railroad tankcars. When fleet installation of these items is complete, the quality of LPG release prevention in the railroad environment can be expected to improve.

Truck accidents involving the release of LPG occur mainly in three situations: during loading and unloading operations, in repair garages, and in collisions or other accidents on the road. Release prevention research in connection with LPG trucking has involved analysis of accident data for the purpose of discovering causes. Human error has been identified in many cases. Recent rulemaking identifies several approaches for improving LPG release prevention in truck transportation. These include the tightening of equipment performance and compliance requirements for tank structural components, valves, supporting and anchoring devices and other fittings.

The LPG industry serves about 18 million customers, and it is estimated that roughly 60 million people use LPG in one way or another. There appears to be no single agency or private organization which has assembled comprehensive statistics on accident experience with consumer LPG equipment.

The National Bureau of Standards recently investigated incidents involving injuries associated with LP gas tanks and fittings in the size range 20 to 100 pounds. The conclusion of this study was that code requirements for devices such as release valves, regulators, shut-off valves, plugs, level gauges and pressure gauges were generally satisfactory. However, questions were raised about the adequacy of release valve pressure requirements and standards for requalifying cylinders, particularly the method of subjective visual inspection. The study emphasized that the detection and reporting of leaks to qualified service personnel would avoid many accidents.

Report V also describes the status of release control practices in the transportation and consumer storage of LPG. A survey of LPG pipeline operators shows that almost all pipelines have both automatic and remote shutdown capabilities for pump stations and that pump stations can be shut down in 2 to 4 minutes either automatically or remotely. The time required to shut down a pipeline depends on whether they can be operated remotely or manually. Up to two hours may be required for personnel to travel to a remote manual valve. Proposed rulemaking includes provisions to limit the spacing of block valves in critical areas and to require that they be automatically or remotely operable. Early detection of a leak or a break could be accomplished by means of pressure or flow transducers closely spaced along the pipeline. However, at present, such equipment is limited almost entirely to pump stations. Leak detection systems are unable to detect small leaks as a result of their intrinsic accuracy and the compressibility of the flow.

Other aspects of hazard control following accidental LPG releases are based on information systems, procedures and communications. There is abundant evidence to suggest that these methods are weak links in release control strategy. Written procedures have often been inadequate or infrequently reviewed. Emergency response training of personnel has been inadequate, and the public who reside in the vicinity have not been sufficiently informed about the product, its hazards and how to respond to accidental releases. New rulemaking addresses some of these problems, and, in fact, regulation appears to be the principal approach for improving release and hazard control for LPG pipelines.

Water is the primary agent used to control LPG releases from derailed tankcars. Water is sprayed from a distance to cool tanks in the flame environment as an attempt to avoid BLEVE's and to extinguish flames from other leaking cars. A recent evaluation has found that current methods of alerting emergency response personnel to the presence of hazardous materials involved in railroad accidents are often unreliable or untimely and rely on unstructured individual actions to provide the necessary information. A hazardous materials emergency response system that documents emergency response alternatives and information needs, and coordinates agency efforts, is not operational. Currently railroads are not required to have an emergency response preparedness capability. However, most major railroads have developed or are developing their own systems. These include the use of the Association of American Railroad Commodity Codes that provide computerized printouts of emergency actions appropriate for each hazardous material on a given train.

A BLEVE is possible in the case of LPG leakage and fire at or near a truck tanker involved in an accident. The response procedures appropriate for a potential railcar BLEVE appear to be applicable and useful to a truck tanker in a similar situation. It appears that adherence to regulations would prevent the majority of LPG accidents in garages and during loading and unloading procedures. Several educational and procedural bulletins are available which offer guidance in emergency response activities.

Human error is involved a large extent in releases of LPG in consumer applications. Present release control methods are similar to those applicable to truck transportation. Bulletins are available that describe procedures and precautions to control leaks in LPG systems. These include shutting off the source of LPG supplying the leak, downwind evacuation and approaching the leak or the fire from the upwind side. Current research, development projects or reports dealing with the improvements in the technology of release control or consumer storage were not discovered.

An overall conclusion, that may be drawn from this study, shows a strong emphasis on regulatory approaches for release prevention and an advisory approach to release control of LPG in the transportation and storage environments.

AMMONIA

Report W - Ammonia: An Introductory Assessment of Safety and Environmental Control Information

The Government and the ammonia industry are addressing safety aspects of handling, storing, transporting and using ammonia. Agencies involved in ammonia spill research include: The U.S. Coast Guard, Federal Railroad Administration, DOE, and Fertilizer Institute. The use of ammonia is expected to increase in the future, both in conventional and in new applications. The increasing use of ammonia may result in more emissions and more frequent accidents. The purpose of this report is to provide appropriate background information and a basis for the ammonia assessment study being performed at PNL.

Literature pertaining to the production, storage, transportation and use of ammonia is reviewed. This report also describes ammonia properties, potential hazards, production methods, accident reports, regulations, and control techniques. Finally, potential research and development needs are identified in the area of ammonia safety and environmental control that need to be considered in more detail as part of the PNL assessment study.

The possible future increased use of ammonia in energy-related applications may cause several new concerns in addition to those associated with the current widespread use of ammonia as a fertilizer. The potential for accidents and large spills especially during transportation is a principal concern. Additional research simulating large scale spills may be needed to fill knowledge gaps in this area. Ammonia and its oxidation products may perturb the atmospheric nitrogen cycle and possibly contribute to acid precipitation problems. Stress corrosion cracking in system components containing ammonia may also require further work. Handling and storage problems of the refrigerated liquid, industrial exposure and the exposure of users appear to warrant further study. Current spill control methods for the small scale user and accident response procedures and capabilities at ammonia facilities and on transportation routes deserve further attention. If ammonia has potential as a future automotive fuel, a comprehensive risk assessment may be required to establish the relative hazards in vehicular use relative to that of gasoline.

The ongoing PNL Ammonia Assessment study will continue to develop perspective and detail in the definition of the above concerns. Future work will include the development of recommendations for R&D strategies that address gaps in current ammonia safety and environmental control knowledge.

Report X - Ammonia as a Fuel

The future uses of ammonia as an energy material are under study as part of the ammonia safety and environmental control assessment being performed by PNL. This report presents a general overview of ammonia characteristics and provides a perspective on its potential use as a fuel.

Ammonia may be burned directly as a fuel or used as a storage medium for hydrogen.[a] The practical use of liquid anhydrous ammonia as an engine fuel dates back to the mid-1930's, and examples of ammonia fuel use are recorded in Europe during World War II. More recently the U.S. Army Material Command considered ammonia as part of its "energy depot" concept. Studies indicated that ammonia would be a more suitable fuel for this purpose than alternative fuels such as hydrogen, hydrazine, or hydrogen-peroxide. Historically, ammonia fuel utilization has been tied to actual or expected shortages of fossil fuel. Future fossil fuel shortages may similarly make ammonia an attractive fuel. The production of ammonia may be a method for converting energy from large-scale alternative energy sources, such as fusion energy, into a convenient fuel for small-scale uses such as transportation. Another significant factor for considering ammonia as

(a) The fuel uses of hydrogen are identified in Report Y.

a fuel is the reduced environmental impact. As a non-carbonaceous fuel, it allows cleaner combustion without atmospheric emissions of CO, CO_2, sulphur-oxide, and trace elements.

Ammonia is potentially a very versatile fuel and can be used in both internal and external combustion engines, as well as in direct and in indirect fuel cells. Ammonia can be used successfully in internal combustion engines at compression ratios typical of gasoline engines if it is introduced as a vapor partially decomposed to hydrogen and nitrogen. Under these circumstances, the hydrogen acts as a pilot fuel to initiate ammonia combustion. Engine output is reduced approximately 70% of the equivalent gasoline model because of the intrinsically lower energy density of ammonia relative to that of gasoline. The compatibility of ammonia and its combustion products with engine materials and lubricants presents no substantial problems. When used as a fuel in diesel engines, ammonia presents difficulties because of poor self-ignition qualities. Theoretically a compression ratio of 35 would be necessary for self-ignition, but this is well beyond current capabilities. When compared with other substitute fuels such as methane, methanol, and ethanol, the principal drawback of using ammonia in diesel engines is the emission of unburned NH_3 and its objectionable odor. As a gas turbine fuel, ammonia has demonstrated approximately a 10% improvement in power output and efficiency compared to hydrocarbon fuels, but a specific fuel consumption reduced by a factor of 2.5 as a proportional result of its lower heating value. The theoretically high specific impulse of ammonia when reacted with liquid oxygen or liquid fluorine gives it great potential as a liquid rocket fuel. Performance of ammonia is only slightly less than that of hydrazine with the same oxidizers, and its cost and availability are significant advantages. As a source of hydrogen or hydrazine, ammonia may also be used in future fuel cell developments. Ammonia-oxygen and ammonia-air cells were demonstrated in the late 1960's. However, present development of fuel cell technology is directed toward the use of fossil fuels, and ammonia may not be reconsidered unless these fuels become scarce or too expensive.

Ammonia has application potential as an energy fuel blending or storage material. Acetylene could be used by itself as an automotive fuel if it were not so difficult to store. When liquefied, it can decompose and explode violently. However, when dissolved in a suitable liquid agent such as acetone, methanol, or ammonia, acetylene becomes much safer to handle. A recent experimental study by General Motors Research Laboratories has shown that a mixture of ammonia and acetylene may be a suitable automotive fuel. The use of ammonia as a vehicle to store hydrogen in liquid form is perhaps the most interesting fuel-use application of ammonia. The storage of hydrogen in liquid ammonia is more compact than any other form of hydrogen storage. Both hydrogen and ammonia vapors escaping from stored fuels are hazardous; however, the control of ammonia vapor emissions which are toxic appear easier to effect than the control of hydrogen emissions which are flammable when mixed with air. Ammonia is hard to ignite, and almost impossible to detonate. Ammonia may, therefore, have its most significant fuel use potential as a hydrogen storage medium in the framework of future "hydrogen economy" concepts that have been proposed.

Most ammonia manufacture is derived from natural gas feedstocks. The current worldwide oversupply of ammonia which is not expected to disappear until the mid-1980's has depressed the cost. Under current economic conditions, the energy cost of an ammonia fuel on a Btu/$ basis is less than 60% of the cost of gasoline. Low cost ammonia fuel may be synthesized in the future using waste heat from nuclear reactors, various biochemical processes, or catalytic processes in sunlight. Yields from these processes are low at present, but there are prospects that they can be increased. This, in turn, suggests ammonia could be produced from inexhaustible resources.

Report Y - Hydrogen Safety and Environmental Control Assessment

A final report has been published that describes the 2-1/2 year assessment program conducted by the Los Alamos Scientific Laboratory (LASL) on concerns in hydrogen safety and environmental control. Report Y is the executive summary of this report.[a] This assessment program considered the pipeline transmission of gaseous hydrogen, liquid hydrogen transportation, metal embrittlement, safety regulations, and environmental aspects of hydrogen production and use. The assessment concludes that, even if hydrogen does not become a major energy material, hydrogen use will increase in close proximity to the general public.

A continuing assessment program in hydrogen safety and environmental control is recommended, including further work in the areas of hydrogen production, storage, and transportation. A program is outlined for assessing the safety and environmental compatibility of hydrogen end uses including hydrogen used as a fuel in transportation systems, in the home and in industry. The final and major recommendation is for research that addresses the dispersion and ignition of combustible hydrogen mixtures resulting from large-scale spills of liquid or gaseous hydrogen.

I.3 STATUS REPORT PURPOSE AND ORGANIZATION

The purpose of this report is to provide a detailed status review of current research addressing issues and needs identified in the DOE's integrated Safety and Environmental Control Research Assessment Program on Liquefied Gaseous Fuels. The coordinated efforts of many individuals, institutions and agencies address a large spectrum of program activities and requirements. Information developed in this program should assist decisions regarding future facilities, the upgrading of existing facilities and new hazard control techniques.

(a) Edeskuty, F. J. et al, Hydrogen Safety and Environmental Control Assessment, Los Alamos Scientific Laboratory, LA-8225-PR, March 1980.

The balance of this report consists of annotated bibliographies in Volume 1 and a compilation of contractor reports in Volumes 2 and 3. Bibliographies on LNG and on LPG Fire Safety and Hazards were prepared by PNL and the ATC, respectively. Contractor reports on LNG (Reports A through S) are compiled in Volume 2. Volume 3 contains reports on the other liquefied gaseous fuels (Reports T through Y) under study in the LGF Assessment Program. To remain topical and preserve the insight of individual authors, these reports are presented without appreciable editing or format standardization. Collectively, they report the substance and current status of the principal activities in this DOE program.

SECTION II

LNG ANNOTATED BIBLIOGRAPHY

Prepared for the
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SUMMARY

This bibliography provides brief summaries of literature related to LNG safety and environmental control, organized alphabetically by author.

Alger, A. S., Corlett, R. C., Gordon, A. S. and Williams, F. A., Some Aspects of Structures of Turbulent Pool Fires. WSS/C1 76-46, October 1976.

Results are reported on the burning of JP-5 and methanol pools 305 cm in dia. Measurements made include radiant energy fluxes outside and within the fire, temperatures and chemical compositions within the fire and rates of weight loss of the pool. Results emphasize structural differences between JP-5 and methanol fires and importance of radiant feedback of energy to the pool surface in controlling rates of burning.

Allan, D., Atallah, S., Drake, E., Hinckley, R. and Mathias, S., Technology and Current Practices for Processing, Transferring and Storing Liquefied Natural Gas. Department of Transportation/OST, Office of Pipeline Safety, Washington, DC, (prepared by Arthur D. Little, Inc., Report No. C-76971) December 1974.

Current state-of-the-art safety information related to the design, location, construction, operation and maintenance of facilities required for liquefaction, transfer, storage, and revaporization of natural gas is assembled and summarized. A detailed review of codes, standards and practices pertaining to LNG installations is presented along with an evaluation of present trends in LNG safety requirements. LNG safety research programs completed or in progress are described and key research results summarized. Finally a methodology for quantitative assessment of risks associated with LNG facilities is outlined.

Almgren, D. W. and Smith, J. L., Jr., "The Inception of Nucleate Boiling With Liquid Nitrogen." Journal of Engineering for Industry. pp. 1211-1216, November 1969.

The phenomena of patchwise boiling are discussed, and the significant parameters restricting the growth of a boiling patch are analytically determined to be: a high nucleate boiling heat-transfer coefficient; a low total heat flux; the absence of cavities with a trapped liquid vapor interface outside the boiling patch; an appropriate value of wall thermal conductivity; a high vapor enthalpy per bubble.

American Gas Association, LNG Fact Book. Planning and Analysis Group, AGA Arlington, VA 22209, 1977.

This report summarizes the American Gas Association view of LNG importation and its advantages. Issues and project status at the time of publication are also reviewed.

An Economic Analysis of Imported LNG in Selected End Use Markets. Prepared for the American Gas Association by Booz Allen and Hamilton, Inc., May 1978.

Economics of LNG usage in space heating, with and without advanced equipment, and in industrial applications is reviewed.

An Experimental Study of the Mitigation of Flammable Vapor Dispersion and Fire Hazards Immediately Following LNG Spills on Land. A report by University Engineers, Inc., to the American Gas Association, February 1974.

A series of fire control, fire extinguishment and vapor dispersion tests were conducted under the high boil-off rates which occur immediately following an LNG spill on land. Correlations of the results provide fire control and extinguishment times with dry chemical agents and high expansion foams. The magnitude of the reduction in downwind concentrations of methane vapors by the application of high expansion foam on the spill was also determined.

Analysis of Risk in the Water Transportation of Hazardous Materials. U.S. Coast Guard Report, CG-D-39-76. NTIS No. AD/A025298, January 1976.

This report assesses the utility and feasibility of using risk analysis to assist in management decisions regarding the regulation of water transportation of bulk hazardous materials. A number of risk analysis studies were surveyed. Barge transportation on inland waterways was chosen for special study, and a probabilistic model of risk was selected. It was concluded that the greatest utility of the methodology lies in answering specific questions with output of a specific predetermined nature.

Andersen, W. H., Garfinkle, D. R., Carpenter, G. E. and Brown, R. E., "Energy Absorption Near and Below the Burning Surface of Hydrocarbon Pools." Paper presented at the 1969 Meeting, Central States Section, The Combustion Institute, March 18-19, 1969.

The burning behavior of a liquid fuel pool is discussed in terms of the heat feedback from the flame that is transported into and through the fuel via conduction and radiation. It is shown that the radiant flux contribution to the total heat flux input is greatest for benzene, and decreases consecutively for gasoline, kerosene, and alcohol.

Anderson, P. J., "Recent Developments in Regulations for LNG Storage in the United States." CONF-790985-1, 1979.

The paper reports on the ongoing debate for a new version of the principal standard for LNG facilities: NFPA-59A. A target date for final approval was set for November 1979.

Anderson, R. P. and Armstrong, D. R., "Experimental Studies of Vapor Explosions." 3rd International Conference on Liquefied Natural Gas, paper 3 of Session VI, Chicago, 1972.

Small scale experiments with molten salts and molten metals, injected into water, are described. In some cases ensuing reactions can turn into vapor explosions.

Anderson, R. P. and Armstrong, D. R., "Experimental Study of Vapor Explosions." Paper presented at the Third International Conference and Exhibition on Liquefied Natural Gas, September 24-28, 1972, Washington, DC.

Present knowledge about various aspects of vapor explosions is summarized. Particular emphasis is placed on methods of evaluating the destructive kinetic energy release from a specified accident. A theoretical method of calculating the maximum destructive energy is outlined.

Andrews, G. E. and Bradley, D., "The Burning Velocity of Methane-Air Mixtures." Combustion and Flame. 19:275-288, 1972.

Results are presented for the variation of burning velocity with equivalence ratio for methane-air mixtures at one atmosphere pressure. Values were determined by the bomb-hot wire and corrected density ratio techniques, for combustion during the pre-pressure period. The former of these methods gives a maximum burning velocity of 45 ± 2 cm/sec, at an equivalence ratio of 1.07.

Anspach, G., Baseler, R. and Glasfeld, R., "A Floating LNG Receiving Terminal." Chem. Eng. Progr. 75(10):86-91, 1979.

The paper presents the floating LNG terminal as a practical alternative to land-based storage and regasification facilities. Lower cost and independence of seismic restraints are its prime advantages. However, so far no such terminal has been designed or ordered.

Anthony, E. J., "Some Aspects of Unconfined Gas and Vapor Cloud Explosions," Journal of Hazardous Materials. 1:284-301, 1975-77.

A critical review is presented of experimental and theoretical work on unconfined vapor explosions with emphasis on modeling studies.

Arnoni, Y. G., "The Marriage of LNG and Offshore Facilities." Chem. Eng. Progr. 75(10):60-65, 1979.

The article deals with the advantages and problems of an LNG offshore facility on technical, economic and sociological grounds. Even though no such facilities have been built, several are in the planning and engineering phase.

Arthur D. Little, Inc., A Report on LNG Safety Research, Vol. I. to A.G.A., A.G.A. Project I U-2-1, A.G.A. Catalog No. M19711, January 31, 1971.

It is concluded that smaller releases are rather rare and usually not damaging; probability is low that a large spill will occur from currently constructed facilities; spills from containers may have acceptable probability but some additional protection should be provided; risk of transfer line failure requires higher level of protection; further consideration should be given to hazards involved with LNG transport.

Atallah, S. and Allen, D. S., "Safe Separation Distances From Liquid Fuel Spill Fires." Paper presented at Central States Section, Combustion Institute Meeting on Disaster Hazards, Houston, TX, April 1970.

This paper critically reviews the methods generally used to calculate safe separation distances from liquid fuel spill fires. Correlations for predicting flame height and other radiative properties are reviewed. Distances at which the thermal radiation flux falls below the minimum level needed to ignite cellulosic materials are calculated and the results are presented in convenient graphical form.

Atallah, S. and Raj, P., "Thermal Radiation From LNG Spill Fires." Paper P-3 presented at the Cryogenic Engineering Conference, Atlanta, GA, August 10, 1973.

This paper reviews the present state of knowledge relating to thermal radiation from LNG fires. Utilizing data from recent AGA-sponsored LNG fires in seven 6-ft, six 20-ft, and one 80-ft diameter pools, equations were derived for predicting LNG flame height and the angle of tilt of LNG flames in the presence of wind. A model for predicting the thermal radiative flux at various locations away from an LNG fire is presented.

Bailey, F. B., "Status of United States Codes and Regulations Affecting Land Based LNG Facilities." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

This report summarizes current safety and non-safety regulations, and activities concerning regulations. NEPA59A versions and applications are listed.

Baitis, A. E., Bales, S. L. and Meyers, W. G., Prediction of Lifetime Extreme Accelerations for Design of LNG Cargo Tanks. U.S. Coast Guard Report CG-D-89-74. NTIS No. AD/779635, March 1974.

A procedure is developed to predict the extreme accelerations needed for design of the cargo tanks in LNG vessels. The validity of the prediction tool is discussed. Comparisons are made with accelerations measured in model and full scale experiments.

The results of a pilot study on a single, large typical LNG ship are presented. Acceleration response variations due to changes in ship load conditions and changes due to longitudinal, lateral and vertical locations are examined.

Becker, H. and Liang, D., "Viable Length of Vertical Tree Turbulent Diffusion Flames." Combustion and Flame. 32:11-137, 1978.

The authors of this paper propose and review correlations for the visible length of turbulent diffusion flames. This paper may be useful for determining the magnitude of thermal radiation from LNG pool fires.

Beer, J. M., "Methods for Calculating Radiative Heat Transfer from Flames in Combustors and Furnaces." Heat Transfer in Flames. Chapter 2, John Wiley and Sons, 1974.

Recent advances in methods for predicting radiative heat flux distribution in furnaces and combustors are reviewed with special reference to the zone method of analysis and the flux methods. Recent experimental studies specially designed to test these prediction procedures under sufficiently severe conditions are discussed.

Bellus, F., Cochard, H., Vincent, R. and Mauger, J., Controlling the Hazards from LNG Spills on the Ground LNG Firefighting Methods and Their Effects Application to Gaz de France Terminals. Gaz de France, DOE-Tr-18.

Three basic areas are examined in this paper. A mathematical model to calculate vapor dispersion from accidental LNG spills on land is described. This model is used to investigate various types of impounding areas and their minimization of methane cloud travel. A method to calculate water spray rates for the protection of LNG tank walls from the energy radiated by an adjacent fire is described and a numerical example is given. The authors describe the details of design and construction of the new 80,000 m^3 LNG tank at the Fos Terminal.

Bellus, F., Vincent, R., Cochard, H. and Mauger, J., "Controlling the Hazards from LNG Spills on Land." Fifth International Conference on LNG, Session III, paper 5, Institute of Gas Technology (in French), 1977.

A new mathematical model is described which allows the calculation of vapor dispersion from accidental spills of LNG on land.

Benedick, W. B., "High-Exposure Initiation of Methane-Air Detonations." Combustion and Flame." 35:89-93, 1979.

The detonation limits of a stoichimetric methane-air mixture have been determined under "free-field" and "confined" conditions. Such a mixture is generally more difficult to detonate than an LNG vapor cloud.

Bennett, C. P., "Marine Transportation of LNG at Intermediate Temperature." Chartered Mechanical Engineer. 26(3):63-66, 1979.

The paper details advantages of transporting LNG at intermediate temperatures in pressure vessels.

Bensesh, M. E., "The Use of Gas Hydrates in Improving the Load Factor of Gas Supply Systems." U.S. Patent 2,090,163 (to Chicago By-Products Corp), 1942.

This method recommended using excess natural gas, during low demand periods, for hydrate formation and storage. The natural gas would be regenerated for peak demand.

Berger, E., "LNG Plants on Floating Structures - Intermediate Reports on an Extensive Test Program." Chemical Economy and Engineering Review. 10(10):22-29, 1978.

The paper reports on progress in designing floating LNG liquefaction plants which could be used for marginal offshore gas fields where sub-surface pipelines are not economical.

Bernert, R. E., "Technical Aspects of Ambient Vaporizers and Superheaters." Applications of Cryogenic Technology. Vol. 6. Proc. Cryo 173 Conf. 6th Los Angeles, CA, October 2-4, 1973, pp. 85-93, 1974.

This paper discusses aspects governing the performance of ambient water and air cryogenic vaporizers and superheaters. This paper also includes some design limits due to ice and frost formation.

Beychok, M. R., "How Accurate are Dispersion Predictions?" Hydrocarbon Processing. pp. 113-116, October, 1979.

This paper cautions the reader against assuming that generalized dispersion models have a fixed accuracy in all applications. Examples of the variability are shown.

Bijl, P., Vet, P. N., "Novel Approach Required for LNG Peakshaving Plant in the Netherlands." Oil and Gas Journal. pp. 81-85, November 28, 1977.

This article describes a unique peakshaving facility which produces both LNG and liquid nitrogen, LN_2. Because of the high N_2 content of the gas in the Netherlands, a slightly modified expander liquefaction cycle was designed which allowed separation of LN_2 form the LNG.

Bingham, G. E., Gillespie, J. H. and McQuaid, J. H., Small Battery-Powered Infrared Absorption Sensor for Methane, Ethane, and Other Hydrocarbons. UCID-17968-79-1, pp. 23-42 Lawrence Livermore Laboratory 1979.

The concept for a portable gas sensor capable of measuring LNG vapor concentrations is described. It is based on infrared absorption by hydrocarbons between 3 and 4 pm.

Biro, P., "Fire Protection for LNG Storage, Transportaion and Distribution Facilities." gwf-gas/erdgas. 118(8):344-346, 1977 (in German).

The requirements for fire protection of LNG facilities are described. Specifically, liquefaction plants, storage facilities, LNG terminals and LNG tankers are addressed.

Blackshear, P. L., ed., Heat Transfer in Fire: Thermophsics, Social Aspects, Economic Impact. John Wiley & Sons, 1974.

The book, in five parts, considers social and economic aspects of fires; geometric parameters for classifying full-scale fires; heat and mass transfer in gaseous and condensed phases; radiative heat transfer associated with fire problems, and radiative transfer parameters.

Blinov, V. I. and Khudyakov, G. N., "Certain Laws Governing Diffusion Burning of Liquids." Doklady Akademii Nauk U.S.S.R. 113:1094-1098, 1957.

An investigation of the burning of gasoline, diesel oil, solar oil and a number of other petroleum products in containers having different diameters enabled the authors to determine some important relationships for diffusion of burning liquids.

Board, S. J., Farmer, C. L. and Poole, D. H., "Fragmentation in Thermal Explosions." International Journal of Heat and Mass Transfer. 17:331-339, 1974.

Experiments involving explosions between molten tin and water are described. Results indicate that thermal explosions usually involve several distinct interactions; a small disturbance can escalate by successive growth and collapse cycles; vapor collapse is the main cause of dispersion in many thermal explosions, and the jet penetration hypothesis can account for both the time scales and energy transfer rates.

Boni, A. A., Wilson, C. W., Chapman, M. and Cook, J. L., "A Study of Detonation in Methane/Air Clouds." Acta Astron. 5:1153-1169, 1978.

A numerical simulation of the detonation in unconfined, gaseous mixtures of methane/oxygen/nitrogen is attempted. Results show that initiation of such detonations requires very large trigger charges (10 to 1000 t of tetryl).

Booth, S. H. and Vance, R. W. (ed.), Applications of Cryogenic Technology, Vol. 8. Scholium International, Inc., New York, 1976.

This text presents papers comparing Cryogenic Applications Symposia on Liquefied National Gas (LNG) presented at CRYO '75 and CRYO '76, conferences of the Cryogenic Society of America.

Bowman, B. R., "Dispersion Model Comparisons." Report B, Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: A Status Report. DOE/EV-0036, Department of Energy, Washington DC, 1979.

Various mathematical models for the dispersion process following an LNG spill are evaluated. Deficiencies are pointed out and needs for further work are outlined.

Bowman, B. R., Sutton, S. B. and Comfort, W. J., "The Impact of LNG Spills on the Environment: A Comparison of Dispersion Models and Experimental Models." Proceedings of the 25th annual technical meeting of the Institute of Environmental Sciences, Seattle, WA, April 1979.

A Gaussian and Three-Dimensional Navier-Stokes model for LNG spills and subsequent dispersion are compared. Data including hydrocarbon concentrations from three 5-m LNG spill tests are used to evaluate the models.

Boyle, G. J., "Vapor Production From LNG Spills on Water." American Gas Association Distribution Conference, May 1973.

The results indicate that LNG spilled onto water will spread outward with a rate that decreases with time; vapor production will equal the discharge rate as long as the discharge is occurring; with a batch spill it is necessary to take into account the LNG which evaporates to calculate the maximum pool and the peak vapor production rate; the dispersion plume from a large LNG spill on water will be wide and shallow.

Boyle, G. J. and Kneebone, A., Laboratory Investigation into the Characteristics of LNG Spills on Water, Evaporation, Spreading and Vapor Dispersion. Re 6Z32, Shell Research Limited, Released by the American Petroleum Institute, March 1973.

This is a laboratory and small-scale wind tunnel investigation of the characteristics of LNG spills on water. One characteristic investigated, that has not been studied by others, is the appreciable incorporation of water in the vapor cloud.

Bradley, D. and Mitcheson, A., "The Venting of Gaseous Explosions in Spherical Vessels I, II." Combustion and Flame. 32:221-237, 1978.

The authors present various theoretical analyses of the pressure rise in partially confined reactive systems. The results of these investigations are then compared with experimental data and recommendations are made for proper venting procedures.

Briscoe, F. and Vaughn, G. J., "LNG/Water Vapor Explosions--Estimates of Pressures and Yields." Paper presented at the Gastech 78 LNG/LPG Conference, Monte Carlo, November 1978.

The essentials for the occurrence of LNG vapor explosions are discussed. The maximum possible yields and pressures in such explosions are determined by various theoretical approaches.

Briscoe, F. and Fog, G. F., A Guide to the Use of BKWAVE - A Computer Program for the Calculation of One-Dimensional Shock Wave Propagation from Explosions. United Kingdom Energy Authority, SRO-R-104, Calceth Warrington, U.K., May 1978.

This report is a description of a computer code, BKWAVE, which can calculate the shock wave resulting from an explosion of known strength. The reaction is assumed to be over instantaneously.

Britter, R. E., "The Spread of a Negatively Buoyant Plume in a Calm Environment." Atm. Envir. 13:1241-1247, 1979.

The paper presents the results of a laboratory experiment to study the spread of a negatively buoyant plume in a calm environment including semi-empirical relation for the cloud leading edge. Under conditions where the effects of wall frictions and ambient wind can be neglected, most or all mixing occurs at the cloud leading edge.

Brown, L. E. and Romine, L. M., "Liquefied Gas Fires: Which Foam?" Hydrocarbon Proc. 58(9):321-332, 1979.

Six different types of foam were evaluated for their effectiveness in controlling liquefied gas fires. Medium and high expansion foams proved to be most efficient.

Brown, L. E., Martinsen, W. E., Muhlenkamp, S. P. and Puckett, G. L., Small Scale Tests on Control Methods for Some Liquefied Natural Gas Hazards. Final Report, prepared by University Engineers, Inc., Norman, Oklahoma, for the U.S. Coast Guard, Report No. CG-D-95-86. NTIS No. AD/A033522, May 1976.

A report of results of small scale (100 ft^2) tests of some liquefied natural gas (LNG) hazard control methods and concepts. Tests of water spray screens showed that the concept is practical and effective for small LNG spills. Tests of water spray screens to reduce radiant heating of exposures demonstrated no practical value.

Brown, T. T. and Hubbard, J. K., Application of Gas Turbine/Compressors in LNG Plants. 1979.

This paper discusses key considerations associated with selection of Gas Turbine Driven LNG Turbo Compressors. Use of gas driven versus steam driven compressors is compared.

Browning, R. L., "Estimating Loss Probabilities." Chemical Engineering. pp. 135-140. December 15, 1969.

This article presents a technique for analyzing industrial risks. Methods for obtaining the loss incident frequencies are described and the relative probabilities of loss incidents are included.

Brzustowski, T. A., "A New Criterion for the Length of a Gaseous Turbulent Diffusion Flame." Combustion Science and Technology. 6:313-319, 1973.

The flame tip is identified with the point on the axis of maximum fuel concentrations where the fuel has been diluted to the lean flammability limit. Flame-length equations are derived using the new criterion, together with data from the literature on entrainment of air into flames, transverse concentration profiles in turbulent jets, and flammability limits.

Brzustowski, T. A., "The Hydrocarbon Turbulent Diffusion Flame in Subsonic Cross-Flow." AIAA Paper 77-222, January 1977.

The flame is modeled as a bent-over initially vertical circular jet with top-hat profiles of composition, temperature, and velocity. The hydrocarbon pyrolyzes in a zero-order reaction and the pyrolysis products are oxidized at a rate proportional to the rate of entrainment of air into the flame.

Buch, E., "Utilizing the Cold of LNG for Power Generation." Energie. 29:182-183, 1977 (in German).

When vaporizing LNG, it would be economical to take advantage of the low temperature of the LNG as a heat sink in a closed gas turbine cycle. Such a scheme could recover 14% of the total LNG energy, which otherwise could be lost in the vaporization process.

Buchholz, C. D. and Senkowski, E., "Unique Design and Operating Features of Philadelphia Electric Company's LNG Plant." Paper presented to Seminar and Study Tour on LNG Peakshaving, Washington DC, March 5-9, 1979.

The design and operating experience of the West Conshohocken LNG Plant is reviewed. The plant utilized a nitrogen expansion cycle for liquefaction, a double-walled, double-roofed above ground storage tank, and submerged combustion vaporizers.

Bull, D. C., Ellsworth, J. E., Hooper, G. and Quinn, C. P., "A Study of Spherical Detonation in Mixtures of Methane and Oxygen Diluted by Nitrogen." J. Phys. D: Apply. Phys. 9:1991-2000, 1976.

Experiments are described which examine the behavior of spherically propagating detonation waves in methane/oxygen/nitrogen mixtures. Such tests have a bearing on the safety question of LNG.

Bull, D. C., Ellsworth, J. E. and Hooper, G., "Susceptibility of Methane-Ethane Mixtures to Gaseous Detonation in Air." Combustion and Flame. 34:327-330, 1979.

Experiments are described which determine the detonation limits of methane-ethane-air mixtures. The presence of even small amounts of the heavier hydrocarbons has a significant effect on these limits.

Burgess, D., Biordi, J. and Murphy, J., Hazards of Spillage of LNG into Water. PMSRC Report No. 4177, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, 1972.

These are reports of experimental investigations of LNG spills on water. The pool spread, evaporation rate, vapor gravity spread, downwind drift and dispersion were studied in spill sizes up to 0.5 m^3. In unconfined spills coherent ice flow formation was not observed. In several cases small scale physical explosions were observed but no attempt was made to study the initiation or burning of the cloud.

Burgess, D. S. and Hertzberg, M., "Radiation From Pool Flames." Heat Transfer in Flames. Chapter 27, John Wiley & Sons, 1974.

Some radiation data from pool flames is summarized and our understanding of the problem is reviewed. Spectral data yield a 1500¼ K temperature for hydrocarbon pool fires, which is consistent with the 40 percent maximum in the fraction of combustion energy radiated, and with limited flame temperatures for the mixing limited systems. A revised correlation of mass burning rate with $\Delta H_c/\Delta H_v$ is presented, and derived fundamentally.

Burgess, D. S., Murphy, J. N. and Zabetakis, M. G., Hazards Associated with the Spillage of Liquefied Natural Gas on Water. Report RI 7448, U.S. Department of the Interior, Bureau of Mines, November 1970.

The hazard of spilling LNG onto water is discussed. After spillage, the initial vaporization rate of LNG was determined to be 0.037 lb/ft^2 sec. If the LNG was confined, this rate was modified by the formation of ice on the water surface. Using a 2000-gallon LNG sample, the maximum diameter (in feet) of the spreading pool was calculated at 6.3 $w_o^{1/3}$ where w_o is the weight of LNG in pounds.

Burgess, D. S., Murphy, J. N. and Zabetakis, M. G., Hazards of LNG Spillage in Marine Transportation Final Report. NTIS No. A0/70578, for USCG, Office of Research Development, February 1970.

The hazard of spilling LNG onto water is discussed. After spillage onto water, the initial vaporization rate of LNG was determined to be 0.037 lb/ft^2 sec. If the LNG was confined, this rate was modified by the formation of ice on the water surface. Using a 2000-gal LNG sample, the maximum diameter (in feet) of the spreading pool was calculated at 6.3 $W_o^{1/3}$ where W_o is the weight of LNG in pounds.

Burgess, D. S., Murphy, J. N., Zabetakis, M. G. and Perlee, H. E., "Volume of Flammable Mixture Resulting from the Atmospheric Dispersion of a Leak or Spill." Application of Cryogenic Technology, Vol. 8. Combustion Institute 15th Symposium on Combustion, 1976.

The paper discusses atmospheric dispersion of flammable vapors, the struture of gas clouds and the explosion potential of flammable mixtures.

Burgess, D. S., Strasser, A. and Gumer, J., "Diffusive Burning of Liquid Fuels in Open Trays." Fire Research Abstracts and Reviews. 3(3):177-192, 1961.

The paper describes the effects of fuel temperature and wind on burning rate, discusses the problem of cryogenic fuels, and suggests that burning rate may be predicted from heats of vaporization and combustion of the fuel. Data on methanol, LNG, liquid hydrogen, amine fuels, and typical hydrocarbons are included.

Burgess, D. S. and Zabetakis, M. G., Detonation of a Flammable Cloud Following Propane Pipeline Break: The December 9, 1970 Explosion in Port Hudson, Missouri. Report RI 7752, U.S. Department of the Interior, Bureau of Mines, 1973.

This report summarizes the incidents that preceded the December 9, 1970, propane-air explosion in Port Hudson, MO. Both near- and far-field damage indicated that this explosion may be attributed to the detonation of propane in air with an energy release equivalent to that from about 50 tons of detonating TNT.

Burgess, D. and Zabetakis, M. G., Fire and Explosion Hazards Associated With Liquefied Natural Gas. Report RI 6099, U.S. Department of the Interior, Bureau of Mines, 1962.

Factors that should be considered in evaluating the fire and explosion hazards relating to any fuel are discussed. These factors are utilized in the design of experiments to evaluate the hazards associated with LNG as compared to those hazards associated with other fuels.

Buschmann, C. H., "Experiments on the Dispersion of Heavy Gases and Abatement of Chlorine Clouds." Proceedings of the Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterway, Jacksonville, FL, October 26-30, 1975, Report No. AD/A023505, pp. 475-488, October 1975.

The experiments comprised four different parts: dispersion of heavy gases offer an instantaneous release; penetration of heavy gases in buildings during the passage of a gas-cloud; influence of a chlorine-cloud on motorized traffic, and suppression and abatement of chlorine-clouds.

Bush, S. H., "Pressure Vessel Reliability." Journal of Pressure Vessel Technology. 97(J):54-70, February 1975.

An informative review pertaining to United States pressure vessels is made and compared to data available from Germany. An attempt to understand the apparent differences in reliability of these two countries on the bases of the ASME codes covering materials, design, and construction, on operating procedures, and on differences in reporting techniques. Some attention is given to failure modes to possibly understand the low incidence of operational failures in the United States.

Byram, G. M., "Scaling Laws for Modeling Mass Fires." Pyrodynamics. 4:271-284, 1966.

The paper is concerned with the development of scaling laws necessary for modeling and is restricted to the stationary mass fire.

Byram, G. M. and Nelson, R. M., Jr., "Buoyancy Characteristics of a Fire Heat Source." Fire Technology. 10(1):68-79, 1974.

Buoyancy production rates for a pure heat source and for a fire heat source of burning woody fuels show that fire may be regarded as a pure source yielding heated air rather than heated combustion products.

Byram, G. M. and Nelson, R.M., Jr., "The Modeling of Pulsating Fires." Fire Technology. 6(2):102-110, 1970.

The authors present scaling relationships for modeling pulsating fires. Data gathered from various sizes of pulsating fires compared favorably with the predicted relationships between fire diameter and pulsation frequency.

Cahn, R. P., Johnston, P. H. and Plumstead, J. A., "Transportation of Natural Gas Hydrate." U.S. Patent 3,514,274 (to Esso Research and Engineering Co.), 1970.

Natural gas was combined at 25 to 40°F and >80 psia with a slurry of propane hydrate in propane. This mixture was cooled to -40°F to give methane hydrate slurry in propane. Treating this product with propane gas at 25-40°F and <80 psia regenerated methane and propane hydrate.

Carne, M., Thomas, J. R. and Hutchinson, E. A., Buxton Bund-Fire Tests. The Gas Council, December, 1971.

Ignition and burnout tests were conducted on LNG contained within walls of clay or pulverized fuel ash. The test objective was to establish whether walls of this construction would be damaged by a combination of cold LNG and flame radiation. Results showed no damage to the walls apart from a superficial calcining of the turf and slight spalling of the concrete covering. Flame radiation agreed reasonably well with predicted values.

Cermak, J. E., "Applications of Fluid Mechanics to Wind Engineering - A Freeman Scholar Lecture." Journal of Fluids Engineering. 97:9-38, March 1975.

The objectives of this review are to establish an initial subject-matter base for wind engineering, to demonstrate current capabilities and deficiencies of this base for an engineering treatment of wind-effect problems, and to indicate areas of research needed to broaden and strengthen the subject-matter base.

Chan, S. T. and Gresho, P. M., A Comparison of Hydrostatic and Nonhydrostatic Models as Applied to the Prediction of LNG Vapor Spread and Dispersion. UCID-18097, Lawrence Livermore Laboratory, March 1979.

Two mathematical models are described and after numerical implementation, results of a series of computations for LNG vapor dispersion are compared. Conclusions are drawn on how to further develop the less elaborate model into a more cost-effective code.

Chan, S. T., Gresho, P. M. and Lee, R. L., Simulation of LNG Vapor Spread and Dispersion by Finite Element Methods. UCRL-82441, Lawrence Livermore Laboratory, July 1979.

Two finite element models are described: one based on solving the time-dependent, two-dimensional conservation equations of mass, momentum, and energy, with buoyancy effects included via the Boussinesq approximation; the other based on solving the otherwise identical set of equations except using the hydrostatic assumption, and applied these models to predict some aspects of the vapor dispersion phenomena associated with LNG spills.

Chatterjee, N., Gaumer, L. S. and Geist, J. M., "Operational Flexibility of LNG Plants Using the Propane Precooled Multicomponent Refrigerant MCR Process." LNGS - International Conference on LNG, Duesseldorf, Germany, August 29-September 1, 1977.

This paper discusses the operation of the MCR liquefaction process over a wide range of conditions. A computer program which models the porcess is described.

Chatterjee, N. and Geist, J. M., Spontaneous Stratification in LNG Tanks Containing Nitrogen. ASME Publication 76-WA/PID-6, December 5, 1976.

LNG containing significant concentrations of nitrogen can stratify spontaneously during weathering in storage tanks. Mixing of stratified layers leads to an increase in boil-off rates, commonly referred to as "rollover". LNG storage tanks can be designed and operated safely if stratification and associated problems are taken into account.

Chatterjee, N. and Geist, J. M., "The Effects of Stratification on Boil-off Rates in LNG Tanks." Paper presented at the A.G.A. Distribution Conference, Atlanta, GA, May 8-10, 1972.

The addition of LNG to a partially filled tank containing liquid of a different density may lead to the temporary formation of stratified layers. The physical phenomena associated with the mixing of stratified layers of LNG have been simulated on the computer. One method for mitigating potential hazards associated with stratification is by limiting the density and the temperature difference between fresh liquid and LNG in the tanks.

Chippet, S. and Gray, W. A., "The Size and Optical Property of Soot Particles." Combustion and Flame. 31:149-159, 1978.

This paper presents the results of an experimental inventigation to determine the spectral transmissivity and size distribution of soot aggregates. Measured attenuation and light scattering were found to be in best agreement with theoretical results when the complex refractive index, $\bar{u}$, was taken to be 1.9-0.35i.

Chiu, Chen-Hwa, "Evaluate Separation for LNG Plants." Hydrocarbon Processing. pp. 266-272, September 1978.

Energy losses from various processes involved in separation of LNG components during liquefaction are discussed. Losses due to compression and liquefication were cited to show areas for improvement in energy use.

Clapp, M. B. and Litziner, L. F., "Marine Terminals for LNG, Ethylene, and LPG." A paper presented at the 68th National AICHE Meeting, Houston, Texas, February 28 - March 4, 1971.

The design and economics of marine terminals for LNG, Ethylene, and LPG are discussed. Some discussion of safety features is included.

Closner, J. J. and Parker, R.O., "A Careful Accident Assessment Key to LNG Storage Safety." Oil and Gas Journal. pp. 47-51, February 6, 1978.

This article discusses potential accidents and related hazards associated with LNG storage facilities. A list of mitigating measures which would prevent an accident or reduce its consequences is included.

Closner, J. J. and Parker, R. O., "Safety of Storage Designs Compared." Oil and Gas Journal. pp. 121-125, February 13, 1978.

Eight different types of LNG storage designs are compared with respect to the likelihood and potential consequences of a spill or accident.

Cole, R. S. and Moulsley, T. J., "The Use of the Atmospheric Acoustic Sounder to Track Methane Gas Plumes." Atm. Envir. 13:1437-1441, 1979.

The usefulness of the acoustic sounder as a method of tracking elevated methane plumes is explored.

Colgate, S. A. and Sigurgeirsson, T., "Dynamic Mixing of Water and Lava." Nature. 244:552-555, August 31, 1973.

It is suggested that lava eruptions under the ocean might result in vapor explosions, similar to those which have been observed when liquid metals or LNG come into contact with water. Violent mixing of water and lava are believed to be the cause of such explosions.

Colton, J. W., Pretreatment of Raw Natural Gas Prior to Liquefaction. U.S. Patent 4,150,962, 1979.

A process for pre-treating raw wellhead gas is described that reduces the liquefaction refrigeration power requirements by expanding the gas through an expansion turbine, which in turn drives the liquefaction compressor.

Conners, T. G., "LNG Primer." Hazardous Chemicals--Spills and Waterborne Transportation. AICHE Symp. Ser. 194, 76, pp. 62-69 1980.

The paper gives a brief description of the cargo operations of an LNG tanker and outlines the basic types of LNG containment and insulation systems.

Corlett, R. C., "Gas Fires With Pool-Like Boundary Conditions: Further Results of Interpretation." Combustion and Flame. 14:351-360, 1970.

A circular, upward-facing burner, supplying uniform flux of fuel gas from a water-cooled surface, preserves the essential features of a pool fire. Addition of up to 2% methyl bromide to several fuels had no effect on heat transfer. At high fuel supply rates, the data tend to correlate independently of the air requirement of the fuel; at low supply rates, the data tend to correlate independently of volumetric supply rate.

Corlett, R. C. and Fu, T. M., "Some Recent Experiments With Pool Fires." Pyrodynamics. 4:253-269, 1966.

Steady burning rates of methanol, ethanol and acetone in thin-walled stainless steel burners of 0.6 to 30 cm diameter have been studied. Radiation levels were estimated and are found consistent with results of earlier experiments with water-cooled gas burners. Measured water absorption rates are in reasonable agreement with those inferred from burning rate data on the basis of heat and mass transfer similarity.

Crawford, D. B. and Eschenbrenner, G. P., "Heat Transfer Equipment for LNG." Chemical Engineering Progress. September 1972.

This article describes liquefaction heat exchangers and vaporizers for LNG facilities. Advantages, disadvantages, and relative costs for each type are included.

Creighton, J. R., A Two Reaction Model of Methane Combustion for Rapid Numerical Calculations. UCRL-79669, Rev 1, Lawrence Livermore Laboratory, September 28, 1977.

Inclusion of chemical kinetics in the computational schemes for multi-dimensional thermo-hydrodynamic codes (involving flame propagation) results in prohibitively expensive computational time. The author of this report attempts to develop a simplified flame propagation model (of possible use in Langrangian-Eulerian hybrid codes)which yields acceptable values of flame velocity, temperature and pressure.

Crouch, W. W. and Hillver, J. C., "What Happens When LNG Spills?" Chem. Tech. 2(4):210-215, 1972.

Authors try to assuage certain exaggerated fears about the safety hazards of LNG spills. They stress, however, the need for more information on the behavior of large spills.

Culbertson, L. and Emery, W. B., "Liquefaction Plant Experience at Lenai." Presented at the 3rd International LNG Conference and Exhibition, Washington, DC, September 24-28, 1972.

This paper reviews the more significant problems encountered and solutions employed in the operation of the Alaska to Japan LNG project. This is a follow-up to earlier papers describing design and startup at the Kenai plant.

Dailey, W. V. and Long, E. V., "Remote Sensing of Combustible and Toxic Gases." Analysis Instrumentation, Vol. 17. pp. 89-96, Pro. 1979 Symposium Measurement Technology for the 80's. Instru. Soc. Am., 1979.

Remote sensing systems with central control readout for detecting and monitoring levels of combustible gas (as, e.g., contained in LNG) are described. Detailed specifications are listed. The systems can be obtained from the Mine Safety Appliance Company.

Davenport, J. A., "A Survey of Vapor Cloud Incidents." Loss Prevention. 11:39-49, A CEP Technical Manual, 1977.

The paper gives a survey of open-air, unconfined vapor cloud explosions which have occurred during the last 25 years. The survey is taken from the viewpoint of a major insurance company and is primarily concerned with the property loss (in $) in the various types of accidents. LNG accidents represent only a minor fraction of all reported cases.

Deaton, W. M. and Frost, E. M., "Gas Hydrate Composition and Equilibrium Data." Proc. Natural Gas Department, American Gas Association. pp. 49-56, 1946.

Phase diagrams as well as equilibrium data were presented.

DeFrondeville, B., "Reliability and Safety of LNG Shipping: Lessons from Experience." Paper presented to the Annual Meeting of the Socity of Naval Architects and Marine Engineers, New York, New York, November 10-12, 1977.

This paper reviews LNG shipping experience in Europe, Japan, and the United States. The review concentrates on reliability and safety aspects. The safety/reliability record for liquefaction/loading ports and receiving are also summarized.

Del Tatto, D. L., "LNG Satellite Peakshaving." Presented at the AGA Distribution Conference, Houston, Texas, May 6-9, 1968.

This paper presented by an engineer from Chicago Bridge and Iron describes one of the first LNG satellite operations in the U.S. Both primary liquefaction and peakshaving plant and the satellite peakshaving facility are discussed.

Department of Transportation, "Liquefied Natural Gas Facilities; Federal Safety Standards: Development of New Standards." Federal Register. pp. 8142-8182, Thursday, February 8, 1979.

The notice proposed establishment of a set of comprehensive safety standards governing design, site selection and construction of LNG facilities used in pipeline gas transportation or interstate or foreign commerece. Implications of the regulations and comments are also discussed.

Department of Transportation, "Liquefied Natural Gas Facilities; Federal Safety Standards; Final Rule and Proposed Rule Making." Federal Register. pp. 9184-9237, February 1980.

The final rule establishing a set of comprehensive safety standards governing the design and construction of liquefied natural gas facilities is given. A proposed rule establishing safety standards governing operation and maintenance is also described.

Department of Transportation, "Liquefied Natural Gas Facilities, (LNG); Federal Safety Standards: Development of New Standards," Federal Register, pp. 70776-70800, Thursday, April 21, 1977.

The article sets forth proposed safety standards for LNG facilities. The proposed rules are based largely on National Fire Protection Association Rules (NFPA 59A 1975) and an Arthur D. Little Report summarizing LNG Technology.

Desgroseilliers, G. J. Radiation from Burning Hydrocarbon Clouds. M.S. Thesis, MIT Department of Mechanical Engineers, p. 88, 1978.

Radiation test data from the combustion of methane, ethane and propane are reported. Tests are of small scale with the vapors initially contained in soap bubbles. A newly-developed mathematical model agrees fairly well with the experimental results.

Devanna, L. and Doulames, G., "Planning is the Key to LNG Tank Purging, Entry and Inspection." Oil and Gas Journal. pp. 74-82, September 8, 1975.

Procedures used by the Lowell Gas Co. to purge a one billion cu-ft tank out of service are described in detail. The article includes a drawing showing the piping, valves, and fittings on the tank which are used for purging.

Diller, D. E., "LNG Thermophysical Properties Data and Custody Transfer Measurements." American Gas Association Monthly. March 1979.

Measurement research for custody transfer discussed along with the economic reason for pursuing these studies. Publications in Thermophysical properties of LNG are referenced.

Di Napoli, R. N., "Design Needs for Base-load LNG Storage, Regasification." Oil and Gas Journal. pp. 67-70, October 22, 1970.

Design of base-load storage and vaporization equipment and facilities is described. The article contains particularly good information on the operation and control of sendout pumps and seawater vaporizers.

DiNapoli, R. N., "LNG Peakshaving Plants Require Careful Cost Estimating." Pipeline and Gas Journal. pp. 28-36, May 1978.

The paper reports a dearth of data on the costs of LNG peakshaving plant construction probably due to the competitive nature of the LNG construction industry. Generalized costs of peakshaving and satellite facilities are presented.

Dincer, A. K., Drake, E. M. and Reid, R. C., "Boiling of Liquid Nitrogen and Methane on Water. The Effect of Initial Water Temperature." Int J. Heat Mass Transfer. pp. 176-177, 1977.

This note reports on the results of studies carried out in a vessel equipped to measure the temperature-time history at a number of locations in the bulk water phase as different cryogens were spilled on the surface. It is concluded that if the initial water temperature is low, heat transfer to the cryogen occurs through a growing ice shield, with little effect on the underlying water. If the water is initially warm, ice forms more slowly and cool surface water is mixed through the bulk.

Drake, E. M., "LNG Rollover--Update." Hydrocarbon Processing. 55:119-122, January, 1976.

The article considers LNG density, effects preceding rollover, rollover time prediction, heat storage, and discusses three documented cases of rollover.

Drake, E. M., Geist, J. M. and Smith, K. A., "Prevent LNG Rollover." Hydrocarbon Processing. 52:87-90, March 1973.

Studies were undertaken of basic mechanisms involved in LNG "roll-over", to predict when they may occur and to evaluate effectiveness of possible preventive measures. Such measures include mixing during filling, limiting variations in LNG composition and lowering tank set point pressure.

Drake, E. M., Jeje, A. A. and Reid, R. C., "Transient Boiling of Liquefied Cryogens on a Water Surface. I - Nitrogen, Methane, and Ethane." International Journal of Heat Mass Transfer. 18:1361-1368, 1975.

The results of an experimental study of the transient boiling rates of pure liquefied nitrogen, methane, and ethane in water are discussed. Nitrogen boiled with the lowest heat flux rate and the highest vapor superheat. For nitrogen, the heat flux rate was found to be proportional to the square root of the liquid head. The heat flux rate for ethane was the lowest and that for methane was intermediate.

Drake, E. M., Jeje, A. A. and Reid, R. C., "Transient Boiling of Liquefied Cryogens on a Water Surface. II - Light Hydrocarbon Mixtures." International Journal of Heat Mass Transfer. 18:1369-1375, 1975.

Light hydrocarbon mixtures similar to liquefied natural gas were boiled on a water surface. The rate of vaporization was measured and the heat fluxes were found to be much higher than that measured for pure liquid methane. Like methane, the rate of vaporization increased during the course of the experiment unless a continuous thick ice layer formed. No significant vapor superheat was noted.

Drake, E. M. and Reid, R. C., "How LNG Boils on Soils." Hydrocarbon Processing. 54(5):191-194, May 1975.

Implications of the paper are that: boil rates of LNG on compacted soils are influenced by soil type, moisture content and LNG composition; reduction in boiling rates can be obtained by sealing the dike surface; dikes of crushed rock or stone will have higher evaporization rates than compacted soil dikes; more studies are needed to assess insulating or sealing materials under LNG spill conditions and on LNG foaming behavior.

Drake, E. M. and Reid, R. C., "The Importation of Liquefied Natural Gas." Sci. Am. 236(4):22-29, 1977.

Arguments in favor and against large-scale importation of LNG are discussed, with the safety question receiving primary attention. On balance, LNG appears to be a relatively safe and promising alternative energy source.

Drake, E. M. and Wesson, H. R., "Review of LNG Spill Vapor Dispersion and Fire Hazard Estimation and Control Methods." Proceedings of A.G.A. Transmission Conference, Las Vegas, NV, May 1976.

This paper reviews techniques presently being used by the LNG industry for evaluating potential LNG vapor dispersion and fire hazards and will describe practical methods for reducing the severity of LNG spill accidents.

Duckham, H. E., "LNG Import Terminal Design Considerations." Cryogenics and Industrial Gases. pp. 41-48, September/October 1972.

This article describes the many processes and mechanical parameters involved in the design of an LNG import terminal. Included are discussions on facilities location, transfer lines, insulation, storage tanks, vapor handling systems, and LNG vaporizers.

Duffy, A. R., Gideon, D. N. and Putnam, A. A., Comparison of Dispersion From LNG Spills over Land and Water. Prepared by Battelle Columbus Laboratories for the American Gas Association, Project SI-3-7, September 4, 1974.

This study examines and compares the available data on dispersion from land and water spills, and explains similarities and differences in results on the basis of differences in experimental techniques and test conditions, and possible differences in pertinent phenomena.

Duffy, A. R., Gideon, D. N., Putnam, A. A. and Bearint, D. E., LNG Safety Program - Phase I - Potential LNG Spills. Report by Battelle Columbus Laboratories and University Engineers, Inc., to the American Gas Association, February 25, 1971.

The report presents data on known spills of LNG or other cryogens, a discussion and analysis of problem areas, and a discussion of consequences of spills including downwind dispersion, radiation from fires, and reactions with water. Conclusions are summarized and recommendations made for future research.

Dunn, W. A. and Tullier, P. M., Spill Risk Analysis Program Phase II Methodology Development and Demonstration. NTIS No. AD/785026, August 1974.

This report describes research and results in the development and demonstration of systematic methods of assessing the effectiveness of either proposed or recently implemented merchant marine safety regulations. The methods have been designed primarily to assist Coast Guard regulatory decision-makers in their selection of alternative means of reducing marine transportation casualties and spills of hazardous or polluting materials.

Durr, C. A. and Crawford, D. B., "LNG Terminal Design." Hydrocarbon Processing. November 1973.

This article discusses the special problems associated with design of an LNG terminal. Particular attention is given to the transfer line and the vapor handling and pressure control system.

Durr, C. A., "Process Techniques and Hardware Uses Outlined for LNG Regasification." Oil and Gas Journal. May 13, 1974.

The following components of an LNG terminal are discussed by a process engineer from M. W. Kellog: LNG unloading, storage, vapor handling, sendout pumps, vaporizers, power generation, nitrogen system, and heat recovery.

Ecosystems, Inc., Expected Behavior of an LNG Release Under Specified Conditions. Report to Federal Power Commission, August 17, 1973.

The report comprised an assessment of hypothetical LNG spill situations in the Staten Island area. Results were calculated using methods of the Esso Research and Engineering Company. Three tasks described are analyses of a 100,000 m^3 spill over water, analyses of evaporation and dispersion following an LNG tank roof failure, and a description of the New York Harbor climate.

Edeskuty, F. J., Critical Review and Assessment of Problems in Hydrogen Energy Delivery Systems. Initial Report, Los Alamos Scientific Laboratory LA-74-PR Progress Report UC-41, August, 1978.

A preliminary risk assessment for the transport of gaseous hydrogen by pipeline and liquid by tank trucks is presented. Metal imbrittlement by liquid hydrogen is discussed and regulations are reviewed.

Edwards, J. G., "A Combustible Gas Detection System for an LNG Terminal." Analysis Instrumentation, Vol. 17. Proc. 1979 Symposium on Measurement Technology for the 80's. Instr. Soc. Am., pp. 84-88, 1979.

For reasons of personnel safety and plant integrity, combustible gas detection systems are required in all LNG facilities. Practical guidelines are given for the reliable operation of such systems.

Edwards, R. M., "The Application of Sub-X Heat Exchanger for Vaporization of Liquid Natural Gas." American Society of Mechanical Engineers publication, 8 pp., September 1967.

The basic design and development of the Sub-X heat exchanger for vaporization of liquefied natural gas is presented in this paper. Detailed drawings and discussions are included.

Eichhoff, H. E. and Grethe, K., "A Flame Zone Model for Turbulent Hydrocarbon Diffusion Flames." Combustion and Flame. 35(2):267-275, August 1979.

The authors present a flame zone model which corrects the deficiency of two previous models (called the flame sheet and equilibrium models) by more correctly accounting for the intermediate reaction species. Comparison with experiment supported their model.

Eichler, T. V. and Napadensky, H. S. Accidental Vapor Phase Explosions on Transportation Routes Near Nuclear Power Plants. U.S. Nuclear Regulatory Commission, NUREG/CR-0075, 1977.

A review of vapor cloud explosion literature is used to develop a method to estimate TNT equivalency for accidental blasts as a tool for calculating exclusion distances for hazardous materials near nuclear plants.

Enger, T., "Explosive Boiling of Liquefied Gases on Water." Conference Proceedings on LNG Importation and Terminal Safety, Boston, MA, June 13-14, 1972.

Explosive boiling of a liquefied gas mixture such as LNG on ambient water can only be produced when the methane content is less than 40 mole percent. The potential hazard of having explosive boiling from an LNG spill is negligible during commercial transportation of LNG. In addition, energy estimates show that the potential damage from explosive boiling of a liquefied gas is minimal.

Enger, T. and Hartman, D. E., "Mechanics of the LNG-Water Interaction." Paper presented at the American Gas Association Distribution Conference, Atlanta, GA, May 8, 1972.

Shell Pipe Line Labs has conducted research since 1970 on rapid phase transformation which can occur when LNG is spilled onto water. "Explosive" LNG-water interaction results because of rapid phase transformation and violent expansion of a thin layer of superheated LNG at the interface between the LNG and water. It is stated that "explosions occur only when LNG is in a weathered state, i.e., when the methane content of LNG is less than 40 mole percent."

Enger, T. and Hartman, D. E., "Rapid Phase Transformation During LNG Spillage on Water." Paper presented at the Third International Conference and Exhibition on LNG, Washington, DC, September 24-28, 1972.

It is shown that "explosions" can only occur with "aged" LNG which contains less than 40 mole percent methane. The "explosive" interaction between a liquefied gas and water is caused by the rapid phase transformation and violent expansion of a thin layer of superheated liquefied gas at the liquefied gas-water interface.

Enger, T., Hartman, D. E. and Seymour, E. V., "Explosive Boiling of Liquefied Hydrocarbon/Water Systems." Paper presented at the Cryogenic Engineering Conference, National Bureau of Standards, Boulder, CO, August 9-11, 1972.

The conditions which produce "explosions" when LNG is spilled on water at ambient temperature have been isolated and verified experimentally. It has been shown that "explosions" can only occur with "aged" LNG which less than 40 mole percent methane. Contact between water and LNG with more than 40 mole percent methane produces normal vaporization.

Enger, T., Hartman, D. E. and Seymour, E. V., "Explosive Boiling of Liquefied Hydrocarbon/Water Systems." Adv. Cryo. Eng. 18:32-41, 1973.

The mechanism of LNG/water interactions, and the conditions under which they can occur, are described. The explosive boiling, which has been observed, is explained as a result of superheating of the liquefied gas.

England, W. G., Teuscher, L. H., Hauser, L. E. and Freeman, B. E., "Atmospheric Dispersion of Liquefied Natural Gas Vapor Clouds Using Sigmet, a Three Dimensional Hydrodynamic Computer Model." Proceedings of the 1978 Heat Transfer and Fluid Mechanics Institute, Washington State University, Pullman, Washington, June 26-28, 1978.

The SIGMET dispersion model is presented in the form that it is applied to LNG vapor dispersion problems. Model results are presented for examples of plume behavior and to verify model predictions. Model numerical methods are also described.

Ermak, D. L. and Bowman, B. R., "Average Dispersion of a Liquefied Natural Gas Vapor Plume." UCID-17968-79-1, pp. 1-10, Lawrence Livermore Laboratory, 1979.

The theoretical predictions for the vapor spread from an LNG spill are compared with experimental data obtained in a China Lake test. Agreement is fair. Prevailing winds are shown to have a significant influence but are hard to model.

Escudier, M. P., "Aerodynamics of a Burning Turbulent Gas Jet in a Crossflow." Combustion Science and Technology. 4:293-301, 1972.

The study extends the entrainment theory for weak plumes by including into its framework the influences of radiative thermal-energy transfer, large density variations, and thermal-energy generation through chemical reaction. Thermal radiation is found to be of secondary importance to plume dynamics. Calculations show that a plume's motion is not significantly influenced by buoyancy forces until well downstream of the reaction zone.

Evaluation of LNG Vapor Control Methods. Report to the American Gas Association by Arthur D. Little, Inc., Cambridge, Massachusetts, October 1974.

It is shown that, for the high spill rates, the maximum downwind hazard zone is not significantly affected by shutdown of the leak in the 10-minute period specified in the NFPA Code. To be effective in reducing downwind hazards shutdown of the leak should be accomplished as soon as possible, preferably under 2 minutes.

Fannelop, T. K. and Waldman, G. D., "The Dynamics of Oil Slicks - Or 'Creeping Crude'." AIAA Paper No. 71-14 presented at the AIAA 9th Aerospace Sciences Meeting, New York, New York, January 25-27, 1971.

The spread of an oil slick into calm water is considered from a theoretical viewpoint. The equations of motion are derived for the gravity-inertial and gravity-viscous flow regimes. For both two-dimensional and radial slicks, similarity solutions are obtained for the two flow regimes which give adequate agreement with available experimental data.

Farley, M., "The LNG Plant Design Engineer." LNG/Cryogenics. pp. 25-27, February/March 1973.

This article, through interviews with six individuals involved in LNG plant design activities, provides a brief overview of some of the problems they have had to cope with on various projects.

"Fast LNG-leak Detector Developed." Oil and Gas Journal. pp. 52, December 19, 1977.

A new device developed and patented by the Direction of Studies and New Techniques of Gaz de France is claimed to provide fast detection and location of leaks in large storage tanks. The location for the detector, at the bottom of the annular space between the walls and next to the internal tank, was determined following tests made on a reduced model tank.

Fauske, H., "The Role of Nucleation in Vapor Explosions." Transactions of the American Nuclear Society. 15:813-815, 1972.

The paper suggests a possible mechanism for vapor explosion and examines the validity of the mechanism in light of available experimental facts.

Fay, C., Desgroseillier, G., and Lewis, D., "Radiation from Burning Hydrocarbon Clouds." Combustion Science and Technology. 20, 1979.

This paper is a report of a series of experiments performed at M.I.T. Small scale fireballs were created in the laboratory and the time-dependent thermal emission was measured by a radiometer. Various correlations concerning fireball parameters (diameter, temperature, etc.) are presented.

Fay, J. A., Scale Effects in LNG Hazard Analysis and Testing. Progress Report for period 12/1/76 to 8/21/77. ERDA Contract No. EE 77-S-02-4204.

The effect of LNG spill size on the physical parameters in hazard analysis has been investigated. Measurements of radiant heat envisions have been made.

Fay, J. A., "Unusual Fire Hazard of LNG Tanker Spills." Combustion Science and Technology. 7:47-49, 1973.

This report gives theoretical expressions for the pool spread and evaporation rate of liquefied natural gas spilled on water, the gravitational spread, and the heating and downwind spread of the vapor cloud. It does not treat the diffusion or mixing of the vapor with air.

Fay, J. A. and Lewis, D. H., Jr., "The Inflammability and Dispersion of LNG Vapor Clouds." Proceedings of the Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterway, Jacksonville, FL, October 26-30, 1975, NTIS No. AD/A023505, pp. 489-498, October 1975.

The paper considers the statistical properties of LNG vapor concentration, the mean vapor concentration in dispersing cloud and downwind distances for two flammability conditions.

Fay, J. A. and Lewis, D. H., "Unsteady Burning of Unconfined Fuel Vapor Clouds." 16th International Symposium on Combustion, 1976.

The problem of fireball hazards associated with LNG and LPG spills is investigated. A derivation of fireball maximum radius, height above surface and time required, are obtained by phenomenological, empirical and dimensional (with some physical and mathematical) analysis. Experimental corroboration is included.

Feirabend, C. E., "Design Considerations for LNG Production Facilities in Arctic Regions." 1978 Operating Section Preceedings, American Gas Association, Montreal, Quebec, May 1978.

Operational and engineering design responses to extremes of temperature and windspeed in arctic regions are considered.

Feldbauer, G. F., Heigl, J. J. and McQueen, W. et al., Spills of LNG on Water - Vaporization and Downwind Drift of Combustible Mixtures. Report No. EE61E-72, Esso Research and Engineering Company, May 24, 1972.

A total of seventeen LNG spill tests, ranging in size from about 250 to 2500 gallons, were carried out under a variety of weather conditions. The main thrust of the experimental work was aimed at measuring the parameters required to predict downwind concentrations. The aim of the experimental work was to measure the plume shape and other information which would permit the data on these variables to be extrapolated.

Felske, J. D. and Tien, C. L., "Calculation of the Emissivity of Luminous Flames." Combustion Science and Technology. 7:25-31, 1973.

A simple analytical basis for determining the total emissivity of luminous flames is developed. The analysis considers flames whose dominant emitting species are water vapor, carbon dioxide and soot particles. Calculations are made to illustrate the relative importance of gas and soot emission under typical flame conditions.

Filstead, C. G., "The Design and Operation of LNG Ships with Regard to Safety." Shipping World and Shipbuilder. pp. 259-262, February 1972.

This article summarizes the safety features and operating procedures of LNG ships particularly the Methane Princess and Methane Progress.

Findlater, A. E. and Prew, L. R., "Operational Experience with LNG Ships." LNG 5 - International Conference on Liquefied Natural Gas, 5th Proceedings, Session IV Paper 5, 16 pp., Duesseldorf, Germany, August 29-September 1, 1977.

Some of the experience gained during the initial years of operation of the shipping phase of the Shell Bruenei/Japan LNG scheme are presented in this paper. The operational planning required for the successful commissioning and operation of a fleet of gas carriers and the wide range of disciplines and expertise involved is also included in this paper.

Fortson, R. M., Holmboe, E. L., Brown, F. B., Kirkland, J. T., Tullier, P. M. and Dayton, R. B., Maritime Accidental Spill Risk Analysis Phase I: Methodology Development and Planning. NTIS No. AD/761362, January 1973.

This report develops a methodological approach and task plan for assessing alternative methods of reducing the potential risk caused by the spill of hazardous cargo as the result of vessel collisions and groundings. In addition to developing the overall study approach, a very preliminary analysis of ship/barge accidents in U.S. territorial waters and port traffic was done to identify types of accidents to be examined in the next phase of the study effort.

Fourth International Conference on Liquefied Natural Gas. Papers, Place of Nations, Algiers, Algeria, June 24-27, 1974.

This book is a collection of papers presented at the conference. The papers have been divided into 8 sessions according to their subject matter.

Fowles, G. R., "Vapor Phase Explosions: Elementary Detonations?" Science. 204:168-169, 1979.

A new theory is outlined which would explain a vapor explosion as an elementary detonation. It predicts the energy resulting from a superheated liquefied methane vapor explosion as 95 J/g.

Garforth, A. and Pallis, C., "Luminar Burning Velocity of Stoichiometric Methane-Air; Pressure and Temperature Dependence." Combustion and Flame. 31:69-83, 1978.

The authors of this paper determine the flame velocity in a stoichiometric methane-air mixture (for initial various temperatures and pressure) experimentally and analytically, with resulting good agreement between the two.

Garland, F. and Atkinson, G., The Interaction of Liquid Hydrocarbon With Water. U.S. Coast Guard, Office of Research and Development, NTIS No. AD/753561, October 1971.

This is an investigation of the phenomena reported in a Bureau of Mines report which studied the hazards of LNG. During the investigation, LNG was dropped onto a variety of liquid samples. Explosions did not occur when pure water was used as the sample, but water contaminated with n-hexane or toluene gave an explosion every time. Peak explosion pressures are given for a variety of experimental conditions.

Gaydon, A. G. and Wolfhard, H. G., Flames - Their Structure, Radiation and Temperature. Chapman & Hall Ltd., London, 1960.

The book includes information concerning premixed flames, flow patterns and shapes, burning velocity; propagation, diffusion, stability, carbon in flames, radiation, temperature, ionization, combustion processes of rocket fuels, and recent progress on some flame problems.

Georgakis, C., Congalidis, J. and Williams, G. C., "Model for non-instantaneous LNG and Gasoline Spills." Fuel. 58:113-120, February 1979.

A predictive model for non-instantaneous spills is presented which is applied to holes in storage vessels for gasoline and LNG. Effects of spill size and shape and combustion are discussed and results are compared to those for instantaneous spills.

Germeles, A. E., "A New Model for LNG Tank Rollover." Paper presented at the Cryogenics Engineering Conference, Kingston, Ontario, July 1975.

A dynamic model is presented which can give very accurate rollover predictions and is a potentially powerful tool in rollover prevention strategies. The excellent agreement between the predictions of the model and observations for the La Spezia rollover indicate that the model is valid. Uncertainties in the model transport coefficients indicate that further validation of the model would be desirable. The model has been computerized.

Germeles, A. E., "Forced Plumes and Mixing of Liquids in Tanks." Journal of Fluid Mechanics. 71:601-623, 1975.

A mathematical model for the mixing of two miscible liquids of different density is presented, from which the tank stratification can be computed.

Germeles, A. E. and Drake, E. M., "Gravity Spreading and Atmospheric Dispersion of LNG Vapor Clouds." Proceedings of the Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterway. Jacksonville, FL, October 26-30, 1975, NTIS No. AD/A023505, pp. 519-539, October 1975.

The paper presents methods for estimating the extent and location of flammable vapors as a function of spill and weather conditions, assuming that ignition does not occur. Models allow the width of the vapor cloud to be computed at the point of ignition for consequence analysis.

Gibson, G. H., "Consider Safety, Reliability, Cost in Selecting Type of LNG Storage." Oil and Gas Journal. pp. 65-69, February 8, 1971.

Several types of LNG storage are compared with respect to safety and cost.

Gideon, D. N. and Putnam, A. A., "Dispersion Hazard from Spills of LNG on Land and on Water." Cryogenics. 17, January 1977.

This report analyzes the pertinent published data on dispersion of vapors from LNG spills on land and water. Correlation of these data is based on the commonly used relationships from dispersion theory. The report has emphasized peak concentration rather than average or 'maximum average' concentrations and for instantaneous spills. The peak concentrations of major interest to safety, are related to the peak vaporization rates.

Gideon, D. N., Putnam, A. A. and Duffy, A. R., Comparison of Dispersion from LNG Spills Over Land and Water. Report to the American Gas Association by Battelle Columbus Laboratories, Project IS-3-7, A.G.A. Catalog No. M19877, September 4, 1974.

The report discusses dispersion variables, spill characteristics on water, a description of LNG programs, and provides comparisons of dispersion data.

Gideon, D. N., Putnam, A. A. and Duffy, A. R., "Safety Aspects of LNG Spills on Land." Advances in Cryogenic Engineering. 21:377-386. Paper presented at 1975 Cryogenic Engineering Conference held at Queen's University, Kingston, Ontario, July 22-25, 1975.

The paper provides information concerning experimental spills of LNG. Instrumentation and procedures, the dispersion hazard, the radiation hazard, and fire control and vapor suppression are discussed.

Gifford, F. A., Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion." Nuclear Safety. 2(4):47-51, June 1961.

The article considers vertical dispersion of a cloud or plume and gives estimates of the lateral spread as well as wind speed and direction.

Goldfeder, L. B., "Control Valves for LNG Facilities." Pipeline and Gas Journal. pp. 58-74, January 1972.

The types, applications and materials of construction of control valves for LNG are reviewed.

Goodwin, R. D., The Thermophysical Properties of Methane, from 90 to 500 K at Pressures to 700 Bar. NBS Tech. Note 653, 1974.

An extensive tabulation of the thermophysical property data for methane is presented. The temperatures covered range from 90 to 500 K and the pressure up to 700 bars.

Green, K. A., Tiffin, D. L., Luks, K. D., and Kohn J. P., "Solubility of Hydrocarbons in LNG, NGL." Hydrocar. Process. 58(5):251-253, 1979.

Experiments are described to verify correlations for multicomponent solid-liquid-vapor behavior of realistic natural gas systems. The resulting test data are in essential agreement with correlations derived earlier.

Griffis, K. A. and Smith, K. A., "Convection Patterns in Stratified LNG Tanks - Cells Due to Lateral Heating." Paper presented at the 3rd Conference on Natural Gas Research and Technology, Dallas, TX, March 6-8, 1974.

The paper treats the subject of layer formation due to a uniform lateral heat flux, such as exists at an LNG tank wall. Experimentally, a water sugar system has been used to model the methane-higher hydrocarbon system. Preliminary results indicate that convective layers will be relatively thin for cases which are germane to LNG storage.

Guise, A. B., "How to Fight Natural Gas Fires." Hydrocarbon Processing. 54:76-79, August 1975.

The following recommendations are made for coping with natural gas fires: 1) assume all fires to be impinging, 2) use potassium bicarbonate-base dry chemical, 3) use multipurpose dry chemical where water is not available, 4) use high velocity concentrated streams, and 5) use protective clothing and face shields.

Gullberg, R. W., "NWNG's Newport LNG Facility First User of CRYEX Purification." Pipeline and Gas J. 206(13):40-48, 1979.

A new concept for removing carbon dioxide from a gas stream is incorporated into Northwest Natural Gas Co.'s LNG peakshaving facility on Yaquina Bay, 114 miles southwest of Portland, Oregon.

Guthrie, J. K. and Gregory, E. J., "Design of Baseload Evaporators for LNG."

The design and operation of an open rack vaporizer and an indirect fired vaporizer are discussed.

Haines, G. H. and Thompson, J., "Offshore Gas Liquefaction Without Offshore LNG Plants. Oil & Gas J. 78:87-91 February 18, 1980.

It is proposed to liquefy natural gas with liquid nitrogen stored aboard a tanker moored to an offshore drilling platform. At the shore-based terminal, the liquid nitrogen in turn is produced with some of the "cold" derived from vaporizing the LNG. It is claimed that such an operation is well within existing technology and is also economical.

Hale, D., "LNG Projects Develop Overseas, Only Regulations Develop in U.S." Pipeline and Gas Journal. pp. 17-21, June 1979.

The article provides an industry summary of LNG activities in 1978 and includes a list of foreign and U.S. LNG facilities.

Hale, D., "Peakshaving Capabilities Ready for 1979 - 1980 Winter Season." Pipeline and Gas J. 206(13):22-25, 1979.

U.S. peakshaving capabilities will be at a record high for the 1979-1980 winter seasons as underground gas storage capacity and withdrawal/send-out capacity reach new peaks and LNG peakshaving capacity reaches an all-time high; new peakshaving capacity is about 70 billion ft^3/day.

Hall, A. R., "Pool Burning." Oxidation and Combustion Reviews. 6:169-225, Elsevier Scientific Publishing Company, 1973.

This review of literature includes: influence on the burning characteristics; temperature distribution in the liquid and the phenomena of hot zone formation and boilover; prevailing concepts of heat transfer from the flame to the liquid; effect of water as a dispersed phase, and as a substrate, on burning.

Hall, D. J., Barrett, C. F. and Ralph, M. O., Experiments on a Model of an Escape of Heavy Gas. LR 217 (AP), Warren Spring Laboratory. Deparment of Industry, Hertfordshire, United Kingdom, 1976.

The report describes model experiments on a release of a heavy explosive gas, propane or butane, into the atmosphere at ground level. Both long and short term released are considered and the validity of the model is discussed. A method of extrapolating the experimental results to full scale is provided.

Hall, R. J., "CARS Spectra of Combustion Gases." Combustion and Flame. 35(1):47-60, May 1979.

The author presents a theoretical basis for obtaining species concentration and temperatures in turbulent, sooty flames using Coherent-Anti-Stokes Ramen Spectroscopy (CARS). Comparisons of theory and experiment are presented.

Hall, S. F., A Simple Homogeneous Equilibrium Critical Discharge Model Applied to Multi-Component, Two Phase Systems. Safety and Reliability Directorate (U.K.), Report SRO R 127, May 4, 1978.

Two models of two phase critical discharge from reservoirs are presented which are applicable for spill calculations from breaches in storage tanks or piping.

Halverson, G., "Automatic Continuous LNG Level-Gauging and Temperature Measuring System." Proceedings of the 1st Biennial Symposium on Cryogenic Instrumentation, Vol. 1, 1976.

This paper describes a system which is being used to make accurate measurements of the liquid level and temperature profile in LNG storage tanks.

Handman, S. E., "Pros and Cons of LNG Safety." Pipeline Industry. pp. 39-42, September, 1979.

This paper reviews types of existing LNG facilities, agencies which have jurisdiction over the facilities, and risks associated with LNG facilities versus risks associated with other human activities.

Hankel, C. C., LaFarc, I. V. and Litzinger, L. F., "Purging LNG Tanks Into and Out of Service Considerations and Experience." Paper presented to the AGA Transmission Conference, Minneapolis, Minnesota, May 6-8, 1974.

This paper discusses detailed procedures used by Chicago Bridge & Iron for purging LNG tanks into and out of service.

Hankinson, R. W. and Thomson, G. W., "Calculate Liquid Densities Accurately." Hydrocarbon Processing. pp. 277-282, September, 1979.

Liquid density calculation methods are compared on 3000 compounds; results on 190 of these are presented. The Costald - Corresponding States Liquid Density method was found to be more accurate than the Yen-Woods or modified Rackett Equation (SDR) methods.

Hardee, H. C., Lee, D. O. and Benedick, W. B., "Thermal Hazards from LNG Fireballs." Combustion Sci. and Techn. 17:189-197, 1978.

LNG fireballs can pose serious burn hazards in their vicinity. Third degree burns from a very large LNG fireball (several 10^7 kg) could occur out to several kilometers from its center.

Harsha, P. T., LNG Safety Program Topical Report: Dispersion Modeling. Report RDA-TR-1100-003, by R&D Associates for the American Gas Association, July 1976.

A variety of techniques exist for near-field LNG dispersion phenomena; Gaussian plume models are inappropriate; hydrostatic models are appropriate; three-dimensional numerical models have been demonstrated; a general LNG vapor dispersion model should incorporate sophisticated state-of-the-art turbulence models.

Haselden, G. G., "Developments in Gas Liquefaction and Separation. " Int. J. Refrig. 2(6):207-210, November, 1978.

Some of the most interesting papers presented to the Gas Liquefaction and Separation Commission of the IIR are reviewed. A novel LNG peak-load storage plant was described in which the excess cooling capacity available during most of the year is used to produce low cost liquid oxygen and nitrogen. On a larger scale, design studies were reported showing the advantages to be gained by cooling natural gas before admitting it to very long transmission pipelines. For duties above 100 x 10^9 m^3/year, piping LNG is recommended.

Haselden, G. G., "The Achievements and Potential of LNG for Energy Storage and Transport." Inst. Chem. Eng. Sym. 44:7-13, 1976.

The paper presents a brief general overview on present LNG technology, highlighting those features that make LNG transport economically attractive.

Hashemi, H. T., Lott, J. L., Wesson, W.,D. and Wesson, H. R., "Effect of Barometric Pressure Changes on Rate of Boiloff in a Storage Tank of Saturated Liquids." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

An analytical model for prediction of boiloff variations due to atmospheric pressure changes in atmospheric storage tanks is presented. LNG examples are shown although the model can be applied to various other cryogenic gases.

Hashemi, H. T. and Wesson, H. R., "Cut LNG Storage Costs." Hydrocarbon Processing. pp. 117-120, August 1971.

Better, more precise designs can be made using a new mathematical model which more closely predicts actual boil-off rates. LNG losses and storage costs are reduced.

Havens, J. A., A Description and Assessment of the SIGMET LNG Vapor Dispersion Model, U.S. Coast Guard Report, CG-M-3-79, 1979.

The mathematical model SIGMET, which has been developed to predict dispersion of LNG vapor clouds from large spills on water, is described in great detail. The particular features of the model are discussed and evaluated. Conclusions and recommendations for further improvement of the model are given.

Havens, J. A., Predictability of LNG Vapor Dispersion From Catastrophic Spills Onto Water: An Assessment. Report prepared by the University of Arkansas for the Cargo and Hazardous Materials Division, Office of Merchant Marine Safety, U.S. Coast Guard, April 1977.

The author has reviewed various mathematical models and the methodology described by SAI and believes that such techniques hold the most promise for accurate prediction of vapor dispersion from catastrophic spills on water. A program designed to evaluate the accuracy of the SAI model or other models should now be considered high priority.

Heat Transfer at the Air-Ground Interface With Special Reference to Airfield Pavements. Report Prepared by the Massachusetts Institute of Technology, Department of Civil and Sanitary Engineering, Soil Engineering Division, Technical Report No. 63, January 1961.

The variables which affect the transfer of heat at the air-earth interface were studied as a part of an investigation to improve techniques for predicting subsurface temperatures. The investigation demonstrates that certain readily obtainable measurements may be utilized to predict the amounts of heat flow at the ground surface due to various atmospheric phenomena.

Henry, R. E., Gabor, J. D., Winsch, I. O. and Spleha, E. A. et al., "Large Scale Vapor Explosions." Argonne National Laboratory, Argonne, IL. Paper presented at the Fast Reactor Safety Meeting, Beverly Hills, CA, April 2-4, 1974.

Experimental results with Freon-22 and water show that the interface temperature homogeneous nucleation model accurately predicts the necessary temperature conditions for the onset of large scale vapor explosions. Test results for many different contact modes revealed that the magnitudes of explosions were highly dependent upon contact mode.

Hertzberg, M., "The Theory of Free Ambient Fire. The Convectively Mixed Combustion of Fuel Reservoirs." Combustion and Flame. 21:195-209, 1973.

The theory of fuel-reservoir fires is extended and amplified into a quantitative formulation that includes all the significant physical processes: mass diffusion, heat conduction, convective mixing, convective heat transport, and radiative heat transport. The predictions are compared with the data for 3 fuels (gasoline, liquid hydrogen, and methanol), and the comparison gives reasonable agreement.

Hertzberg, M., Cashdollar, K., Litton, C. and Kansa, E., "The Diffusion Flame in Free Convection. Buoyancy-Induced Flows, Oscillations, Radiative Balance and Large-Scale Limiting Rates." Paper presented at the Central States Section, Combustion Institute Meeting on Fluid Mechanics of Combustion Processes, Cleveland, OH, March 29-30, 1977.

Early studies of flame oscillations are reviewed and new data are presented for the fundamental infrared flicker frequencies of methanol pool flames and other diffusion flames. Measured frequencies decrease monotonically with increasing size, in good agreement with independent data obtained photographically and acoustically.

Heskestad, G., Kung, H. C. and Todtenkopf, N. F., "Air Entrainment into Water Sprays and Spray Curtains." ASME Winter Annual Meeting, New York, New York, 1976.

Theoretically derived volumes of entrained air were found to agree with experimental values to within 17%. While no explicit reference is made to LNG, the results are sufficiently general to apply to the vapor stage of an LNG spill.

Hindle, W., Artic Islands LNG. Presented to the American Gas Association Transmission Conference, Montreal, Quebec, May 8-10, 1978.

Trans Canada has begun the study and design of an LNG project which would transport LNG from the high Arctic Islands to Quebec. The type of ship that would be used, an icebreaking LNG carier, is described.

Hoehne, V. O. and Luce, R. G., "The Effect of Velocity, Temperature, and Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon Gases." Proceedings, Division of Refining. API, 50:1057-1081, 1970.

Various diameter jets of methane, ethane, butane, and heptane gas were directed perpendicular to the wind stream in a wind tunnel. Measurements were made to define the flammable zone caused by the jet-wind interaction. The application of the test results to practical process plant vent spacing to minimize hazards during windy atmospheric conditions is illustrated.

Holman, O. B., "LNG Peakshaving Plant Design Features and Operating Experiences." Paper presented to Seminar and Study Tour on LNG Peakshaving, Washington DC, March 5-9, 1979.

This paper reviews the design features and operating experiences of the Philadelphia Gas Works Richmond Peakshaving Plant. The plant uses a cascade liquefaction process, a prestressed concrete type design for storage and running film vaporizers.

Hottel, H. C. and Sarofim, A. F., Radiative Transfer. Chapter 6, McGraw-Hill Book Company, 1967.

Chapter 6 deals with gas emissivities and absorptivities.

Hoult, D. P., "The Fire Hazard of LNG Spilled on Waters." Proceedings on LNG Importation and Terminal Safety. NTIS No. AD/754326, Boston, MA, June 13-14, 1972.

The paper considers the rate of evaporation of LNG spilled on water, the negatively buoyant plume, heat transfer to the plume, the buoyant puff, and concludes that there is no single rule whereby the fire hazard of an LNG spill may be estimated.

Howard, J. L., and Andersen, P. G., "Barge-Mounted Gas Liquefaction and Storage Plant." Chem. Eng. Progr. 75(10):76-81, 1979.

The design and operation of a floating LNG facility for liquefaction, storage and export of natural gas are described. This new plant was to be built in modules by shipyards in highly industrialized areas and to be towed to Iran for installation near Kangan.

Howard, M. A., "Second Generating Peakshaving Plant Benefits from Experience." Pipeline and Gas Journal. November 1978.

Northern Natural Gas has two peakshaving plants, one built in 1975 and other in 1978. This article discusses the lessons learned at the first facility and the various design changes in the second facility that resulted.

Humbert-Basset, R. and Montet, A., "Dispersion dans l'Atmosphere d'un Nuage Gazeux Forme par Epondage de G.N.L. sur le Sol." Paper presented at the Third International Conference on LNG, September 1972.

An experimental study conducted by GAZ de FRANCE at the test station of NANTES is described. To investigate the hazards occurring from spillage, measurements of evaporation rates of LNG on various soils were made. In addition, measurements were made of the extent that clouds generated from spillage in diked areas up to 200 m^2*. A mathematical model was utilized in the extensive study of the hazards problem.*

Jamison, L. R., "United States Codes and Regulations Affecting the Marine Aspects of LNG Movements." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

This paper presents a collection of regulations which influence marine movement of LNG. Agencies regulating this transport are the U.S. Coast Guard, Intergovernmental Marine Consultative Organization, and the Republic of Liberia Bureau of Marine Affairs.

The Japan Gas Association, A Study of Dispersion of Evaporated Gas and Ignition of LNG Pool Resulted From Continuous Spillage of LNG Conducted During 1975. April 1976.

LNG spill tests were conducted for continuous releases to determine the characteristics of evaporation, dispersion, and ignition of pool fires. Tests were concerned mainly with the vapor cloud dispersion and the resultant cloud dimensions and character.

Jaquette, D. L., Possibilities and Probabilities in Assessment of the Hazards of the Importation of Liquefied Natural Gas. Rand Corporation. Study P-5411, AD/A019353, 1975.

Currently prevailing assessment of the safety hazards of LNG spills is criticized. The unknowns of such spills are listed and the need for more definitive information is stressed.

Javelle, B. and Raynaud, J., "Structural Problems in Methane Carriers." Shipping World and Shipbuilder. pp. 831-833, September 1975.

The authors briefly discuss stress calculations for LNG ships. They include fatigue, lamellar teaming, crack propagation, and liquid motions.

Jeje, A. A. and Reid, R. C., "Boiling of Liquefied Hydrocarbons on Water." Paper presented at the Third Conference on Natural Gas Research and Technology, Dallas, TX, sponsored by the American Gas Association, March 1974.

The cryogens studied were liquid nitrogen, methane, ethane, and several typical LNG compositions. In general, boiling fluxes increased slightly as the initial water temperature was lowered and as more cryogen was spilled. For LNG mixtures, significant foaming resulted and it is also suspected that ice is rapidly formed and remelted by eddy circulation in the upper layer of water.

Jeje, A. A. and Reid, R. C., Transient Pool Boiling of Cryogenic Liquids on Water.

Boiling rates of LNG and LPG on water are determined as a function of water temperature and liquefied gas composition.

Jensen, D. E. and Jones, G. A., "Reaction Rate Coefficients for Flame Calculations." Combustion and Flame. 34:1-34, 1978.

Current functional forms for chemical reaction notes and corresponding uncertainty factors are presented.

Jensen, D. E., Spalding, D. B., Tatchell, D. G. and Wilson, A. S., "Computation of Structures of Flames with Recirculating Flow and Radial Pressure Gradients." Combustion and Flame. 34(3):300-326, April 1979.

The authors present a technique for modeling steady-state, axis symmetric, highly-turbulent chemically reacting flow from a rocket engine. This technique has many features relevent to LNG pool fire modeling.

Kato, D., "Ultra Low-Temperature LNG Compressors." Fifth International Conference on LNG, Session II, paper 10, Institute of Gas Technology, 1977.

Special compressors for recompression of LNG boil-offs in storage facilities are described.

Katz, D. L., "LNG-Water Explosions." NTIS No. AD/775005, 1973.

The "limit of superheat" is identified as the cause of LNG-water explosions. However, theoretical support for this argumentation is mainly speculative.

Katz, D. L., "Superheat-Limit Explosions." Chemical Engineering Progress. 68:68-69, May 1972.

The rapidity of this superheat-limit event as compared to nucleated bubble growth in a partially superheated liquid provides an explanation for vapor explosions discussed in the literature.

Katz, D. L. and Sliepcevich, C. M., "LNG/Water Explosions: Cause and Effect." Hydrocarbon Processing. 50:240-244, November 1971; also NTIS No. AD/775005.

The paper discusses the limit of superheat, the methane-water system, LNG mixtures, massive LNG spills, and considers other systems such as liquid methane poured into pure pentane in the absence of water.

Katz, D. L. and West, H. H., "LNG Shipping and Storage." Paper Presented to the Engineering Foundation Conference on Risk/Benefit Methodology and Application, Asilomar, California, September 21-26, 1975.

This article gives an overview of the history and development of the LNG industry with emphasis on storage and shipping. Potential hazards associated with LNG are discussed briefly.

Kaustinen, O. M., "Polar Gas Project." Presented to the American Gas Association Transmission Conference, Montreal, Quebec, May 8-10, 1978.

Some of the alternative methods of moving natural gas from Canada's Arctic Islands are discussed.

Kee, R. J. and Miller, J. A., "A Split-Operator, Finite Difference Solution for Axisymmetric, Laminar-Jet Diffusion Flames." AIAA Journal. 16(2), February, 1978.

An economical numerical solution of a vertical diffusion flame is presented. The complete chemical kinetics of the problem are included. Discussions of possible numerical treatment of the thermo-hydrodynamics and the "stiff" chemical kinetics are presented. "Majorant" splitting (as opposed to ADI methods) and the Gear-Hindmarsh "stiff" equation methods are utilized in the paper.

Kee, R. J., The Computational Nature of Combustion Modeling, Sandia Laboratories, SAND78-8245, Albuquerque, New Mexico, July 1978.

The report presents a fundamental approach to computations for combustion systems. Specific problems and numerical algorithms are presented.

Keeny, R. L., Kulkarni, R. B. and Nair, K., "Assessing the Risk of an LNG Terminal." Technology Review. pp. 65-71, October 1978.

The report presents a description of LNG risk analysis methods for an import terminal using as its example the risk study prepared for the proposed Elaspsed Natural Gas Co. Matagordo Bay Terminal.

Kelley, C. S., Radiative Transfer Between Flame Burning Zone and Unburned Fuel. EATR-4555, Edgewood Arsenal, Maryland, NTIS No. AD/732405, October, 1971.

An assessment of the complex role of radiative heat transfer in the interaction of fuel and flame is presented. The thermo-physical properties of the fuel are included in the analysis.

King, W. S., On the Fluid Mechanics and Heat Transfer of Liquefied Natural Gas Spills. RAND Corp., P5396, 1975.

A new mathematical model for the interaction between LNG and water is proposed. However, no details are supplied on the analytical and numerical details for practical use of the model.

Kletz, T. A., "Consider Vapor Cloud Dangers When You Build a Plant." Hydro-Carb. Proc. 10:205-212, 1979.

A catalog of 15 items is presented which should be considered when building a facility in which vapor cloud explosions could occur (such as in an LNG plant).

Kneebone, A. and Prew, L. R., "Shipboard Jettison Tests of LNG Onto the Sea." Paper presented at the Fourth International Conference on LNG, Session 5, Paper 5, 1974.

The first part of the paper describes the procedures and results of a series of jettison tests carried out on board ship and discusses the operational safety aspects of such discharges. The second part is concerned with the environmental hazards associated with the release of large quantities of LNG to the sea in terms of the extent of vapor cloud formed; its characteristics and rate of dispersal.

Kogarko, S. M., "Detonation of Methane-Air Mixtures and the Detonation Limits of Hydrocarbon-Air Mixtures in a Large Diameter Pipe." Soviet Physics. 3, 1958.

A review is made of the Russian literature on methane-air detonation. The author describes his work using tubes with diameters up to 0.305 meter and lengths to 12.2 meters. Gas mixtures were initiated with 50/50 amatol explosive charges. The author concludes that the limits and the possibility of a detonation vary with the diameter.

Lancaster, John F., "What Causes Equipment to Fail?" Hydrocarbon Processing. pp. 74-76, January 1975.

This article deals with four main causes of service failure in process equipment. They are: fatigue, general corrosion, stress corrosion cracking and manufacturing defects. Comments and suggestions for reducing each type of failure are included.

Lawrence, G. H., "Comments of the American Gas Association on Delegation of Functions by the Secretary of Energy to the Administrator of the ERA and FERC." American Gas Association, November 15, 1978.

The American Gas Association requests revision of the delegation due to confusing and inconsistent language, a failure to correct jurisdictional overlaps, and the increasing cost of regulations.

Lee, R. H. C. and Happel, J., "Thermal Radiation and Methane Gas," I&EC Fundamentals. 3:167-176, May 1964.

The infrared absorption of methane in three wavelength regions (2.37, 3.31, and 7.65 microns) has been determined at various temperatures and optical depths. The semi-empirical expressions for the bank absorption so obtained are used to calculate the total and band emissivities of methane from 0.01 to 2.0 ft-atm. and from 500° to 3750°R.

Lees, F. P., "Some Data on the Failure Modes of Instruments in the Chemical Plant Environment." Chem. Engineer. 277:418-421, September 1973.

Failure mode data are given based on a previously presented survey of failure rate data for 9500 instruments in chemical works.

Lehto, D. L. and Larson, R. A., Long Range Propagation of Spherical Shockwaves From Explosions in Air. NOLTR 69-88, NTIS No. AD/698121, U.S. Naval Ordinance Laboratory, White Oak, Maryland, July 22, 1969.

Hydrocode calculations for spherical shock propagation using the artificial-viscosity method are carried out to 0.2 psi overpressure for a nuclear explosion and for a TNT explosion. An ideal-gas integration from the literature is used to extend the results to 1.6×10^{-4} *psi. Below 1.0 psi, 1 kiloton nuclear is equivalent to 0.7 kilotons of TNT.*

Leonard, D. A., and Caputo, E., Technical Report: Remote Sensing of LNG Spill Vapor Dispersion Using Raman LIDAR. UCRL-13984, Computer Genetics Corp., Wakefield, MA, 1979.

The feasibility of using a Raman LIDAR scheme for the measurement of LNG vapor concentration has been demonstrated. The report describes the test apparatus and discusses the quality of the obtained results.

Lester, T. W. and Wittig, S. S. K., "Soot Nucleation Kinetics in Pre-mixed Methane Combustion." Presented at the 16th International Symposium on Combustion, 1976.

This paper is an investigation of the early chemical kinetics of soot formation in fuel rich methane flames.

Levine, A. D., Theoretical Models of LNG Dispersion Studies (Phase III - LNG Safety Program), Part I: Modeling of LNG Spills. AGA Project IS-129-1, Technical Report TLN-1, October 17, 1975.

A series of theoretical models relating to the growth and evaporation of cryogenic pools is reviewed, and new ones added in order to allow for complete empirical correlation. Agreement with all experimental results is quite good although the scaling law is somewhat questionable. Continuous spills are modeled using harmonic function analysis with adequate results.

Levine, A. D., Theoretical Models for LNG Dispersion Studies. Report on A.G.A Project IS-129-1, 1975.

Progress reports survey basic relations of detonation phenomena used to emphasize the importance of kinetics and induction time for the initiation process. Current knowledge of explosives in open air gas mixtures suggest that induction time may be very important in correlating experiments with theory.

Levy, M.M., "The Cove Point LNG Terminal: Its First Year of Operation." Paper presented to Seminar and Study Tour on LNG Peakshaving, Washington DC, March 5-9, 1979.

The design and operating experience of the Cove Point LNG terminal is reviewed.

Lewis, D. H., The Dispersion and Ignitability of LNG Vapor Clouds. M.S. Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, June 1974.

The flammability of vapor clouds resulting from instantaneous spills of LNG is determined quantitatively using statistical methods. A new physical theory on the vapor dispersion process is presented and compared to available experimental data. Numerical predictions of distance to various flammability limits are presented graphically.

Lind, C. D., Explosion Hazards Associated With Spills of Large Quantities of Hazardous Materials - Phase I. U.S. Coast Guard Report CG-D-30-75. NTIS No. AD/A001242. October 1974.

This report documents the results of a program to quantify the explosion hazards associated with spills of material such as LNG, LPG, or ethylene. The results are: a phenomenological description of a spill; an examination of the detonation properties of methane; a qualitative theory of non-ideal explosions; a plan for Phase II of the study.

Lind, C. D. and Whitson, J. C., Explosive Hazards Associated with Spills of Large Quantities of Hazardous Materials. Phase II. U.S. Coast Guard Report CG-D-85-77. NTIS No. AD/A047585, 1977.

Tests have been conducted to investigate the burning behavior of LNG type materials. No detonations have been observed in any of these tests.

Lind, C. D. and Strehlow, R. A., "Unconfined Vapor Cloud Explosion Study." NTIS No. AD/A023505, presented at the Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, FL, October 26-30, 1975.

Five-meter radius hemispherical bag tests of ignition of 10% methane/propane-air mixture were conducted. Results indicated that ignition of fuels in this amount does not produce a detonation or damaging pressure waves.

Lind, C. D. and Whitson, J. D., "China Lake Spill Tests." Report L, Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: A Status Report. DOE/EV-0036, Department of Energy, Washington, DC, 1979.

The 1978 LNG spill tests at China Lake are briefly described. No data analysis is included.

Liquid Natural Gas, Characteristics and Burning Behavior. Conch Methane Services, Ltd., Villers House, Strand/London, W.C. 2, England.

A synopsis of a comprehensive engineering report prepared for Conch Methane Services Ltd., based on large-scale field tests conducted near Lake Charles, Louisiana, plus laboratory data from the Bureau of Mines and available information in the literature. Field tests measured the levels of radiation by use of thermopiles; and extinguishment trials, using various extinguishment media, were conducted in conjunction with burning tests.

LNG Safety Program - Interim Final Report. (Draft) R&D Associates Report RDA-TR-1100-006 to the American Gas Association, September 30, 1976.

This program represents a comprehensive LNG safety study and includes the following tasks: LNG spread and boiloff rates, subscale land experiments performed in a wind tunnel, dispersion modeling, radiation and detonation studies, and a field test program definition which represents a major focal point of all other tasks. Emphasis is placed on scaling, instrumentation, and data analysis methodologies.

LNG Safety Program - Interim Report on Phase II Work. A.G.A. Project IS-3-1, Report to the American Gas Association by Battelle Columbus Laboratories, July 1, 1974.

Models for dispersion and radiation were developed, which fit data for 80-ft spills and will predict the hazard for spills into dikes up to 400 to 500 ft dia. Experiments verified reduction of dispersion hazards by insulated dike floors and high dikes. Predictions are given of downwind distances of travel of flammable vapors and radiation intensities on targets near fires on soil, and in low dikes up to 500 ft in dia.

LNG Terminal Risk Assessment Study for Los Angeles. Report by Science Applications, Inc., for Western LNG Terminal Company, December 22, 1975.

Science Applications, Inc., concludes on the basis of this study that LNG risks to populated areas near the Los Angeles Harbor site are extremely low. The physical characteristics of LNG, the design of the facility and tankship and the planned operating rules account for the low risk values.

LNG Wind Tunnel Simulation and Instrumentation Assessments. Report RDA-TR-105700-003, Draft by R&D Associates for the U.S. Energy Research and Development Administration, April 1977.

Information is presented on LNG flame radiation, test site criteria, wind tunnel modeling, and test instrumentation.

Love, T. J., Hood, J. D., Shahrokhi, F. and Tsai, Y. W., "A Method for the Prediction of Radiative Heat Transfer From Flames." ASME Publication 67-HT-47 presented at the ASME-AIChE Heat Transfer Conference and Exhibit, Seattle, WA, August 6-9, 1967.

This paper presents a method, based on the transport equation, to predict the radiative heat flux from methanol and acetone flames of arbitrary size and geometry. Predicted and measured values of the radiative flux were compared for several larger flames and found to be in good agreement for free-burning flames of acetone and methanol.

Mackay, D. and Matsugu, R. S., "Evaporation Rates of Liquid Hydrocarbon Spills on Land and Water." The Canadian Journal of Chemical Engineering. 51:434-439, August 1973.

Experiments on the evaporation of cumene, water and gasoline are described and the evaporation mass transfer coefficient correlated with the windspeed, liquid pool size and the vapor phase Schmidt Number. Comparison of the correlation with flat plate mass transfer correlations shows satisfactory agreement and suggests that turbulent transfer occurs, the rate being enhanced by liquid surface roughness.

Maezawa, M., Experiments on Fire Hazards of Liquefied Flammable Gases. Osaka Gas Company, Ltd., May 1973.

Part I discusses the fire properties of liquefied flammable gases. Part II presents the results of an experiment in fire extinguishing. Part III is concerned with a dispersion experiment. Briefly, the flame temperature of each liquefied gas is 700 to 800°C compared to gasoline at 1100°C. LNG burning rates are much larger than gasoline. Radiation energy is also larger than gasoline.

Magnussen, B. F. and Huertager, "Mathematical Modeling of Turbulent Combustion with Special Emphasis on Soot Formation and Combustion." Presented at the 16th International Symposium on Combustion, pp. 719-729, 1976.

This paper presents a mathematical model of turbulent diffusion and/or premixed flames. Methods for thermal radiation and soot formation predictions are also presented. Soot formation is analyzed as a two-step process (nucleation site formation and soot particle formation). Thermal radiation is evaluated using a two-flux equation.

Maher, J. B. and Van Gelder, L. R. "Rollover and Thermal Overfill in Flat Bottom LNG Tanks." Pipeline and Gas Journal. 199:46-48, September 1972.

Conclusions are that high venting incidents involve thermal overfill; surface layer phenomena occurs in flat bottom LNG tanks filled through bottom with a liquid of saturation pressure greater than pressure capability of the tank; bottom filled tanks should provide venting over entire fill time consistent with degree of thermal overfill; if top layer is continually agitated during filling, thermal overfill will not occur.

Markstein, G. H., "Scaling of Radiative Characteristics of Turbulent Diffusion Flames." Paper presented at the 16th International Symposium on Combustion, 1977.

It is shown that radiative properties of gaseous-fuel turbulent diffusion flames can be scaled successfully over a fairly wide range of fuel flow rates. In addition, radiometric scans were found to provide quantitative information on flame length and diameters and their scaling properties. The work was part of a program to develop a generally applicable model of fire radiation.

Martinsen, W. E., S. P. Muhlenkamp, J. Olson, "Disperse LNG Vapors With Water." Hydrocarbon Processing. 56(7):261-266, July 1977.

This paper discusses the potential for enhancing LNG vapor cloud dispersion by water sprays into the cloud. Experiments showed increased mixing due mainly to mechanical turbulence induced by the watery sprays and a resultant decrease in the distance a vapor cloud spreads before reaching the lower flammability limit.

Masliyah, J. H. and Steward, F. R., "Radiative Heat Transfer From a Turbulent Diffusion Buoyant Flame With Mixing Controlled Combustion." Combustion and Flame. 13:613-625, 1969.

A mathematical model of a turbulent buoyant diffusion flame is postulated. The radiative interchange between the flame and a plane surrounding its base is determined. From this radiative distribution, it is possible to determine the radiative heat flux to the liquid fuel which is vaporizing to feed the flame. A graphical solution is presented which yields the rate of burning of a liquid fuel of given physical properties in a fixed diameter fuel source.

Mathiesen, T. C., Flatseth, H. H., Solberg, D. M. and Tueit, O. J., "Risk Management in Marine Transportation of LNG," 1979.

Measures are being described for dealing systematically with LNG hazards as they might occur in marine transportation. The measures are largely based on reliability engineering results.

May, W. G. and McQueen, W., "Radiation From Large LNG Fires." Combustion Science and Technology. 7(2):51-56, 1973.

Radiation from flames of burning LNG were measured in a burning pool contained in a trench. Burning rates over the range of 13,500 to 40,000 BBL/D of LNG were studied. Measured flux varied from 60 to 480 Btu/hr/ft^2 at ground level and 300 to 600 feet from the flame center and from elevated points. An inverse square law of radiation versus distance held fairly well.

May, W. G., McQueen, W. and Whipp, R. H., "Dispersion of LNG Spills." Hydrocarbon Processing. 52:105-109, May 1973.

The paper discusses data analysis of plume shape and plume dispersion characteristics. Correlations show that dispersion of LNG vapors can be predicted from observed facts and controlled conditions.

May, W. G., McQueen, W. and Whipp, R. H., "Spills of LNG on Water." Paper presented at the American Gas Association Distribution Conference, Washington, DC, May 14, 1973.

The conclusions reached cover: effect of variables on flow rate; inequality of downwind flow rate and evaporation rate; effect of density on plume shape; dependence of plume density on air humidity; effect of plume heating; weather effects; predictions of downwind plume travel.

May, W. G., McQueen, W. and Whipp, R. H., "Spills of LNG on Water." Proc. Div. of Refining, API, pp. 626-653, 1973.

The vapor dispersion from large LNG spills on water was experimentally determined. The tests, carried out by Exxon, were intended to verify and extend results obtained earlier in the Bureau of Mines and Gaz de France tests.

May, W. G., and Perumal, P. V. K., The Spreading and Evaporation of LNG on Water. ASME paper 74 - WA/PID-15, 1974.

The paper proposes a semi-empirical relationship for estimating the total evaporation from a LNG spill on water. Correlations are based on LNG spread rate, maximum pool diameter and evaporation rate per unit area.

McCarthy, D., A Comparison of Mathematical Models for the Prediction of LNG Densities. NBSIR 77-867, National Bureau of Standards, October 1977.

Four mathematical models of the equation of state for LNG like mixtures are compared using experimental data optimized for each model. The objective of predicting LNG densities to within ±0.1% could not be assessed due to discrepacies in the input data. Model listings are included.

McNaughton, D. J. and Berkowitz, C. M., "Overview of U.S. Research Activities in the Dispersion of Dense Gases." Symposium Schwere Gase (Heavy Gas), Battelle-Institute, Frankfurt, F6 R, September 3-4, 1979.

This paper presents an overview of U.S. research in heavy gases particularly LNG. Topics include mathematical modeling, experiments, and facility controls available to decrease gas release or increase gas cloud dilution. Recommendations on further research are included.

Meinen, E., "LNG Storage in Prestressed Concrete Safety Walls - 1." Oil and Gas Journal. May 14, 1979.

The concrete safety wall incorporated in the design of the Maasvlakte LNG plant in the Netherlands is described. The properties of steel and concrete at cryogenic temperatures are reviewed.

Meinen, E., "LNG Enclosure Design - 2." Oil and Gas Journal. May 21, 1979.

The design, testing and construction steps for the retaining wall and the tank foundation of the Maasvlakte LNG plant are outlined. Analytical procedures and test results are described.

Mellor, G. L. and Yamada, T., "A Hierarchy of Turbulence Closure Models for Planetary Boundary Layers." Journal of the Atmospheric Sciences. pp. 1791-1806, October 1974.

Turbulence models centered on hypotheses by Rotta and Kolmogoroff are complex. In the present paper, we consider systematic simplifications based on the observation that parameters governing the degree of anisotropy are small. Discussion is focused on density stratified flow due to temperature.

Meroney, R. N., Neff, D. E. and Cermak, J. E., "Wind Tunnel Modeling of LNG Spills." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

The author's report scales of spill conditions that may be successfully simulated in Colorado State University wind tunnels. Simulations of 1974 AGA LNG land spill experiments and uses of wind tunnels in experimental design are also discussed.

Miller, B., "Possibilities in Hydrate Storage of Natural Gas." Gas Age. 97:37-40, May 1942.

The formation of methane and LNG hydrates was reviewed. Data concerning hydrate storage, properties and decomposition pressures were discussed. Refrigeration and heat requirements for hydrate storage and regeneration were also presented.

Miller, R. C. and Hiza, M. J., "Experimental Molar Volumes for Some LNG-Related Saturated Liquid Mixtures." Fluid Phase Equilibria. 2:49-57, 1978.

Saturated (orthobaric) liquid molar volumes are reported for some methane-rich mixtures containing ethane, propane, isobutane, normal butane and nitrogen at temperatures between 100 and 115 K. These data were obtained with a gas-expansion system calibrated against pure methane orthobaric liquid molar volumes. Comparisons are shown between the experimental molar volumes and the results of some recent calculational methods.

MITRE Corp., A Summary of Accidents Related to Non-Nuclear Energy. EPA 600/9-77-012, PB-271506, 1977.

This report is an executive summary of a more extensive EPA study on accidents, in non-nuclear energy. LNG accidents are covered rather briefly, since only a few accidents have occurred in this category.

Modak, A. T., "Thermal Radiation From Pool Fires." Paper presented at Western States Section, The Combustion Institute Meeting, La Jolla, CA, October 18-20, 1976.

This analysis computes: radiative energy fluxes to surfaces located external to the fire in any arbitrary orientation; variations of radiative heat flux along the fuel surface; total radiative heat transfer from flames to fuel surface; forward radiative heat transfer from fire to virgin fuel bed external to the fire; angular distribution of radiative flux emitted by the pool fire; total radiative power output of the fire.

Montoya-Lirola, C., "Manufacture of Gels, Especially Liquid Fuels, and Their Subsequent Reversible Liquefaction." Chem. Abstrac. 76:27001g, Span. 362, 146 (to Gelsa S. A.), 1970.

LNG could be gelled by generating a mixture of 20 percent water containing 2.5% of a vegetable albuminoid, saponin or viscous resinous gum with 80% LNG.

Morton, B. R., "Modeling Fire Plumes." Paper presented at the Tenth International Symposium on Combustion, Cambridge, UK, August 17-21, 1964.

Theoretical treatments for turbulent diffusion flames and for the strongly heated regions of fire plumes in a still environment may be based on those developed for weakly buoyant plumes. A discussion is given of some of the modifications that are needed, and the effects of large variations in density on the plume dynamics are aspects of heat transfer by radiation are presented separately.

Mullen, F. et al., Thermal Radiation and Overpressures from Instantaneous LNG Release into the Atmosphere - Phase II. TRW Systems Group Report No. 08072-9, to A.G.A., A.G.A. Catalog No. M60015, May 1969.

This report considers the fluid mechanics and thermochemistry of thermal radiation; boil-off, LNG vapor/air mixture dispersion experiments, and blast of overpressure; dike design; and a discussion of the flame program and vapor cloud studies.

Multhauf, L. G., Frank, A. M. and Koopman, R. P., Remote Measurement of LNG Vapor Dispersion Using LIDAR. UCID-17968-79-1, pp. 15-22 Lawrence Livermore Laboratory, 1979.

This is essentially an abbreviated version of Lawrence Livermore Laboratory report UCID-18237.

Multhauf, L. G., Frank, A. M. and Koopman, R. P., Remote Sensing for Diagnosing Vapor Dispersion in Spills of Liquid Energy Fuels. UCID-18237, Lawrence Livermore Laboratory, 1979.

A laser ranging (LIDAR) technique is described for measurement of gas concentrations in vapor clouds emanating from LNG spills. Results of a feasibility test at China Lake are discussed.

Munson, R. and Clifton, R. A., "Natural Gas Storage with Zeolites." PB Report No. 203892. U.S. National Technical Information Service, 1971.

Zeolites were used as an adsorbent for methane. For instance, Calcium A zeolite would retain up to 5 weight percent methane at 72°F and 200 psia. The potential of zeolites for vehicular natural gas storage was discussed.

Murgai, M. P., "Radiative Transfer Effects in Natural Convection Above Fires." Journal of Fluid Mechanics. 12(3):441-448, March 1962.

This paper describes the results of examining the influence of radiative heat transfer on turbulent natural convection above fires in an atmosphere of constant potential temperature, under both the 'opaque' and 'transparent' approximations. It turns out that on the basis of the overall approximations introduced in this investigation, the former case reduces to that of no radiative transfer.

Murgai, M. P. and Emmons, H. W., "Natural Convection Above Fires." Journal of Fluid Mechanics. 8:611-624, 1960.

The turbulent natural convection above fires in a dry calm atmosphere with a constant lapse rate has been the subject of several recent investigations. The present paper presents solution curves from which the natural convection may be computed over a fire of arbitrary size in an atmosphere with arbitrary lapse-rate variation.

Murray, F. W., Atmospheric Dispersion of Vaporized Liquefied Natural Gas. Rand Corp. Rpt. P5360, AD/A010940, 1975.

A sophisticated mathematical model for the dispersion of LNG clouds is proposed. However, no details on the equations and on their numerical treatment are given.

Murray, F. W., Jaquette, D. L. and King, W. S. Hazards Associated with the Importation of Liquefied Natural Gas. Rand Corp., NTIS No. AD/A037928, June 1976.

Four previous reports by Rand Corporation are summarized and updated in this most recent publication, which discloses probable cause of accidental spills of LNG, the hazards surrounding these spills, and methods of estimating the probabilities of major accidents. In assessing the risks associated with LNG transport and processing, it is concluded that not enough evidence has been collected to comment on the safety of LNG or the ability to extrapolate from past experience.

Muscari, C. C., The Evolution of Liquid Natural Gas on Water. M. S. Thesis, MIT, 1974.

Governing equations are given for the simultaneous spread and evaporation (burning) of an LNG spill on water. Equation solutions determine the 1) maximum radial extent of the spill, 2) time duration of complete dissipation of spill volume, 3) graphics of spill volume versus time, evaporation rate versus time and spill thickness versus distance (from origin of spill).

Nakagawa, A., "Japanese LNG Receiving Terminal is Reliable." Oil and Gas Journal. pp. 174-182, January 28, 1980.

The design, operation, and maintenance characteristics of the Sodegaura Terminal are described. The computer control system and the preventive maintenance operations are outlined.

Nakanishi, E. and Reid, R. C., "Liquid Natural Gas-Water Reactions." Chemical Engineering Progress. 67:36-41, December 1971.

This paper cites previous studies and discusses both quantitative and qualitative experimental results. Consideration is given to water on cryogens, underwater release of cryogens, cryogens on ice, cryogen spills on water and on coated liquids. Finally, a tentative hypothesis is presented for the explosion phenomena.

Neary, R. M., "Safety in LNG Semi-Trailer Design." Paper presented to the AGA Transmission Conference, Las Vegas, Nevada, May 3, 1976.

Included in this paper is a description of LNG semi-trailers and the various DOT regulations regarding them. Also included is a discussion of and a picture of an LNG trailer that was exposed to a fire as a result of an accident.

Nelson, W., "A New Theory to Explain Physical Explosions." Combustion. 44, May 1973.

This paper summarizes some known facts about explosions, with emphasis on physical explosions, describes a new explosion mechanism, and suggests current and future applications of the new theory to prevent smelt-water explosions in kraft chemical recovery furnaces.

Newell, R. G., "Station Coordination Critical in LNG Pipeline Efficiency." Oil and Gas J. 77(18):239-244, 1979.

Pumping and cooling stations along an LNG pipeline must be designed for unattended operation and must use only LNG as the source of energy. Technology for such pipeline operation is proven. The paper presents guidelines for the overall design of an LNG pipeline.

Nielson, H. J. and Tao, L. N., "The Fire Plume Above a Large Free-Burning Fire." Paper presented at the Tenth International Symposium on Combustion, Cambridge, U.K., August 17-21, 1964.

A model which describes the variation with altitude of the composition, temperature, and velocity of the gases within a plume above a large free-burning fire is presented. This model is an extension of previous analysis of buoyant plumes which includes the effects of combustion, composition variation, and radiation losses from the hot gases.

Nierman, A. J., "Transportation of Natural Gas as a Hydrate." U.S. Patent 3,975,167 (to Chevron Research Co.), U.S. Patent Office, 1976.

Transportation of LNG hydrate by submarine was described. This procedure required supplementary refrigeration, a hold or void in which natural gas can be hydrated, and a membrane pervious to gas and water within the hold. Provisions were suggested for in situ removal of hydrate heat of formation.

Nikodem, H. J., Flothmann, D., Geiger, W., Schnatz, G. and Schneider, W., "Risk Assessment Study for an Assumed LNG Terminal in the Lysekil Area." prepared for the Swedish Energy Commission by the Battelle-Institute E.V. Frankfurt BR-R-31.109-1, 1978.

This report presents a risk assessment for a proposed LNG terminal and distribution system in Sweden using state-of-the-art dispersion and gravity/spread models. Risks included direct contact with LNG, suffocation, radiation and pressure wave destruction.

Nuclear Regulatory Commission, "Safety Evaluation by the Office of Nuclear Reactor Regulation Regarding the Proximity of Cove Point LNG Facility: Baltimore Gas and Electric Company Calvery Cliffs Nuclear Power Plant Units Nos. 1 and 2." Docket Nos. 50-317 and 50-318, March 13, 1978.

An analysis is described which shows the effects of various hypothetical LNG accidents at Cove Point on the Calvert Cliffs Power Plant. Results indicated that no new operating restrictions or other limitations needed to be placed on the plant to assure normal operations.

Office of Technology Assessment, Transportation of Liquefied Natural Gas. Congress of United States, Washington, DC.

A review of LNG transportation technology provided as support for Congress on Future Energy Legislation. The LNG import system is criticized; public concerns are summarized; and laws, permit requirements and pending legislation are examined.

"Offshore LNG Terminal Deemed Feasible." Marine Equipment News. pp. 6-7, Spring 1977.

This article discusses the potential of offshore receiving terminals and describes several generic types that could be used. There are currently no offshore terminals in operation or construction, however, due to onshore siting difficulties they are being given serious attention.

Ohsaka, K. et al., Membrane Structure in a Liquefied Gas Storage Tank. U.S. Patent 4,149,652, 1979.

An improved structural design for LNG storage tanks is described. It minimizes thermal strains and practically eliminates potential sources of leaks that were present in earlier designs. Required labor for installing the new tanks is also greatly reduced.

Opschoor, G., "Investigations into the Spreading and Evaporation of LNG Spilled on Water." Cryogenics. 17:629-633, 1977.

Analytical expressions for the spreading of LNG spills on open and confined areas of water have been derived. They agree with known available experimental data.

Ordin, Paul M., Bibliography on Liquefied Natural Gas (LNG) Safety. NASA Technical Memorandum, NASA TM X-73408, April 1976.

This bibliography contains citations concerned with the safety of LNG and liquid methane. The raw data for this report was a computer printout based on a keyword search strategy of descriptions in the cryogenic safety data bank dealing with LNG.

O'Rourke, P.J. and F. Bracco, "Two Scaling Transformations for the Numerical Computation of Multidimensional Unsteady Laminar Flames." Journal of Computational Physics. 3(2), November 1979.

The authors of this paper address the problem of flame propagation in a multi-dimensional system. Problems involving sonic propagation and small flame thickness are solved by means of a transformation. An actual simulation of combustion of methane in a chemical bomb are presented.

Otterman, B., "Analysis of Large LNG Spills on Water - Part 1: Liquid Spread and Evaporation." Cryogenics. 15(8):445-460, August 1975.

The first part of this two-part review considers the theoretical and experimental results obtained on liquid spread and evaporation of large LNG spills on water. Both instantaneous spills, in which the spill time is much smaller than the time for complete vaporization, and continuous spills are considered. Also, applications of the correlations are discussed.

Overly, J. R. and Overholsen, K. A., "Calculation of Minimum Ignition Energy and Time Dependent Luminar Flame Profiles." Combustion and Flame. 31:60-83, 1978.

The authors simplify the calculational method of Spalding by use of a transformation of variable. The authors employ this technique to calculate ignition energy and flame propagation.

Panofsky, H. A., "The Atmospheric Boundary Layer Below 150 Meters." Annual Review of Fluid Mechanics. 6:147-177, 1974.

The article considers profiles and fluxes over homogeneous terrain (surface layers, extension to the tower layer) and profiles over changing terrain (wind profiles, temperature characteristics, energy budgets, horizontal velocity components, temperature and humidity spectra, cospectra, and boundary layer models).

Parent, J. D., "The Storage of Natural Gas as Hydrate." Institute of Gas Technology Bulletin No. 1. 1948.

A very thorough review of the technical literature was presented. This included phase diagrams, heats of reaction, equilibrium ratios, cooling requirements, and operating pressures.

Parker, R. O., "Calculating Thermal Radiation Hazards in Large Fires." Fire Technology. 10(2):147-152, 1974.

The author has developed, and discusses here, a method for assessing the thermal radiation hazards to objects from fires. A comparison of the calculations to an actual fire experience seems to indicate that the method is reasonably accurate, though somewhat conservative.

Parker, R. O., "Study of Downwind Vapor Travel From LNG Spills." Paper presented at the American Gas Association Distribution Conference, May 1970.

The problem can be treated as a heat transfer calculation at the earth-liquid interface yielding the input; a second heat transfer problem if there is no wind, or if there is wind, an atmospheric dispersion problem. The conclusion is that it is very unlikely that vapor concentrations of more than 1/2 the lower flammable limit will exist 600 or more feet downwind of the lee dike.

Parker, R. O. and Spata, J. K., "Downwind Travel of Vapor From Large Pools of Cryogenic Liquids." Paper presented at LNG-1 Conference, Chicago, IL, 1968.

A method is developed for calculating vapor concentrations downwind of large pools of cryogenic liquids. Vapor concentrations at any downwind position is found as a function of time, wind speed, and wind structure. Lateral and vertical dispersion coefficients are determined using meteorological observations. Practical applications include hazard studies and air pollution estimates.

Parrish, W. R., Arvidson, J. M. and LaBrecque, J. F., "Evaluation of LNG Sampling Measurement Systems for Custody Transfer." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

A method for sampling moving LNG streams for composition and heating value is described. The main component of the technique and the main source of error is a gas chromatograph.

Parrish, W. R., Arvidson, J. M. and LaBrecque, J. F., "System is Accurate, Precise for LNG Sampling." Hydrocarbon Processing. April 1978.

A three component system including a sampling probe, vaporizer, and gas analyzer is described which can be used to monitor heating value from moving streams of LNG. Detection error is derived mainly from error in the gas analyzer.

Parrish, W. R., Brennen, J. A. and Siegwarth, J. D., "LNG Custody Transfer Research at the National Bureau of Standards." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

This paper presents a summary of research on determining the thermophysical properties of LNG components, on flowmeters, and on LNG sampling and composition measurements.

Patankar, S. V. and Spalding, D. B., Heat and Mass Transfer in Boundary Layers. International Textbook Company, Ltd., 2nd edition, London, U.K., 1970.

The authors of this text describe a computational technique for solving the time dependent conservation equations (mass, momentum, energy and species) needed to describe flame propagation in one-dimensional planar, cylindrical or spherical geometry.

Pergament, H. S. and Fishburne, E. S., "Influence of Buoyancy on Turbulent Hydrogen/Air Diffusion Flames." Paper presented at the Central States Section Combustion Institute Meeting on Fluid Mechanics of Combustion Processes, Cleveland, OH, March 29-30, 1977.

The results show that: flame properties scale with nondimensional distance for Froude numbers (Fr) greater than about 10^6*; buoyancy affects temperature decay rates downstream of the location of maximum temperature (after all the* H_2 *has burned); the predicted influence of Fr on buoyant flame lengths is consistent with the available data.*

Petsinger, R. E. and Vance, R. W., LNG Terminals and Safety Symposium - Applications of Cryogenic Technology Volume 9, 1979.

The proceedings of the LNG Terminals and Safety Symposium held October 12-13, 1978, in San Diego, CA, are provided. Session topics include: LNG Export Terminals, LNG Import Terminals, and LNG Research and Safety.

Petrash, D. A., Barber, J. R., Chambellan, R., and Englund, D. R., "Gelled Liquid Methane." NASA Spec. Publ. NASA SP-5103, Sel. Technol. Gas Ind. pp. 86-88, 1975.

Results of work toward use of LNG as fuel for supersonic aircraft was reported. The problem of "boiloff" due to decrease of pressure with altitude was eliminated by preparing LNG gels with water or methanol. LNG-methanol gel was recommended due to the total heat of combustion.

Pfoertner, H., "Ignition Behavior of Natural-Gas/Air Mixtures in Free Clouds." Gas-Wasserfach, Gas/Erdas. 120(1):19-24, 1979 (in German). (For translation see Lawrence Livermore Laboratory UCRL-TRANS-11478.)

Based on combustion analysis it is concluded that only deflagrations and no detonations would occur when a natural-gas/air cloud is ignited. This conclusion is backed up by a series of tests.

Pipkin, O. A. and Sliepcevich, C. M., "Effect of Wind on Buoyant Diffusion Flames." Industrial and Engineering Chemistry Fundamentals. 3:147-154, 1964.

Buoyant diffusion flames of natural gas were observed in wind tunnel experiments to determine the extent of bending by wind. A flame drag coefficient, C_f, is introduced in the flame momentum balance. A single straight-line correlation of In C_f(Re) versus In Re is obtained after extracting the influence of flame angle of tilt and applying an empirical correction to account for increasing flame roughness at larger diameters.

Ploum and Arnold, J. W., "The Brunei Liquefied Natural Gas Plant." LNG 5 - International Conference on Liquefied Natural Gas, Duesseldorf, Germany, August 29-September 1, 1977.

This paper reviews and highlights some of the design concepts and operating experiences gained particularly from the liquefaction plant at Brunei.

Porricelli, J. D., Keith, V. E. and Paramore, B., Recommended Qualifications of Liquefied Natural Gas Cargo Personnel, Volumes I, II and III. NTIS No. AD/A026109, AD/A026110, April 1976.

The report presents recommendations, based on task analysis, concerning training and other qualification requirements appropriate for personnel of liquefied natural gas (LNG) ships and barges.

The study was a pilot effort to demonstrate a method of determining qualifications for new technology ship occupations when there are few or no operating examples to study.

Porteous, W. M. and Blander, M., "Limits of Superheat and Explosive Boiling of Light Hydrocarbons, Halocarbons, and Hydrocarbon Mixtures." AIChE Journal. 21:560-566, May 1975.

Thirteen light hydrocarbons and 4 light halocarbons were tested to determine their limits of superheat at one atmosphere pressure using a superheating column. Even with some variation in temperature to which a compound could be superheated before boiling explosively, the reduced limits T_L/T_C were always close to 0.88. Super heat limits of binary hydrocarbon systems and tertiary mixtures were close to mole fraction averages of the limits of the pure compounds.

Porteous, W. M. and Reid, R. C., "Light Hydrocarbon Vapor Explosions." Chemical Engineering Progress. 73:83-89, May 1976.

This article includes information relating to spills on water of propane, propylene, isobutane, binary mixtures containing ethane, pure alkanes and pure alkenes. Some explosive compositions and ranges for hydrocarbon spills are also given. Previous studies are cited and factors affecting violence of explosions are discussed.

Priestley, C. H. B. and Taylor, R. J., "On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters." Monthly Weather Review. 100(2):81-92, February 1972.

Data from a number of saturated land sites and open water sites in the absence of advection suggest a widely applicable formula for the relationship between sensible and latent heat fluxes.

Putnam, A. A., "A Model Study of Wind-Blown Free-Burning Fires." Paper presented at the 10th Symposium on Combustion, The Combustion Institute, 1965.

Specifically, the dimensionless flame height varied with the negative 1/4-power of the Froude number based on cross-wind velocity and undisturbed flame height, above a Froude number of 0.2. The horizontal extension of the flame, on the other hand, increased rapidly with increasing cross wind at first, and then less rapidly with the 1/6-power of the Froude number.

Putnam, A. A., "Area Fire Considered as a Perimeter-Line Fire." Combustion and Flame. 7:306-307, 1963.

The hypothesis that line fires and area fires are basically related was tested by examining available data on sources in a line and in a hexagonal pattern. A mathematical analysis is given to justify the hypothesis.

Putnam, A. A. and Grinberg, I. M., "Axial Temperature Variation in a Turbulent, Buoyancy-Controlled, Diffusion Flame." Combustion and Flame. 9(4):419-420, 1965.

An analytical expression was formulated which correlated the temperature profile of a turbulent diffusion, buoyancy-controlled flame to fuel properties and flow conditions. The expression is valid in the region after combustion is completed, and is valid at higher temperature levels than previously used correlations which are accommodated as a limiting case.

Putnam, A. A. and Speich, C. F., "A Model Study of the Interaction of Multiple Turbulent Diffusion Flames." Paper presented at the 9th International Symposium on Combustion, 1963.

This research program has shown that a valid model for studies of mass fires can be produced using multiple jets of gaseous fuels. The basic requirement is that the fuel jets produce turbulent diffusion flames which are buoyancy controlled. A specific operating range where this requirement is met was found for this model.

<u>Radiative Transfer in Multidimensional Systems of Non-Gray Molecular Gases - Effects on Combustion</u>. Columbia University. A.G.A. Project on LNG Fire Study. (See LNG 1976 Annual Report).

An analytical technique has been developed to treat band radiation from non-gray molecular gases. The technique has been simplified so that the frequency integrations can be performed with simple quadrature formulae. The simplified technique is being applied to multidimensional radiative transfer problems as well as problems involving combustion.

Raj, P. and Atallah, S., "Thermal Radiation from LNG Spill Fires." <u>Advances in Cryogenic Engineering</u>.

The authors of this paper present results of experimental measurements made in LNG fires which were 6, 20 and 80 ft in diameter. Correlations are given for the wind induced plane tilt angle and length to diameter ratio of the flame. Also measured are the radiative absorption coefficient, radiative flux at a distance from the plume and the fraction of energy which leaves the fire as thermal radiation.

Raj, P. and Emmons, H. W., "Burning of a Large Flammable Vapor Cloud." Paper presented at the Central States Section, Combustion Institute Meeting, San Antonio, Texas, April 21-22, 1975.

A theoretical analysis is presented to estimate the ground level width of a two-dimensional turbulent flame as a function of time for the burning of a large combustible vapor cloud in the atmosphere for a given turbulent flame speed. The base width of the flame is assumed to be controlled by the rate at which the vapor is fed into the combustion zone and the air entrainment rate.

Raj, P. and Kalelkar, A. S., Assessment Models in Support of the Hazard Assessment Handbook. A report by Arthur D. Little, Inc., to the Department of Transportation, U.S. Coast Guard, Report Numbers CG-D-65-74. NTIS No. AD/776617, January 1974.

Analytical models are derived to describe the hazards caused by the accidental release of chemicals into the atmosphere or spills onto water. The models encompass a variety of physical phenomena that can occur such as dispersion of vapor in the atmosphere, dispersion of liquid in water, spreading on water, burning of a liquid pool, etc. Analyses include the modeling of the phenomenon and solution to equations.

Raj, P. and Kalelkar, A. S., "Fire Hazard Presented by a Spreading, Burning Pool of Liquefied Natural Gas on Water." Paper presented at the Western States Section, Combustion Institute Meeting, 1973.

A time-growth rate for an LNG spill on water is obtained and the fire duration, determined by complete evaporation time, is established. An effective flame height is established and the radiation field about the flame calculated. Based on thermal radiation flux and fire duration, safe separation distances from the LNG pool fire for people and combustible materials (wood) are determined.

Ramsdell, J. V., Jr. and Hinds, W. T., "Concentration Fluctuations and Peak-to-Mean Concentration Ratios in Plumes From a Ground-Level Continuous Point Source." Atmospheric Environment. 5:483-495, 1971.

Diffusion data were collected by 63 incremental samplers during four short duration, continuous releases of ^{85}Kr. Cumulative frequency distributions and the intensity of short-term concentrations are shown to be a function of the relative crosswind position within the mean plume. Peak-to-mean concentration ratios are shown as a function of relative crosswind position within the plume and the ratio of the durations of the mean and peak.

Rasbach, D. J., Rogowski, A. W. and Stark, G. W. V., "Properties of Fires of Liquids." Fuel. 35:94-107, 1956.

Alcohol, petrol, benzole and kerosene fires, burning freely in a vessel of 30 cm dia, have been studied. Measurements were made on the temperature, rate of burning and change in composition of the liquid, and on the dimensions, upward velocity, temperature and emissivity of the flames. It was estimated that with hydrocarbon liquid fires, heat transfer to the surface was mainly by radiation, but for the alcohol fire mainly by conduction.

Rausch, A. A. and Levine, A. D., "Rapid Phase Transformations Caused by Thermodynamic Instability in Cryogens." Cryogenics. 13:224-229, April 1973.

Thermodynamic metastability and incipient stability are used to explain the cause of rapid phase transformations. When liquid cryogen comes into sudden contact with a warmer host liquid, it is heated and forms a thin layer of metastable, superheated liquid at the interface. A heat transfer and thermodynamic model is used to predict the host liquid temperature that will cause a shockwave for a given cryogen.

Raynor, G. S., Michael, P., Brown, R. M. and SethuRaman, S., "A Research Program on Atmospheric Diffusion from an Oceanic Site." BNL 18924 presented at the Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, CA, September 9-13, 1974.

Analyses of meteorological data collected in this program show that wind profiles measured on the beach are representative of those over the ocean during onshore flows. Data obtained from tracer releases show that diffusion over the sea differs appreciably from that over land at the same time and is largely determined by the air-water temperature difference.

Raynor, G. S., Michael, P., Brown, R. M. and SethuRaman, S., Studies of Atmospheric Diffusion From a Near-Shore Oceanic Site. BNL 18997, Brookhaven National Laboratory, June 1974.

Preliminary results show that diffusion is governed primarily by water and air temperature differences. With colder water, low-level air is very stable and diffusion minimal but water warmer than the air induces vigorous diffusion.

Reid, R. C., "Possible Mechanism for Pressurized-Liquid Tank Explosions or BLEVE's." Science. 203:1263-1265, 1979.

The hypothesis is made that rapid depressurization of hot saturated liquids may result in an explosion. Such a situation could arise, e.g., if a tank filled with liquefied propane would be engulfed in a fire due to some accident.

Reid, R. C., "Superheated Liquids." American Scientist. 64(2):146-156, March - April 1976.

The article cites numerous studies concerning superheated liquids and indicates that significant evidence suggests that superheated liquids are a trigger leading to the extensive arrangementation that may well set off large vapor explosions.

Reid, R. C. et al., Flameless Vapor Explosions. American Gas Association, Catalog No. M20177, 1977.

Flameless vapor explosions are discussed for a wide variety of substances, including LNG. Theoretical explanations are based on the superheat limit temperature.

Reid, R. C. and Smith, K. A., "Behavior of LPG on Water." Hydrocarbon Processing. pp. 117-121, April 1978.

Boiling of LPG is described as initially but very briefly violent followed by quilt evaporation. Boiling rates are not sensitive to changes in composition.

Reid, R. C. and Smith, K. A., Boil-Off Rate of Liquid Nitrogen and Liquid Methane on Insulated Concrete. Interim Report from MIT LNG Research Center to A.G.A., December 1975.

Experiments were conducted to measure the boil-off rate of both liquid nitrogen and liquid methane on insulation concrete. Results are fragmentary but do allow approximations of the rate of vapor generation that could result from spills of cryogens on typical insulating concretes.

Reid, R. C. and Wang, R., "The Boiling Rates of LNG on Typical Dike Floor Materials. Cryogenics. 18(3):401-404, 1978.

The insulating qualities for various types of floor materials for LNG dike storage compounds have been determined in LNG boiling tests. Their numerical values are tabulated.

Reisler, R. E., Ethridge, N. H., LeFevre, D. P. and Giglio-Tos, L., Air Blast Measurements From the Detonation of an Explosive Gas Contained in a Hemispherical Balloon (Operation Distant Plain, Event 2a). Ballistic Research Laboratories, BRL MR 2108, AD/73216, U.S. Army Aberdeen Research and Development Center, Aberdeen Proving Ground, Maryland, July 1971.

Air blast was measured from the detonation of a mixture of oxygen and propane equivalent to 20 tons of TNT in a hemispherical balloon anchored to the ground surface. Comparisons made of overpressure waveshape and impulse as a function of shock overpressure show an equivalent yield of 20 tons or larger and a dynamic pressure impulse about 60 percent larger than for a corresponding 20 ton TNT charge.

Rhoads, R. E. and Johnson, J. F., "Risk in Transporting Materials for Various Energy Industries." Nuclear Safety. 19(2):135-149, March-April 1978.

A risk assessment model is presented to assess the comparative safety of various energy systems in relation to other natural or man-related risks. Examples from assessments using the analysis technique are also presented along with future assessment plans. This paper encourages risk sensitivity studies and risk comparisons to provide a basis for decisions.

Ricou, F. P. and Spalding, D. B., "Measurements of Entrainment by Axisymmetrical Turbulent Jets." Journal of Fluid Mechanics. 11:21-32, 1961.

Measurements have allowed the deduction of an entrainment law relating mass flow rate, jet momentum, axial distance, and air density. When the injected gas burns in the jet the entrainment rate is up to 30% lower than when it does not.

Riedl, R. G., "Consumers' Gas LNG Satellite Firms Ottawa Valley Gas Supply." Pipeline & Gas J. 206(13):30-36, 1979.

New LNG peakshaving satellite plant, supplied from Montreal LNG peakshaving/ liguefaction plant, is ideally located in middle of service area and has proven itself in both emergenices and for peakshaving service.

Rigard, J. and Vadot, L., "Evaluate LNG's Storage Hazards." Hydrocarb. Process. pp. 267-268, July 1979.

It is shown that experimental water modeling, based on Neyrtrec's water analog technique, can be a useful aid to planning protection of LNG tankage.

Rivard, W. C., Farmer, O. A. and Butler, T. D., RICE: A Computer Program for Multicomponent Chemically Reactive Flows at All Speeds. LA-5812, March 1975.

A computer code capable of solving the thermal-hydrodynamics of chemically reactive flows is presented. A strong point of the code is that it is not limited by sonic propagation constraints.

Rosenberg, S. D. and Vander Wall, E. M., "Gelled Cryogenic Liquids and Method of Making Same." U.S. Patent 4,011,730 (to Aerojet-General Corp.), 1977.

LNG or methane hydrates were prepared by introducing finely divided solid water or methanol into the cryogenic liquid. Less than 2 weight percent decreased the solubility of nitrogen in LNG to nearly zero at -280°F.

Russ, R. M., Detection of Atmospheric Methane Using a 2-Wavelength H_eN_e Laser System. Masters Thesis, Mass. Institute of Tech., June 1978.

The report describes the design of a system to reliably measure concentrations of methane in air of o.1 to 100% which may arise in LNG spill tests. Discussions of design requirements, alternatives, and model and laboratory test results are presented.

Santman, L. D., "The Department of Transportation's Role in LNG Safety Regulations." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

DOT authority over LNG safety is derived from the ports and waterways safety Act of 1972 and the natural gas pipeline safety Act of 1968. Proposed regulatory action on HR. 11622 is discussed.

Sarkes, L. A., Iribe, P. C. and Smith, R. B., "LNG: Current Status Confirms Its Technical Maturity." Pipeline and Gas Journal. November 1978.

The history and current developments in the LNG industry are summarized. Some of the safety concerns and safety related research are discussed.

Sarsten, J. A., "LNG Stratification and Rollover." Paper presented at the API Division of Refining, Philadelphia, PA, May 17, 1973.

This report covers an incident where LNG was stratified in an LNG storage tank during filling and how that stratification subsequently resulted in a rollover of the tank contents and the release of a large quantity of gas. A repetition will be positively prevented by the installation of a jet mixing nozzle that will thoroughly mix off-loaded cargo with different composition initial tank heels.

Schneider, A. L., "Liquified Natural Gas Safety Research." American Gas Association - Cryogenic Society of America, LNG Terminal and Safety Symposium, San Diego, 1978.

The paper summarizes experimental research programs for safety issues related to LNG transportation and storage.

Schneider, A. L., "LNG Research Overview." Proceedings of the Marine Safety Council, 36(3):52-54, 1979.

A condensed overview is given on U.S. Coast Guard sponsored safety projects connected with the marine transportation of LNG. The projects and their main results are listed briefly.

Schuller, M. R., Murphy, J. C. and Glasser, K. F., "LNG Storage Tanks for Metropolitan Areas." Paper presented at the 4th International LNG Conference, Algiers, Algeria, June 24-27, 1974.

This article describes in some detail the special design features of the 290,000 BBL storage tank built for Consolidated Edison of New York by the Pittsburg Des Moines Steel Company. The special design features, including a 9% Ni outer tank shell and a concrete berm wall around the outside of the tank, were used because of the heavily populated surrounding area and the proximity of the facility to LaGuardia Airport.

Science Applications, Inc., LNG Terminal Risk Assessment Study for Los Angeles, California. SAI-75-614-LJ, for Western LNG Terminal Company, Los Angeles, CA, 1975.

SAI analyzed the potential risk of a proposed LNG import terminal in Los Angeles Harbor.

Sergeant, R. J. and Robinett, F. E., An Experimental Investigation of the Atmospheric Diffusion and Ignition of Boil Off Vapors Associated With a Spillage of Liquefied Natural Gas. TRW Systems Group Report No. 08072-7, to A.G.A., A.G.A. Catalog No. M19715, November 14, 1968.

Results of experimental spills of LNG into scaled earthen dikes are described. Emphasis of this phase of the program was directed toward qualitatively determining the path of the boil-off vapors, quantitatively measuring the gas/air mixture in the surrounding environment, and demonstrating the extent of the flammability with an ignition source. Correlation of the experimental data into empirical form is presented; radiation data were also obtained.

Seroka, S. and Bolan, R. J., "Safety Considerations in the Installation of an LNG Tank." Cryogenics and Industrial Gases. pp 22-27, September/October, 1970.

Design codes and standards for LNG storage tanks are detailed. Diagrams showing instrumentation for a typical tank are included.

Shaheen, E. I. and Vora, M. K., "Worldwide LNG Survey Cites Existing, Planned Projects." Oil and Gas Journal. pp 59-71, June 20, 1977.

This article discusses the various types of LNG facilities and briefly describes several existing facilities. A list of all the LNG facilities worldwide is included.

Shaw, P. and Briscoe, F., Evaporation from Spills of Hazardous Liquids on Land and Water. SRD R-100, 1978.

Mathematical models for an analytical description of cryogenic liquid spills both on water and on land are being developed and evaluated. Numerical results are given.

Shell International Research, "Transportation of Liquefied Natural Gas." Chem. Abstr. 66:97298b, Neth. Appl. 6,506,843, 1966.

An aqueous isopentane emulsion was used as a recyclable thermal carrier for heating or cooling LNG. A solid phase, such as silica-gel, was also suggested.

Shultz, F. D., "Safety at an LNG Peakshaving Facility." Presented at the ASME Winter Meeting, New York, NY, November 17-22, 1974.

Design and operation of the many safety related aspects of Long Island Lighting Company's Holbrook LNG plant is described. Such features include gas detectors, fire protection and vapor dispersion systems, and the emergency shutdown systems.

Sidjak, W., Arctic Pilot Project. Presented to the American Gas Association Transmission Conference, Montreal, Quebec, May 8-10, 1978.

This paper describes a pilot study involving a barge-mounted liquefaction and storage facility in the Arctic. The pilot study is in support of the Arctic Islands LNG project (see above).

Siegwarth, J. D., Radio Frequency Liquid Level Gauging In Propane Tank Car Safety Tests - A Feasibility Study. NBSIR 79-1660, National Bureau of Standards, 1979.

The report presents details of experiments to gauge liquid levels in tank cars using the change in resonant radio frequencies. Precision was tested and the method was recommended for routine tank car gauging.

Simanek, J. and Pick, P., "Hydrates of Natural Gas." Plyn. 53:167-9, June 1973.

Crystallographic data was presented concerning the unit cell and crystal dimensions. In natural gas, up to seven components can participate in mixed hydrate formation. Phase diagrams for several of the mixtures were shown.

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

A method for assessing the societal risk of transporting LPG and LNG is described. From an estimated 52 significant accidents per year with LPG tank trucks at the present truck-associated transportation rate of 20 billion gallons of LPG per year, a fatality rate of 1.2 per year is calculated. For the projected 1980 importation of 33 billion gallons by tanker ship, a fatality rate of 0.4 per year is calculated.

Simplified Methods for Estimating Vapor Concentration and Dispersion Distances for Continuous LNG Spills into Dikes with Flat or Sloping Floors. A. D. Little, Inc. for American Gas Association, AGA No. X50978, April 1978.

The report describes a set of techniques which allow calculation of dispersion of LNG spilled on a flat or sloped dike floor. Calculations include leakage flow rate, LNG flash vaporization, LNG boiling and vapor overflow, and vapor dispersion.

Sindt, C. F. and Ludtke, P. R., "Characteristics of Slush and Boiling Methane and Methane Mixtures." Proceedings of 13th Int. Congr. of the Int. Institute of Refrigeration. pp. 315-320, 1971.

Experiments were performed to determine the boiling behavior of methane and methane mixtures and also of the slush which is formed when vacuum pumping the ullage over the mixture.

Singer, I. A., "The Relationship Between Peak and Mean Concentrations." Journal of the Air Pollution Control Association. 11:336-341, July 1961.

A method of predicting average concentrations has been presented. It has been shown that the simplified normal bivariate distribution describing the average concentration pattern is composed of various short-term periodic distributions which may differ from it significantly. A descriptive, empirical method has been described.

Singer, I. A. and Smith, M. E., "Atmospheric Dispersion of Brookhaven National Laboratory." Air and Water Pollution - An International Journal. 10:125-135. 1966.

A variety of data relating to atmospheric dispersion has been obtained at the Brookhaven Laboratory site and its environs. Concentration measurements were made at distances ranging from 10 m to 60 km. Dispersion patterns developed are discussed in detail and values of the parameters appropriate for various theoretical treatments are summarized.

Slade, D. H., "Atmospheric Dispersion Over Chesapeake Bay." Monthly Weather Review. pp 217-224, June 1962.

It was found that, after the air had traveled for about 7 miles over the water, its direction fluctuations were always less than they had been before reaching the water. The wind speed usually increased as the air crossed the water. The ratio of overland to overwater dispersive capacity varied from less than 5:1, for heating from below, to greater than 35:1 for cooling from below.

Slawson, P. R. and Csanady, G. T., "The Effect of Atmospheric Condition on Plume Rise." Journal of Fluid Mechanics. 47:33-49, 1971.

The buoyant rise of chimney plumes is discussed for relatively large distances from the source, where atmospheric turbulence is the dominant cause of mixing (rather than turbulence due to the plume's own upward motion). A simple theory is developed which shows a number of different shapes plumes can have under different atmospheric conditions (particularly in an unstable environment).

Sloan, E., Dendy, Khoury, F. M., and Kobayashi, R., "Water Content of Methane Gas in Equilibrium with Hydrates." Ind. Eng. Chem. Fundam. 15:318-23, April 1976.

Experimental measurements of water content of methane gas in equilibrium with hydrate were presented at 1000 and 1500 psia for temperatures greater than -10°F. The differences between methane and natural gas hydrates were stressed.

Smith, J. M. S., Mathew, R. C. and Cool, J. A. F., "The Safety of Gas Carriers with Particular Reference to the ICS Tanker Safety Guideline (Liquefied Gas)." Presented at Gastech 75, Paris, September 30-October 3, 1975.

This paper provides an overview of the hazards of operating an LNG carrier with particular emphasis on personnel training.

Smith, K. A., Lewis, J. P., Randall, G. A. and Meldon, J. H., "Mixing and Rollover in LNG Tanks." Paper presented at the Cryogenic Engineering Conference, Atlanta, GA, August 8, 1973.

Criteria and data are presented for deciding whether a specific LNG installation need have both top and bottom fill capacity. In general, a large facility will benefit from such capability if it is to receive a variety of LNG compositions from a variety of ships. It is further shown that the top fill device requires surprisingly careful design in order to assure good mixing at the free surface.

Smith, K. A. and Reid, R. C., The Effect of Composition on the Boiling of LNG on Water. M.I.T. LNG Research Center, 1976 Annual Report, Task IV, to the American Gas Association BR 87-6, January 1977.

The results obtained thus far with binary and ternary mixtures indicate that a preferential evaporation of methane does indeed take place, followed by the preferential evaporation of the next more volatile component ethane. Propane is the last component to evaporate. Although a preferential evaporation takes place, the vapors are a mixture very rich in the volatile component but a mixture after all.

Smith, K. A. and Reid, R. C., Electrostatics and its Hazards in Petroleum Industry and LNG Systems. M.I.T. LNG Research Center, 1976 Annual Report, Task V, to the American Gas Association BR 87-6, January 1977.

The paper discusses streaming potentials and sedimentation potentials in relation to static charge generation as a consequence of hydrocarbon flow through pipes.

Smith, K. A. and Reid, R. C., Boiling of LNG on Dike Floor Materials. M.I.T. LNG Research Center, 1976 Annual Report, Task VI, to the American Gas Association BR 87-6, January 1977.

The rate of vaporization of LNG spilled on a number of substrates was measured experimentally. Included in the materials tested: insulated concrete of two densities, soil, sand, pebbles, wet and dry polyurethane. In all cases, the early rate of vaporization could be well correlated with simple, one-dimensional conduction heat transfer.

Smith, M., ed., Recommended Guide for the Prediction of the Dispersion of Airborne Effluents. Published by the American Society of Mechanical Engineers, May 1968.

The guide discusses meteorological fundamentals, airborne effluents, stack height, dispersion and deposition, data sources and experimental methods, and gives calculation methods and examples.

Smith, R. V., "The Influence of Surface Characteristics on the Boiling of Cryogenic Fluids." J. of Eng. for Industry. 91:1217-1221, 1969.

The influence of a solid heating surface on the boiling behavior of liquid helium, hydrogen and nitrogen is being discussed. This is a review article and contains essentially no new information.

Snellink, I. G., "Hazard Assessment of LNG Supply and Storage." Communication of the Netherlands Delegation, January 1978.

The author describes a risk analysis of the supply and storage of LNG at a facility near the river Maas on the Dutch coast.

Solberg, D. M., Nylund, J. and Hansen, H. R., "Safety and Reliability of Floating LNG Protection Facilities." Fifth International Conference on LNG, Session III, paper 6, Institute of Gas Technology, 1977.

Safety guidelines for the construction and classification of floating facilities for gas processing, liquefaction, and storage are being reviewed.

Solomon, B., "Cove Pt. LNG Terminal to Resume Operation After Accident." The Energy Daily. pp. 1-2, October 19, 1979.

A recent accident at the Cove Point, Maryland liquefied natural gas facility is described. Seepage of LNG from a high pressure pump resulted in a gas explosion which killed one employee and critically injured another.

Spangler, C. V., "Storing Gases." U.S. Patent 2,663,626 (to J. F. Pritchard and Co.), 1953.

Natural gas was cooled to slightly above its boiling point and adsorbed on activated carbon or silica gel. Release of adsorbed gas was achieved by contacting heated natural gas with the solid support.

Speir, G. A., "Indonesia's Badak LNG Project Sets New Records." Pipeline and Gas Journal. June 1978.

This article discusses design, construction, startup and operation of the Badak export terminal. The facility liquefies gas for shipment to Japan.

Srinivason, K., et al., "Effect of Floating Insulation on Free Surface of Cryogenic Liquids in Open Containers." 6th Internat. Cryog. Eng. Conf., pp. 258-262, IPC Science and Technology Press Ltd., Guilford, England, 1976.

The effect of floating insulation materials on the evaporation rate of cryogenic liquids is investigated. Normally, this rate can be reduced by up to 25%.

Stanfill, I.C., "Startup Experiences and Special Features at Memphis LNG Plant." Presented at the First LNG International Conference, Chicago, IL, April 7-12, 1968.

This paper describes four major and several minor equipment malfunctions which occurred during startup and the first six months of operation at the Memphis LNG plant. Several process flow diagrams for the Memphis plant are included.

Stein, W., LNG Fireball Thermal Radiation. UCID-18190, Lawrence Livermore Laboratory, 1977.

The highly simplified computational method is presented for the determination of thermal radiation, emanating from a LNG fireball. Quantitative results are given in a series of diagrams.

Stein, W., Vapor Generation from a 40 m^3 Instantaneous LNG Spill into a 100 m^2 Diked Soil Area. UCID-18188, Lawrence Livermore Laboratory, 1978.

A simple heat transfer model is presented in the evaporation of LNG spilled into a diked area. Some numerical results are given.

Stein, W., "The Spreading of Differential Boil-Off for a Spill of LNG on a Water Surface." Report A, Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program; A Status Report. DOE/EV-0036, Department of Energy, Washington, DC, 1979.

A computer program is described which calculates pool size, differential boil-off and spreading rate for LNG spills on water. Results compare favorably with experimental data.

Stephan, K., "Evaporation Rate of Liquid Natural Gas in Large Containers." Thermo and Fluid Dynamics. 11:53-61, 1978.

Natural gas is often stored in large isolated metal containers. Heat flow through the bottom, the side wall and the cover to the stored liquid are practically independent from each other due to the large dimensions of such containers. Based on this simplification the evaporation rate of the liquid is calculated by means of the Laplace Transformation and a specific difference equation. With the results it is possible to determine the time after which freezing in the surrounding soil commences. The rate of heat flow to the condensed gas proved to be practically unaffected by the ice-formation in the soil. (in German)

Steward, F. R., "Linear Flame Heights for Various Fuels." Combustion and Flame. 8(3):171-178, September 1964.

The flame heights of linear diffusion flames for several different fuels have been correlated with a single parameter derived from a model assuming mixing controlled combustion. The assumptions involved are stated clearly.

Steward, F. R., "Prediction of the Height of Turbulent Diffusion Buoyant Flames." Combustion Science and Technology. 2:203-212, 1970.

A mathematical model of a turbulent diffusion buoyant flame based on a number of simplifying assumptions is presented. It was found that the height at which 400% excess air has been entrained corresponds to the visible flame height according to data taken in our laboratory as well as that presented by a number of other workers.

Strehlow, R. A., "Unconfined Vapor Cloud Explosions - An Overview." Paper presented at the 14th Symposium on Combustion, The Combustion Institute, Pittsburgh, PA, 1973.

The author summarizes the history of accidental vapor cloud explosions, reviews the work that has been done to understand the dispersion, ignition, propagation and blast effects produced, then points out areas for future investigation.

Strehlow, R. A. et al., "On the Measurement of Energy Release Rates in Vapor Cloud Explosions." Combustion Science and Technology. 6:307-312, 1973.

The method is based on the finite amplitude isentropic acoustics of a centered spherical wave and involves the reduction of data from 3 pressure gauges which are measuring the explosion. The method of characteristics is used to back calculate to an effective spherical piston which replaces the explosion so energy release rates of the explosion can be calculated.

Strehlow, R. A. and Baker, W. E., "The Characterizaiton of Accidental Explosions." Prog. Energy Combustion Science. Pergammon Press, 1976.

The authors review actual explosion incidents and classify them into several categories. Basic theory in blast wave damage is also discussed along with the effects of "non-ideal" blast waves. Future areas of research are recommended.

Strehlow, R. A., Luckiatz, R. T., Adamczyk, A. A. and Shimpi, S. A., "The Blast Wave Generated by Spherical Flame." Combustion and Flame. 35(3):297-310, August 1979.

The authors report on their work for determining the overpressures and impulses resulting from reactive fronts. Some results are presented for hydrocarbon mixtures. This paper may have application to blast wave effects estimation.

"Strong Global LNG Trade Growth Seen." Oil and Gas J. 77:36-37, December 1979.

It is expected that world LNG trade will double in the next 5 years, reaching about 3 trillion cu ft/yr by 1985. However, U.S. import policy will remain uncertain because of safety, siting, liability, and insurance issues.

Stuckly, J. M. and Walker, G., "Hydraulics a Key to Optimizing LNG Pipelines." Oil and Gas J. 77(17):68-70, 1979.

By carrying out detailed numerical calculations for the considered LNG pipeline, it is shown that under optimized conditions a liquid carrying pipeline offers improved fuel efficiency when compared with a conventional vapor-phase line.

Stuckly, J. M. and Walker, G., "LNG Long-Distance Pipelines--A Technology Assessment." Oil and Gas J. 77(16):59-63, 1979.

An outline design study for a 1,430-mile LNG pipeline in Northern Canada is described. The tradeoffs between operating temperatures, pressures, pipe diameter, insulation, and material requirements are discussed in some detail. So far no large-diameter, long-distance LNG pipelines have actually been built, but they have received a lot of attention recently.

Study of LNG Safety - Parts I and II. Tokyo Gas Company Ltd., Central Laboratory, February 1971.

This two-part study presents experimental results on LNG evaporation, combustion and dispersion characteristics in a dike, and on LNG evaporation, ice formation, and LNG dispersion on water.

Sunvala, P. D., "Dynamics of the Buoyant Diffusion Flame." Journal of the Institute of Fuel. 40:492-497, 1967.

A new theoretical treatment of the axial velocity growth and mass concentration decay in a buoyant diffusion flame is presented. It has been found that for the flame lengths of burning of various fuel gases, organic liquids as well as fuel oils, the one-fifth power index for the Froude Number holds good. However, for the flame lengths of burning firewood in cribs, the two-fifths power index for the Froude Number is suggested.

Sutherland, V. and J. E. Hughes, "Subterranean LNG Storage." Energy Digest. 3:15-17, October 1978.

The construction of six storage cavities in underground salt formations is described. Each cavity can hold about 60 x 10^6 m^3 LNG at pressures between 120 and 270 bar.

Sutton, S. B., Overpressure Prediction. UCID-18189, Lawrence Livermore Laboratory, 1977.

A simple calculation is performed to determine the energy within a burning cloud of LNG. This energy is assumed to have the same pressure effect as an energy-equivalent quantity of TNT.

Taki, S. and Fujiwara, T., "Numerical Analysis of Two-Dimensional Nonsteady Detonators." AINA Journal. 16, January 1978.

This paper is a report about the numerical calculation of two-dimensional detonation propagation in a confined channel. A simplified chemical kinetics was employed. The method may have application to the study of detonation probabilities for methane-air mixtures.

Tanker Structural Analysis for Minor Collisions. U.S. Coast Guard Report CG-D-72-76. NTIS No. AD/A031031, December 1975.

This report describes the work accomplished during the course of the project of the Evaluation of Tanker Structure in Collision. The intent of the report is to present the investigations performed in evaluating the phenomena that contribute to the ability of a longitudinally framed ship, particularly a tanker, to withstand a minor collision. A minor collision is one in which the cargo tanks remain intact. The ability to withstand a minor collision is quantized by the total energy that can be absorbed during the collision.

Tarifa, C. S., Del Notario, P. P. and Valdes, C. F., Open Fires. Final Report, U.S. Department of Agriculture, Forest Service, Grant FG-SP-114 and 146, May 1967.

An experimental study was made of some basic laws of open fires by utilizing the pool fire techniques. Data were obtained for burning rates, energy balances and flame characteristics, including the influence of fuel type, vessel size and vessel configuration.

Taylor, P. B. and Foster, P. J., "Some Gray Gas Weighting Coefficients for CO_2-H_2O Soot Mixtures." International Journal of Heat Mass Transfer. 19:1331-1332, 1975.

Two tables are provided which give 1) the values of constants which specify weighting factors for various soot concentrations applicable in the temperature range 1400 to 2400°K and 2) values of constants which specify the gray gas absorption coefficient applicable in the 1200 to 2400°K temperature range.

Terry, M. C., "Floating LNG Facilities May Solve Many Problems." Pipeline and Gas Journal. pp. 25-28, June 1977.

This article discusses the history of development of offshore liquefaction facilities. Various generic types of floating facilities are discussed and their potential evaluated.

Thermal Radiation and Overpressure from Instantaneous LNG Release into the Atmosphere. TRW Systems Group Report No. 08072-4, to A.G.A., April 26, 1968.

The report conclusions express belief that 1) a stoichiometric mixture of natural gas and air at atmospheric pressure will not detonate with a charge of high energy explosive equivalent to 625 grams of TNT; 2) the parameters of charge energy, mixture composition and confining wall geometry should be further investigated.

Thomas, P. H., "The Size of Flames From Natural Fires." Paper presented at the 9th International Symposium on Combustion, 1963.

Uncontrolled fires produce flames where the initial momentum of the fuel is low compared with the momentum by buoyancy. The heights of such flames with wood as the fuel are examined and discussed in terms of both a dimensional analysis and the entrainment of air into the turbulent flame. Some recent experiments on the effects of wind on such flames are also reported.

Thomas, P. H., Baldwin, R. and Heselden, A. J. M., "Buoyant Diffusion Flames: Some Measurements of Air Entrainment, Heat Transfer, and Flame Merging." Paper presented at the 10th International Symposium on Combustion, the Combustion Institute, 1965.

Thistledown has been used as a tracer to measure the flow of air toward ethyl alcohol and wood fires 91 cm in diameter, and a smaller town gas fire. The measured mean axial temperature rise at the mean flame height was about 300° to 350°C for wood and alcohol and 500°C for town gas.

Timmerhaus, K. D. and Flynn, T. M., "Safety with Cryogenic Systems." <u>Advances in Cryog. Eng.</u> <u>23</u>:721-729, 1978.

Safety aspects of cryogenic fluids are discussed from a practical point of view. Rules and suggestions for the safe handling of such fluids are given.

Tomkins, B. G., "LNG Plant Computer System: A Conceptual Philosophy." <u>Oil and Gas J</u>. 77(48):56-60, 1979.

A computer in an LNG plant must be designed around the plant operating plan. Consideration must also be given to maintenance and safety plants. Suggestions for useful hard and software selections are provided.

Tonnessen, A., <u>Insulated Tanks for Liquefied Gas</u>. U.S. Patent 4,141,465, 1979.

To reduce boil-off in spherical LNG tanks, the tank skirt is supplied with a special low conductivity ring insert, made of 18-8 SS. Such a heat flow resistance can reduce the heat leak through the skirt by about 50 percent.

Tsai, S. S. and Chan, S. H., <u>A General Formulation and Analytical Solution for Multi-Dimensional Radiative Transfer in Non-Gray Gases</u>. A.I.Ch.E., A.S.M.E. Heat Transfer Conference, Salt Late City, Utah, (77-HT-51), August 1977.

The equations of radiative transfer (spectral) are cast into band absorptance from the multidimensional geometries. Optically thick and thin limiting expressions are thus deduced and discussed.

Tsatsaronis, G., "Prediction of Propagating Laminar Flames in Methane, Oxygen, Nitrogen Mixtures." Combustion and Flame. 33:217-239, 1978.

A fundamental analysis of one dimensional flame propagation (including chemical kinetics and transport [processes] of methane flames) is performed. Flame speed, flame structure and pressure effects are enumerated.

"Turbine/Compressor Serves First 50/50 Methane-Nitrogen Cycle Gas System." Diesel and Gas Turbine Progress.

A unique liquefaction plant at a peakshaving facility is described. Considerable detail, including several photographs, on the refrigerant compressor is provided.

Turner, D. B., Workbook of Atmospheric Dispersion Estimates. Publication No. 99-AP-26, Public Health Service, 1969.

This workbook presents methods of practical application of the binormal continuous plume dispersion model to estimate concentrations of air pollutants. Estimates of dispersion are those of Pasquill as restated by Gifford. Emphasis is on the estimation of concentrations from continuous sources for sampling times up to 1 hour.

Tutko, T. J., "How to Design an Integrated Security System for an LNG Facility." Pipeline and Gas Journal. 121:50-62, July 1979.

The need for a integrated security system at all major LNG facilities is demonstrated. Various suggestions are given as how to best implement such a system.

Uhl, A. E., Amoroso, L. A. and Seitir, R. H., "Safety and Reliability of LNG Facilities." Presented at the ASME Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, New Orleans, LA, September 17-21, 1972.

The prime factors behind the fine operational safety and reliability record of LNG facilities are the early definition and understanding of the nature of LNG, the establishment and utilization of relevant codes, the casting and observation of pertinent quality assurance programs, and thorough training of plant operators. This paper discusses each of these factors in detail.

Uldenvan, A. P., "The Unsteady Gravity Spread of a Dense Cloud in a Calm Environment," paper presented at the International Technical meeting on Air Pollution Modeling and its Application, NATO-CCMS, Rome, October 26, 1979.

Simplified bulk momentum equations for one dimensional and axisymmetric gravity spreading of dense clouds are presented. Analytical solutions indicate that a steady state is not reached during cloud spreading.

U.S. Comptroller General, Need to Improve Regulatory Review Process for Natural Gas Imports. ID-78-17, General Accounting Office, July 14, 1978.

The article highlights difficulties in the review process for LNG importation facilities and makes recommendations to Congress and federal agencies to mitigate the impacts.

U.S. General Accounting Office, Information on the U.S. Importation of Liquefied Natural Gas. EMD-79-48, March 22, 1979.

The report deals with questions on LNG consumption in the U.S., the sources and prices for the imported LNG and with its end use by the utility companies. It also addresses size and ownership of the LNG tanker fleet.

Valencia-Chavez, J. A. and Reid, R. C., "The Effect of Composition on the Boiling Rates of Liquefied Natural Gas for Confined Spills on Water." Int. J. Heat Mass Transfer. 22:831-838, 1979.

Boiling rates for spills of LNG on a confined area of water (calorimeter) were measured for various LNG compositions. A simplified model was developed which compared well with experimental results.

Vanderwall, E. M., "Investigation of the Suitability of Gelled Methane for Use in a Jet Engine." NAS 3-14305, NASA CR-72876, 1971.

Methanol gelled cryogenic methane was storable at -263°F for periods exceeding 100 hours with no significant gel structure degradation. The gel could be transferred through properly designed heat exchangers at comparatively high flow rates (10 lb/hr) without clogging. Fuel consumption by jet engines was not excessive due to the gelant.

Van Horn, A. J. and Wilson, R., Liquefied Natural Gas: Safety Issues, Public Concerns, and Decision Making. BNL 22284, Energy and Environmental Policy Center, Jefferson Physical Laboratory, Harvard University, November 1976.

The report provides background information on LNG and discusses safety issues, LNG facilities siting disputes, public concern for LNG facilities siting, LNG decision making, and gives recommendations concerning LNG terminal siting facilities.

Vanta, E. B. et al., Detonability of Some Natural Gas-Air Mixtures. Technical Report AFATL-TR-74-80, Air Force Armament Laboratory, Elgin Air Force Base, April 1974.

A bag test method to screen natural gas-air mixtures (5.2 to 12.5% by vol. natural gas) to determine detonability. At the 8.6 to 8.8% concentration level, erratic, uneven detonations were initiated and explosive charges ranged from 1001 to 1020 grams. Deflagration occurred at all other fuel concentrations. The detonations propagated the length of the bag, but a steady Chapman-Jouguet type wave front was not observed.

Van Ulden, A. P., "On the Spreading of a Heavy Gas Released Near the Ground." Loss Prevention and Safety Promotion in the Process Industries. Bushman, C. H., ed. Proceedings of the First International Loss Prevention Symposium. The Hague/Delft, The Netherlands, May 28-30, 1974, Elsevier Scientific Publishing Company, 1974.

It is shown that the spreading of a heavy gas differs essentially from the spreading of a neutral gas. Horizontal spread is increased considerably by gravity effects, whereas vertical spread is limited. Calculations are compared with experimental results.

Varma, R. K., Murgai, M. P. and Ghildyal, C. D., "Radiative Transfer Effects in Natural Convection Above Fires - General Case." Proc. Roy. Soc., London, A314, 1970.

The effect of radiation, on the overall dynamics of a hot plume above fires, has been considered. An approximate multidimensional transfer equation for heat radiation is derived from the Schwarzschild's equation. The plume material is assumed to be grey and the outside atmosphere is considered calm and is, otherwise, in a state of arbitrary lapse rate variation.

Verma, S. B. and Cermak, J. E., "Mass Transfer From Aerodynamically Rough Surface." International Journal of Heat and Mass Transfer. 17:567-579, 1974.

Mass transfer rates were determined by directly measuring the actual volume of water evaporated from saturated wavy (sinusoidal) surfaces in micrometeorological wind tunnel. Simultaneous measurements of mean velocity, humidity and temperature distributions were made over these saturated waves.

Vielvoye, R., "Abu Dhabi Activity Soars, but Government Keeps Lid on Production." Oil and Gas Journal. p. 74, July 9, 1978.

Included in this article is a discussion of some of the problems which have plagued the Das Island export terminal. These include cracked cryogenic pipelines, corrosion from high-sulfur gas, and a leak in the inner shell of a storage tank which eventually caused a crack in the outer shell.

Vora, M. K., Shaheen, E. I. and Knieves, D. V., "U.S. Energy Future: Higher LNG Imports Will be Needed." World Oil. pp. 134-148, June 1978.

The future U.S. energy needs and the potential of LNG imports are discussed. It is predicted that LNG could supply 4.7% of total U.S. energy requirements by 1985. This would require an import of 4.86 tcf including 1.17 tcf from Alaska.

Vreedenburger, H., "Steel or Prefab Concrete for Inshore Plants." Chemical Engineering Progress. pp. 82-85, 1979.

The use of steel and concrete in the construction of a floating LNG receiving terminal is discussed. Concrete can offer some advantages in the storage tank design and construction.

Wakeshima, H. and Takata, K., "On the Limit of Superheat." Journal of the Physical Society of Japan. 13(11):13-1403, November 1958.

A new method was devised in which small drops of a sample liquid are heated as they rise up in the nonsoluble heating liquid with a suitable temperature gradient upward. The limit of superheat was determined for saturated hydrocarbons and polymethylenes. The agreement between (Doring's) theory and experiment was satisfactory.

Welker, J. R., Brown, L. E., Ice, J. N., Martinsen, W. E. and West, H. H., Fire Safety Aboard LNG Vessels. U.S. Coast Guard Report No. CG-D-94-76. NTIC No. AD/A030619, January 1976.

This report presents results of an analytical examination of cargo spill and fire hazard potential associated with the marine handling of liquefied natural gas cargo. Principal emphasis was on cargo transfer operations at receiving terminals, and more specifically on the LNG tanker's cargo handling and hazard sensing and control equipment and operations.

Welker, J. R., Wesson, H. R. and Brown, L. E., "Use of Foam to Disperse LNG Vapors?" Hydrocarb. Process. pp. 119-120, 1974.

Tests have shown that a blanket of high-expansion foam effectively reduces ground-level methane concentrations downwind of an LNG spill.

Welker, J. R. et al., "LNG Spills: To Burn or Not to Burn." Paper presented at the A.G.A. Operating Section Distribution Conference, 1969.

This paper concludes that: flammable mixtures from large spills will penetrate a long distance downwind; a major spill should be ignited as soon as possible; a high-expansion foam system offers the best protection by suppressing either LNG evaporation or the burning rate and present standards that specify separation distance irrespective of pool size are meaningless.

Welker, J. R., Pipkin, O. A. and Sliepcevich, C. M., "The Effect of Wind on Flames." Fire Technology. 1(2):122-219, 1965.

A simplified and improved correlation for the drag coefficient of windblown natural gas flames is given. Experimental results leading to the correlation were obtained in a low-speed wind tunnel specifically designed for such studies at the University of Oklahoma North Campus.

Welker, J. R. and Sliepcevich, C. M., "Bending of Wind-Blown Flames From Liquid Pools." Fire Technology. 2, 1966.

The bending of a flame by wind influences the amount of heat transferred by radiation and convection, the fuel burning rate, and the flame spread rate. To what extent will a flame be bent by wind? The author presents correlations of data taken from liquid pool fires, which enable us to predict flame bending and trailing for large fires.

Welker, J. R., West, H. H., Mento, M. A. and Ice, J. N., A Survey of the Effectiveness of Control Methods for Fires in Some Hazardous Chemical Cargoes. U.S. Coast Guard Report CG-D-64-76. NTIS No. AD/A026300, March 1976.

Assessment of fire safety of marine bulk chemical carriers was attempted. It is recommended that standard fire control test methods be developed together with standardized test data collecting and reporting methods and that large-scale fire tests be made on chemicals from different families to attempt to develop methods of correlation with small-scale test results. If a reliable correlation can be developed, small-scale tests could be used in the future with more confidence to both predict behavior of chemical cargoes under fire conditions and to assess large fire extinguishing effectiveness.

Wesson, H. R., Lott, J. L., Feldman, R. and Closner, J. J., "Thermal Performance of a Fire Resistant Coating Applied to Prestressed Concrete." 1978 Operating Section Proceedings, American Gas Association, Montreal, Quebec, May 1978.

The fire resistance of coatings designed to protect weakening of prestressing wire in cryogenic tanks is tested. Degree of protection with coating thickness is discussed.

Wesson, H. R., Welker, J. R. and Brown, L. E., "Control LNG-Spill Fires." Hydrocarb. Process. 51:61-64, December 1972.

Control of LNG-spill fires is obtained by application of high expansion foam. Follow-up with dry chemical fire extinguishers will quickly extinguish the fire.

West, H. H., Brown, L. E. and Welker, J. R., "Vapor Dispersion, Fire Control, and Fire Extinguishment for LNG Spills." NTIS No. AD/A023505, pp. 509-518, Proceedings of the Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterway. Jacksonville, FL, October 26-30, 1975.

Dry chemical fire extinguishment systems can provide rapid extinguishment of LNG fires. High expansion foam can reduce the radiant flux from LNG fires, provide protection for the surroundings until the fire burns out, and reduce the concentration of methane in the vapor cloud downwind from an LNG fire.

West, H. H., Brown, L. E. and Welker, J. R., "Vapor Dispersion Fire Control and Fire Extinguishment for LNG Spills." The Combustion Institute, 1975 Spring Technical Meeting. San Antonio, Texas, 1975.

The paper reports results on AGA tests of LNG evaporation and pool fire radiation reductions by foam application. Tests also demonstrated flame extinguishment by dry chemicals if applied a short time after pool fire ignition.

Westbrook, C. K., A Generalized ICE Method for Chemically Reactive Flows in Combustion Systems. UCRL-78915, Rev. 1, Lawrence Livermore Lab., August 1977.

The ICE method is modified to allow the pressure calculated at a new time step to include the effects of changes in internal energy and species over that time step. This is important for reactive flows in which the change in temperature and/or species contributes significantly to changes in pressure.

Westbrook, C. and Haselman, L., Chemical Kinetics of LNG Detonations. UCRL-82293, Lawrence Livermore Laboratory, February 1979.

The authors of this paper theoretically investigate the effect of ethane on the detonability of methane. Small amounts of ethane were found to significantly increase the possibility of a detonation occurring. The chemical kinetics of the reaction mechanism are also presented.

Weston, H. and Brown, L.E., "Analyze Fire Protection System." Hydrocarbon Processing. pp. 89-92, August 1977.

This paper outlines a systems approach to fire safety and gives an example application to LNG Fire Control.

Wilcox, D. C., "Model for Fires With Low Initial Momentum and Nongray Thermal Radiation." AIAA Journal. 13(3):381-386, March 1975.

A new ambient-air entrainment law accounts for rapid fluid acceleration from initially low velocity at a liquid pool, to higher velocities established under buoyant rise of the combustion products. Radial-radiation heat transfer is computed with the exact radiation transport equation. Fire-model predictions fall within scatter of experimental flame-height and spectral-radiation data for LNG fires.

Wilcox, D. C., Non-Gray Thermal Radiation From a Flame Above a Pool of Liquid Natural Gas. Report by TRW Systems to A.G.A., A.G.A. Catalog No. M19714, February 1971.

This report indicates that a) spectral distribution of the radiation heat flux vector can be calculated, b) minimal data are required to extrapolate from small to large fires, c) an important scaling relationship may have been uncovered, and d) the flame model and associated computer program represent a solid foundation for investigation of radiation properties of a large LNG fire.

Williams, F. A., Combustion Theory - The Fundamental Theory of Chemically Reacting Flow Systems. Addision-Wesley Publishing Company, Inc., 1965.

Chapter 2 discusses Rankine-Hugoniot relations and pages 25-27 the properties of the Hugoniot curve.

Wissmiller, I. L. and Mattocks, E. O., "How to Use LNG Safely." Pipeline and Gas Journal. March 1972.

This article provides a general description of LNG equipment and facilities and how they are designed and operated for safety.

Withrington., J. K., "Analytical Methods for Verifying the Structural Integrity of LNG Carriers." LNG 3 - International Conference on Liquefied Natural Gas, Washington DC, September 24-28, 1972.

This paper identifies some of the structural problems that might occur with a very rapid increase in the size of LNG carriers and advocates the adoption of additional analytical methods to be used in conjunction with the normal procedures of the Classification Societies.

Witte, L. C. and Cox, J. E., Nonchemical Explosive Interaction of LNG and Water. ASME Preprint 71-WA/HT-31, 1972.

When LNG contacts water, an explosive incident may occur due to extremely rapid production of LNG vapor as heat is transferred from the surrounding water. Pertinent literature is summarized on similar reported explosions when hot molten materials contact cool liquids. Fragmentation of the LNG is believed to be the triggering mechanism for explosive vapor formation. Recent results of fragmentation research are presented.

Witte, L. C., Cox, J. E. and Bouvier, J. E., "The Vapor Explosion." Journal of Metals. 22:39-44, February 1970.

The article reviews the four theories of entrapment, violent boiling, shell theory, and Weber Number Effects. A common factor exists in that when molten material is fragmented prior to liquid contact, explosion danger is lessened.

Witte, L. C., Vyas, T. J. and Gelabert, A. A., "Heat Transfer and Fragmentation During Molten-Metal/Water Interactions." Journal of Heat Transfer. 95:521-527, November 1973.

This study indicates strongly that fragmentation occurs when a sample is molten and fragmentation is a response to an external stimulus. Alternate causes of fragmentation are proposed and are predicated upon the initial collapse of a vapor film around the molten metal.

Wolf, Sidney M., "Liquefied Natural Gas." The Bulletin of the Atomic Scientists. 25, Chicago, December 1978.

Wolf presents a review of LNG import questions including safety, security, and price applicable at the time of publication.

Wood, B. D., Blackshear, P. L., Jr, and Eckert, E. R. G., "Mass Fire Model: An Experimental Study of the Heat Transfer to Liquid Fuel Burning From a Sand-filled Pan Burner." Combustion Science and Technology. 4:113-129, 1971.

Heat flux data and the radiation heat flux data indicate that radiation contributes between 20 and 40 percent of the thermal load to the fuel surface for the methanol flame. For the acetone flame, approximately 40 to 60 percent of the total heat flux is radiation during the two steady burning rate periods.

Woolers, R. G., Marine Transportation of LNG and Related Products. Cornell Maritime Press, Cambridge, MD, 1975.

This book describes aspects of marine transport of LNG including ship design, container design, control systems, and a description of hazards and LNG importation. The hazards section describes experiments performed by the Bureau of Mines to determine the effects of LNG spillage on water.

Yamanouchi, N., and Nagasawa, H., "Using LNG Cold for Air Separation." Chem. Eng. Progr. 75(7):78-82, 1979.

By using the cryogenic energy contained in LNG, liquid oxygen, liquid nitrogen and liquid argon can be produced at a 40% saving in power consumption. In the same process LNG is evaporated. Three plants based on this principle are already operating in Japan, and a fourth one is under construction.

Yamazaki, D., Yokoyama, N, and Hino, M., "Storing and Transportation of Hydrocarbon Gases." Chem. Abstr. 80:85488q. Japan Kokai 73-92, 401 (to Mitsubishi Heavy Industries, Ltd.), 1973.

Natural gas was contacted with aqueous aliphatic amine solutions to obtain the hydrate. The hydrate product had a vapor pressure of 35 kg/cm^2 at 40°F.

Yang, K., "Explosive Interaction of Liquefied Natural Gas and Organic Liquids." Nature. 243:221-222, 1973.

Small scale experiments are described in which LNG is poured into organic liquids. In some cases resulting reactions were rather violent, indicating the possibility of vapor explosions.

Yilmaz, B. S., Clarke, S. F. and Westwater, J. M., Heat Transfer From Water in Film Boiling to an Upper Layer of Paraffinic Hydrocarbon. ASME paper 76-HT-24, 1976.

Laboratory experiments have been performed to measure the flux from a layer of water in the state of film boiling to a superimposed layer of various types of hydrocarbons.

Yumoto, T., "Heat Transfer From Flame to Fuel Surface in Large Pool Fires." Combustion and Flame. 17:108-110, 1971.

The study was made to obtain experimentally the ratio of radiation and convection transfers to total heat transfer from the flame to the fuel surface in the range where the burning rate has a constant value regardless of pan diameter.

Zahn, C. W. and Clayton, H. A., Recovery of Natural Gas Liquids by Partial Condensation. U.S. Patent 4,142,876, 1979.

A complex control scheme is proposed which sets the minimum temperature of the natural gas stream to the separator, allowing for the recovery of natural gas liquid by partial condensation of the inlet feed stream.

Zuber, K., "LNG Facilities - Engineered Fire Protection Systems." Fire Technology. 12:41-48, 1976.

Dry chemical fire extinguishers used in conjunction with high expansion foam have been used successfully in tests to extinguish LNG spill fires.

Zubiate, R., Pomonik, G. and Mostarda, S., "Single Point Mooring System for Floating LNG Plant." Ocean Industry. pp. 75-78, November 1978.

The advantages of portable floating offshore LNG terminals are discussed as a preface to a description of a mooring system for such a facility.

SECTION III

LPG ANNOTATED BIBLIOGRAPHY

N.M. Butcher
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SUMMARY

This bibliography was initiated under U.S. Department of Energy Contract No. DE-AC05-78-EV06020. The literature survey was to identify and analyze published literature describing installations, equipment, processes, transportation, and storage of LPG (liquefied petroleum gas). The principal emphasis was on literature pertaining directly to fire safety of LPG during transportation and storage, and other literature relevant to the assessment of the risks and hazards presented by accidental releases of LPG.

The references include some proposed and presently operable regulations used by the LPG industry; journal articles; reports of experimental projects related to the LPG and LNG industries; foreign manuals that influence regulations for handling and transporting LPG in the United States; reports and descriptions of accidents and incidents; and discussions of failure rates, modes, and effects.

The volume of U.S. government accident reports available for review is large. The literature survey includes only selected reports directly related to the hazard analysis. Numerous articles found in trade journals such as Fire Journal and Fire Command were excluded because of their very general descriptive contents on accident incidents. Where possible, U.S. government or industry accident reports were substituted as sources for these articles.

Several references in the bibliography are studies and reports dealing with liquefied natural gas and other cryogens. These studies were cited and annotated due to their applicability to LPG studies.

Although effort was made to include all information relevant to analyzing spill and fire hazard in the LPG industry, this study was necessarily limited by time. As a consequence, some materials may have been excluded from the bibliography.

APPENDIX II

TABLE OF CONTENTS

ABSTRACTS

Abramson, H.N., et al., "Liquid Slosh in LNG Carriers", Symposium on Naval Hydrodynamics, 10th Proceedings, Paper & Discussion, Cambridge, Mass., June 24-28, 1974, p. 371-388.

Results of several research programs to investigate sloshing in Liquid Natural Gas (LNG) Carriers are presented. The history of slosh-related problems in LNG carriers is discussed including a listing of recorded tank damages from LNG sloshing. Sloshing considerations for different tank designs are also presented. In addition, theoretical and experimental studies for determining liquid response characteristics for different tank geometries and fill levels are delineated. The scaling of LNG slosh loads from model data to full scale is also discussed and available full scale load measurements are presented. Areas requiring further investigations are also enumerated as well as design implications from the studies to date.

Alexander, S.J. and N. Taylor, "The Frequency and Severity of Gaseous Explosions", 39th Autumn Research Meeting, The Inst of Gas Engrs, Techn Pap, London, 20th and 21st of November, 1973. Publ by the Institution of Gas Engineers, Communication 925 (1973).

Paper describes the findings and conclusions drawn from a survey of structural damage caused to residential and other non-industrial premises by gaseous explosions and other accidental loadings. The survey covers two years, from 1st April 1971 to 31st March 1973, for the whole of Great Britain.

Alleaume, M., "Marine Transportation of Liquefied Gases", Natural Gas-LNG & LPG, 3, (6), 9-17, (1970).

A very general discussion of the development in the technology of vessels capable of carrying LPG. Brief description of the development in tanks, self-standing tanks, membrane tanks, and spherical tanks, is presented.

American Gas Association, "Tanker and Tanker Terminals. A Bibliography for the Natural Gas Industry 1960-1974", Virg., 1975.

A concise bibliography on all aspects of safety, operation, design, construction, etc., for tankers and tanker terminals dealing with liquefied gases.

American National Standards Institute, "American National Standard Safety Requirements for Marine Terminal Operations", ANSI MH9.1-1972, NY, 1972.

Safety requirements for facilities and equipment used in cargo transfer at marine terminals (including LPG and LNG).

American Petroleum Institute, "Design and Construction of LP-Gas Installations at Marine and Pipeline Terminals, Natural Gas Processing Plants, Refineries, and Tank Farms", API Standard 2510, Third Edition, May 1970.

API standard for design and construction of LP-gas installations (except frozen earth pits and underground storage caverns or wells) which may be associated with one or more of the following: railroad, truck, or marine loading or unloading racks or docks.

The American Society of Mechanical Engineers, "ASME Boiler and Pressure Code, Section VIII, Pressure Vessels - Division I", New York, 1977.

The commonly accepted code for the design, construction, and testing of pressure vessels (including those larger than 120 gal capacity used for pressurized storage of LPG). Frequently incorporated by reference in regulatory codes and standards.

---. "Chemical Plant and Petroleum Refinery Piping", ANSI B31.3-1976. New York, 1977.

The ANSI standards for metallic and non-metallic piping for use in chemical plants, petroleum refineries, and gas transmission and distribution systems. Welded, flanged, and threaded pipe are included as are flared and compression tubing joints. The standards cover design, fabrication, erection, inspection, and testing of pipe systems.

---. "Addenda to Chemical Plant and Petroleum Refinery Piping", ANSI B31.3a-1978. New York, June 15, 1978.

---. "Addenda to Chemical Plant and Petroleum Refinery Piping", ANSI B31.3b-1978. New York, September 29, 1978.

---. "Liquid Petroleum Transportation Piping Systems", ANSI B31.4-1974, New York, 1974.

This standard covers the requirements for materials, design, fabrication, inspection, and testing of liquid petroleum transportation piping systems.

---. "<u>Referenced Standards Addendum</u>", ANSI B31.4a-1978, New York, 1978.

Anderson, Arthur R., "Design and Construction of a 375,000 bbl Prestressed Concrete Floating LPG Storage Facility for the Java Sea". Offshore Technol Conf 8th Annu Proc, Houston, Texas, May 3-6, 1976.

Discusses design details of a concrete barge for holding steel LPG tanks.

Anderson, Charles, et al., "Railroad Tank Car Fire Test: Test No. 7", (Maryland, Ballistic Research Laboratories; Springfield, VA: NTIS, PB-241 145, 1973).

The rate and mechanism of heat transfer into the lading (propane) of a one-fifth scale model pressurized railroad tank car engulfed in fire are discussed. The tank car model had a thermal insulation of 4 inches (10.16 cm) of polyurethane encased in a 0.125 inch (0.318 cm) steel jacket. The heat flux was reduced by a factor of 7.4 compared to the uncoated test model discussed as Test No. 6.

---. "The effects of a Fire Environment on a Rail Tank Car Filled with LPG", (Maryland: Ballistic Research Laboratories; Springfield, VA: NTIS, PB-241 358, 1974).

The 127 kiloliter (33,600 gallon) railroad tank car was instrumented and placed in a large JP-4 fuel pool fire. After 24.5 minutes, the car failed catastrophically via stress-rupture.

Anderson, Charles, William Townsend, and John Zook, "Railroad Tank Car Fire Test: Test No. 6", (Maryland: Ballistic Research Laboratories; Springfield, VA: NTIS, PB-241 207, 1973).

The rate and mechanism of heat transfer into the lading (propane) of a one-fifth scale model pressurized railroad tank car engulfed in fire are discussed.

Anderson, Phillip J. and Edward J. Daniels, "LNG Terminals: Existing and Proposed Systems Compared", Pipeline and Gas Journal, 202, (11), 44-66, (1975).

Major components of a typical LNG terminal including docking, liquid transfer, vapor handling, storage, and vaporization facilities are discussed.

Anderson, Phillip J. and William W. Bodle, "Safety Considerations in the Design and Operation of LNG Terminals", 4th Int Gas Union, et al., Liquefied Nat Gas Conf Proc, Session V, 16 pp., 1974, (Pap No. 4).

Paper outlines safety considerations applicable to the major components of a terminal facility, which include the docking facility, LNG tanker liquid transfer and vapor handling, storage, and sendout vaporization.

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

The results from experiments on variations in burning velocity with changes in methane-air ratio are presented. The maximum burning velocity was determined to a 45 $\pm$ 2 m/sec with a mixture near stoichiometric.

Anthony, E.J., "Some Aspects of Unconfined Gas and Vapour Cloud Explosions", Journal of Hazardous Materials, 1, (4), 289-301, (1977).

Experimental and theoretical works on the various phenomena normally considered under the heading of unconfined explosions are critically assessed. Special attention was paid to experimental studies which may provide theoretical models. Conclusion of the survey indicates the major need for more experimental and theoretical work on non-ideal explosions.

ASL Engineering, Inc., "Environmentally Induced Cracking of Natural Gas and Liquid Pipelines", Volume 1, Technical Report, Volume 2, Appendices A and B (Calif.: ASL Engineering; Springfield, VA: NTIS, PB-282 923, 1977).

An in-depth look at environmentally induced cracking in natural gas and liquid pipelines. The mechanical stresses and electrochemical reactions that lead to creation, growth, and propagation of cracks are explained in detail. Non-destructive test methods for detecting such cracks are also described. The failure statistics included in the report show that environmentally induced cracks account for only a small percentage of pipeline failures. An extensive list of references pertaining to pipeline failures, non-destructive testing, corrosion, and leak detection is also included.

Association of American Railroads, "Analysis of 1/5 Scale Fire Tests", RA-11-5-26, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1973.

The results of tests in which seven 1/5 scale railroad tank cars were exposed to all-enveloping fires are presented. Five of the tests used commercial propane as lading; two were uninsulated, three insulated.

---. "Analysis of Tank Car Tub Rocketing in Accidents", RA-12-2-23, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1972.

Development of a tub rocketing computer model is described. The analysis considers various tub launch angles for tubs filled with ammonia, propane, or vinyl chloride.

---. "Dollar Loss Due to Exposure of Loaded Tank Cars to Fire-1965 Thru 1970", RA-02-1-10, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1972.

A listing of 228 loaded railroad tank cars that suffered some fire damage is presented. The incidents were selected from data on 3840 tank cars damaged in 2087 accidents during the period 1965-1970. The car lading, cause of fire, and extent of damage are included. This is a good source of summarized data on railroad tank cars damaged by fires.

---. "Effects of Fire on LPG Tank Car", RA-11-1-5, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1971.

The response of a DOT 112A340W tank car to a fire environment is investigated theoretically in this study, giving particular attention to propane lading. The possibility of tank rupture arising from variations in filling density, tank thickness, safety-relief valve setting and discharge rate is analyzed for fire conditions ranging from a unit heat input of 34,500 BTU/HR-FT^2 over the entire tank surface to approximately one quarter of this value.

---. "Evaluation of RPI-AAR and BRL Torch Fire Tests of Tank Car Insulations", RA-11-8-36, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1976.

This report covers an analysis of torch fire (approximately 2150°F flame temperature) tests of thermal shield systems of the insultated-jacketed type for railroad pressure type tank cars (class 112A, 114A). The systems tested included one inch of ceramic fiber and mineral fiber insulations of varying densities covered by an 11 gage steel jacket.

---. "Full Scale Fire Tests", RA-11-6-31, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1975.

This report presents an analysis of the results obtained in two tests of propane-laden DOT class 112/114A340 tank cars completely immersed in all-enveloping fires generated using JP-4 fuel.

---. "Report on Accident Review", RA-02-2-18, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1972.

This report presents data on 625 railroad tank cars that lost lading due to mechanical damage in accidents during the period 1965-1970. The data concerning the lading released include source and type of damage, cost of lost lading, etc. The data are analyzed to determine the effects of tank car type, coupler shields, head shields, etc., and to determine which preventive measures are economically justifiable. This is a good source of summarized data on railroad tank car accidents.

---. "Sequence of Events Following Crescent City Derailment", RA-01-1-1, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1970.

A summary concerning the behavior of 10 LPG tank cars following a derailment in Crescent City, Illinois. This summary is more limited in scope than other reports of the accident.
See: National Transportation Safety Board, "Railroad Accident Report - Derailment of Toledo, Peoria, and Western Railroad Company's Train No. 20...".

---. "Summary of Ruptured Tank Cars Involved in Past Accidents", RA-01-2-7, Railroad Tank Car Safety Research and Test Project, Chicago, Ill, 1972.

A summary of 113 railroad tank cars that ruptured, due to mechanical or thermal causes, during the period 1958-1970 is presented. The car lading, type of fracture, and area of crack initiation are included.

Authen, T.K. and E. Skramstad, "Gas Carriers - The Effects of Fire on the Cargo Containment System". Gastech 76, LNG/LPG Conference, New York, October 5-8, 1976.

Two different marine cargo containment systems for LNG are considered, for which two major analyses are presented: 1) a thermal analysis of the heat transfer and temperature distribution in a hull exposed to fire; 2) an analysis of the effect of high temperatures on the cargo containment system and the hull.

Bagge, L.P. and R.H. Shipman, "Research, Developments, and Field Applications of High Intensity LPG Combustion Systems", J Institute of Fuel, 45, (357), 391-396, (1972).

This paper discussed the factors behind the increasing research and development activity covering the utilization and application of LPG in industry - particularly butane. Four examples are described of successful developments which exploit the premium properties of the fuel. Not safety related.

Baldock, P.J., "Accidental Releases of Ammonia - An Analysis of Reported Incidents", Paper presented at Loss Prevention Symposium, American Institute of Chemical Engineers, Houston, Texas, April 2-5, 1979, 15 pp.

An analysis is presented of 121 reported ammonia releases (worldwide) involving 140 fatalities. Probabilities of ammonia release are determined from an analysis of 79 incidents involving 86 fatalities reported during the 12-year period 1967-1978. Cause of release and an analysis of the resulting ammonia cloud and its dispersion are presented for catastrophic vessel failures, major continuous releases, serious minor releases, releases from refrigeration plants (including fires and explosions), and mobile transportation.

"Barge 'Cherokee' to Carry LPG on Inland Waterways", Marine Eng/Log, 76, 66, (Oct 1971).

General dimensions of the Cherokee, built by Bethlehem Steel Corporation for Warren Petroleum Corporation. The barge was designed to transport butane. Not safety related.

Basu, Samir and Raidis Zemdegs, "Method of Reliability Analysis of Control Systems for Nulcear Power Plants", Microelectronics and

Reliability, 17, (1), 105-116, (1978).

A reliability analysis of a nuclear power plant liquid zone control system is presented. The reliability techniques used include fault trees, failure mode and effect analysis, and other rather standard methods. Some failure rate data for instruments and control equipment in a Canadian nuclear plant are included.

Bearint, D.E., et al., "Transportation of Highly Volatile, Toxic, or Corrosive Liquids by Pipeline", (Ohio: Battelle Columbus Laboratories; Springfield, VA: NTIS, PB-253 218, 1976).

An in-depth summary is presented of the results of a literature survey and questionnaire responses from 19 liquid pipeline companies describing 25 LPG transporting systems and 4 anhydrous ammonia transporting systems. The data is presented in terms of the hazards involved, the system design, construction and operation, and the maintenance practices of operators of pipeline systems transporting highly volatile, toxic, or corrosive liquids.

Beckman, Robert B., et al., "System for Evaluation of the Hazards of Bulk Water Transportation of Industrial Chemicals", (Washington, D.C.: National Academy of Sciences; Springfield, VA: NTIS, AD-782 476, 1974).

Severity level guidelines in assessing fire hazards, health hazards, water pollution, and reactivity are presented as the over-all potential hazards connected with bulk water shipment of industrial chemicals.

Benedick, W.B., "High-Explosive Initiation of Methane-Air Detonations", Combustion and Flame, 35, 87-91, (1979).

The quantity of high explosive required to initiate a stable detonation in a stoichiometric methane-air mixture is discussed. Cf. Bull, D.C., 1976.

Benedick, W.B., J.D. Kennedy, and B. Morrison, "Detonation Limits of Unconfined Hydrocarbon-Air Mixtures", Combustion and Flame, 15, 83-84, (1970).

The detonation limits for unconfined hydrocarbon-air mixtures were investigated using high explosives to initiate detonation of gas-air mixtures contained in large plastic bags. The detonation

limits for commercial propane were determined to be approximately 3 to 7%. The amount of high explosive initiator required was a minimum (150 grams) at 4.3% propane. It is also noted that detonations of propane-air mixtures were obtained on very calm days without the use of a plastic bag.
Cf. Brown, John A., 1973.

"Big LPG Carrier Delivered by Hitachi", Marine Eng/Log, 78, (13), (1973).

General description of the Esso Fuji given. The tanker is capable of loading propane or butane. Not safety related.

Bland, R., et al., "Offshore Vessel Traffic Management (OVTM) Study, Volume I, Executive Summary", (Washington, D.C.: DOT; Springfield, VA: NTIS, ADA-059 655, 1978).

Groundings, collisions, and rammings of tankers and tank-barges over 1,000 gross tons from 1971 to 1977 are analyzed and evaluated for alternative vessel traffic management systems and oil-pollution prevention in U.S. waters.
Cf. Bovet, David M., 1973.

Bloebaum, W.D., Jr., "Transportation of LNG for Remote or Interruptible Service", Proceedings of the International Conference on LNG, 1st, Chicago, Ill, April 7-12, 1968, 9pp., (Pap No. 40).

The parameters involved in the design of an over-the-road LNG truck are discussed. Cost figures for truck shipments are presented. The use of LNG as a fuel for mobile equipment is also discussed. A schematic diagram of a truck mounted LNG tank and the associated piping is included. Not safety related.

Bloomquist, Charles E. and Richard A. Kallmeyer, "Development of KSC Program for Investigating and Generating Field Failure Rates, Volume II: Recommended Format for Reliability Handbook for Ground Support Equipment", Final Report, (Calif.: PRC Systems Sciences Co.; Springfield, VA: NTIS, N73 20268, 1972).

Field failure rates and confidence factors are presented for 88 identifiable components of the ground support equipment at the John F. Kennedy Space Center. For most of these, supplementary information regarding failure mode and cause is tabulated. Complete reliability assessments are included for three systems, eight subsystems, and nine generic piece-part classifications. Procedures for updating or augmenting the reliability results are also included.

---. "Development of KSC Program for Investigating and Generating Field Failure Rates. Reliability Handbook for Ground Support Equipment", Final Report, (Calif.: PRC Systems Sciences Co.; Springfield, VA: NTIS, N72 28513, 1972).

Continues previously cited report: Bloomquist, Charles E. and Richard A. Kallmeyer, 1972.

Bodurtha, F.T., P.A. Palmer, and W.H. Walsh, "Discharge of Heavy Gases from Relief Valves", in 7th Symposium on Loss Prevention in the Chemical Industry, American Institute of Chemical Engineers, New York City, Nov 28-30, 1972, pp. 61-66.

The behavior of unflared discharges and accidental ignition of heavier than air gases are discussed. The authors recommend that vent stacks be designed such that the exit velocity is as high as possible to aid in dilution of the stream before it sinks to ground level.

Boe, C., T. Heimley, and T.K. Jenssen, "Risk From LNG-Transport in Tokyo Bay: A Case Study", Det norske Veritas, 1975.

The probability of an LNG release due to a collision in Tokyo Bay is calculated to be in the range of 1×10^{-7} per voyage. The analysis considers vessel weight and speed, the point of collision, and the number of ship movements.

Bonekemper, Edward H., III, "LNG/LPG Marine Terminal Safety", 56th, Proceedings Annual Convention Gas Processors Association, Technical Paper, Dallas, Texas, March 21-23, 1977. Published by Gas Processors Association, pp. 106-110, Tulsa, Okla., (1977).

Presentation centers on safety and environmental hazards of LNG and LPG (emphasis is mostly on LNG). United States Coast Guard regulations for liquefied gas ship design, construction, inspection and operation, as well as proposed Liquefied Natural Gas Transportation Act discussed. General procedures for USCG inspection of liquefied gas vessels reviewed.

Boudet, Rene, "Shipping and Terminals", 56th, Proceedings Annual Covention Gas Processors Association, Technical Paper, Dallas, Texas, March 21-23, 1977. Published by Gas Processors Association, pp. 137-138, Tulsa, Okla., (1977).

The world wide fleet of LPG/NH_3 carriers is reviewed. Estimates are made as to the fleet makeup until 1980. The supply/demand of

LPG/NH_3 tankers until 1982 is predicted. U.S. LPG import terminals are reviewed (both terminals in operation and under study). The economics of LPG transport by large (70,000 m^3) tankers is presented. The conclusions reached are 1) most new LPG/NH_3 tanker capacity will be in the 50-75,000 m^3 range, 2) over tonnage in the LPG/NH_3 shipping trade will exist until 1979-82, 3) major additions to U.S. LPG import terminal capacity are needed, and 4) the present (1977) market rate for LPG transportation to the U.S. from the Persian Gulf is far below the rate computed for large capacity vessels.

Bourgeois, Jean-Pierre, "The Sea Transportation of LPG", Europe & Oil, 10, (4), 40-42, (1971).

The author predicts that LPG production will increase, LPG ship size will increase, and dedicated routes will become more important than spot deliveries or tramping.

Bourne, A.J., "A Criterion for the Reliability Assessment of Protective Systems", Control, 11, (Oct. 1967).

A detailed method for mathematically predicting the readiness of a protective system is presented. Emphasis is placed on unrevealed failures and the fractional dead time of the system.

Bovet, David M., "Preliminary Analysis of Tanker Collisions and Groundings", (Washington, D.C.: USCG; Springfield, VA: NTIS, AD-757 175, 1973).

Collision and grounding damage to tankers are studied by analyzing casualty reports. Penetration depth is used as the variable to relate to various parameters defining the collision. Cf. Grimes, C., 1972.

Boyd, R., "Marine Transportation of Refrigerated LPG and Ammonia", Part I. Marine Engineers Review, 37, (42), 37-42, (1971).

The design and operation of a typical LPG tank ship is presented in some detail. Topics discussed include cargo tank design, insulation, inert spaces, inert gas generators, reliquefaction units, cargo piping, and instrumentation. Safety aspects of these topics are considered. A good overview of LPG shipping.

---. "Marine Transportation of Refrigerated LPG and Ammonia", Part 2. Marine Engineers Review, 37, (39), 37-39, (1971).

The design and operation of a typical LPG tank ship is presented in some detail. Topics discussed include installation of the cargo handling system, operation of the cargo handling system during loading and unloading, and particular problems associated with LPG cargoes. Safety aspects of these topics are considered. A good overview of LPG shipping.

Brown, John A., "A Study of the Growing Danger of Detonation in Unconfined Gas Cloud Explosions", Final Technical Report, New Jersey, John Brown Associates, Inc., December 1973.

This paper is a review of research work on the possibility of detonation of an unconfined fuel-air cloud. The probability of detonation of an unconfined cloud is thought to be very small; the propane pipeline leak at Port Hudson, Missouri, being cited as the only known example.

Brown, L.E. and L.M. Romine, "Liquefied Gas Fires: Which Foam?", Hydrocarbon Processing, 58, (9), 321-332, (1979).

The article presents the results of fire control tests using low expansion and high expansion foams on 100 ft^2 LPG, ethylene, and butadiene fires. The authors report that 500:1 high expansion foam, applied at very high rates, extinguished the LPG fire in three of the four tests. (The description of the tests leaves some doubt as to whether or not the fires were actually extinguished). The test procedure that was used makes it difficult to interpret the results.

Browning, R.L., "Estimating Loss Probabilities", Chemical Engineering, 76, (27), 135-140, (1969).

The Monsanto program for estimating financial loss. Contains possibly pertinent generalized failure rates.

---. "Safety and Reliability Decision Making by Loss Rates", in 7th Symposium on Loss Prevention in the Chemical Industry, American Institute of Chemical Engineers, New York City, Nov 28-30, 1972, pp. 1-6.

Discussion is presented on how to predict loss rates using the basic fault tree techniques.

Bull, D.C., et al., "A Study of Spherical Detonation in Mixtures of Methane and Oxygen Diluted by Nitrogen", J Phys. D: Appl. Phys., 9, 1991-2000, (1976).

The minimum mass of high explosive needed to initiate detonation of methane/oxygen/nitrogen mixtures was studied experimentally. Detonation velocities were measured and all are close to calculated Chapman-Jouguet velocities.

Bull, D.C., J.E. Ellsworth, and G. Hooper, "Concentration Limits to Unconfined Detonation of Ethane-Air", Combustion and Flame, 35, (1), 27-40, (1979).

The critical mass of high explosive Tetryl required to initiate spherical detonation was determined for ethane-air mixtures at one atmosphere pressure as a function of stoichiometry. These are already known.

Bull, D.C. and J.A. Martin, "Explosion of Unconfined Clouds of Natural Gas", Paper to be presented at the American Gas Association Transmission Conference, St. Louis, May 1977.

This paper reviews the work of others and presents the authors' data concerning explosions and detonations in unconfined natural gas clouds. Data are also presented for the detonability of other hydrocarbons, including propane; approximately 0.09 kg of the high explosive Tetryl is required to initiate detonation in a stoichiometric propane-air mixture.

Bureau of Motor Carrier Safety, "1968 Accidents of Large Motor Carriers of Property", (Washington, D.C.: DOT; Springfield, VA: NTIS, PB-189 224, 1969).

The data contained in the report represents a major segment of the intercity transportation of property by commercial motor vehicles and are said to be adequate to identify accident trends and problem areas peculiar to interstate operations.

Burgess, D.S., et al., "Volume of Flammable Mixture Resulting From the Atmospheric Dispersion of a Leak or Spill", Combustion Proc International Symp, 15th (Tokyo, Japan, Aug 25, 1974). Combustion Institute, Pittsburgh, Penn., 289-303, (1975).

The atmospheric dispersion of propane, heptane, methane, hydrogen, and ammonia vapors is calculated using standard Gaussian techniques for two different spill types; a continuous leak of 25 m^3/sec for 10 minutes and an instantaneous release of 15,000 m^3. Although the total quantity of released vapor is the same, the instantaneous release results in a larger flammable cloud that exists for a shorter period of time. In both cases, only a small fraction of the total quantity of released vapor is contained within the flammable portion of the plume, thus the TNT equivalent of a vapor cloud explosion is generally less than 10% of the theoretical yield.

---. "Large-Scale Studies of Gas Detonations", Report of Investigations 7196, Washington, D.C., U.S. Department of the Interior, Bureau of Mines, 1968.

The results of various gas-air detonation experiments, conducted in closed tunnels, are presented. With 10 grams of PETN high explosive as the initiator, the detonable limits for propane-air mixtures were determined to be nearly equal to the flammable limits; 2.2 - 9.2% and 2.1 - 9.5% respectively.

Burgess, D.S., J. Biordi, and J.N. Murphy, "Hazards of Spillage of LNG into Water", Final Report, Washington, D.C., U.S. Department of the Interior, Bureau of Mines, 1972.

Flameless vapor explosions and vapor dispersion of LNG spilled on and under water were studied. The experiments showed that propane spilled onto hot water (≥68 ° C) resulted in a flameless vapor explosion.

Burgess, D.S., J.N. Murphy, and M.G. Zabetakis, "Hazards of LNG Spillage in Marine Transportation", Washington, D.C., U.S. Department of the Interior, Bureau of Mines, Feb 1970.

LNG spilled on water, ice, and brine; liquid nitrogen spilled on water; and dispersion of the resulting vapor clouds were studied experimentally. A vaporizing pool of LNG on water was determined to spread to a maximum diameter of 6.25 $W^{1/3}$ where W was the LNG weight, in pounds. The initial vaporization rate was about 0.037 lb LNG/ft^2 - sec. Peak LNG concentrations in the vapor cloud downwind of a spill were about twenty times the average concentrations. Small-scale explosions were observed when LNG was spilled on water, as was layering of the LNG vapor clouds over water.

---. "Hazards Associated with the Spillage of Liquefied Natural Gas on Water", Washington, D.C., U.S. Department of the Interior, Bureau of Mines, Nov 1970.

Condensed version of: Burgess, D.S., J. N. Murphy, and M.G. Zabetakis, "Hazards of LNG Spillage in Marine Transportation", Bureau of Mines, Feb 1970.

Burgess, D.S. and M.G. Zabetakis, "Detonation of a Flammable Cloud Following a Propane Pipeline Break. The December 9, 1970 Explosion in Port Hudson, Mo.", Report of Investigations 7752, Washington, D.C., Bureau of Mines, 1973.

An analysis of an unconfined propane-air vapor cloud explosion following a propane pipeline leak is presented. The analysis includes methods for calculating the extent of the vapor cloud and determining a TNT equivalent for the explosion. This has become a standard reference in the field of vapor cloud explosions.

Buschmann, C.H., "Experiments on the Dispersion of Heavy Gases and Abatement of Chlorine Clouds", preprint, 4th International Symp on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, Florida, 26-30 October, 1975.

The results of a series of experiments on the dispersion of heavy vapors are presented. Both chlorine and Freon 12 were used in the experiments. The results show that horizontal spreading of a heavy vapor cloud is much greater than predicted by a conventional Gaussian dispersion formula: vertical spreading is much lower than predicted.

Bush, Spencer H., "Pressure Vessel Reliability", Journal of Pressure Vessel Technology, 97, Series J, 54-70, (1975).

Data on pressure vessel reliability, taken from a number of domestic and foreign sources, are presented. Most of the data apply to boilers in power generating stations. The probability of disruptive failure for a large class of pressure vessels is cited as 1×10^{-5} per year per tank.

Carlson, Gene P., "Making Decisions at Tank Fires", Fire Engineering, 128, (4), 26-7, (1975).

Guidelines for immediate decision making for fire fighting operations following a major incident involving hazardous materials.

Caudle, D.D. and J.D. Alexander, "Propane Absorption Data for Gas Plant Design". 48th Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1969, pp. 105-108.

Discusses experimental development of dynamic absorption capacity for propane. Not directly pertinent to hazard analysis.

Cave, L. and M. Kazarians, "Probability of LNG Spills in Boston Harbor: A Comparison with Conventional Tanker Spills", Paper Presented at the Transmission Conference, American Gas Association, New Orleans, May 21-23, 1979.

An analysis of tanker collision data and the resulting estimation of the probability of a large (>10,000 tons), rapid spill of LPG in Boston Harbor is presented. Certain adjustments are made in the data base to account for the special precautions imposed on LNG ship movements in the harbor and the structural peculiarities of LNG ships. The estimated spill probability (spill due to collisions, ramming, groundings, fires and explosions, and abnormal environmental conditions) is in the range of 2×10^{-6} to 2×10^{-5} per year.

Chakraborty, Sunil K., Bholanath N. Mukhopadhyay, and Bimal C. Chanda, "Effect of Inhibitors on Flammability Range of Flames Produced from LPG/Air Mixtures", Fuel, 54, (1), 10-16, (1975).

A study of inhibition of flammability limits and burning velocities for flames from an LPG/air mixture, using chlorinated hydrocarbons as inhibitors. Inhibitors used were methylene, dichloride, chloroform, and carbon tetrachloride, listed in ascending order of inhibition efficiency. An increasing number of dissociable chlorine atoms reduced maximum burning velocity (which is associated with propagation to detonation) and narrowed flammability limits, increasing the lower limit and decreasing the upper limit. This study is useful background for theoretical examination of mode of operation of fire extinguishing agents.

Chay, S.C., W.D. Loftus and M. Mazumdar, "A Probabilistic Approach to Safety System Testing and Maintenance", Journal of Engineering for Power, 96, (3), 175-80, (1974).

A method is presented for evaluating the availability of any redundant standby system which can tolerate on-line testing and repairing. The method was developed for nuclear reactor protection systems but is applicable to other safety systems if the necessary data are available. System availability is treated as a function of component failure rates, test interval, test time, and repair time.

Clapp, Merwin B. and Leo F. Litzinger, "Design of Marine Terminals for LNG, LPG, and Ethylene", Pipeline & Gas Journal, 198, (7), 72-82, (1971).

Differences in handling refrigerated liquids, LNG, LPG, and ethylene, presented with emphasis placed on required individual design for each. Safety, reliability, ease of operation and economy in design consideration of cryogenic storage and handling discussed.

Clarke, R.K., et al., "Severities of Transportation Accidents", SLA-74-0001. New Mexico, Sandia Laboratories, 1976.

Accident rates and the corresponding accident severity are analyzed for air, highway, and rail transportation. The accident rate was determined to be 1×10^{-8} per mile for civil aircraft (U.S. Air Carriers - all operations), 2.5×10^{-6} per mile for truck shipments (Bureau of Motor Carrier Safety records), and 1.5×10^{-6} car accidents per car mile for trains (Federal Railroad Administration data). Probabilities of accidents of given severity are deduced for each mode of transportation.

Closner, John J. and Tadeusz Marcha, "Prestressed Concrete for Primary Storage of LNG or LPG on Ships or Barges and as a Secondary Barrier", Proceedings of the Conference on Concrete Ships and Floating Structures, University of California/ Berkeley, Sept 15-19, 1975.

The application of prestressed concrete to storage and transportation of cryogenic liquids, specifically LNG, is discussed briefly in terms of hull design and as part of the hazard protection system.

Comer, William J., "Fatal Blast Comes With Surplus Tank", Fire Engineering, 131, (2), 22, (1978).

Surplus mixing tank, used by a Cleveland demolition company and sold to a manufacturer of dyes, exploded in Patterson, New Jersey. The detonation occurred due to residue of a military explosive in the tank. Two steel LPG tanks, 20 feet from the exploding tank, withstood the blast.

Comley, D.J., "Liquefied Petroleum Gases", Bull Assoc Petrol Acts Adm., 14, (2), 31-43, (1975).

British utilization, operation of plants, distribution, fire prevention, fire fighting operations, and emergency procedures for LPG are described.

Compressed Gas Association, Inc., "Tentative Standard: Insulated Tank Truck Specification CGA-341 for Cold Liquefied Gases", Pamphlet CGA-341. New York, 1970.

Specifications for insulated tank trucks carrying cold liquefied gases. Design temperature of the tank must be -320°F or colder and the design pressure must be not less than 25 psig nor more than 500 psig. Intended primarily for liquefied gases with boiling points below LPG.

Connell, Kenneth F. and Robert B. Smith, "Analysis of Cause and Determination of Possible Means for Prevention of External Damage to Pipelines", New York, American Gas Association, 1968.

The analysis of failures of 156 natural gas pipelines due to dirt-moving activities by graders, bulldozers, ditchers, etc., concluded that ineffective pipeline marking and labeling, lack of communication, the inability of company patrols to detect short-term activities, and/or operator negligence or carelessness were the causes of the incidents. (Although specific to natural gas pipelines, the findings are probably applicable to LPG lines as well).

Cook, W.B., W.M. Prindible, and Ing. Bambang Sumatri, "Design Requirements for a Major Offshore Processing Facility", Offshore Technol Conf 8th Annu Proc, Houston, Texas, May 3-6, 1976. Volume I, Pap OTC 2483, p. 633-642.

Discusses design details of a sea based LPG processing facility.

Coulter, John L., "Refrigerated LPG Storage and Loading Facilities in Kuwait". 43rd Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1964, pp. 40-43.

Describes propane and butane storage facilities of the Kuwait Oil Company. Propane is stored at -45°F and butane at +20°F. 100,000 and 120,000 barrel, double-walled cylindrical tanks are used for propane storage, while butane is stored in two 65,000 barrel, single-walled spherical tanks. Information is given as to refrigeration equipment, relief valving and pump motor size. Mention is made of an LPG tank failure due to overpressure resulting from an accidental blockage of the propane flare (vent) line by liquid butane (no other details are given).

Courtney, W.J., G. Yie, and D. Kalkbrenner, "Effectiveness of Programs for Prevention of Damage to Pipelines by Outside Forces", (Illinois:

IIT Research Institute; Springfield, VA: NTIS, PB-281 866, 1977).

This report summarizes some of the pipeline accident data collected by OPSO from 1970 to 1975 and analyzes the data to determine what effect various damage prevention techniques have had on accident frequency. The damage prevention programs were found to be of widely varying effectiveness.

Crawford, D.B. and C.A. Durr, "Design of LNG Receiving Terminals", Advances in Cryogenic Engineering, v. 19, 1974, for Cryog Eng Conf, Ga Inst of Technol, Atlanta, Aug 8-10, 1973, 261-268.

Basic components of an LNG receiving terminal and problems encountered in design are analyzed, with emphasis placed on ship unloading and vapor handling systems.

Crouch, W.W. and John C. Hillyer, "What Happens When LNG Spills?", Chemical Technology, 2, 210-215, (1972).

The paper reviews the development of LNG technology, cites a number of misconceptions regarding LNG, and reviews information on the behavior of LNG during and after spills.

Cubbage. P.A. and M.R. Marshall, "Pressures Generated by Explosions of Gas-Air Mixtures in Vented Enclosures", 39th Autumn Research Meeting, The Inst of Gas Engrs, Techn Pap, London, 20th and 21st November, 1973. Publ by the Institution of Gas Engineers, Communication 926, London (1973).

Data from tests performed at Potters Marston, Leics., on homogeneous and nonhomogeneous mixtures of air and gas exploding in enclosed areas. Relationships for predicting the maximum pressures obtainable for a given gas mixture in a vented enclosure are detailed. Breaking pressures for glass and brick enclosures are presented.

Cude, A.L., "Application and Limitations of the ICI Vapour Barrier", Safety Note 74/13A. London, Imperial Chemical Industries, Ltd., 1974.

Discussion centers on the use of the ICI steam curtain vapor barrier designed to disperse, independently of the wind, clouds of heavy flammable vapors.

---. "The Generation, Spread and Decay of Flammable Vapour Clouds", London, ICI, Ltd., (n.d.).

Equations for calculating leak rates of gases, liquids, and vaporizing liquids are given. Equations for calculating the atmospheric dispersion of the resultant vapor cloud are also presented. The effects of density and velocity of the escaping vapor are included. Some data (presumably from other sources) are presented but are poorly documented.

Daenzer, Bernard John, "Fact-Finding Techniques in Risk Analysis", New York, American Management Association, Inc., 1970.

A risk analysis questionnaire to determine insurance coverage is presented. Some of the points discussed in section one, the need for practical fact-finding techniques, can be applied to fault-tree analyses.

Danahy, Philip J. and Bruce S. Gathy, "Equivalent Safety and Hazardous Materials Transportation", American Society of Mechanical Engineers, Paper 73-ICT-86, for Meet Sept 23-27, 1973, 11 p.

A method of assessing hazards, safety, and safety requirements for marine transportation of hazardous materials is discussed. The method grades each material and vessel on relative scales of hazard and safety, respectively. An overall relative safety rating for a given hazardous material and ship type is obtained by combining the two ratings. Propane and butane are included in the cargo ratings.

Davenport, John A., "A Study of Vapor Cloud Incidents", paper presented at 83rd National Meeting, American Institute of Chemical Engineers, Houston, Texas, March 1977.

This paper surveys a large number of vapor cloud incidents, with and without ignition. Information given for each incident includes, where possible, cause and source of spill, spill volume, cloud size, ignition source, wind conditions, TNT equivalent, and explosive yield. (A useful compilation of vapor cloud incidents).

Decker, D.A., "An Analytical Method for Estimating Overpressure from Theoretical Atmospheric Explosions", paper presented at the Annual Meeting, National Fire Protection Association, Seminar No. 2, May 23, 1974.

This report presents methods for estimating explosive overpressures from atmospheric explosions. The Pasquill atmospheric dispersion

model is used to estimate the extent of the explosive cloud. A TNT equivalent is then calculated based on 10 percent of the total heat of combustion. Overpressures at various distances are predicted by Sacks' cube root scaling law. An example is presented using 5300 gal of propane released instantaneously. The TNT equivalent is given as 25,000 lb. A useful summary of methods commonly used to predict damage potential from atmospheric explosions.

de Frondeville, Bertrand, "Reliability and Safety of LNG Shipping: Lessons from Experience", Pap., Annual Meeting, The Society of Naval Architects and Marine Engineers, New York, November 10-12, 1977, 18 p.

The LNG shipping experience since 1964 is reviewed. LPG shipping is also reviewed briefly. The discussion covers safety related incidents at liquefaction and receiving terminals as well as on board ship. A useful compilation of operating experiences.

de Talhouet, Loic, "Carrying L.P.G. by Sea", Shipbuilding and Shipping Record, 769-771, (1964).

The history, basic ship description, and the economics of LPG transportation by sea are briefly presented.

---. "Sea Transport of LPG and Ammonia", Tanker and Bulk Carrier, 18, (12), 10-14, (1972).

The world traffic in LPG/NH_3 is discussed. A discussion of transportation techniques, including the steps necessary when changing cargoes, is presented. The conclusion is that there are present (1972) economic difficulties in the liquefied gas trade due to an over supply of ships. This problem is predicted to continue until the 1980's.

Dick, M.N. and M. H. Tims, "The Prediction of Vapour Offtake Rates from LPG Cylinders", Journal of the Institute of Fuel, 43, (357), 407-412, (1970).

A mathematical model for predicting vapor offtake rates from LPG cylinders is presented. Results from experiments on small LPG cylinders show good agreement with the model. The model predicts the compositions of the vapor being withdrawn and the remaining liquid, the liquid temperature, and cylinder pressure at any time.

Dominion Fire Commissioner, "Standard for Storage and Handling of Piers and Wharves, (Flammable and Combustible Liquids)", DFC No. 109. Ont., Ottawa, Department of Public Works, Feb 1977.

Standards for flammable or combustible liquid storage and handling on piers and wharves.

Drake, Elisabeth M., Ayodeji A. Jeje, and Robert C. Reid, "Transient Boiling of Liquefied Cryogens on a Water Surface. Part I. Nitrogen, Methane and Ethane", Int. J Heat Mass Transfer, 18, 1361-1368, (1974).

Reviews previous related work and presents results from experimental studies of transient boiling rates of pure liquefied nitrogen, methane, and ethane on a water surface. These experiments were conducted in a special insulated apparatus which provided a 77.3 cm^2 heat-transfer area (i.e., cryogen-water interface area). Data include mass-vaporization/time curve, vaporization rate curves, and approximate heat-transfer rates for the experimental conditions.

This study provides important background for studies evaluating hazards due to vapor dispersion from spills of cryogens on water. It is supplemented by a second study by the same authors and title, Part II. Light Hydrocarbon Mixtures.

---. "Transient Boiling of Liquefied Cryogens on a Water Surface. Part II. Light Hydrocarbon Mixtures", Int. J. Heat Mass Transfer, 18, 1369-1375, (1974).

Reviews related studies and presents results from experimental studies of transient boiling rates of synthetic binary mixtures of methane with ethane, propane, and n- and iso-butane spilled on water. Experiments were conducted in a special insulated apparatus which provided a 77.3 cm^2 heat-transfer (cryogen to water) surface. Data are presented as mass boiled as a function of time.

This study with Part I of the same title provides important background for studies evaluating hazards due to vapor dispersion from spills of cryogens on water.

Dunster, H.J., "The Transport by Road of Hazardous Substances. Technical, Regulatory and International Problems", Fire, 70, (873), 485-486, (1978).

Accidents cause by road transportation of hazardous substances in the United Kingdom and suggested adoption of uniform worldwide regulations are discussed.

Echternacht, John E., "Special Hazard Systems for Offshore Platforms", Fireline, 2, (4), (1977).

General platform design of typical North Sea Offshore structures given. Several different types of manual and/or automatic systems suggested for developing an integrated system design for fire fighting.

Eifel, Paul J., "Railroad and Highway Transportation of LPG", Proc of the International Conference on LNG, 1st, Chicago, Ill, April 7-12, 1968... Pap 38, 10 pp.

Various modes of transportation are discussed. Cryogenic railroad tank cars are detailed. Economics of railcar versus trucking is graphically illustrated.

Eisenberg, Norman A., Cornelius J. Lynch and Roger J. Breeding, "Vulnerability Model. A Simulation System for Assessing Damage Resulting from Marine Spills", (Maryland: Enviro Control, Inc.; Springfield, VA: NTIS, AD-A015 245, 1975).

The Vulnerability Model (VM) is a computerized simulation system for assessing public damage resulting from marine spills of hazardous materials; the final report describes the first stage of development which consists of the design and implementation of an operational computer simulation.

Enger, T. and D.E. Hartman, "Mechanics of the LNG-Water Interaction", paper presented at the American Gas Association Distribution Conference, Atlanta, Georgia, May 8, 1972.

The results of experiments on flameless vapor explosion that can happen when LNG is spilled on water are presented and discussed. The "explosive" LNG-water interaction is said to be caused by the rapid phase transformation (homogeneous nucleation) and violent expansion of a thin layer of superheated liquefied gas at the LNG-water interface. These "explosions" occur only when the methane content of the LNG is less than 40 percent. The damage potential from this source is low.

---. "Rapid Phase Transformation During LNG Spillage on Water", Third International Conference and Exhibition on LNG, Washington, D.C., September 24-28, 1972.

Flameless vapor explosions that can occur when LNG is spilled onto water are attributed to "explosive" formation of vapor bubbles produced by homogeneous nucleation caused by superheating. These explosions can occur on open water at ambient temperature only when the LNG has aged so that the methane content is below 40 percent. The mechanical energy released is given as about 0.5 cal/cm^2 of interface area.

Enger, T., D.E. Hartman, and E.V. Seymour, "Explosive Boiling of Liquefied Hydrocarbon/Water Systems", Advanced Cryogenic Engineering, 18, 32-41, (1973).

The results of experiments on flameless vapor explosions of liquefied gases spilled on ambient and heated water are presented. Concentration limits for some liquefied gas mixtures and temperature limits for pure liquefied gases were determined experimentally. The cause of the explosions is said to be superheating followed by homogeneous nucleation of vapor within the liquefied gas. For pure propane, no explosions occurred unless the water temperature was above 127°F. (The data actually came from 2 previously cited papers).

Engerrand, J., "Safety Problems Special to Liquefied Gas Carriers", Bulletin Technique du Bureau Veritas, 48, (3), 45-7, (1966). (In French)

General discussion presented on problems faced in designing ships for the transportation of liquefied natural and petroleum gases. Stress is placed on the cargo tanks, insulation, and piping arrangement for the cargo.

---. "Safety Problems Specific to Ships for the Transport of Liquefied Gases", Bulletin Technique du Bureau Veritas, 48, (4), 65-9, (1966). (In French)

General discussion continues previous article on securing the ship's interior (i.e. electrical wiring for pumps and compressor's, using boiloff gas as fuel), and the exterior construction of a ship, guarding against spillage after a collision or grounding.

European LPG Association, "Catalytic Combustion Heaters Using Liquefied Petroleum Gas", AEGPL UN/1E. Paris, France, 1977.

Specifications cover unflued appliances whose output does not exceed 4000 kcal/h. Deals mainly with the construction and performance requirements (including safety) and compliance testing methods.

---. "Instruction Manual for Drivers of Road Tankers Transporting LPG", AEGPL TSD/1E. Paris France, 1975.

General instructions for LPG transport drivers. Includes characteristics of LPG and responsibilities of the driver in loading, unloading, and emergency situations.

---. "Recommendations for the Design, Construction and Inspection of Non-Refrigerated, Above-Ground, Fixed Cylindrical Propane Storage Tanks of Water Capacity Up to 5 Cubic Meters", AEGPL TSD/4E. Paris, France, 1976.

The specifications, recommended materials, and construction for the specified tanks. Includes gas tightness, external protection, and basic dimensions for tanks. An appendix provides method of calculating minimum discharge rate for safety relief valves.

---. "Recommendations for the Design, Construction Fittings and Inspection of LPG Road Tankers", AEGPL TSD/3E. Paris, France, 1975.

Specifications including the basis of design, quality of materials, orifices, fittings, inspection, testing, and mounting of the pressure vessel on the road tanker. Guidelines for pipework, hose systems, valves, fittings, and transfer equipment are also noted. Vehicle design safety requirements cited. The appendices include temperature/volume and temperature/density correction factor tables and minimum rate of discharge of tanker with pressure ratings of the safety relief valves as the determining factor.

---. "Recommendations for the Installation and Inspection of Small Bulk LPG Fixed Storage Tanks of Up to 5 m^3 Capacity", AEGPL COMM.TSD/2E. Paris, France, 1974.

The recommendations are based on practices currently in operation in major European countries and are applicable to the domestic, commercial, agricultural, and industrial usages of LPG.

---. "Recommendations for the Installation of Fuel Containers and Equipment for the Use of Liquefied Petroleum Gases as Engine Fuel on Motor Vehicles", AEGPL UN/3E. Paris, France, 1978.

Recommends minimum standards for safe installation of fuel containers, piping, and equipment for use of LPG as engine fuel on motor vehicles. Includes pertinent definitions, information on containers, container valves, pipe fittings, equipment and operating procedures of each.

Fawcett, H.H., "Proceedings: Conference on Hazardous Cargoes (7th) held at the U.S. Coast Guard Academy, New London, Connecticut on 8-9 July 1970", (Washington, D.C.: National Academy of Sciences; Springfield, VA: NTIS, AD-754 891, 1970).

Presents the proceedings of papers and discussion on chemical reactions (as in accidental and uncontrolled mixing of two cargoes) and hazard information control systems as they relate to hazardous materials in transport.

Fay, James A., "Unusual Fire Hazard of LNG Tanker Spills", Combustion Science & Technology, 7, (2), 47-9, (1973).

The spreading and evaporation rates of an instantaneous LNG spill on water are estimated theoretically.

Fay, James A., G.J. Desgroseilliers, and D.H. Lewis, Jr., "Radiation From Burning Hydrocarbon Clouds", Report D in: Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: A Status Report, DOE/EV-0036, 1979.

The motion, growth, and thermal radiation from methane, ethane, and propane fireballs are reported for initial fuel volumes of $\sim 20cm^3$ to $\sim 200cm^3$.

Fedor, Otto H., William N. Parsons, and John De S. Coutinho, "Risk Management Technique for Design and Operation of LNG Facilities and Equipment", Fireline, 11-15, (1976).

A proposed method of risk management for LNG facilities, centering on New York with NASA and New York Fire Department inputs.

Feldman, Julius, John M. Cece, and Michael W. Taylor, "LNG/LPG Ship Safety: Lessons from the Past", Oceans 77 Conf Rec 3rd. Los Angeles, Calif, Oct 17-19, 1977 (77CH 1272-40EC) V. 2 Poster No. 01 - Poster No. 10.

Contains the history of LNG/LPG shipping. Details ship development with regard to the various types of tanks used. Includes short histories of the important ships and their roles in the overall picture of LNG shipping. Also contains a history of the Coast Guard's regulation development.

Ffooks, R.C. and R.G. Jackson, "The Technical and Commercial Development of Liquefied Natural Gas Tankers", 2nd International Gas Union, et al., Liquefied Natur Gas Conf Proc, Session III, 16pp., 1970 (Pap No. 4).

The paper summarizes the historical development of ships and tank designs for liquefied natural gas.

Fortson, R. Malcolm, et al., "Maritime Accidental Spill Risk Analysis. Phase I: Methodology Development and Plan", (Maryland: Operations Research, Inc.; Springfield, VA: NTIS, AD-761 362, 1973).

The spill risk assessment methodology includes the probability that a spill will occur given a single "standard conflict situation" and the expected number of spills per year per standard conflict situation. The risk analysis is based on collision, ramming, or grounding of an ocean-going tanker or tow/tank barge due to human errors or ship mechanical failures in ports and harbors.

Frangesh, Neal E. and George A. Randall, Jr., "Distrigas LNG Barge Operating Experience", paper presented at the Cryogenic Engineering Conference, Kingston, Ontario, July 23, 1975.

The transportation and storage experience of the ocean-going barge Massachusetts is discussed. The LNG carrier is also suitable for carrying LPG and ethylene.

Gardner, C.G. and R.K. Swanson, "Electrostatic Hazards Associated with Liquefied Petroleum Gas Truck Loading", Final Report, NGPA Project #15-2123. Natural Gas Processors Association, Tulsa, Okla., 1967.

A search of the technical literature pertaining to the static electricity hazard as it might occur in LPG tank truck loading-unloading operations was made. A bibliography of selected references was prepared. The literature search indicated that processes exist whereby a tank truck might become charged to a hazardous potential. A limited series of experiments was performed to determine whether a dry sand parking surface offers sufficient insulation to prevent rapid discharge of a hazardously charged truck. It was found that oven-dried sand could retain a charge sufficient to ignite a gas-air mixture for as long as 42 minutes, provided the ambient relative humidity was no greater than about 30 percent.

Gas Processors Association, "LP-Gas Loading Practices Manual", GPA 8162-70, Tulsa, Okla., 1974.

Presents safety practices and procedures pertaining to loading and unloading of LPG from tank trucks, tank cars, ships, and barges. The bibliography lists twenty-one national codes pertaining, at least in part, to LPG transfer.

---. "Liquefied Petroleum Gas Specifications and Test Methods", GPA 2140-77, Tulsa, Okla., 1977.

The GPA recommended procedures for testing and specifying LPG are presented. Most of the tests listed are ASTM tests.

---. "Method for the Underground Storage of Natural Gas Liquids", GPA 8175-77, Tulsa, Okla., 1977.

The GPA standard for designing and constructing solution mined and mechanically mined underground storage chambers for natural gas liquids is presented.

---. "Safe Practices for Loading LP-Gas into Tank Trucks, as Recommended by Natural Gas Processors Association", Tulsa, Okla., Rev. Jan 1966. (Posters)

A listing of procedures to be followed for loading LPG into tank trucks.

---. "Standard Table of Physical Constants of Paraffin Hydrocarbons and Other Components of Natural Gas", GPA 2145-77, Tulsa, Okla., 1977.

A table of physical constants for common components of natural gas is presented.

---. "United States LP-Gas Import Terminals, 1977", Tulsa, Okla., 1977.

Presents information on U.S. marine terminal facilities capable of receiving LPG. Data includes terminal locations, ship restrictions, type and capacity of unloading system, storage capacity, etc.

Georgakis, Christos, John Congalidis and Glenn C. Williams, "Model for Non-Instantaneous LNG and Gasoline Spills", Fuel, 58, (2), 113-120, (1979).

Predictions of the development and decay of the dimensions of liquid fuel spills on water in which ignition of the spill occurs immediately on rupture of a single fuel tank on a large LNG or gasoline tanker. The predicted spill shapes are narrow and long with aspect ratios, at maximum area, of 10:1 for LNG and 5:1 for gasoline. (Applicable for prediction of large LPG spills on water).

Goldberg, Elliott and E.X. Saltz, "LNG Terminal Is Designed for Safety", Pipeline and Gas Journal, 200, (3), 42, 44, (1973).

A review of some of the more important design features used for the Distrigas LNG Marine Terminal on Staten Island, New York. Only basic details presented are a terminal site plan and a typical cross-section of 900,000 bbl LNG storage tank.

Gonduin, M. and F. Murat, "Transportation and Storage of LNG", Chemical Engineering Progress, 68, (9), 71-76, (1972).

Discusses techniques that are economically successful and provide a high degree of safety and durability for building LNG storage tanks and ocean transports. The corrugated membrane technique is described in its latest applications to both LNG ships and land storage tanks. The design of self-supported spherical tank ships developed by Technigaz and applied in the LNG carrier Euclides is also discussed.

Graves, K.W., "Development of a Computer Program for Modeling the Heat Effects on a Railroad Tank Car", (New York: Calspan Corporation; Springfield, VA: NTIS, PB-241 365, 1973).

Discusses the theoretical development and use of a FORTRAN IV computer program to model the response to a fire environment of a railroad tank car laden with a volatile, flammable fluid. The program is listed.

Gray, R.C. and L. Johnson, "The Design and Construction of Liquefied Gas Carriers", Transactions North East Institution of Engineers &

Shipbuilders, 87, (3), 69-82, (1971).

Reviews the history of liquefied gas carriers, different ship types, ship design features, and operating procedures. Useful for general background.

---. "The Design and Construction of Liquefied Gas Carrying Vessels", Motor Ship, 51, (608), 538-540, (1971).

Describes four basic types of liquefied gas carriers. Type 1: fully pressurized ships; type 2: semi-pressurized ships; type 3: semi-pressurized/fully refrigerated tankers; and type 4: fully refrigerated at atmospheric pressure. Discusses basic design features, secondary barriers, and operating procedures (with choice of equipment) relative to the type of ship required. (Useful for general background).

Greer, John S., "Feasibility Study of Response Techniques for Discharges of Hazardous Chemicals That Float on Water", (Evans City, Ill: MSA Research Corp.; Springfield, VA: NTIS, ADA-049 921/OSL, 1976).

Spill response techniques were evaluated for ameliorating the vapor hazard from discharges of hazardous chemical that float on water. These techniques involved surfactant films, foams, solvents, gelling agents, and cooling with cryogens, all of which were judged (on the basis of existing data) to be of potential benefit.

Grimes, C., "A Survey of Marine Accidents with Particular Reference to Tankers", J of Navigation, 25, (4), 496-510, (1972).

Discusses marine accident history of tankers in N.W. European waters, during the period 1959-68. As a result of the survey, a detailed permanent comprehensive data bank, containing details of 22,000 accidents, was created.

Gross, S.S., "Evaluation of Foams for Mitigating Air Pollution from Hazardous Materials Spills", Proceedings of National Conference on Hazardous Materials Spills, April 1978.

High, medium and low-expansion foams, generally used by the fire services, were used for vapor mitigation tests on a representative sample of polar and non-polar hydrocarbons. The paper concludes that foams currently in use can be beneficial in controlling the hazards from hazardous chemical materials.

Guise, Arthur B., "Extinguishment of Natural Gas Pressure Fires", Fire Technology, 3, (3), 175-193, (1967).

Presents results of several series of tests on extinguishing natural gas pressure fires with dry chemicals. Includes equations for calculating the size of the fire (based on the cube root of the gas flow rate). The data demonstrate that potassium bicarbonate is superior to sodium bicarbonate in extinguishing this type of fire, the required rate of dry chemical application increases as the gas flow rate increases, and impinging fires are more difficult to extinguish than non-impinging fires.

Gunn, Robert D., "Natural Gas Liquids: Prediction of Vapor-Liquid Equilibria for Process Design". 52nd Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1973, pp. 5-9.

A computer program for calculating multicomponent phase equilibria at cryogenic temperatures is discussed. No safety aspects.

Habercom, Guy, Jr., "Natural Gas: Marine Transportation (A Bibliography with Abstracts)", (Springfield, VA: NTIS, PS-78-0729, 1978).

Abstracts of studies on marine transportation of LNG including forecasts, cargo tank design, terminal facilities, spills, safety aspects, special tanker design, and handling equipment.

Hagglund, Bengt, "The Heat Radiation From Petroleum Fires", FOU-Brand, (1), 18-24, (1977).

Presents radiative data from square pool fires of JP-4. The pools were 1, 1.5, 2, 3, 5, and 10 meters square. Use of the data in calculating the radiation from liquid fuel fires is discussed. Specifically for JP-4 but the theory is applicable to LPG fires.

Halliburton, W.A., Jr., "Low Temperature Gas Processing Operations". 47th Annual Natural Gas Processors Association Convention, Tulsa Okla., 1968, pp. 128-133.

How to "make" LPG. Operation of a cryogenic-type gas processing plant for recovering propane as LPG. Useful for background information.

Hansen, S.F., "The Coast Guard Role in LNG/LPG Importation", LNG Importation and Terminal Safety, Conf Proc, Boston, Mass., June 13-14, 1972.

Coast Guard responsibility for ship inspections and monitoring of LNG/LPG transfers between ships or barges and land based facilities are briefly discussed. The Coast Guard action during specific ship arrivals and cargo discharges are also presented.

Hardee, H.C. and D.O. Lee, "Expansion of Clouds from Pressurized Liquids", Accid. Anal. & Prev., 7, 91-102, (1975).

Discusses formation of a flammable cloud resulting from a liquid (or liquefied gas) leaking from a pressurized tank. Theoretical and experimental results are shown for 930 lb propane releases. For 8000 gal of propane released through a 0.5 ft^2 opening, a maximum cloud radius of 200 ft and a time at risk of about 30 sec are predicted.

---. "Thermal Hazard From Propane Fireballs", Transportation Planning & Technology, 2, 121-128, (1973).

Theoretical analysis of fireball size and thermal hazard associated with the rupture of a propane tank shows that a 40,000 gallon tank of propane could create a fireball 820 ft in diameter, cause third degree burns and ignite wood or trash within a radius of 1200 ft, and cause second degree burns within a 1/2 mile radius. Due to some of the assumptions made, these results represent the maximum hazard; the actual hazard zones should be somewhat smaller than the calculations predict.

Hauk, V., H. Knappik and H. Miller, "Transfer Equipment for Low-Temperature Liquid Media", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, September 30 - October 3, 1975.

Transfer unit for loading and unloading low temperature liquid products, such as ethylene and LNG is described. Mention is made of some of the safety installations used in case of an emergency.

Hayward, E.T., "Developments in Ship Fire-Fighting Procedures", Fire International, 5, (52), 18-21, (1976).

Very brief discussion on using foams, dry chemicals, and CO_2 for ship fire-fighting.

Heffelfinger, R.E., "Survey of Equipment and Techniques to Identify and Quantify Discharged Hazardous Chemicals", (Ohio: Battelle

Columbus Laboratories; Springfield, VA: NTIS, AD-A029 840, 1976).

This report describes the results of a research effort to determine equipment and techniques that may be utilized by the Coast Guard to identify and quantify hazardous chemical discharges via field oriented equipment incorporated in a mobile unit.

Henn, A.E. and T.R. Dickey, "New Regulations for Liquefied Gas Carriers", Gastech 75, LNG & LPG Technology Proceedings, Paris, September 30 - October 3, 1975.

A short history of agencies regulating liquefied gas. New proposed regulations are discussed in contrast to present IMCO standards to assure ships are designed to meet letter of compliance program. Ambient design temperatures, grades of hull steels for LNG, location of crack arresters, and stress factors for independent tank types B & C are only provisions included.

Henn, A.E. and J.G. Hicks, "Liquefied Gas Carriers - Statistical Analysis of Ambient Design Temperatures for the United States", Gastech 76, LNG/LPG Conference, New York, October 5-8, 1976.

Provides temperature data for liquefied gas tanker hull design (strength) or certification for service.

Herenstein, Leon, "Manuel Pour le Stockage du Propane et du Butane", 8th edition, Paris, Societe du Journal Des Usines a Gas, 1976. (Manual for the Storage of Propane and Butane; in French).

Basic manual used by the French gas industry for regulations, transportation, storage, and safe handling of propane and butane.

High, Richard W., "The Saturn Fireball", Annals of New York Academy of Sciences, 152, I, 441-451, (1968?).

Presented is an analysis of rocket propellant fireballs. The diameter (ft) and duration (sec) of the fireball are given as $9.82\ W^{0.23}$ and $0.232\ W^{0.32}$ respectively where W is the weight of the combustibles in pounds. The thermal radiation from a very large rocket propellant fireball is also examined empirically and analytically.

"A High Velocity Venting Valve", Tanker & Bulk Carrier, 18, (2), 38, (1971).

The recently developed tanker venting valve which works under either pressure or vacuum, ejects gases from tanks at high velocity so that they are well above the ship's working areas before dispersal begins. A working diagram is shown and operation of the valve is explained. Because the main moving part is a rubber diaphram, use of the valve on refrigerated LPG tanks is doubtful.

Hiltz, Ralph H. and J.V. Friel, "Application of Foams to the Contol of Hazardous Chemical Spills", Proceedings of National Conference on Control of Hazardous Materials Spills, April 1976.

The use of low expansion and high expansion foams for reducing the downwind vapor concentrations from spills of hydrocarbon fuels, cryogens, and some water soluble chemicals is discussed. The possible effects of foam on LPG spills are only briefly mentioned.

"Hitachi LP-Gas Ship Will be the Largest Ever", Oil and Gas International, 11, (8), 68, 73, (1971).

Brief description of a new LPG tanker built for Esso Transport Co., Inc., is presented. The vessel has four independent LPG tanks externally insulated using YND steel.

Horton, E.T. and John W. Lesch, "Design Features of Natural Gas Liquids Import Terminals", 57th Annual Gas Processors Association Convention, Tulsa, Okla., 1978, pp. 202-206.

A general discussion of the many elements to be considered in designing an LPG import terminal. Includes a limited description of the general process steps used at one terminal, emphasizing specific capacities and daily throughput for tankers, pipelines, and storage. Discusses only a terminal that uses salt-dome storage, heats the gas liquid at the terminal to eliminate long runs of cryogenic piping, and stores liquids in salt domes at temperatures no less than 35°F. Includes discussion of receiving several gas liquids simultaneously. (General background material).

Horton, John T., "Refrigerated Storage of LP-Gas", 41st Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1962, pp. 36-39.

Discusses the construction and economic aspects of steel refrigerated LPG containers. Includes a brief discussion of a weld failure and crack in an LPG tank.

Hunt, J.W., "Special Considerations Related to Large-Scale Refrigerated LNG/LPG Custody Transfer Measurements", Journal of the

Institute of Petroleum, 58, (561), 158-163, (1972).

Discusses possible sources of error in measuring the total volume of LNG/LPG being transferred from seller to buyer. Factors considered include heat input, liquid density, temperature and composition, and instrumentation. Not safety related.

Imperial Chemical Industries, Ltd., "Assessing Projects - Risk Analysis", Book 5, London, Methuen, 1968.

A workbook for learning how to assess projects with probability analysis.

"Information Sheets on Hazardous Materials. n-Butanol", Fire Prevention, (122), 47-8, (1977).

Physical characteristics and hazards of n-butanol are listed with storage precautions and fire-fighting methods.

The Institute of Petroleum, "Pressure Piping Systems Inspection Safety Code", Part 13 of the Institute of Petroleum Model Code of Safe Practice in the Petroleum Industry, London, Heyden & Son, 1979.

The Code gives general requirements regarding adequate documentation, in service inspection, the control of modifications and repairs, inspection frequency, protective safety devices, and testing of pressure piping systems used in the petroleum, petrochemical and chemical industries.

---. "Pressure Vessel Inspection Safety Code", Part 12 of the Institute of Petroleum Model Code of Safe Practice in the Petroleum Industry, London, Heyden & Son, 1976.

The Code gives general requirements regarding adequate documentation, in-service inspection, the control of modifications and repairs, inspection frequency, protective safety devices, and testing of pressure vessels used in the petroleum and chemical industries.

The Institution of Gas Engineers, "Safety Recommendations, IGE/SR/6, Liquefied Petroleum Gases", Communication 762, London, 1968.

Recommendations for the safe storing, handling, and transport of liquefied petroleum gas: storage at refineries and bulk plants;

industrial, commercial and domestic storage; portable container filling; transport. Essentially, a British version of NFPA 58.

Inter-Governmental Maritime Consultative Organization, "Code for Existing Ships Carrying Liquefied Gases in Bulk", Publication No. 76.11.E., London, 1976.

Provides international standards for the design, construction, and operation of liquefied gas ships built prior to October 31, 1976. These standards, with a few exceptions, form the basis of the U.S. regulations for ships carrying liquefied gases in bulk.

---. "Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk", Publication No. 76.01.E., London, 1976.

This code provides international standards for the design, construction, and operation of liquefied gas ships built after October 31, 1976. These standards, with a few exceptions, form the basis of the U.S. regulations for ships carrying liquefied gases in bulk.

International Chamber of Shipping, "Safety in Chemical Tankers", London, 1977.

Manual of rules and regulations based on recommended procedures by the Inter-Governmental Maritime Consultative Organization (IMCO).

---. "Tanker Safety Guide (Liquefied Gas)", London, 1978.

Guidelines are presented for the safe operation of ships carrying liquefied gases in bulk. The guide is intended for use by those serving on such ships. Includes normal operating procedures, emergency procedures, hazards of various liquefied gases, and general information on cargo containment systems.

This is a good general reference on operations aboard a liquefied gas tank ship.

"International Conference on Safety of Life at Sea, 1960", Pub No. 70.06.B, London, Inter-Governmental Maritime Consultative Organization, (IMCO), 1960.

The regulations adopted by the 1960 International Conference of Safety of Life at Sea are presented. These include rules governing construction, navigation, communication, fire protection, life saving, etc. The fire protection provisions are of particular interest with respect to LPG ships as they are referred to in the IMCO Code for Existing Ships Carrying Liquefied Gases in Bulk.

---. Supplement 1, Pub No. 70.07.B, Inter-Governmental Maritime Consultative Organization (IMCO), 1970.

---. Supplement 2, Pub No. 74.05.B, Inter-Governmental Maritime Consultative Organization, (IMCO), 1974.

Supplements 1 and 2 include additional regulations and modifications adopted at IMCO assemblies through 1968 and 1973 respectively.

"International Conference on Safety of Life at Sea, 1974", Pub No. 75.01.E, London, Inter-Governmental Maritime Consultative Organization (IMCO), 1975.

Presented are the regulations adopted by the 1974 International Conference of Safety of Life at Sea. These include rules governing construction, navigation, communication, fire protection, life saving, etc. The fire protection provisions are of particular interest with respect to LPG ships as they are referred to in the IMCO Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

James, L., A. McDiarmid, and C.W.P. Maynard, "Hazard Prevention - A North American Experience", 115th Annual General Meeting, The Institution of Gas Engineers, Techn Pap, Blackpool, 16-18 May, 1978. Publ by The Institution of Gas Engineers, Communication 1053, London, 1978.

Brief history of U.S. hazard prevention, legislation, proposed standards and regulations in relation to the gas industry is discussed. Equal measures for Great Britain are compared, including leakage problems in distribution systems, centralized Dial-Up information systems, computerization, emergency and operational procedures.

Jamison, Lee R., "United States Codes and Regulations Affecting the Marine Aspects of LNG Movement", AGA Operating Section Proceedings, 1970, Transmission Conf (Montreal, Quebec, May 8-10, 1978) and Distribution Conf (Denver, Colo., May 22-24, 1978). American Gas Association, Virg., T233-5, (1978).

A concise discussion of the various U.S. Government codes and regulations that concern marine transport of LNG. Most of these same codes and regulations also apply to LPG.

Jessen, P.F. and A. Melvin, "The Fundamentals of Combustion - A Review", Paper to be presented 40th Autumn Research Meeting, The Inst of Gas Engr, Techn Pap, London, November 1974. Publ by the Institution of Gas Engineers, Communication 948, (1974).

A short discussion on the behavior of laminar flames, burning velocity, the diffusion flame structure, the laminar aerated flame, NO_x formation in flames and incomplete combustion. Several diagrams are provided.

Jirik, Charles J., et al., "A Survey of Salt Deposits and Salt Caverns - Their Relevance to the Strategic Petroleum Reserve", (Washington, D.C.: Federal Energy Administration; Springfield, VA: NTIS, PB-255 948, 1976).

The report summarizes activities, past and present, of salt deposits as they pertain to LPG storage, salt production, and sulphur production operations. Not safety related.

Johnson, Bruce, "Tacoma Gives Birth to Unique LPG Storage Unit", Western Construction, 50, (4), 34-37, (1975).

Concrete Technology Corp. of Tacoma, Washington, produced a pre-stressed concrete floating platform for Indonesia. Discusses the twelve 168 foot long steel tanks, holding a total of 375,000 barrels of liquid propane refrigerated to -50°F.

Johnson, J.P. and L.R. Jamison, "Pipeline to Japan - Five Years of LNG Shipping", Chemical Engineering Progress, 71, (7), 97-100, (1975).

Discusses the design, operation and problems of two LNG ships, the "Polar Alaska" and the "Arctic Tokyo". Most unscheduled maintenance has been on normal marine equipment.

Johnson, M.R., et al., "Fire Induced Stresses in Tanks Containing Liquefied Gas", ASME 74-PVP-6, Paper presented at Pressure Vessels & Piping Conference, Miami Beach, June 24-28, 1974.

A theoretical thermal stress analysis of a horizontal cylindrical tank partially filled with a liquefied gas shows that LPG tanks

exposed to fire and likely to fail circumferentially due to the combined thermal stress and internal pressure. A small amount of thermal insulation applied to the exterior of the tank is said to result in substantial reduction of the thermally imposed stress, thus significantly reducing the probability of local tank wall failure. An excellent analysis of one failure mode for pressurized LPG tanks.

Jones, Fred A. and Bruce L. Kline, "Conservation of Utilities in Design and Operation of Natural Gas Plants", 53rd Annual Gas Processors Association Convention, Tulsa, Okla., 1974, pp. 149-158.

Details methods for conserving energy in the operation of natural gas plants.

Jones, George P., et al., "Risk Analysis in Hazardous Materials Transportation", Volume 1, (Calif: University of Southern California, Los Angeles, Inst of Aerospace Safety and Management, RAPO-73-7; Springfield, VA: NTIS, PB-230 810, 1973).

Data gathered from the Department of Transportation and the Association of American Railroads concerning LPG truck and railroad tanker accidents are reported and a cursory analysis of the risks involved is presented.

Jordan, Charles, H., "Recent Development in Cryogenic Materials and Equipment", 46th Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1967, pp. 76-80.

A very general discussion of materials of construction and equipment suitable for cryogenic service. Not specific enough to be of practical use for hazard studies.

Kaiser, G.D. and B.C. Walker, "Releases of Anhydrous Ammonia From Pressurized Containers - The Importance of Denser-Than-Air Mixtures", Atmospheric Environment, 2, (12), 2289-2300, (1978).

This paper examines the dispersion of ammonia vapors following the failure of a pressurized container. The authors develop a model that includes gravity slumping, rate of air entrainment, and ground heating effects. Model predictions are compared to two actual occurrences. The authors conclude that ammonia-air mixture is denser than air; this density difference causes the cloud to slump and hug the ground forming a broad, shallow plume; and that unless the wind speed is very low, the cloud will remain denser than air. Applicable to LPG since both LPG and ammonia vapors are denser than air.

Kamata, Isao, et al., "Experimental Studies on Insulation Efficiency on an Experimental LNG Carrier and a LPG Carrier", Hitachi Zosen Tech Rev, 38, (1), 9-18, (1977).

Performance test of polyurethane foam insulation. Experiments and theory agreed on overall thermal conductivity. Not safety related.

Katz, William B., "Handling Flammable Product Spills Without Doing Environmental Damage", Fire Engineering, 130, (8), 36-40, (1977).

Three petroleum spills and the resultant effort by local fire departments to wash the spill away, the potential environmental damage and total cost of clean-up, are given as examples of what not to do in the case of a spill. Training, knowledge and effective spill sorbents or dispersants are emphasized for use by local fire departments.

Kaufman, C. Chris, "Microprocessor Eases LP-Gas Storage", Oil and Gas Journal, 75, (46), 88-91, (1977).

Shows flow loops, metering points and logic for product and flow control system in LP salt-cavern storage system and pipeline. Not highly relevant to safety study.

Kicks, B.J., "Natural Gas Storage in Refrigerated LPG", Gas World and Gas Journal, 182, (4706), 506-507, (1977).

A method for storing natural gas by absorbing it in LPG is presented. At high pressure and low temperature conditions (e.g. -40°C and 40 bar), more gas can be stored in solution in LPG than can be stored in the same geometrical volume using conventional dry gas storage at the same pressure and temperature. Not safety related.

Kiefner, John F. and Robert B. Smith, "An Analysis of Reportable Incidents for Natural Gas Transmission and Gathering Lines 1970 Through 1975", American Gas Association, 1977.

The 1970-1975 analysis of 2459 reportable service incidents (failures) concludes that the causes were outside forces (56.3%), material failure (16.9%), and corrosion (14.9%). (Although specific to natural gas pipelines, the findings are probably applicable to LPG lines as well).

---. "Report on Analysis of the Office of Pipeline Safety Operations 1970-1975 Reportable Incident Data for the Natural Gas Distribution Companies", American Gas Association, 1977.

The evaluation of DOT-OPSO reportable incident data from natural gas distribution systems was updated to include the 1975 data. Trends for the period 1970-1975 were also evaluated. (Although specific to natural gas pipelines, the findings are probably applicable to LPG lines as well).

King, Ralph, "Gas Explosions", Industrial Safety, 23, (3), 6, 8, (1977).

Differences in town gas and natural gas leaks in Britain are discussed. The conclusion is, 'when turning off the main gas line, make absolutely sure that it is all of the way off'.

King, W.S., "On the Fluid Mechanics and Heat Transfer of Liquefied Natural Gas Spills (Possibilities and Probabilities in Assessment of the Hazards of the Importation of Liquefied Natural Gas", Rand Corp. Pap P-5396, Calif., The Rand Corporation, June 1975, 16pp.

A mathematical model of the interaction between an evaporating liquefied natural gas spill on the ocean and the ambient water is presented. It is shown that the effect of mass addition that was neglected in previous analysis on the fluid mechanics and heat transfer of the spill is significant. A new mathematical model of the spill is proposed, approximations are discussed, and solution techniques are indicated.

Klehm, Julius J., Jr., and John E. Singletary, "Design and Startup of the Sea Robin Gas Processing Plant", 53rd Annual Gas Processors Association Convention, Tulsa, Okla., 1974, pp. 167-170.

Discusses the design and startup of an offshore, cryogenic gas processing plant. No safety aspects.

Kletz, Trevor A., "The Application of Hazard Analysis to Risks to the Public at Large", World Congress of Chemical Engineering, Amsterdam, July 1, 1976.

This paper discusses the probability of fatality to workers and the public at large due to various voluntary and involuntary risks. The author suggests that the probability of a fatality to the public at large due to risks posed by industrial activities be kept below 10^{-7} per person per year. Useful compilation of the probability of death due to various voluntary and involuntary risks are included.

---. "The Protection of Pressure Vessels Against Fire", <u>Fire International</u>, <u>5</u>, (53), 18-29, (1976).

Discussion centers on how pressure vessels can be protected against the effects of fire by sloping the ground, thermal insulation, cooling with water, and lowering the pressure in the vessel.

---. "Unconfined Vapour Cloud Explosions. An Attempt to Quantify Some of the Factors Involved", paper for presentation at the American Institute of Chemical Engineers Loss Prevention Symposium, Houston, Texas, March 21-24, 1977.

The author discusses the various factors involved in calculating the effects of unconfined vapor cloud explosions. The paper is basically an overview of the current thinking in regards to such explosions. A list of references which contain additional and more detailed information is included.

Kober, D. and E. Martin, "Safety Aspects of LNG Transportation with Special Consideration of Inland Waterways and Coastal Ports", International Conference and Exhibition on Liquefied Natural Gas, 3rd, Washington, D.C., Sept 24-28, 1972. Inst Gas Technology, Chicago, Ill, Session VI/Pap 8, 15pp., 1972.

The effects on an 1800 m^3 inland gas tanker or a 2800 m^3 coastal tanker ramming another ship of the same size are discussed in terms of ramming speed, penetration depth, spill rate, and spill size. The two types of tankers considered are common in Europe but are not often found in the U.S.

Krasner, L.M., S.A. Wiener, and J.L. Buckley, "Hazardous Materials Transportation Intrusion Protection for Hazardous Cargo Tanks", (Washington, D.C.: National Highway Traffic Safety Administration; Springfield, VA: NTIS, PB-207374, 1971).

Tanker population data and data resulting from accidents involving over-the-road flammable liquids tank carriers were analyzed with respect to incidence of lateral intrusion.

Kroeber, A.C., "Fire Protection at Sea with Halon Systems", Fire International, 5, (58), 87-88, (1977).

Discussion on general comparison of CO_2 systems with a Halon 1301 system for fire extinguishment on board ship.

Lakey, R.J., "The IMCO Code for Gas Tankers. A Review of the Finalized Code", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, September 30 - October 3, 1975.

Presents an outline of the IMCO Code for the construction and equipment of ships carrying liquefied gases in bulk. Contained in a list of the products covered by the code are butane, propane, and butane/propane mixtures (LPG).

Lathrop, James K. and Wilbur L. Walls, "Fires Involving LP-Gas Tank Trucks in Repair Garages", Fire Journal, 68, (9), 18-20, (1974).

Three LPG tank truck fires and their causes are discussed. It is noted that standard regulations were applicable and compliance with these regulations might have prevented personal injury and costly damage.

Leach, David M., "World's First Totally Offshore NGL Facility - Java Sea, Indonesia", 54th Annual Gas Processors Association Convention, Tulsa, Okla., 1975, pp. 166-170.

An offshore facility for recovery, storage, and export of NGL is described. NGL recovery unit and refrigerated LPG storage barge (prestressed concrete hull with steel tanks) are described in detail. No safety aspects.

Leclercq, J. and H. Baker, "Cargo Leak Detection Systems for Cryogenic Tankers", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, September 30 - October 3, 1975.

A review of the sections of the IMCO code that pertain to cargo leak detection systems is given. The principles of operation and advantage/disadvantages of the various methods available for detecting the presence of a flammable gas are discussed. Sampling system design, operation, and maintenance are also discussed.

Lees, F.P., "Some Data on the Failure Modes of Instruments in the Chemical Plant Environment", The Chemical Engineer, 277, 418-21, (Sept 1973).

This paper discusses failure modes of instruments in a chemical plant and includes a summary of failure rates. (Failure rates for about 9500 instruments in three plants were given in a previous paper which is referenced: Cf. Anyakora, S.N., 1971).

Leese, Albert, "Highly Flammable Liquids and Liquefied Petroleum Gases Regulations", J British Fire Serv Asso, 4, (1), 5-7, (1976).

Fire losses, protection, and prevention in the United Kingdom are discussed. Emphasis is placed on highly flammable liquids and their fire hazards.

LeFloch, M., "The Importance of the Human Element in the Transportation of Liquid Gas", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, September 30 - October 3, 1975.

Discusses, in qualitative terms, the elements needed by the personnel involved in liquid gas transportation. Not relevant to safety study.

Levine, Donald and David M. Dancer, "Fire Protection of Railroad Tank Cars Carrying Hazardous Materials - Analytical Calculations and Laboratory Screening of Thermal Insulation Candidates", (Washington, D.C.: Federal Railroad Administration; Springfield, VA: NTIS, AD-747 974, 1972).

The report describes a laboratory screening program to select two thermal insulation candidates for use in future fire tests of fifth scale and full scale LPG tank cars. Also included are analytical calculations to predict pressures and liquid levels in LPG tank cars being heated by fires.

Lewis, H.W., et al., "Risk Assessment Group Report to the U.S. Nuclear Regulatory Commission", (Washington, D.C.: U.S. Nuclear Regulatory Commission; Springfield, VA: NTIS, PB-286 859, 1978).

This report is a critical review of the WASH 1400 report, "Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants". The report concludes that WASH 1400 was a conscientious and honest effort to apply the methods of fault tree/event tree analysis to a nuclear reactor but the error bands of the calculated event probabilities are understated due to an inadequate data base, poor statistical treatment, and inconsistent propagation of uncertainties throughout the calculations.

Lewis, J.P. and K.A. Smith, "Geysering Effects in LNG Lines", American Gas Association, Oper Sect Proc, 1975, for Meet, Los Angeles, Calif, and Bal Harbour, Fla, May 5-7 and May 19-21, 1975, T96-T103.

Discusses the causes and effects of geysering in liquid filled lines. Equations relating to the prediction of geysering and degree of gas and liquid expulsion are developed. Methods of preventing geysering are discussed.

Lind, C.D., "Expulsion Hazards Associated with Spills of Large Quantities of Hazardous Materials, Phase I", (Calif: Naval Weapons Center; Springfield, VA: NTIS, AD-A001 242, 1974).

Large quantitites of hazardous materials, such as liquefied natural gas, liquefied petroleum gas, and ethylene, are studied, hypothetically, to quantify the explosion hazards associated with spills. Results of the program are a phenomenological description of a spill, an examination of the detonation properties of methane, a qualitative theory of non-ideal explosions and, a plan for Phase II of the study.

Lind, C.D. and R.A. Strehlow, "Unconfined Vapor Cloud Explosion Study", 4th International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, Florida, October 1975.

Discusses an experimental program to study flame propagation in large scale combustible mixtures and to evaluate flame acceleration under partially confined conditions. Only 5 m radius hemispherical bag tests have been carried out.

Lind, C.D. and J.C. Whitson, "Explosion Hazards Associated with Spills of Large Quantities of Hazardous Materials, Phase II", (Washington, D.C.: U.S. Coast Guard; Springfield, VA: NTIS, ADA-047 585, 1977).

Flame speeds and overpressures associated with spark ignited gas-air mixtures (including propane) enclosed in 5 m and 10 m polyethylene film hemispheres are reported. Although attempts were made to optimize conditions for transition from burning to detonation in unconfined mixtures, no transition occurred. Flame accelerations did occur; however, the flames appeared to reach a constant velocity after an initial acceleration, and accelerations which would be expected to lead to a transition to detonation in larger clouds were not observed.

"Liquid Petroleum Gas Carrier The Abbas", Engineering, 197, 288, (February 1964).

The conversion of the MV "Broughty" to the MV "Abbas", the first semi-refrigerated LPG carrier in the United Kingdom is discussed briefly. Four cylindrical cargo tanks (maximum working pressure of 100 psi) were installed to give a capacity of between 400 and 500 tons of LPG.

"Liquefied Petroleum Gas Carrier Paul Endacott", Engineering, 218, 259-61, (August 1964).

The cargo tanks, cargo handling system, and propulsion machinery of the 26,000 m^3 capacity LPG carrier, "Paul Endacott, are discussed. The design is unusual in that both refrigerated and pressurized tanks are incorporated.

"LPG Carrier Phillips Arkansas", Tanker & Bulk Carrier, 15, (12) 705-6, (1969).

The 26,500 m^3 refrigerated LPG carrier "Phillips Arkansas" is described briefly.

"LPG Filling Stations: Installation Recommendations", Fire Prevention, (112), 42, (1976).

The London Fire Brigade's Petroleum Branch recommendations for installing LPG fueling equipment for refilling LPG fueled vehicles at ordinary petrol filling stations.

"LPG/LNG 1971", Shipbuilding and Shipping Record, 31-69, (Jan 29, Feb 5, 1971).

The present (1971) and future U. S. LNG demand and foreign supply routes are discussed briefly in addition to trends in LNG tanker design, an offshore floating liquefaction/storage plant design, and applications of LPG and LNG in the food, fertilizer, chemical and plastics industries. The LPG/LNG fleet and tanker capacities as of 10/1/70 are listed.

"LPG Ship Carriers Split Cargo", Marine Eng/Log, 69, 45-7, (1964).

The cargo tanks, cargo handling system and propulsion machinery of the 26,000 m^3 capacity LPG carrier, "Paul Endacott", are discussed. The design is unusual in that both refrigerated and pressurized tanks are incorportated.

"LPG Storage Depot", Fire Prevention, (121), 37, (1977).

Describes a fire at an LPG bulk storage terminal in England. A reinforced rubber LPG hose used to unload tank trucks failed while unloading was in progress. The cause of ignition was not determined. The water spray system, designed to cool the storage tanks in case of a fire, failed to operate properly.

MacDuff, T., "The Probability of Vessel Collisions", Ocean Industry, 9, (9), 144-148, (1974).

The probability of ships (average length 150 m) in the Dover Strait grounding, colliding head on, ramming or colliding with stationary objects (such as production platform in the North Sea) are determined and compared with collision statistics for the five years before and the several years after June 1967. Geometric probability theory is also developed.

McClanahan, D.N., "Energy Required to Supply Propane", Report prepared for Texas LP-Gas Association and National LP-Gas Association, June 1976.

Discusses the energy required to supply propane by truck, rail, barge and pipeline transport. Contains much information concerning the movement of propane in the United States and average distances that propane is transported by various means. Contains potentially useful information for safety study.

McDaniel, Dale E., "Fire Extinguishing Effectiveness of a Synthetic Surfactant Foam", (Washington, D.C.: U. S. Department of Transportation; Springfield, VA: NTIS, AD-786 631, 1974).

The effectiveness of a particular synthetic foam concentrate and protein concentrate was compared for JP-4 and JP-5 fires on U. S. flag tank vessels. The synthetic foam gave a shorter extinguishment time for a given application rate, but was more adversely affected by wind conditions. Proportioning concentrate rates above the required minimum had little effect on extinguishment times. No data given for LPG fires.

objects (such as production platform in the North Sea) is determined and compared with collision statistics for the five years before and the five years after June 1967. Geometric probability theory is also developed.

McQuaid, J., "A Survey of the Use of Water Sprays for Gas Dispersion", Safety Note 77/2, London, Imperial Chemical Industries, Ltd., 1977.

Current usage and knowledge of water-sprays for gas dispersal are examined and leakage situations where water-sprays would be applicable are identified. Areas requiring further research are noted.

---. "Minimizing the Frequency and Effects of Plant Leakages, with Particular Reference to the Use of Steam and Water-Spray Curtains", Safety Note No. 77/8, London, Imperial Chemical Industries, Ltd., 1977.

Designs to reduce: 1) the risk of leakage, 2) the total inventory which could be released, 3) the rate of fluid release and, 4) the extent of the hazardous area covered by the fluid released are discussed briefly. The use of steam or water curtains to aid in dispersing hazardous vapors is discussed in some detail.

Marcus, Henry S., "An Alternate: Offshore Terminals", American Gas Association, Oper Sect Proc, 1979, for Meet, Hollywood, Fla., and New Orleans, La., May 7-9 and May 21-23, 1979, T233-T236.

The relative merits of onshore and offshore LNG terminals are discussed briefly.

Maruvada, Surya N., "Reliability Analysis for Generating Equipment", Power Engineering, 81, (6), 81-84, (1977).

Deals with half-sizing boilers for greater availability. Possibly pertinent to LPG failure analysis.

Masaitis, Gregory J., "How Safe are LNG Tankers?", Ocean Industry, 9, (4), 225-227, (1974).

Risks to an oil tanker and LNG tanker are compared for collision, grounding, fire spillage, and structural failure. Design and operating requirements are cited as factors that make structural failure of an LNG tanker much less probable in comparison to oil tankers.

Mascaro, F. and C. Jansky, "The World's First LPG Offshore Floating Terminals", Gastech 74, LNG and LPG Technology Congress, Amsterdam, November 13-14, 1974.

The paper describes a proposed LPG offshore floating terminal, to be moored in the Java Sea. The design calls for a prestressed concrete hull containing 12 cylindrical, refrigerated LPG storage tanks. No safety aspects.

Mast, Robert F., "The ARCO LPG Terminal Vessel", Proceedings of the Conference on Concrete Ships and Floating Structures, University of California/Berkeley, September 15-19, 1975.

ARCO's prestressed concrete floating LPG terminal (60,000 m^3 capacity) is discussed in terms of structural strength and endurance. Not safety related.

Masters, Gene, "Marine LP-Gas Supply Lines to the U.S.", Gas Industries (LP-Gas ed.), 18, (1), 2-3, (1973).

Overseas supply of LPG to the U.S. is discussed briefly. No safety aspects.

Mathijsen, H. Th., "Total Flooding System for Machinery Space Fire Protection on Ships", Fire Protection Review, 39, (428), 318-321, (1976).

A Halon 1301 total flooding, fire protection system (for machinery space fires) is discussed and a flow diagram is shown.

Menzie, Charles A., "An Approach to Estimating Probabilities of Transportation - Related Spills of Hazardous Materials", Environmental Science & Technology, 13, (2), 224-228, (1979).

Discusses an approach to estimating probabilities of transportation-related spills of hazardous materials. The approach involves, first, determining accident rates for appropriate modes of transportation and, second, determining the fraction of accidents that result in spills. Statistics are presented concerning the accident frequency of both truck and rail transport. Contains useful information for safety study.

Miller, E.J. and K.W. Stevenson, "Design Technology Applied to Propane Compressors", 46th Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1967, pp. 84-88.

Discussion limited to propane compressor design for refrigeration service. Not pertinent to study of hazards.

Miller, Myron J., "Risk Management and Reliability", Risk Management, 25, (10), 19-30, (1978).

The author evaluates the effectiveness of fire extinguishing systems including water sprinkler, dry chemical, CO_2, and steam systems. He concludes that sprinkler systems operated effectively in more than 90 percent of the recorded cases. Human errors (closed valves, etc.) were identified as major causes of failures.

Mitchell, P.R., "Gas Carriers - Some Constructional and Practical Considerations", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, September 30 - October 3, 1975.

Discusses, in general terms, shipbuilding meeting the IMCO Code for gas carriers, training and experience of crews, and problems associated with loading of cargoes (purging, etc.) and repairs.

Montgomery, C.F., "Changing Modes of Transportation for LP-Gas", 43rd Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1964, pp. 43-46.

A historical look at changes in modes of LPG transportation.

Moroney, R.N., D.E. Neff, and J.E. Cernak, "Wind Tunnel Modeling of LNG Spills", American Gas Association, Oper Sect Proc, 1978, for Meet, Montreal, Quebec, and Denver, Colo., May 8-10 and May 22-24, 1978, T217-T223.

LNG spill scenarios that may be simulated in meteorological wind tunnels are presented and the feasibility of such modeling is demonstrated by comparing wind tunnel experiments with the 1974 AGA LNG spill tests.

Moss, T.R., "The Reliability of Pneumatic Control Equipment: A Case Study in Mechanical Reliability, (Great Britain: National

Centre of Systems Reliability; Springfield, VA: NTIS, NCSR-R-4, 1975).

The reliability assessment of automatic feedwater control systems to be installed in a nuclear power station is compared to fault data from similar feedwater control systems. It was shown that equipment failures were initially distributed according to Weibull functions and that a constant rate of failure (i.e., simple exponential distribution) emerges at some later stage.

MSA Research Corporation, "Vapor Mitigation for Spilled Volatile Chemicals by Film and Foam Covers", (Excerpted from Vapor Suppression, MSA Research Corporation, Evans City, PA, 10 May 1979).

This article discusses the capabilities of low expansion and high expansion foams to aid in decreasing downwind vapor concentrations from hazardous chemical spills. No mention is made of LPG.

Munk, W.D. and D.L. Parry, "The Use of Acoustic Emission for Buried Pipeline Flaw Detection", Oper Sect Proc, 1979, for Meet, Hollywood, Fla., and New Orleans, La., May 7-9 and May 21-23, 1979, T314-319.

Acoustic emission analysis, as a non-destructive testing method to find leaks and stress corrosion cracking in buried pipelines, is discussed briefly.

Nair, Keshavan, et al., "Cargo Spill Probability Analysis for Deep Water Port Project", Final Report, (Oakland, CA: Woodward-Lundgren & Associates; Springfield, VA: NTIS, AD-758 330, 1973).

A method using the Bayesian (inductive and subjective) statistical approach was established to determine the probability of liquid cargo (specifically oil) spills from tankers and tanker-related loading/unloading facilities.

Nash, George, "Petrochemical and Fire Safety. The Development of Special Equipment and Fire-Fighting Techniques", Fire, 70, (868), 253-6, (1977).

Strategy, planning, gas protection, and tank fires are a few of the areas discussed for fire protection for hydrocarbon fires.

Nash, P., "Fire Protection of Flammable Liquid Storages by Water Spray and Foam", Building Research Establishment, Current Paper CP 42/75, Boreham Wood, 1975, 12 pp.

Combines two previously published articles by the same author:

1. "The Performance of Fire-Fighting Foams on Flammable Liquid Fires." Fire Prevention Science & Technology, (10), 1974.
2. "The Performance of Water Sprays on Flammable Liquid Fires." Fire Prevention Science & Technology, (10), 1974.

The former discusses the feasibility and testing standards for various low-expansion foams in fighting liquid fire. The latter discusses the feasibility of utilizing water sprays as a means to control and extinguish the three main classes of liquid fires.

National Academy of Sciences, "Compatibility Guide for Adjacent Loading of Bulk Liquid Cargoes", (Washington, D.C.; Springfield, VA: NTIS, AD-A015 171, 1975).

A systematic compatibility guide for the hazards of reaction between binary chemical components of adjacently loaded bulk cargoes is presented. Includes all reactive materials likely to be shipped by sea.

---. "Evaluation of the Hazard of Bulk Water Transportation of Industrial Chemicals. A Tentative Guide", (Washington, D.C.: National Research Council; Springfield, VA: NTIS, PB-189 845, 1969).

The fire hazards, health hazards, water pollution and reactivity of some 209 industrial chemicals are presented in terms of the over-all potential hazard connected with bulk water shipment.

---. "Evaluation of the Hazard of Bulk Water Transportation of Industrial Chemicals. A Tentative Guide", (Washington, D.C.; Springfield, VA: NTIS, AD-775 756, 1973).

The expanded revised edition evaluates 337 industrial chemicals transported in bulk by water transportation.

National Fire Protection Association, "Flammable & Combustible Liquid Tank Vehicles 1974", NFPA No. 385, Mass., 1974.

The standard applies to tank vehicles to be used for the transportation of asphalt or normally stable flammable and combustible liquids with a flash point below 200°F. Not pertinent to LPG.

---. "Lessons - From an LP-Gas Utility Plant Explosion and Fire", Fire Command, 39, (4), 19-25, (1972).

A report of an LP-Gas utility plant fire and propane truck explosion (BLEVE) is given. The plant was located in Tewksbury, Mass. A good description is given as to the cause of the fire and actions of plant personnel and firefighters.

---. "Storage and Handling Liquefied Petroleum Gases 1979", NFPA No. 58, Boston, Mass., 1979.

This standard covers design, construction, installation, and operation of LPG systems except for refrigerated storage, marine and pipeline terminals, gas processing plants, refineries, and utility gas plants. It is intended mainly for commercial and residential LPG users (other than utility companies) and also covers truck transportation of LPG.

---. "LP-Gases at Utility Gas Plants 1979", NFPA No. 59, Boston, Mass., 1979.

This standard covers the construction and operation of LPG equipment at utility gas plants. Refrigerated and nonrefrigerated storage are both included.

National Petroleum Council, "U.S. Petroleum and Gas Transportation Capacities", NPA Committee on Oil and Gas Transportation Facilities, Washington, D.C., 1967.

This is a compilation of data on natural gas and petroleum product transportation by pipeline, railroad tank cars, and trucks. Some data are included on LPG pipeline locations and capacities and on the number and capacity of trucks and railroad tank cars capable of transporting LPG. This information was current in 1967 but is now outdated.

National Research Council, "Human Error in Merchant Marine Safety", (Washington, D.C.: Maritime Transportation Research Board; Springfield, VA: NTIS, ADA-028 371, 1976).

The analytical methods and results of a study to determine the underlying causes of casualties resulting from human error in the U.S. merchant marine are presented.

---. "Pressure Relieving Systems for Marine Bulk Liquid Cargo Containers", Committee on Hazardous Materials, Washington, D.C., 1971.

Pressure relief systems for marine bulk liquid cargo containers venting vapor, liquid, or liquid/vapor mixtures are discussed in terms of overpressure caused by fire, chemical reaction, loss of insulation, or improper operation.

National Transportation Safety Board, "Chicago, Burlington and Quincy Railroad Company, Train 64 and Train 824, Derailment and Collision with Tank Car Explosion, Crete, Nebraska, February 18, 1969", (Washington, D.C.: NTSB-RAR-71-2; Springfield, VA: NTIS, PB-198 790, 1971).

A tank car in train 824 was completely fractured upon impact with derailed cars of train 64 and released its lading of 29,200 gallons of anhydrous ammonia into the atmosphere. The complete fracture of the tank car on impact was contributed by the brittleness of the steel of the car caused by the low ambient temperature. Six people were killed and 53 injured.

---. "Highway Accident Report - Multiple-Vehicle Collision Followed by Propylene Cargo-Tank Explosion, New Jersey Turnpike, Exit 8, September 21, 1972", (Washington, D.C.: NTSB-HAR-73-4; Springfield, VA: NTIS, PB-225 032, 1972).

A tractor-semitrailer (tank) carrying propylene liquid petroleum gas sideswiped a bus. After several collisions with other cars, the tractor-semitrailer straddled the turnpike's median guardrail while fire erupted and spread to the propylene which was leaking from the cargo tank's damaged plumbing.

---. "Highway Accident Report - Propane Tractor-Semitrailer Overturn and Fire. U.S. Route 501, Lynchburgh, Virginia, March 9, 1972", (Washington, D.C.: NTSB-HAR-73-3; Springfield, VA: NTIS, PB-221 986, 1973).

The vehicle carrying pressurized LPG overturned, slid on its side and was ruptured by a rock embankment, releasing the LPG. The propane-air mixture ignited, killing two persons and injuring five others.

---. "Highway Accident Report - Surtigas, S.A., Tank-Semitrailer Overturn, Explosion, and Fire, Near Eagle Pass, Texas, April 29, 1975", (Washington, D.C.: NTSB-HAR-76-4; Springfield, VA: NTIS, PB-254 034, 1976).

The tractor-tank-semitrailer carrying LPG swerved to avoid an automobile ahead slowing for a turn. The tank-semitrailer separated from the tractor, struck a concrete headwall and ruptured. The ensuing fire and explosions burned 51 persons, killed 16 (including the truckdriver) and destroyed a building and 51 vehicles in the area.

---. "Highway Accident Report - Transport Company of Texas, Tractor-Semitrailer (Tank) Collision with Bridge Column and Sudden Dispersal of Anhydrous Ammonia Cargo, I-60 at Southwest Freeway, Houston, Texas, May 11, 1976", (Washington, D.C.: NTSB-HAR-77-1; Springfield, VA: NTIS, PB-268 251, 1977).

A tractor-semitrailer (tank) transporting 7509 gallons of anhydrous ammonia struck and then penetrated a bridge rail on a ramp connecting I-610 with the Southwest Freeway. The tractor and trailer left the ramp, struck a support column of an adjacent underpass, and fell onto the Southwest Freeway, (approximately 15 feet below), releasing the anhydrous ammonia. Six persons died, 78 persons were hospitalized and about 100 other persons were treated for injuries.

---. "Illinois Central Railroad Company, Train Second 76 Derailment at Glendora, Mississippi, September 11, 1969", (Washington, D.C.: NTSB-RAR-70-2; Springfield, VA: NTIS, PB-194 696, 1970).

A pedestrian on the railroad tracks caused the engineer to apply full emergency braking. One of the vinyl chloride tank cars which derailed was punctured and its contents spilled. After dispersion of much of the vapors, ignition by an unknown source took place. Another tank car of fire-inpinged vinyl chloride later exploded violently, seriously damaging the surrounding area.

---. "Pipeline Accident Report - Dow Chemical U.S.A., Natural Gas Liquids Explosion and Fire, Near Devers, Texas, May 12, 1975", (Washington, D.C.: NTSB-PAR-76-5; Springfield, VA: NTIS, PB-255 979, 1976).

An 8-inch pipeline, which was closed in under pressure, ruptured and natural gas liquids (ethane - propane mixture) at 1425 psig pressure erupted from a fracture near the top of the pipeline. The escaping LPG vapors were ignited by an automobile which entered the flammable zone. The resulting explosion and fire killed the four persons in the automobile.

---. "Pipeline Accident Report - Mid-America Pipeline System Liquefied Petroleum Gas Pipeline Rupture and Fire, Donnellson, Iowa, August 4, 1978", (Washington, D.C.: NTSB-PAR-79-1; Springfield, VA: NTIS, PB-296 136, 1979).

An 8-inch propane pipeline failed due to the combined stresses that were exerted on the pipeline when it was lowered 3 months before the accident and to a dent and gouge which had weakened the pipe. Three persons died and two were critically burned.

---. "Pipeline Accident Report - Phillips Pipe Line Company, Natural Gas Liquids Fire, Austin, Texas, February 22, 1973", (Washington, D.C.: NTSB-PAR-73-4; Springfield, VA: NTIS, PB-225 845, 1973).

A 10-inch pipe failed in an area of stress concentration which was due to improper pipeline repair welding procedures. The failure was caused by the repeated heaving and swelling of the soil at the leak site, which broke the pipe in the area of the stress concentration. NGL vapor which had leaked from the break was ignited by the restarting of the engine of a van which had stalled in the flammable zone.

---. "Pipeline Accident Report - Phillips Pipe Line Company, Propane Gas Explosion, Franklin County, Missouri, December 9, 1970", (Washington, D.C.: NTSB-PAR-72-1; Springfield, VA: NTIS, PB-209 876, 1970).

Probable cause of the accident was the rupture of an insufficiently bonded longitudinal weld, which had been further weakened by internal corrosion. The detonation and initial fire consumed 756 barrels of propane, giving rise to an estimated explosive force of 100,000 lbs of TNT. Contributing to the intensity of the explosion and fire were the weather inversions present which acted as a lid on the detonation and helped deflect the resultant forces earthward. (This is probably the best documented incident involving the detonation of an unconfined propane cloud and is cited by many authors).

---. "Pipeline Accident Report - Washington Gas Light Company, Natural Gas Explosions at Annandale, Virginia, March 24, 1972", (Washington, D.C.: NTSB-PAR-72-4; Springfield, VA: NTIS, PB-214 328, 1972).

A contractor's backhoe snagged a 2-inch steel gas main, operating at 22 psig, and pulled the main out of a compression coupling 22 feet away. Forty minutes later, gas company personnel arrived and failed to shut off the gas or check area houses for the presence of gas. One hour after the break, three nearby houses exploded - three persons were killed and another injured.

---. "Railroad Accident Report - Derailment and Subsequent Burning of Delaware and Hudson Railway Freight Train at Oneonta, New York, February 12, 1974", (Washington, D.C.: NTSB-PAR-74-4; Springfield, VA: NTIS, PB-237 336, 1974).

The train derailed as it moved northward around a 30° 30' curve just north of Oneonta, New York. Cause of the derailment was the inability of the track to resist the lateral forces which canted the outside rail outward and widened the gage of the track. The tank of one of the seven cars loaded with LPG split open and ignited. Four of the remaining tank cars ruptured about 30 minutes after the derailment.

---. "Railroad Accident Report - Derailment of a Burlington Northern Freight Train at Belt, Montana, November 26, 1976", (Washington, D.C.: NTSB-RAR-77-7; Springfield, VA: NTIS, PB-273 915, 1977).

An overloaded rail section failed due to an undetected transverse fissure and 24 cars derailed. One of the cars punctured an above-ground tank near the track which immediately ignited. Simultaneously, an LPG rail tank car was punctured, the vapors ignited, and the tank immediately rocketed 400 feet. Other rail cars containing No. 6 fuel oil and LPG were also involved in the fire and explosion. Twenty-two persons were injured and 2 reported missing.

---. "Railroad Accident Report - Hazardous Materials Railroad Accident in the Alton and Southern Gateway Yard in East St. Louis, Illinois, January 22, 1972", (Washington, D.C.: NTSB-RAR-73-1; Springfield, VA: NTIS, PB-217 429, 1973).

An overspeed tank car loaded with propylene collided with a standing hopper car and the overriding coupler on the empty car punctured the tank head. The pressurized propylene leaked from the tank car, forming a large vapor cloud, which ignited and exploded, injuring more than 230 people.

---. "Railroad Accident Report - Southern Railway Company Train 154 Derailment with Fire and Explosion, Laurel, Mississippi, January 25, 1969, (Washington, D.C.: NTSB; Springfield, VA: NTIS, PB-190 208, 1969).

Cause of the derailment was a broken wheel. Fifteen tank cars loaded with LPG were involved in the fire and explosions immediately following the derailment. Two fatalities occurred and 33 persons were hospitalized.

---. "Special Study-Safe Service Life for Liquid Petroleum Pipelines", (Washington, D.C.: NTSB-PSS-78-1; NTIS, PB-290 368, 1978).

LPG pipelines were involved in only 10 percent of the reported incidents but caused 62 percent of the property damage. The most common causes of LPG pipeline leaks that led to injury or fatality were pipeline corrosion and damages caused by excavating equipment. More stringent federal controls on LPG pipelines are recommended.

Neary, R.M., "Safety in LNG Semi-Trailer Design", American Gas Association, 1976 Operating Section Proceedings, Transmission Conference, Las Vegas, Nevada, May 3-5, 1976.

LNG tank truck design, connections, and driver training are discussed briefly.

Nelson, Wayne, "Charts for Confidence Limits and Tests for Failure Rates", J. Qual Technol, 4, (4), 190-195, (1972).

Defines Poisson and exponential confidence limits for a product failure rate and presents simple charts for determining upper confidence limits and statistical demonstration tests. Illustrates methods with actual data on electrical components.

"New LPG Ship Joins Phillips Fleet", Marine Eng/Log, 74, 70-71, (March 1969).

The 26,500 m^3 refrigerated LPG carrier "Phillips Arkansas" is discussed briefly. Not safety related.

"New Seagoing "Deepfreeze" is Designed for LPG Cargoes", Marine Eng/Log, 72, (10), 70-2, (1967).

The semi-refrigerated LPG carrier "Clerk Maxwell" is discussed briefly. Not safety related.

Newton, Phillip, W.R. Von Tress, and J.S. Bridges, "Liquid Storage in the CPI", Chemical Engineering/Deskbook Issue, 85, (8), 9-15, (1978).

The authors present basic information on the various types of tanks and vessels used in the chemical processing industry. The factors to be considered when selecting a storage system are discussed. Too general to be of use in safety study.

Noeltner, Robert H., Jr., and William J. Martinec, "Cargo Instrumentation and Control System for Floating LPG Terminal", Offshore Technol Conf, 7th Annu Proc, Houston, Texas, May 5-8, 1975. V. III, Pap OTC 2426, p. 829-838.

A description of the instrumentation and control systems for the first floating LPG terminal is presented. The terminal is a concrete barge and will be located in the Java Sea off Indonesia. A complete discussion of the instrumentation is given, including the alarm system and instrument redundancy. The system utilizes capacitance level sensors, LVDT type pressure sensors, an attitude sensor, central processing computer and a complete console which provides displays, printer, controls and alarm annunciators.

Norman, Edward C. and Howard A. Dowell, "The Use of Aqueous Foams to Mitigate Vaporization from Hazardous Chemical Spills", paper presented at the Large Scale Toxic Gas Releases Symposium held at the 86th National Meeting of the American Institute of Chemical Engineers, Houston, April 1-5, 1979.

The results of tests to reduce vapor emissions are reported for six foams applied to eleven different chemicals. Three foams were shown to be effective on laboratory scale butane spills.

Okrent, O., "Risk-Benefit Methodology and Application: Some Papers Presented at the Engineering Foundation Workshop, September 22-26, 1975, Asilomas, California, (California: The University of California at Los Angeles; Springfield, VA: NTIS, PB-261 920, 1975).

The papers were presented to assess quantitatively the state-of-the-art on risk/benefit methodology in terms of nuclear reactors and shipment and storage of liquefied natural gas. Includes:

Katz, Donald L. and Harry H. West, "The Overall Problem - Risk/Benefit for LNG Shipping and Storage".

Besumer, P.M., et al., "The Combined Use of Engineering and Reliability Analysis in Risk Assessment of Mechanical and Structural Systems".

Fairley, William B., "Criteria for Evaluating the "Small" Probability of a Catastrophic Accident from the Marine Transportation of Liquefied Natural Gas".

Gibson, S.B., "The Use of Quantitative Risk Criteria in Hazard Analysis".

Erdmann, R.C., "Comments on the Risk/Benefit Methodology Workshop".

Parsons, P.L., "Trials of Foam on Petrol Fires", Fire Engineers Journal, 37, (105), 10-15, (1977).

The results of tests using five foams to extinguish petrol fires are presented and discussed. Protein foam was found to be ineffective as an extinguishment agent. Does not apply to LPG safety study due to fuel differences.

Pinson, J.A., "A Review of Gasoline Plant Property Losses", 49th Annual Natural Gas Processors Association Convention, Tulsa, Okla., 1970, pp. 163-164.

A general discussion of failure modes and effects in gasoline plants, emphasizing fire events. Although discussion is quite general, some information is useful as generic data. Provides a tabulation of dollar losses from 96 events during the period 1959-1968, but information is not useable for failure-rate data.

Pluta, P.J. and R.G. Williams, "U.S. Coast Guard LNG Regulations", American Gas Association, Oper Sect Proc, 1979, for Meet, Hollywood, Fla., and New Orleans, La., May 7-9 and May 21-23, 1979, T214-220.

This paper discusses the basis for the Coast Guard's authority in establishing regulations for liquefied gas ships and the role of the IMCO committee. The reasoning behind the adoption of certain regulations is presented. Instances where the USCG and IMCO requirements differ are highlighted.

Poten & Partners, "Liquefied Gas Ship Safety, The Historical Record, 1964-1977", New York, 1978.

Report on factual history of gas ship safety, from 1964-1977, collected from marine accident reports and other casualty reports submitted to insurance carriers. Includes statistical summary of the data:

World fleet of 171 ships larger than 5000 m^3 (1964-1977)
a) delivered 16,000 cargoes
b) accumulated 960 ship-years of service
c) accounted for only 28 serious incidents involving potential hazards at import terminals
d) of the 28 incidents, only one involved leakage of cargo (leaky valve) and none apparently involved ignition of the main cargo (the collision of the Yuyo Maru and the Pacific Aries is not included as a cargo fire because "it is not clear whether the LPG tanks eventually failed". The LPG tanks did vent and the venting gas did burn).

---. "Liquefied Gas Ship Safety Historical Record, 1978", New York, 1978?.

This report is an update of the 1964-1977 report and includes the factual history of gas ship safety for 1978, collected from marine accident reports and other casualty reports submitted to insurance carriers. Includes statistical summary of the data:

World fleet of 192 ships larger than 5000 m^3 (1978)
a) no accidents involving cargo leaks, spills, or fires

"Protecting Liquid Petroleum Gas Vessels From Fire", Engineer, v. 221, March 25, 1966, p. 475-7; Discussion, v. 221, May 27, 1966, p. 818; v. 222, July 22, 1966, p. 125.

The use of water spray systems to protect LPG storage vessels from exposure to fire is discussed. Results from a large scale experiment led the authors to recommend a coverage rate of 0.2 gal/ft^2-min.

"Protective Systems for Ensuring Fire Safety at Sea", Fire Protection Review, 40, (445), 12-15, (1977).

This article reviews some of the published information on fire safety requirements applicable to ships and oil platforms. The papers reviewed cover such matters as sprinkler and spray systems for maritime use, the carriage by sea of hazardous cargoes requiring environmental control, fireboats and ship fires, and foam sprinkler installation on simulated oil rig fires.

Rabe, Walter M., "Refrigerated LP-Gas Tanker Operations", 53rd Annual Gas Processors Association Convention, Tulsa, Okla., 1974, pp. 138-142.

The principles of operation of a typical LPG tank ship are presented. Lists of the LPG tank ship fleet and U.S. LPG marine terminals are given along with a discussion of the future demand for more LPG tankers. Useful background information.

Raj, P.K., et al., "LNG Spill Fire Tests on Water - An Overview of the Results", American Gas Association, Oper Sect Proc, 1979, for Meet, Hollywood, Fla., and New Orleans, La., May 7-9 and May 21-23, 1979, T246-T251.

The authors report on a series of 16 tests involving the spill and ignition of LNG on water. Two kinds of fires were studied: pool fires and vapor cloud fires. The quantities of spilled LNG varied between 3 and 5.5 cm^3 with spill durations from 30 to 250 sec. A mean value of 210 kW/m^2 (66,600 $Btu/hr\text{-}ft^2$) has been obtained for the flame emissive power in the pool fire on water experiments. From the spectral record the flame temperature is estimated to be 1500 K. The visible flame heights were in agreement with Thomas' correlation predictions. Ignition of dispersed vapor clouds resulted in a propagating plume fire, with relatively low flame heights. The mean emissive power value for the vapor fires was comparable to the pool fire result. While the vapor fires progressed back toward the source, halting of the vapor fire spread for a substantial duration at the land-water interface was observed. Possible mechanisms to explain this unexpected phenomenon are discussed.

Rasch, J.M.B. "Petter", "Design Features and Availability of Liquefied Gas Carriers", 57th Annual Gas Processors Association Convention, Tulsa, Okla., 1978, pp. 195-201.

A review of the various types of tanks used to contain LPG aboard LPG tank ships is presented. Those portions of the IMCO code and USCG regulations that pertain to tank design are discussed.

Reid, Robert A., "Design and Operation of Refrigerated LP-Gas Terminals and Requirements for New Terminals", 53rd Annual Gas Processors Association Convention, Tulsa, Okla., 1974, pp. 143-144.

The design and operation of various U.S. LPG marine terminals are discussed. An increase in the number of terminals needed is predicted.

---. "Mass Storage of Liquefied Petroelum Gases in the U.S.A.", World Gas Conf, 13th, London, Jun 7-11, 1976. Publ by Int Gas Union, London, 1976, v. 4, Pap IGU/H4-76.

The development, location, and types of LPG mass storage (capacity greater than 4,000 metric tons) in the U.S. are discussed.

---. "Safety Considerations in the Design and Operation of a Refrigerated LP-Gas Marine Terminal", American Petroleum Institute, Proceedings, Sect III, Refining, Vol. 54, for Meet, 1975, Chicago, Ill., May 12-15, 1975, p. 471-483.

General discussion of plant, layout, operations, and safety at Petrolane's marine import terminal, San Pedro, California.

Reid, Robert C. and Kenneth A. Smith, "Behavior of LPG on Water", Hydrocarbon Processing, 57, (4), 117-121, (1978).

Heat transfer model of boiling rate for LPG, with a growing ice shield, described. Adding small quantities of ethane or n-butane to the propane had essentially no effect on the heat flux curves. Thus, the boiling of LPG may be modeled satisfactorily by using pure propane. Ethane - a moving boundary model might be applicable in the same manner as employed for propane spills. In theory, after an ice shield forms, the heat transfer rate is significantly above that of LPG; although in the very short period following a spill, LPG boils at a rate very much faster than ethane. Ethylene - model same as LPG and ethane. n-butane - the rate of boiling is far less than other liquefied hydrocarbons studied.

---. "Confined Boiling Rates of Liquefied Petroleum Gas on Water", Washington, D.C., U.S. Department of Energy, Div of Environmental Control Technology, Report No. HCP/P4548-01, 1978.

Presents results of experimental "spills" of LPG, propane, ethane, ethylene, and n-butane on water in a specialized experimental apparatus having a 191 cm^2 heat transfer surface. Two tests with propane on ice and propane on agar gel were also run. Results are presented as mass vaporized as a function of time. A basic science study applicable to study of LPG spills and vaporization as input to dispersion models.

Robinson, H.S., "An Underwriter's Viewpoint on Gasoline Plants - They Can Burn", 49th Annual Natural Gas Processors Association

Convention, Tulsa, Okla., 1970, pp. 161-162.

Provides Oil Insurance Association's minimum fire protection recommendations for a well-protected gasoline plant. Includes general mention of serious fire protection design deficiencies observed by underwriters. Useful only as general background.

Rosenblatt & Son, Inc., "Tanker Structural Analysis for Minor Collisions", (Washington, D.C.: USCG; Springfield, VA: NTIS, ADA-031 031, 1975).

An analytical procedure and its numerical application are presented for estimating the plastic energy absorbed by longitudinally framed ships, particularly tankers, when involved in either right angle or oblique collisions.

Ryburn, John E., "Design Considerations and Start-Up Problems in the Wasson Plant Low Temperature Process", 49th Annual Gas Processors Association Convention, Tulsa, Okla., 1969, pp. 130-135.

The operation of a gas processing plant for the recovery of ethane and propane is described. Measures taken to reduce the risk of fire or explosion within the plant are discussed.

"Safe Handling of LPG Cylinders", Construction Plant & Equipment, 6, (8), 36-7, (1978).

A brief discussion is presented on the misuse of LPG cylinders and hose connections. Basic safety precautions are suggested.

Schneider, Alan L., "Liquefied Natural Gas Safety Research Overview", Paper, 1978 American Gas Association - Cryogenic Society of America LNG Terminal & Safety Symposium, San Diego, Calif., 12-13 October, 1978.

A significant review of 105 research papers on LNG safety research. This is an important resource book for study of LPG safety because of the transferable applicability of results for LNG to LPG. Necessarily limited in detail, but provides adequate information selection from the cited papers.

Searson, A.H., "Petrochemical and Fire Safety. Plant and Equipment Design", Fire, 70, (867), 179-80, (1977).

General summary of the safety considerations which would be typical of a petroleum or petrochemical plant design.

Sharry, John L. and Wilbur L. Walls, "LP-Gas Distribution Plant Fire", Fire Journal, 68, (1), 52-57, (1974).

The fire resulting from a ruptured LPG railroad tank car in Kingman, Arizona on Thursday, July 5, 1973 is discussed. The tank car ruptured due to fire exposure. A ground-level fireball (150-200 ft in diameter) was immediately followed by a "flaming mushroom cloud" (800-1000 ft in diameter). Twelve fire fighters died of extensive burns. (This accident is cited repeatedly as an example of the potential hazards of LPG).

Siewert, R.D., "Evacuation Areas for Transportation Accidents Involving Propellant Tank Pressure Bursts", (New Orleans, 1972 Joint Army, Navy, NASA Air Force (JANNAF) Propulsion Meeting; Springfield, VA: NTIS, N73 29987, 1973).

Based on data from railway accidents involving spills of flammable liquid chemicals with high vapor pressure and tank car explosions, it is estimated that an evacuation area with a minimum radius of 600 m (2000 ft) is required to limit the statistical probability of fatality to 1:100 such accidents.

Simmons, John A., "Risk Assessment Method for Volatile Toxic and Flammable Materials", Preprint, 4th Int Symp, Transport of Hazardous Cargoes by Sea & Inland Waterways, Jacksonville, Florida, 26-30 October, 1975.

The author presents a method for assessing risks associated with chlorine, LNG, and LPG spills. Parameters considered are spill size, vapor dispersion (Gaussian plume formula), time of ignition, and population density. The method assigns a probability to each parameter; the product of the four probabilities is the expected frequency of the event. Data and results for LPG tank truck accidents are presented.

---. "Risk Assessment of Storage and Transport of Liquefied Natural Gas and LP-Gas", Virginia, Science Applications, Inc., 1974.

An assessment of the probability of fatality associated with tank truck transportation of LPG and tank ship transportation of LNG is presented. The risk assessment considered such factors as probability of an LPG truck accident (resulting in a spill), vapor dispersion from the spills, ignition probability, and population density. The calculated probability of 1.2 fatalities per year for LPG truck fires compares favorably to the historical rate of 1.23 deaths per year (37 fatalities between 1931 and 1961). A compilation of LPG spills associated with tank truck operations from July 1971 to December 1973 is included as is a list of accidental LPG releases that resulted in flash fires.

Simmons, John A. and Robert C. Erdmann, "Risk Assessment Strategy for Marine Transportation", Preprint, 4th Int Symp, Transport of Hazardous Cargoes by Sea & Inland Waterways, Jacksonville, Florida, 26-30 October, 1975.

This paper briefly discusses methods that might be used to reduce the probability of fatality due to a large spill of a hazardous material during marine transport.

Siscoe, Ines, "Phenomenology of LNG Accidents, A Selected Bibliography", California, The Rand Corporation, 1974.

The bibliography covers the chemical, physical, and environmental aspects of liquefied natural gas and its transportation. The references extend from 1965 to 1974.

Smith, J.M.S., R.C. Mathew and, J.A.F. Crook, "The Safety of Gas Carriers with Particular Reference to the I.C.S. Tanker Safety Guide (Liquefied Gas). Movement, Control and Personnel Training", Gastech 75, LNG & LPG Technology Congress Proceedings, Paris, 71-81, September 30-October 3, 1975.

A general philosophy of safety with respect to LNG and LPG tank ships is presented. Design and construction, training, traffic control, and ship-to-shore communications during cargo transfer are all discussed.

Stannard, James H., Jr., "Thermal Radiation Hazards Associated with Marine LNG Spills", Fire Technology, 13, (1), 35-41, (1977).

Presents calculations estimating the thermal radiation from an LNG fire ignited shortly after the spill has occurred. A 25,000 m^3 instantaneous spill is used as an example. A safe separation distance of 2900 ft is recommended.

Strehlow, Roger A., "Unconfined Vapor Cloud Explosions - An Overview", International Symposium on Combustion at Pennsylvania State University, 1972.
(Paper included as Appendix in: Brown, John A., "A Study of

the Growing Danger of Detonation in Unconfined Gas Cloud Explosions", Final Technical Report, New Jersey, John Brown Associates, Inc., December 1973).

This paper surveys unconfined vapor cloud explosions that occurred during the period 1930-1972 and evaluates research efforts concerning dispersion, prediction of blast effects, and initiation of detonations. The reference list is extensive and includes research papers dealing with dispersion and explosion and a number of descriptions of notable vapor cloud explosions.

Strehlow, Roger A. and Wilfred E. Baker, "The Characterization and Evaluation of Accidental Explosions", Aeronautical and Astronautical Engineering Department, University of Illinois at Urbana, 1975.

A review of accidental explosion causes and results is presented. Accidental, intentional and natural explosions are covered. Blast damage analysis and prediction is extensively discussed. Vessel ruptures, fireballs, and unconfined vapor cloud explosions are all examined. A good state-of-the-art review as of 1975.

Sutton, S.B. and E.W. McCauley, "Assessment of Hazards Resulting from Atmospheric Propane Explosions at LLL", (Calif: California University, Livermore, Lawrence Livermore Laboratories; Springfield, VA: NTIS, AD-A015 171, 1975).

The authors present a technique for estimating blast wave overpressure and radiative heat flux values for hypothetical explosions and failure of propane tanks. Calculated overpressure and heat flux values have been determined for instantaneous energy releases and slow leak releases for a typical 30,000 liquid gallon propane tank.

Sylvia, Dick, "Seminar Looks at Safe Handling of Hazardous Materials in Transit", Fire Engineering, 128, (8), 96-8, 100, 103, (1975).

Ways of handling hazardous materials involved in transportation emergencies are discussed in relation to the problems fire fighters will face at the leak, spill, or fire. The paper is very general but does include some information on handling LPG truck and railroad tank car accidents.

Temple, Baker and Sloane, Inc., "World LPG Forecast and Implications for the U.S. Merchant Marine, 1978-1990", (Mass: Temple, Baker and Sloane, Inc.; Springfield, VA: NTIS, PB-282 306, 1978).

Objective of this study was to analyze the potential for the development of a fleet of U.S. flag LPG ships through the year 1990, and offers an economic analysis for shipping LPG. Includes an LPG and LNG/LPG vessel list in the appendix.

Thomas, William duBarry, "Record of Voyages Completed by the World Fleet of LNG Carriers", issued irregularly, compiled for the El Paso LNG Company. Issues number one through five.

An analysis of the voyages completed by the world fleet of LNG carriers. Included are all commercial voyages, plus some experimental voyages, arranged in three main groups according to receiving terminal location.

Thomas, William duBarry and Alfred H. Schwendtner, "LPG Carriers: The Current State of the Art", paper to be presented at the Annual Meeting, The Society of Naval Architects and Marine Engineers, New York, November 11-12, 1971, [Oceanology, 19-24, (March 1972)].

Describes basic design of LNG ships. The only mention of LPG is that some of the ships have reliquefaction equipment installed that enables them to carry other cryogenic cargoes.

Townsend, William, et al., "Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment", (Maryland: Ballistic Research Laboratories; Springfield, VA: NTIS, PB-241 702, 1974).

Two (33,700 gallon) 128 kiloliter high pressure railroad tank cars (one coated with 1/8 inch (0.318 cm) Korotherm insulation), loaded with LPG were exposed to a large hydrocarbon fire approximately four times as long as the uncoated tank car.

Townsend, William and Richard Markland, "Preparation of the BRL Tank at the DOT, Transportation Test Center, Pueblo, Colorado", (Maryland: Ballistic Research Laboratories; Springfield, VA: NTIS, PB-251 151, 1975).

The design, fabrication, instrumentation, calibration, and operation of the tank car torch test facility are reported. The torch test is designed to evaluate effectiveness of thermal insulation coatings on retarding heat transfer into pressurized tank cars exposed to fires.

Underwriters Laboratory, Inc., "Pressure Regulating Valves for LP-Gas", Ul 144, 4th ed., Ill., 1978.

Construction, performance tests, quality control, and marking are discussed for pressure regulators to be used with LP-Gas equipment other than in automotive or marine applications or gas-welding and cutting operations. Applications at plants, pipeline and marine terminals, and related storage facilities at such locations are also excluded. The standard applies mainly to residential and industrial LPG systems for heating, etc.

---. "Standard for Container Assemblies for LP-Gas", UL 644, 4th ed., Ill., 1977.

Construction, testing, and marking of LPG container assemblies up to 2000 gal capacity are discussed. The items discussed in the standard include valves, level gauges, pressure gauges, and regulators that, in addition to an ASME coded tank, comprise a container assembly.

---. "Valves for Anhydrous Ammonia and LP-Gas (Other Than Safety Relief)", UL 125, 3rd ed., Ill, 1974.

Construction, performance tests, quality control, and marking are discussed for valves in anhydrous ammonia and LPG service. The requirements do not apply to LPG valves for use in refrigerated storage systems, marine and pipeline terminals, chemical plants, etc. The requirements apply mainly to valves in ammonia or LPG service where the material is stored and used on-site (e.g., residential or industrial heating) and utility company LPG gas plants.

United States Atomic Energy Commission, "Primary Fuel Transport and Storage", (Washington, D.C.; Springfield, VA: NTIS, TID-26758-P9, 1974).

An outlined program formulated for recognition of many areas in fuel transportation, distribution, and storage that could benefit from improved construction and operating techniques, advances in management systems, and development of new and improved materials.

United States Coast Guard, "CHRIS: A Condensed Guide to Chemical Hazards", (Washington, D.C.; Springfield, VA: NTIS, AD-A002 390, 1974).

The condensed guide provides information needed to use CHRIS, the availability of other information systems, chemical data sheets (chemical identification data, general response information and information on fire, exposure, and water pollution), general chemical group reactivity (in case of accidental mixing) and synonyms of chemical compounds. The system consists of four volumes:

CG-446-1 A Condensed Guide to Chemical Hazards
CG-446-2 Hazardous Chemical Data
CG-446-3 Hazard Assessment Handbook
CG-446-4 Response Methods Handbook

U.S. Congress, Office of Technology Assessment, "Transportation of Liquefied Natural Gas", Washington, D.C., Government Printing Office, 1977.

LNG technology, components of the LNG import system (tanker construction, operations and regulations; terminals; LNG project certification; safety research on LNG facilities; facility siting; liability for accidents; reliability of supply; and pricing policy), public awareness, and actions desired by various groups are discussed. Much of the discussion is also applicable to LPG.

U.S. Department of Energy, "Unconfined Boiling and Spreading Rates of Liquefied Petroleum Gas (LPG) Spilled on Water", Renewed Proposal. Robert C. Reid and Kenneth A. Smith, Massachusetts Institute of Technology, 1978.

A literature review on contact boiling between two immiscible liquids, heat transfer to boiling liquid mixtures, and boiling of cryogenic liquids on solids and water is presented. Data from some LNG spills on water are compared to the total time to evaporate and maximum pool diameter as calculated by three different mathematical models; agreement was not good. The author's one-dimensional boiling and spreading model is then discussed in detail. A proposed experimental program for studying simultaneous boiling and spreading of LPG spills on water is described. Preliminary experiments with the proposed test apparatus showed that ice formed on the area of the water surface immediately upon contact with LPG; this is contrary to previous LNG tests where no ice formation was observed.

U.S. Department of Energy, Environmental Control Technology Division, "Liquefied Gaseous Fuels Safety and Environmental Control, Assessment Program: A Status Report", (Washington: Pacific

Northwest Laboratories; Springfield, VA: NTIS, DOE/EV-0036, May 1979).

This document reports on both the current planning and overview aspects of the Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program and on progress made in FY 1978 in technical areas by government contractors.

U.S. Department of Transportation, Coast Guard, "Federal Register, Vol. 44, No. 87, Thursday 3, 1979. Safety Standard for Self-Propelled Vessels Carrying Bulk Liquefied Gases; Special Interim Regulations for Issuance of Letter of Compliance to Barges and Existing Liquefied Gas Vessels".

Amendments to 46 CFR, Part 31, 34, 40, 54, 56, 98, 154, and 154a are presented. The major amendment changes the old 46 CFR, Part 154 to new Part 154a, "Special Interim Requirements for Issuance of Letters of Compliance to Barges and Existing Liquefied Gas Vessels". The old Part 154 is replaced by new Part 154, "Safety Standards for Self-Propelled Vessels Carrying Bulk Liquefied Gases". Both of these new parts generally require that the vessels meet the applicable IMCO codes, with certain exceptions and additions.

---. "Fifth Coast Guard District Liquefied Natural Gas Emergency Contingency Plan", Virginia, 1978.

A detailed plan for handling emergencies such as fires, groundings, etc., on LNG vessels calling on Cove Point, Maryland. The desired plans of action by the ship operators, terminal operators, and USCG are presented.

---. "LNG/LPG Contingency Plan", Captain of the Port, Providence, Rhode Island, 1975. (Supplement - Revised 25 April 1977).

This document details all special requirements called for by the USCG Captain of the Port of Providence, Rhode Island, for the transport and discharge of LNG and LPG within the Port of Providence. These requirements are generally in addition to those imposed by IMCO and the CFR. Technical guidelines for handling LNG and LPG emergencies are also presented.

---. "LPG Contingency Plan", Corpus Christi, Texas, Marine Safety Office, 1979.

Special requirements, called for by the USCG Captain of the Port of Corpus Christi, are detailed for the safety of Liquefied Petroleum Gas (LPG) bulk shipments transiting the various ports within the Corpus Christi Marine Safety Zone. Guidelines for emergency procedures are also provided. These requirements are generally in addition to those imposed by IMCO and the CFR.

---. "The Port of Boston. LNG/LPG Operation/Emergency Plan", Massachussetts, Marine Safety Office, 1978.

This document details all special requirements called for by the USCG Captain of the Port of Boston, Mass., for the transport and discharge of LNG and LPG within the Port of Boston. These requirements are generally in addition to those imposed by IMCO and the CFR. Information concerning actions to be taken in the event of an incident involving an LNG or LPG ship in the port is also included.

U.S. Department of Transportation, Materials Transportation Safety Board, "Liquid Petroleum Report, 1970-1978", Washington, D.C., 1979.

Tabulated data on liquid petroleum by carrier systems involved, cause of accident, origin of liquid or vapor release, injuries, state accident summary, and casualty summary.

U.S. General Accounting Office, "Pipeline Safety - Need for a Stronger Effort", (Washington, D.C.; Springfield, VA: NTIS, PB-280 321, 1978).

Presented is the testimony of February 27, 1978, on the results of a review of the federal pipeline safety program and a summary of the pipeline safety issues "which should be receiving priority attention by the U.S. Department of Transportation".

United States Nuclear Regulatory Commission, "Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH 1400, Washington, D.C., October 1975.

This report is primarily concerned with safety in the nuclear power industry. However, Appendix III is an extensive compilation of data on human and equipment failure rates that can be applied to safety analyses of other systems, e.g., LPG plants.

Wakamiya, S.K. and N.J. Calvano, "Safety Problems Associated with Pressure Containers", (Washington, D.C.: National Bureau of Standards; Springfield, VA: NTIS, PB-264 691, 1977).

Accident report data from hospital emergency rooms and interview reports with the accident victims involving fire extinguishers and LPG tanks are summarized. Relevant standards are discussed.

Warner, Vincent A., "Emergency Planning for Liquefied Natural Gas Facilities", Professional Safety, 20, (11), 47-51, (1975).

A method for formulating a plan for handling emergency shutdowns at an LNG plant is presented. The method is basically an event tree analysis and involves both on-site and extra-facility agency interfacing. The method is applicable to LPG.

Waters, D., "Petrochemicals and Fire Safety. The Fire Protection of Plant and Equipment", Fire, 70, (867), 185-186, 189, (1977).

Philosophy and approach of Imperial Chemical Industries, Ltd., in Great Britain, for fire-fighting flammable liquids and vapors are presented. Suggested methods used in plants, fire protection equipment, water supplies and applications fire plans, etc., are discussed.

Welker, J. Reed, et al., "Fire Safety Aboard LNG Vessels", (Norman, Oklahoma: University Engineers, Inc.; Springfield, VA: NTIS, ADA-030 619, 1976).

The results of an analytical examination of cargo spill and fire hazard potential associated with marine transport of LNG are presented. The principal emphasis is on cargo transfer operations at receiving terminals. The onsite fire fatality rate is said to be 10^{-10} fatalities per person-hour exposure. Risk from cargo spills caused by ramming of a docked LNG tankship is said to be possibly excessive.

---. "A Survey of the Effectiveness of Control Methods for Fires in Some Hazardous Chemical Cargoes", (Norman, Oklahoma: University Engineers, Inc.; Springfield, VA: NTIS, ADA-026 300, 1976).

The results of a survey to determine the recommended fire fighting methods for hazardous chemical cargo fires are presented. Dry chemical fire extinguishing agents are recommended for propane and butane, both of which are also listed as possibly presenting a greater hazard (i.e., explosive vapor) when unignited.

Welker, J. Reed and H. Peter Schorr, "LNG Plant Experience Data Base", American Gas Association, Oper Sect Proc, 1979, for Meet, Hollywood, Fla., and New Orleans, La., May 7-9 and May 21-23, 1979, T263-T266.

The rates of equipment malfunction or failure, (gathered from 25 LNG peak shaving plants) are presented. Failure rates are given for tanks, compressors, valves, pumps, control systems, etc. The data show that the mean time between fires where LNG or natural gas were involved is about 200,000 hours.

Wood, William S., "Transporting, Loading and Unloading Hazardous Materials", Chemical Engineering, 80, (15), 72094, (1973).

Discusses bulk transportation (liquid and solid) of hazardous chemicals by truck, rail, ship, barge, and pipeline. A general discussion is presented for the safety systems of each type of transportation.

Worboys, R.V. and S.F. Young, "The Development of an Internal Insulation System for LPG Carriers", Gastech 74, International LNG & LPG Congress, Amsterdam, November 12-14, 1974.

The paper discusses the Shell International Insulation System, the use of polyurethane foam as both insulation and containment system, for the cargo of fully refrigerated LPG ships with the objective of reducing the capital cost. The system is not suitable for the carriage of ammonia.

Yamamoto, Katsuro, "A Semi-Membrane Tank System for Gas Ships", Shipping World and Shipbuilder, 165, (3871), 869-871, (1972).

Brief description is presented of the construction of the cargo tanks for the ethylene carriers and large ocean-going LPG tankers (all of which were built in accordance with the Bridgestone semi-membrane system), and of the proposed design for the construction of large ocean-going LNG tankers.

Zalosh, Robert G., "Gas Explosion Tests in Roomlike Vented Enclosures", Paper submitted for presentation at the Thirteenth Loss Prevention

Symposium, 86th National Meeting of the AIChE, Houston, Texas, April 2-5, 1979.

A test program is described to help determine explosion venting requirements for hydrocarbon gas explosions in large rooms and process enclosures. Small-scale and large-scale tests have been conducted with methane-, propane-, and ethylene-air mixtures.

ADDENDA

The American Society of Mechanical Engineers, "Addenda to Chemical Plant and Petroleum Refinery Piping", ANSI/ASME B31.3-1976. New York, November 12, 1979.

Anyakora, S.N., G.F.M. Engel, and F.P. Lees, "Some Data on the Reliability of Instruments in the Chemical Plant Environment", The Chemical Engineer, 255, 396-402, (Nov 1971).

Reports the results of a survey of three chemical plants concerning reliability of instrumentation. Data are presented for a wide variety of instruments in widely different working environments. It is concluded that instruments in severe environments have failure rates up to four times greater than equivalent instruments in protected environments.

Britter, R.E., "The Spread of a Negatively Buoyant Plume in a Calm Environment", Atmospheric Environment, 13, (9), 1241-1247, (1979).

This paper presents the results of a laboratory experiment to study the spread of a negatively buoyant plume in a calm environment. A semi-empirical analysis is in agreement with the experimental results which indicate that the position of the leading edge of the plume advancing over a horizontal smooth surface is given by

$$r_m = (0.84 \pm 0.06)(Q_1 g')^{1/4} t^{3/4}$$

where $Q_1 g'$ is the negative buoyancy flux emanating from the source. An important physical conclusion is that there is little, if any, mixing between the plume and the environmental except at the leading edge.

Bullerdick, W.A., et al., "A Study to Reduce the Hazards of Tank Car Transportation", (New York: Comell Aeronautical Laboratory, Inc.; Springfield, VA: NTIS, PB-199 154, 1979).

The objectives of the 4-month study were to define thermal inputs and associated vapor generation rates for hazardous materials transported in tank cars when subjected to fire exposure; develop performance specifications and conceptual design and application requirements for safety devices that would prevent catastrophic car failures; and formulate a research program for the design and test verification of recommended safety devices. A key finding was that the controlling condition in sizing for propane relief valves should be the liquid feed, or "upset" car condition, and not the vapor feed per the current (1970) criterion.

Geffen, C.A. and A.L. Franklin, "An Assessment of the Risk of Transporting Propane by Truck and Train", Paper Presented at the Second DOE Environmental Control Symposium, Reston, Virg., March 17-18, 1980. (Proceedings to be published)

An analysis of the risk to society from transporting propane by truck and train is presented. Accident probabilities, release probabilities, release scenarios, and consequences of these scenarios were combined to estimate the system risk. A risk spectrum (expected frequency of a given level of consequences versus consequence level) is included. The results of this study indicate that the risk to the public from truck and train transport of propane is higher than the risks involved in shipping nuclear materials, but is generally lower than man-caused or natural disaster events.

Kirk, John T., Jr., and Royden H. Rogers, "Design and Operating Problems Involved in the Marine Transportation of LPG", Preprint, Annual Tanker Conference of the Central Committee on Transportation by Water, American Petroleum Institute, Abscon, New Jersey, May 1-4, 1960.

A brief history of the development of LPG vessels by Standard Oil Company (NJ) is presented. Design and operating problems encountered in the water transportation of LPG as well as safety factors are also discussed. Of historical interest.

Martinsen, William E., David W. Johnson, and J. Reed Welker, "Extinguishment and Control of LPG Fires", Paper Presented at the Second DOE Environmental Control Symposium, Reston, Virg., March 17-18, 1980. (Proceedings to be published)

This paper reports the results of approximately 100 LPG fire control and extinguishment tests. High expansion foam applied at greater than 0.1 gpm/ft^2 provided good extinguishment fire control (i.e.,

75% reduction in radiant heat flux) within a few minutes but did not extinguish the fires. Three dry chemical extinguishing agents were used to extinguish fires ranging from 25 ft^2 to 400 ft^2. The application rates required for extinguishment were similar to those required for hexane fires and greater than for LNG fires. Additional tests on boiloff and burning rates are discussed; the steady-state burning rate being about 0.45 in/min for pools larger than 20 ft diameter.

Reid, Robert C., "Possible Mechanism for Pressurized-Liquid Tank Explosions or BLEVE's", Science, 203, (23), 1263-1265, (1979).

The hypothesis is made that rapid depressurization of hot, saturated liquids may result in an explosion. The temperature of the hot liquid must, however, be above the superheat limit temperature at 1 atmosphere, and the drop in tank pressure must be very rapid. Two examples of large-scale pressure-letdown explosions are cited and possible preventative measures suggested.

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16. Abstract

The DOE Assistant Secretary for Environment has responsibility for identifying, characterizing, and ameliorating the environmental, health, and safety issues and public concerns associated with commercial operation of specific energy systems. The need for developing a safety and environmental control assessment of liquefied gaseous fuels was identified as a result of discussions with various Government, industry, and academic persons having expertise with respect to particular materials. A program to address relevant issues has evolved. (Full plan contained in DOE/EV-0036, May 1979)

The goal of the Program Plan is to gather, analyze, and disseminate technical information that will aid future decisions by industry, regulators, and the public relating to facility siting, system operations, and accident prevention. (This research complements related programs supported by other Government agencies and industry.) To accomplish the goal, three objectives have been identified: verified predictive capability; verified prevention methods; verified control methods.

Volume 1 of this document outlines the DOE Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program, briefly summarizes the 25 technical reports, and includes annotated bibliographies for LNG and LPG. Volume 2 contains 19 research reports focused on LNG. Volume 3 contains 6 research reports on LPG, hydrogen, and anhydrous ammonia. These reports discuss key developments between January 1979 and April 1980.

Preceding documents reporting earlier information are DOE/EV-0036 (May 1979) and DOE/EV-0002 (February 1978).

17. Key Words

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