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LNG SAFETY RESEARCH IN THE U.S.A.*

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Summary

This paper describes recent LNG safety research activities in the United States. Most of these activities have been sponsored by the U.S. Department of Energy and the Gas Research Institute. The scope of this coordinated research effort is presented under three headings:

1. *Hazard assessment.* These are projects aimed at the development of experimental data and analytical models to describe radiation from LNG spill fires, the extent of flammable vapor cloud dispersion, rapid phase transitions and other potential hazards. Also included are studies aimed at improving the database needed to analyze risks resulting from an accidental LNG release at LNG facilities or during marine or land transport.
2. *Accident prevention.* These are studies directed toward the development of qualification tests and reliable data on the properties and behavior of LNG tank wall materials, insulations and other components. These studies are expected to reduce the probability of occurrence of a major LNG release.
3. *Hazard control.* These are projects which address the conceptual design, testing and engineering development of new or improved response technologies and operational procedures that are expected to reduce the severity of an accident given a LNG release.

1. Introduction

Although the overall rate of LNG consumption in the U.S.A. is relatively small, LNG plays a very important role in supplementing conventional sources of natural gas and ensuring the availability of uninterrupted gas service during exceptionally cold winters. The continued safe operation of the more than one-hundred LNG peakshaving and satellite facilities and five marine terminals in the U.S.A. has been of great concern to the gas industry, regulatory bodies and the public. Recent federal standards [1] have placed certain limitations on the siting and operation of new LNG facilities, as well as on existing facili-

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ties contemplating major changes. Because of insufficient technical information and the perception by the public of LNG as a major hazard, these standards are believed to be conservative. A number of research projects are under way in the U.S.A. to develop more accurate models to quantify potential LNG hazards, to minimize the frequency of accidents through the development of preventive measures and to reduce the severity of these accidents should they occur by developing effective response measures.

During the past decade, research on LNG safety was carried out by the Bureau of Mines, American Gas Association (AGA), U.S. Coast Guard and later jointly by the U.S. Coast Guard and AGA. More recently, LNG safety research responsibilities have shifted to the U.S. Department of Energy (DOE) and the Gas Research Institute (GRI). The research programs sponsored by these two organizations are closely coordinated with each other as well as with the U.S. Coast Guard, U.S. Maritime Administration and organizations in Europe (e.g. Shell, British Gas Corp., Gaz de France, U.K. Health and Safety Executive) and Japan (e.g. Tokyo Gas, Osaka Gas).

What follows is a summary of projects that have been recently completed or are under way. All final reports on these projects are or will be available from the National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, VA 22161, U.S.A.

2. Hazard assessment

The projects described under this heading may be classified into four areas:

(1) the development of theoretical models that may be used to quantify the potential hazards of LNG;

(2) the verification of these models through laboratory experiments, wind-tunnel simulations and large-scale tests;

(3) the ancillary development of specialized instrumentation for use during large-scale tests; and

(4) the collection of reliable data needed to conduct risk analyses.

2.1 Theoretical model development

Under contract to DOE, the Lawrence Livermore National Laboratory (LLNL) has been carrying out a number of theoretical studies aimed at the development of new and improved models to describe LNG vapor cloud dispersion, laminar flame propagation in LNG vapor/air mixtures, the chemical kinetics of LNG/air detonations, and combined unsteady gaseous combustion and fluid dynamic processes. Progress on these ongoing projects has been documented in ref. [2].

In one of these studies a one-dimensional numerical fluid dynamic model of the spreading of liquefied gaseous fuels on water was developed by Stein and Ermak [3]. The model was based on the one-dimensional, time-dependent equations of conservation of mass and momentum, with the assumption that the pool of liquid fuel spreads in a radially symmetric manner. It included the effects of vaporization, shear at the fuel—liquid interface, and buoyancy due to the density difference between the fuel and the liquid onto which it is spilled. Both instantaneous and continuous spills of finite volume were treated. The height and spreading velocity of the pool of spilled fuel were calculated as functions of time and radius by numerically solving the conservation equations with a finite difference method.

In a parallel study, Zeman [4] examined the phenomenon of gravity currents with specific attention to heavier-than-air cold gas releases such as during LNG spills. A one-layer model was developed that was capable of dealing with the inherently three-dimensional nature of such releases and that included realistic initial conditions simulated by prescribing the gas boil-off velocity, W_b, within the spill area with scale L_0. Dynamic similarity of the gravity currents was examined, and similarity parameters were proposed. It was shown that a characteristic gravity spreading velocity varied as $W_b^{1/3}\ L_0^{1/3}$ with the depth scale of the layer proportional to $(W_bL_0)^{2/3}$. These scaling laws agreed with the results from numerical experiments.

More recently, Chan et al. [5] developed a fully three-dimensional, non-Boussinesq and non-hydrostatic vapor cloud dispersion model. The model solves the set of three-dimensional, time-dependent, conservation equations governing incompressible flows with variable density via a simplified finite element method and a basically explicit time integration scheme. The code has been applied to simulate a number of field tests and the model predictions appear to compare quite favorably with recently conducted field measurements for a number of 40 m^3 LNG spills [6]. The code has also a capability of considering terrain effects [7].

In another DOE program, Fay et al. [2] developed a simple semi-empirical dispersion model that is intermediate in complexity between the SIGMET three-dimensional unsteady flow model described by Havens [8] and the classical model of Germeles and Drake [9]. Available wind-tunnel and field test data are compared with model predictions in a final report to be published shortly.

The U.S. Coast Guard, with GRI cofunding, has embarked on a three-year program at the University of Arkansas to test a number of mathematical models for the estimation of near- and far-field dispersion of heavier-than-air gas mixtures. The study will utilize experimental data collected from large-scale releases of anhydrous ammonia, LPG, LNG and halon 122. In addition, small-scale experiments will be carried out to investigate the initial gravity spreading process and associated air entrainment.

Woodward et al. [10] compared the predictions of several vapor dispersion models with the results of selected large-scale gas releases. The proprietary and complex ZEPHYR and MARIAH models, which are similar to the SIGMET model documented by Havens [8], the simple "top hat" models of Germeles and Drake [9] and Eidsvik [11], and the "advanced top hat" HEGADAS II model of Colenbrander [12] were tested against data from 40 m^3 halon/air mixture releases at Porton Down, England [13] and the Esso/API LNG spills at Matagorda Bay, Texas [14]. Woodward et al. concluded that the different models complement one another and are applicable over different ranges of conditions. The sophisticated models appear to be needed in cases where terrain effects and obstacles are important. These models may not be suitable for predicting the hazardous extent of a toxic vapor cloud where small concentrations define the boundaries of the hazardous region. Apparently, the accumulation of integration errors can become significant in these complex models, whereas "top hat" models are less susceptible to such errors.

For several years the LNG Research Center at Massachusetts Institute of Technology (MIT) under GRI sponsorship has been conducting research on potential problems associated with LNG storage and the behavior of accidental LNG releases on water and land.

Dainis and Reid [15] designed, constructed and carried out preliminary tests on an apparatus to measure the boiling and spread rates of LNG on water under carefully controlled conditions. Using the same apparatus, Chatlos and Reid [16] found that boiling rates were initially high, but rapidly decreased (approximately inversely proportional to the square root of time) to values around 25 kW m^{-2}. Ice formed quickly after the spreading front of the cryogenic fluid covered the water. Conduction heat transfer across the growing ice layer provided a reasonable explanation for the decay in boiling rate. Spreading rates, at short times, were found to be similar to those expected if the liquid were nonvolatile. At longer times, however, spreading rates were slower due to boiling of the cryogen. Spreading rates were unaffected by small changes in cryogen composition. An analytical model developed earlier for LPG spills, when modified for liquid methane (and LNG), allowed the successful prediction of the spread rate. Predictions were, however, sensitive to the choice of the bubble density in the boiling methane.

Previous studies at MIT [17] have shown that the electrical conductivity of LNG is less than 10^{-17} ohm^{-1} cm^{-1}. Hirsch and Smith [18] attempted to develop a mechanistic understanding of electrical charge generation by constructing a novel apparatus similar to a Couette viscometer for the electrification of hydrocarbon liquids. However, a generalized model that would predict charge generation in hydrocarbon flow systems could not be developed because of the large number of factors that influence charge generation, such as the concentration of dissolved and suspended impurities, wall/liquid interfacial conditions and flow characteristics.

Several studies have also been carried out at MIT [19—23] to identify the conditions under which vapor explosions or rapid phase transitions (RPT) occur when LNG contacts water. In the most recent study, Corbin and Reid [24] constructed an apparatus to test the concept of initiating an RPT in methane-rich LNG on water by collapsing the vapor film with a shock wave. Helium overpressures were achieved by breaking a diaphragm in an attached high-pressure helium chamber. Pressure transducers recorded subsequent events. No RPTs were noted for liquid nitrogen, liquid ethane, liquid methane or methane-rich LNG even with helium driver pressures up to 62 bar. The helium did, however, greatly enhance the boiling rate of the cryogen on water. On the basis of analytical modeling, it was concluded that RPTs would be very improbable for a methane-rich LNG contacting ambient water in a mode where the surface pressures were high. A new thermodynamic model was developed as a possible explanation for an RPT in cases where the hot liquid temperature would exceed the critical temperature of the cryogen.

The phenomenon of rollover in LNG tanks is not a frequent occurrence. It happens when LNG is allowed to stratify in the tank due to density differences among the LNG layers. The sudden mixing of layers (rollover) could release large volumes of natural gas vapor damaging the tank if it is not adequately vented to accommodate the resulting pressure buildup.

The conditions leading to rollover are being examined at MIT. Once these conditions are well defined, changes in tank design and filling operations may be instituted to prevent or minimize the probability of rollover.

Griffis and Smith [25] concluded that stratified cells will readily form in an LNG tank as a result of side-wall heat leak unless the tank contents are initially very well mixed. Mixing appears to delay the long-term rollover potential which is present when LNG is transferred to a tank containing LNG of a different composition. By using salt and sugar solutions, two mechanisms of cell formation were found, and their occurrence predicted theoretically. Further studies are under way to elucidate heat and mass transfer mechanisms across the interface between stratified layers.

The influence of ambient pressure perturbations on the boil-off rate from LNG storage tanks is the subject of another continuing study at MIT. Bendjemil [26] recorded boil-off histories following the imposition of step pressure changes varying from +400 to −1000 mm H_2O in a 160 liter cryogenic tank filled with liquid nitrogen. A theoretical model of the tank dynamics was developed. It took into consideration the transport processes occurring within the tank. Model predictions were in good agreement with the data.

Tests are under way in a 350 liter tank to confirm the scalability of the model. In a related project, the U.S. Department of Energy has recently initiated a study at the Institute of Gas Technology to instrument industrial LNG tanks and collect data that may be used to verify or modify the MIT model.

2.2. Experimental programs

In 1978, a series of 5 m^3 LNG vapor dispersion tests was conducted at the Naval Weapons Center, China Lake, California. LNG was spilled on water at the rate of about 5 m^3 min^{-1} with wind speeds varying between 3 and 10 m s^{-1}. These tests were primarily for the purpose of instrument evaluation. A limited number of gas concentration measurements were made. The results compared favorably with LLNL's computer model predictions [27]. Additional tests were carried out where spills of 3—5 m^3 of LNG on water were ignited to determine the radiative flux from LNG vapor and pool fires. A mean flame emissive power of 210 kW m^{-2} was measured [28].

During 1980 and 1981, two series of nominal 40 m^3 LNG spills were carried out at the same site with and without ignition. To date, only the data from nine vapor dispersion tests have been analyzed [29]. Data from the ten RPT and vapor burn tests are currently being analyzed. In the dispersion tests, the spill volume ranged from 24 to 39 m^3, the spill rate from 11.3 to 18.4 m^3 min^{-1}, the wind speed from 1.8 to 9.1 m s^{-1} and the atmospheric stability from unstable to slightly stable. Wind speed and direction, gas concentration, temperature, humidity, and heat flux from the ground were measured at different distances from the spill point and at different elevations relative to ground level. The results showed that the gas-concentration and wind-field measurements were consistent with respect to the general alignment of gas-concentration contours with wind-field flow lines for all experiments. Reasonable agreement of integrated gas flux with the amount of LNG spilled was found. The turbulent processes in the lower atmospheric boundary layer dominated the transport and dispersion of gas for all experiments except for one that was conducted under very low wind-speed conditions and where the gravity flow of the cold gas displaced the atmospheric flow. High-frequency (3—5 Hz) gas-concentration measurements indicated that fluctuations above 5% volumetric concentration were common with 10 s average concentrations as low as 1%. Differential boil-off of LNG was observed with resultant enrichment of ethane and propane in the cloud toward the end of each test.

Although not expected for the methane-rich (93.6—96.4%) LNG used in these spills, several energetic RPTs did occur under at least two different circumstances with a maximum over-pressure of 0.72 psi (6300 g TNT equivalent) measured at a distance of 30 m.

In support of these large-scale test activities, GRI sponsored studies at the Colorado State University (CSU) wind-tunnel facility where models having a scale of 1:240 of the China Lake LNG release pond and surrounding topography were constructed and placed in CSU's meteorological wind tunnel. Utilizing argon to simulate LNG vapor, mean and transient concentration contours were mapped and the overall plume geometry and behavior were recorded photographically under various simulated weather conditions [30].

The results of these simulations were used to allow field test personnel at China Lake to place monitoring equipment at appropriate locations downwind of the spill site so that it would be more likely to intercept the plume. The use of a topographical map allowed the anticipation of any unpredictable effects of natural obstructions and terrain roughness on plume shape and behavior.

Post-field tests were carried out to determine the capabilities of the physical model to simulate actual atmospheric dense gas dispersion [31]. Within the constraints of accurate wind simulation and the varying characteristics of the field—wind conditions, the wind tunnel reproduced the behavior of the field tests fairly accurately except at low wind speeds where gravity flow displaced atmospheric flow. Predictions of maximum LFL distances from wind-tunnel data appeared to be very credible, while time-dependent characteristics were no more reliable than information about surface roughness and wind direction and profile.

In addition to these studies, CSU employed a 1:250 scale model to determine the effects of surface obstacles on the dispersion of LNG and neutral density plumes at wind speeds of 4 m s^{-1} and 7 m s^{-1}, a continuous boil-off rate of 30 m^3 min^{-1} and 21 surface obstacle configurations. The results [32] showed that the turbulence created by air flow around structures can significantly enhance plume dispersal, especially when the characteristic length of the structure was equal to or greater than the spill diameter.

2.3. Instrumentation development

Among the difficulties in conducting large-scale LNG release tests is the lack of adequate gas sensors. Ideally, the detector should be able to measure methane, ethane and propane concentrations separately and continuously. It should be inexpensive, stable, accurate, rugged and small so as not to interfere with the vapor cloud flow pattern. It should have a short time constant, a range of 0—100% for each hydrocarbon in air, and require a small amount of energy to operate. Interference due to dust, temperature changes, atmospheric gases and water vapor should be minimal.

During 1978, with U.S. Coast Guard, GRI and NASA support, the Jet Propulsion Laboratory (JPL) developed and field-tested two rapid-response instruments for the detection of methane in the vapor resulting from an LNG spill [33]. The instruments were a laser device with a 0.005 s response time and 0.1% sensitivity, and a two-band differential radiometer (TBDR) with a 0.15 s response time and 1% sensitivity. A thermistor sensor was also developed for the rapid (0.2 s) measurement of vapor temperature. These were tested during the 5 m^3 instrument evaluation spill tests at China Lake, California, in 1978. LLNL also tested a modified predecessor of an infrared absorption gas sensor. Other gas sensors, including the Shell sensor and a number of commercial gas sensors, were also evaluated.

In 1980, under joint support from NASA, U.S. Coast Guard, GRI and DOE, the Jet Propulsion Laboratory developed a four-band differential radiometer (FBDR) [34]. The FBDR measures the concentrations of the three major components of LNG by measuring the near-infrared absorption at four different wavelengths: one wavelength each for methane, ethane and propane and a fourth wavelength to measure background absorption of air and dust. The wavelengths are between 2 and 2.5 μm, and are emitted by a 2150 K incandescent lamp. The radiation is divided by a four-aperture chopper and filtered to the desired wavelengths. Four lead sulfide photoconductive detectors and associated electronics systems complete the device. Conversion of absorption data to concentration is accomplished using Beer's law, which assumes a linear relationship between absorption and concentration. The FBDR was tested and used during the 40 m^3 spill tests at China Lake. Some problems were encountered when the FBDR was used in dense fog.

In 1979 and 1980 LLNL, with support from DOE, designed and developed a large (51-station), portable data acquisition system complete with meteorological instrumentation and gas sensors. In parallel with the design of the data acquisition system, an infrared gas sensor was optimized for detecting methane, ethane, and propane in the dense fog regions of LNG spills. The resulting small, low-powered, microprocessor-controlled sensors could measure five samples in the 3—4 μm region. Two channels were used to determine the effects of the dense fog; one channel for methane and one channel for the combined measurement of ethane plus propane. These sensors have proved to be rugged, stable and accurate during two years of testing at China Lake in 1980 and 1981.

2.4 Improved database for risk assessment

2.4.1 Mean time between failures

In assessing the risks associated with the operation of LNG peakshaving and baseload facilities, a fault tree is generally constructed in which all paths (branches) leading to an undesirable event (e.g. tank failure) are identified. Probabilities are then assigned to each "branch" of the tree and an overall probability for the occurrence of the event of concern is calculated. Paths and events with unacceptably high probabilities of occurrence may then be identified and eliminated or their frequencies of occurrence reduced by implementing changes in the design or operation of the system or its components.

To date, the data used in conducting fault tree analyses of LNG facilities have been derived from information collected by the chemical industry and the U.S. Department of Defense. Mean time between failure (MTBF) data are available for some commonly used valves, pumps, compressors, pipes, control devices, etc., operating under non-cryogenic conditions. Few reliable data have been publicly available on the failure rates of equipment and devices employed at LNG facilities [35].

Johnson and Welker [36] have recently completed the collection of data from several LNG peakshaving and baseload facilities. These data were critically reviewed and analyzed, and the mean time between failure was derived for various operating equipment and emergency response systems. The results for major failures (defined as those causing an unscheduled shutdown for a period of 24 h or more) at LNG facilities are summarized in Table 1.

2.4.2 Ignition sources in urban areas

In quantifying the risk to the public of an LNG release, some assumptions must be made about the distance the flammable vapor cloud will travel before it ignites. The assumption that the hazardous area is bounded by the maximum extent of the lower flammable limits is highly conservative, particularly if LNG is released near an urban area where ignition sources abound. Data allowing an accurate assessment of the likelihood of ignition as a function of cloud penetration into populated areas are not available.

In fact, uncertainties in the place and time of ignition of the vapor cloud may have a greater effect on the results of risk assessment than the lack of a more precise characterization of LNG pool fires and vapor clouds.

In a study sponsored by GRI, Arthur D. Little, Inc. [37] has identified over

TABLE 1

Summary of reported major failures [36]

Plant area	Operating hours	Number of major failures	MTBF (h)
Gas pretreatment	675 000	25	27 000
Heat exchangers	2 837 000	16	177 000
Vaporizers	188 000	26	7 200
Cryogenic storage tanks	1 809 000	2	904 500
Cryogenic storage systems	1 809 000	4	452 000
Compressor systems	2 256 000	116	19 000
Cryogenic pumps	366 000	86	4 000
Cryogenic valves	6 278 000	4	1 569 000
Cryogenic piping	355 000 000[a]	2	177 000 000[a]
Process control systems	1 505 000	9	167 000
Human errors	4 779 000[b]	19	252 000[b]
Spills and leaks	1 626 000	11	148 000
Truck loading and unloading	1 156 000	0	1 156 000
Fire protection systems			
fire water systems	1 450 000[c]	14	104 000[c]
dry chemical systems	1 423 000[c]	2	712 000[c]
gaseous systems	364 000[c]	2	182 000[c]
foam systems	88 000[c]	0	88 000
Hazard detection systems			
gas detectors	16 703 000	44	380 000
low-temp. detectors	2 631 000	2	1 315 000
flame detectors	10 570 000	12	881 000
high-temp. detectors	8 418 000	0	8 418 000

[a] meter-hours.
[b] operator-hours.
[c] in-service hours.

150 potential ignition sources present in an urban area and within the LNG facility, assessed their likelihood of igniting methane—air mixtures and characterized their temporal and spatial distribution as a function of key descriptors such as population density, predominant type of activity (commercial, industrial, residential), geographic/climatic location and seasonal conditions. Experiments were carried out to characterize questionable ignition sources such as automotive electrical systems, traffic signals and cigarettes. Results to date indicate the following:

(1) Under normal operating conditions, automotive electrical systems are not an ignition source. Ignition was observed for very loose starter wires and broken ignition wires.

(2) Traffic light relays are a potential ignition source if the switching energy is 600 W or more. This usually occurs when traffic lights are in the flashing mode.

(3) Smoldering cigarettes do not cause ignition even when puffed. Obviously, lighting a cigarette with an open flame causes ignition; however, a hot-surface cigarette lighting device (a car lighter) does not cause ignition.

All tests were carried out with 7% methane in air. Future tests are planned to address the effect of the presence of heavier hydrocarbons in the gas mixture on the ease of ignition.

3. Accident prevention

The probability of an accidental hazardous release of LNG may be reduced by ensuring that the materials used for containing or transporting LNG can withstand the extreme operational conditions to which they may be subjected. Preventive measures also include the safe siting and layout of the plant, the separation of hazardous operations and the minimization of the potential for human error.

3.1 Development of thermal endurance tests

Construction materials, electrical and thermal insulations, paints and coatings utilized at LNG facilities are required to meet various standards set by regulatory authorities and/or company specifications. The thermal requirements generally refer to endurance tests that do not necessarily simulate the potential exposure of the tested material to LNG or an LNG fire. For example, in the U.S.A., fire endurance tests for structural members expose a specimen in a furnace where the temperature rises in accordance with a standard temperature—time curve. This curve was originally derived from the average temperature history of a commercial building fire.

GRI is sponsoring the development of standard thermal endurance tests to evaluate various construction materials employed at LNG facilities and in transportation systems. As a first step, Factory Mutual Research Corporation [38] assessed existing regulations, engineering specifications and their test requirements, examined credible LNG release/fire scenarios at LNG facilities and identified future test development needs in this area.

3.2 Crack arrest capabilities of 9% Ni-steels

A large number of LNG primary containment (inner) tanks are constructed of 9% nickel-steels. Questions have been raised about their capability to arrest a propagating crack [39]. In response to these questions, GRI sponsored a study to evaluate the results of tests conducted on 9% nickel-steels since 1975 when a similar study was carried out by Pense and Stout [40] for the International Nickel Company.

The final report by the same authors [41] identified four research needs:

(1) a clarification of the significance of the weld-heat-affected zone, which may have less fracture toughness than the base plate, to the ability of 9% nickel-steels to arrest a propagating crack;

(2) a study of the degree of correlation that exists among the various crack-initiation and crack-arrest tests;

(3) a characterization of present production heats of 9% nickel-steel as affected by mill practice and composition (including impurity levels); and

(4) an investigation of the effect of simulated fabrication defects on crack initiation in 9% nickel-steels.

Because of its international significance, a well-coordinated research program has been initiated by GRI with the help of a number of co-sponsors. Studies are under way in Japan under the technical guidance of Nippon Steel and Osaka Gas and with the support of several Japanese firms. GRI and several U.S. and European sponsors are funding additional research at the Welding Institute (England), Battelle—Columbus Laboratories (U.S.A.) and Materials Research Laboratory (U.S.A.). The results of all of these activities and others that may be initiated later will be compared, correlated and coordinated under the general guidance of Lehigh University.

3.3 Material properties database

In addition to these studies, GRI is continuing its support of the National Bureau of Standards (NBS) to develop accurate data on the properties of materials utilized by the LNG industry [42]. Currently, insulating polymeric and concrete foams are being studied. The objectives are to provide users of thermally insulating foams with basic knowledge and reliable data about the behavior of expanded plastics and concretes at cryogenic temperatures and to generate the methodology and standardized materials necessary to allow experimental determination of the properties of commercially available materials. NBS will also serve as a center of insulation material information for users of cryogenic fuels. This work addresses the development of methods to characterize foams and to test for their thermal and mechanical properties, which include thermal contraction, thermal conductivity and shear, tensile and compressive strengths and their moduli.

3.4 Human error and control panel design

Recent studies sponsored by DOE [43] and GRI [36] have shown that the probability of an accident at an LNG facility may be significantly reduced by minimizing the potential for human error and by improving control panel design. GRI has initiated a study at Battelle—Pacific Northwest Laboratories with the following objectives:

(1) to develop an improved database for human error rates applicable to LNG facility operations;

(2) to evaluate the ability of the operator/control panel system to function effectively during routine operating conditions and credible emergencies;

(3) to explore the significance of human factors in control panel design and identify areas where control panel design can be improved; and

(4) to recommend future research needs in this area.

4. Hazard control

Research on LNG hazard control deals with the development and testing of responsive measures which either may be applied or are effective *after* LNG has been accidentally released with the intention of reducing the severity of the accident.

4.1 Reduction of LNG tanker fire hazards

Under DOE sponsorship, Arthur D. Little, Inc. [44] examined various concepts for reducing fire hazards that may result from LNG tanker collisions and evaluated the technical feasibility of these concepts. Among them were modifications to shipborne LNG containers so that in the event of a container rupture a smaller fraction of the contents would spill and/or the contents would spill at a reduced rate. Changes in the cargo itself, including making the LNG into a gel, solidifying it, converting it to methanol, and adding flame suppressants were also evaluated. The relative effectiveness and costs of implementing these methods in terms of increased cost of gas at the receiving terminal were examined.

The vulnerability of an LNG tanker and its crew to the thermal effects of a large pool fire caused by a collision spill was estimated and methods for protecting the crew were considered. To prevent further deterioration of a damaged ship it was shown that the protection of ship and crew would require the design and installation of extraordinary and costly insulation and life-support systems.

Methods for salvaging or disposing of cargo from a damaged and disabled ship were evaluated. If the cargo cannot be transferred to an empty LNG tanker, burning of the cargo at a location somewhat distant from the disabled tanker appeared to be a promising approach.

4.2 Gelation of LNG

Gelled fuels have been examined by NASA as potential propulsion sources for jet engines. The gelling of liquefied methane with water and methanol was investigated by Vander Wall [45] and the potential safety benefits during handling and transport were evaluated. Under GRI sponsorship, basic studies were carried out at MIT [46—48] to examine the microstructure and composition of these gels, relate their shear stresses to gelant concentration and evaluate the energy requirements for producing gelled LNG.

Under contract to DOE, the Aerojet Energy Conversion Company has conducted laboratory studies [49, 50] to characterize LNG gelled with 2—4% water or methanol. Various flow properties were determined, and the potential for safety enhancement attainable by gelation was examined. In addition, an economic analysis and a preliminary design of an industrial-scale gelation system were carried out. Initial experiments [49] revealed the superiority of water over methanol as a gelling agent for LNG on the basis of minimization of gelant required to obtain a given gel structure. Yield stresses were measured over a range of gel conditions and were found to increase with increasing gelant content. Similarly, rheological characteristics were determined. These studies revealed the effects of gelant concentration in the carrier gas and end product on gel properties. Gels flowed easily through coils, exhibiting shear thinning with no evidence of gel structure degradation even after repeated shearing. Gel expulsion from tanks was found to be dependent on tank surface area. Expulsion efficiencies greater than 90% of those exhibited by LNG were obtained for gels using a tank with a surface area-to-volume ratio as large as 28 m^{-1}. There was little difference found between boil-off rates of LNG and gelled LNG under simulated storage conditions of low and moderate heat fluxes. Small unconfined spills (1.5—20 liters) showed that gelation significantly increased total spill vaporization times and decreased maximum spill spread areas. Aerojet also evaluated the design of an industrial-scale gelation system capable of producing tank truck loads of gelled LNG in 2 h. The increased cost of gelation using this equipment was estimated at $0.23/$10^6$ Btu for plants with liquefaction facilities. This value did not allow for the removal of the gelant during vaporization.

In a second study [50], Aerojet refined its characterization of the rheological properties of gelled LNG, assessed relative leakage rates through perforations of gelled vs. ungelled LNG and compared their spread and vaporization rates on land and water.

Under GRI sponsorship, Aerojet [51] attempted to scale up its proprietary continuous laboratory gelling device and construct a mobile LNG gelator capable of producing 1 m^3 h^{-1}. The unit was to be eventually transported and used in the conduct of large-scale fire and vapor dispersion tests at China Lake, California, to acquire comparative data on the safety benefits that may accrue through gelation. A skid-mounted unit was constructed, but failed to produce an adequate gel. This was attributed to the need for a high degree of accuracy in controlling temperature, pressure and gelant/LNG contact time. GRI has decided to discontinue further development of this gelation approach because of the anticipated difficulties in scaling up such a system for commercial use. The operational and safety problems that still have to be resolved with respect to the storage, handling and vaporization of gelled LNG and the expected marginal improvements in safety when compared with the cost of retrofitting an LNG facility to handle the gel make this approach impractical.

Another gelation concept was recently investigated by Tarpley et al. [52] in which LNG operations would remain as they have been in the past with the exception that a response system is activated if and when a crack develops in the wall of a storage tank or a pipe. A response system disperses a solid gelant quickly and effectively in the LNG to control and limit its release rate. Like a fire extinguisher, such a system may never have to be used during the lifetime of the facility, but it is there for added safety insurance. Ideally, such a gelant must be compatible with LNG. It must be storable for long periods of time at LNG temperature so that the LNG vapor generation rate is kept to a minimum when the gelant is mixed with LNG. Its storage volume requirements must be small and methods must be developed for its quick and effective dispersal in a large volume of LNG.

Thirty candidate solid gelants were evaluated. Fumed silica and carbon black produced gels with high yield stresses but at concentrations of 10—15 wt%. Because of the small bulk density of these gelants, storage volume requirements at these concentrations would be greater than the volume of the LNG to be gelled. Although this study has been concluded, GRI is evaluating proprietary developments in this area where it has been reported that adequate LNG gels have been produced at much lower concentrations of the same gelants.

4.3 Water spray curtains

Federal safety standards in the U.S.A. [1] require that all new LNG facilities be designed and sited so that vapor generated during a credible accidental release of LNG will not propagate beyond the plant boundaries. One approach for achieving this level of dilution is through the use of water spray curtains [53—55].

Under GRI sponsorship, Factory Mutual Research Corporation has embarked on a three-phase research project to develop engineering design guidelines for the use of water spray curtains to disperse LNG vapor clouds. Calculations to date [56] show that vapor dilution by a water spray is substantial at low wind speeds, but decreases markedly at wind speeds of about 4 m s^{-1} and higher. Spray heating of the cold vapor cloud and air entrainment render the cloud buoyant and significantly reduce the downwind ground-level methane concentrations.

Future phases of this project involve small-scale and wind-tunnel tests to verify the theoretical models. Data presently being developed by the Health and Safety Executive (United Kingdom) on water sprays are also being included in the analysis. The final phase is expected to involve large-scale demonstrations of the validity of the design guidelines.

4.4 Dike floor materials

Should LNG be accidentally released in a diked area, the rate of vapor formation depends primarily upon the thermal properties of the materials in contact with the LNG. At present, most dike floors (and walls) are made from compacted earth or concrete, but serious consideration is being given to the use of less conductive materials such as insulated concrete.

To be able to evaluate the boil-off rates from typical dike floor materials, a research program was carried out by Reid [57] in which slabs of various materials were placed in an insulated box and LNG (and other cryogens) spilled on the surface. The rate of boiling was measured as a function of time and the thermal properties of the substrate determined. In addition, all previous boiling studies of LNG spilled in diked areas were reviewed and compared with the experimental data.

Soil, sand, two types of commercially available insulating concretes, crushed rock, polyurethane and corrugated aluminum over soil were tested. The soil, sand and concrete results could be correlated by a simple one-dimensional heat-transfer conduction model where the boiling rate is given as the product of a substrate-dependent constant times the inverse square root of time. Boiling rates on the insulating concretes were about an order of magnitude less than on soil or sand. Dry polyurethane showed boiling rates about one-half of the insulated concretes.

One of the more interesting materials tested was corrugated aluminum laid in sheets over packed soil. The boiling rate was not well-correlated by the conduction model, but a theoretical analysis and experimental study showed that the boiling rate would be expected to be approximately linear in time for about an hour (after cool-down of the corrugated metal). The boiling rate is also significantly below that obtained from spills on uncovered packed soil.

The optimum use of insulating materials covering a dike floor made of packed soil was also studied. It was shown that little advantage was gained by using insulation of more than 5—10 cm thick.

5. The future of LNG research in the U.S.A.

The U.S. DOE has recently announced that it plans to discontinue funding its Liquefied Gaseous Fuel research program. The Gas Research Institute is now the primary funding agency in the U.S. for LNG research. Recognizing that large-scale tests are beyond its budgetary means, GRI has called for an international cooperative program whereby LNG safety research needs will be identified and common problems resolved through a well-coordinated research activity. The cost of certain prohibitively expensive projects may then be shared by all interested parties. Furthermore, information exchange agreements among the participants minimize the potential for duplication of effort and allow the pooling of data from complementary research projects.

In addition to the active research program on 9% nickel-steels described above, plans are being formulated for three international cooperative programs:

(1) Verification of theoretical vapor dispersion models with available data from large-scale releases of heavier-than-air gases.

(2) The conduct of large-scale tests to examine the effects of obstructions and terrain on LNG vapor cloud dispersion.

(3) The conduct of large-scale tests to formulate and refine design guidelines and evaluate the effectiveness of water spray curtains in dispersing LNG vapor clouds.

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