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FOSSIL ENERGY

FIRE SAFETY OF LPG IN MARINE TRANSPORTATION

Final Report

By
W. E. Martinsen
D. W. Johnson
J. R. Welker

June 1980

Work Performed Under Contract No. AC05-78EV06020

Applied Technology Corp.
Norman, Oklahoma

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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FINAL REPORT

FIRE SAFETY OF LPG IN MARINE TRANSPORTATION

June 1980

TECHNICAL REPORT

for

UNITED STATES DEPARTMENT OF ENERGY

DIVISION OF ENVIRONMENTAL CONTROL TECHNOLOGY

Contract No. DE-AC05-78EV06020

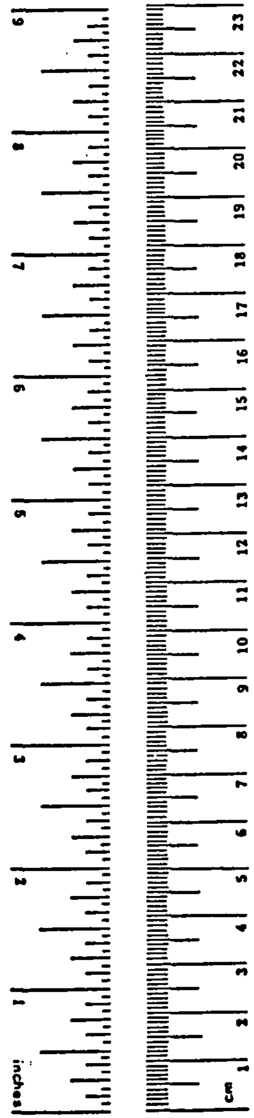
Applied Technology Corp.
P. O. Box FF
Norman, OK 73070

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
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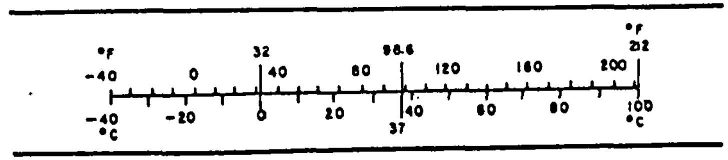

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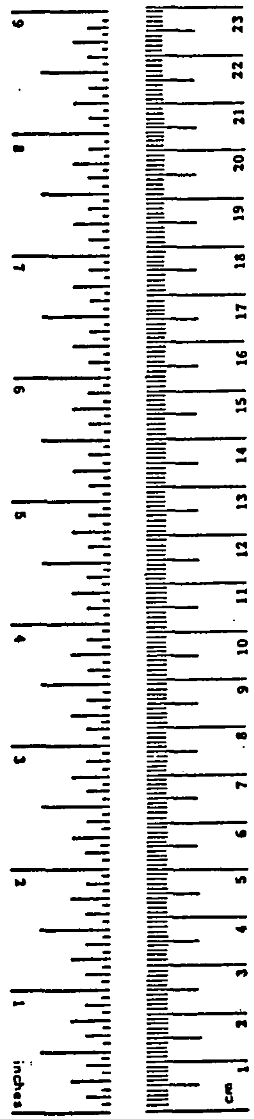

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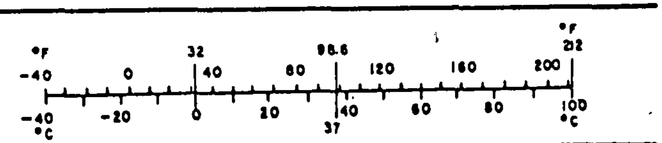

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FIRE SAFETY OF LPG IN MARINE TRANSPORTATION

EXECUTIVE SUMMARY

Introduction

Transporting and storing liquefied petroleum gas (LPG) is common and widespread throughout the U.S. Some components of LPG, normally propane and butane, are widely used as fuel gases for residential and commercial heating, cooking, etc.; these and many other components are also important as industrial chemicals, especially in the production of various petrochemicals.

Most LPG is stored under pressure at ambient temperature, however, a few large storage facilities use insulated tanks and store the LPG at a temperature near its boiling point and a pressure only slightly above atmospheric. Transportation tends to follow this same trend. Most land transportation systems (i.e. tank trucks, railroad tank cars, and pipelines) transport the LPG under pressure at ambient temperature. Marine transportation is divided between pressurized (mainly in barges and small ships) and refrigerated (larger ships).

Although only a small fraction of the total quantity of LPG transported in the U.S. is carried in barges or ships, the safety of this mode of transportation is being examined because of the large amount of LPG that can be involved in a single shipment (e.g. one 40,000 m^3 ship is equivalent to over 200 railroad tank cars of 50,000 gal capacity). The safety analysis reported herein concerns those events that could endanger marine terminal operators or the public. This was assumed to be possible only when a vessel is in port or traversing an inland waterway. The main emphasis of the safety analysis is on estimating the probability of occurrence of LPG releases during dockside operations since the cargo is then being transferred, not just stored.

Design of LPG Vessels

The choice of mode of transport of LPG is partly historical and partly economic. LPG (primarily propane and butane in the United States) has traditionally been transported as a pressurized cargo at ambient temperature. The reason is apparently because most transportation and storage has been in relatively small quantities and large-scale facilities for transportation and storage of LPG have not been required. Because of the historical use pattern, marine transportation of LPG along inland waterways is also basically by pressurized tanks mounted on barges. Figure S-1 shows a schematic of a typical LPG barge. The pressurized cargo containers are thick-walled pressure vessels, and the practical limit for vessel size is about 5000 m^3.

Some semi-refrigerated LPG ships are used. These ships use insulated cargo tanks with the pressure above atmospheric pressure and the temperature less than ambient temperature. The maximum cargo capacity of a semi-refrigerated LPG tanker is about 15,000 m^3. They are rarely seen in U.S. ports.

Fully refrigerated LPG vessels range in size from about 5000 m^3 to 125,000 m^3. Those in U.S. waters are generally bringing LPG from foreign countries. Several tanker designs may be used, but in all cases the LPG is carried at a pressure only slightly above atmospheric pressure, and the cargo tanks are heavily insulated. Figure S-2 is a schematic of a large refrigerated LPG tanker showing one of the possible tank configurations. In the United States the wing tanks and topside tanks cannot contain flammable liquids. Refrigeration systems are usually provided to reliquefy the boiloff gas.

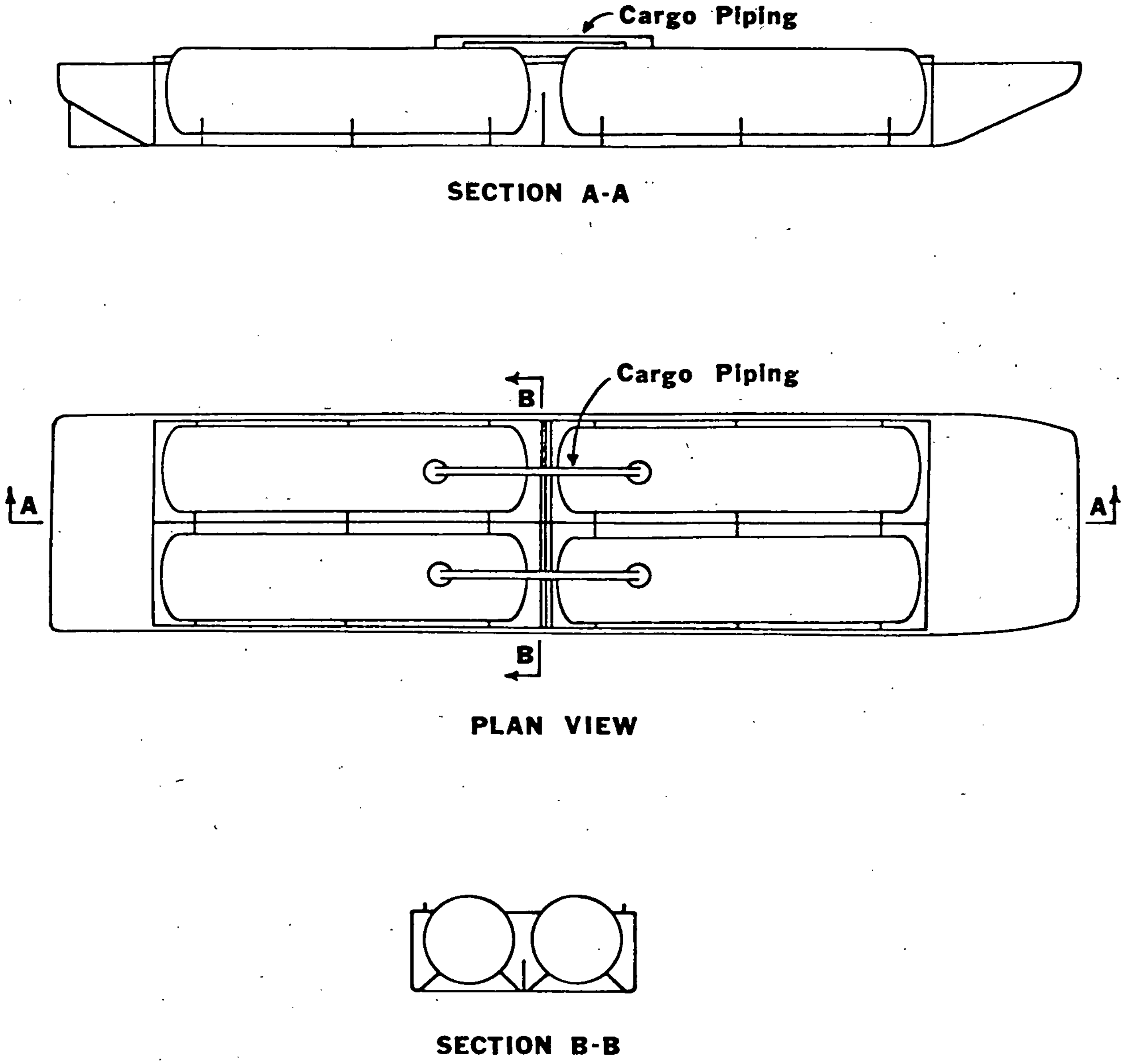


FIGURE S-1. SCHEMATIC OF A TYPICAL LPG BARGE.

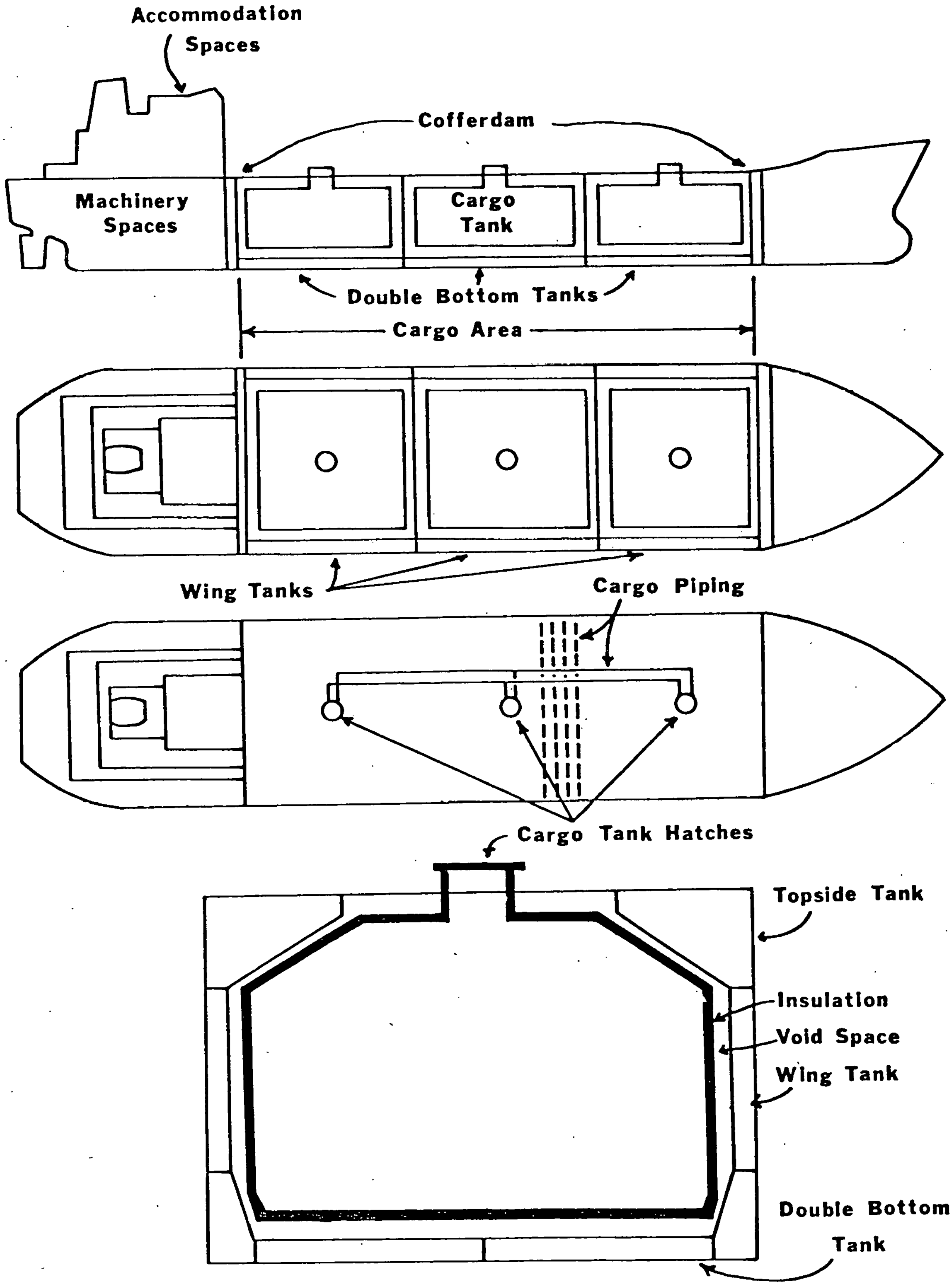


FIGURE S-2. SCHEMATIC OF A TYPICAL LPG TANKER.

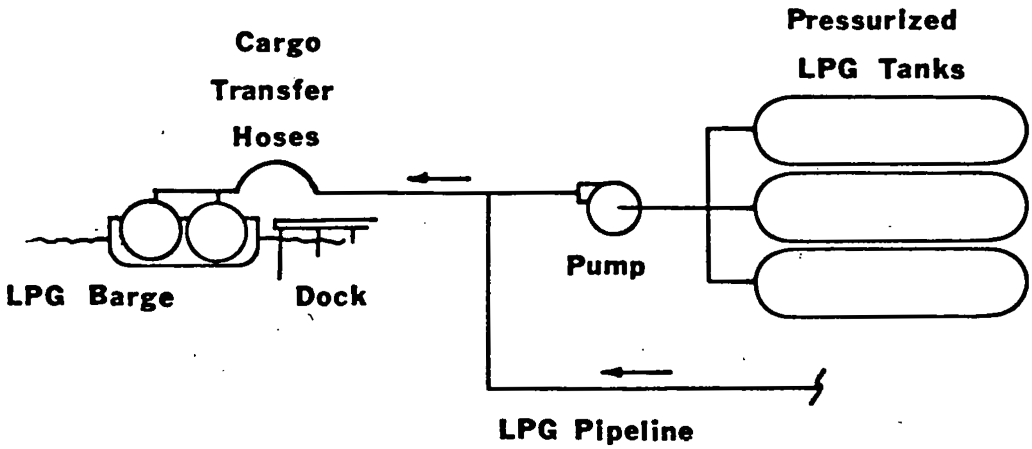
Operations on LPG Vessels

During transit, there are usually no activities carried out on a vessel that require transferring LPG (other than reliquefaction or tank cooling). Once in port, the vessel may be either loaded or unloaded. If a vessel is being brought into service or taken out of service, the cargo tanks must be purged to avoid the presence of a flammable gas-air mixture.

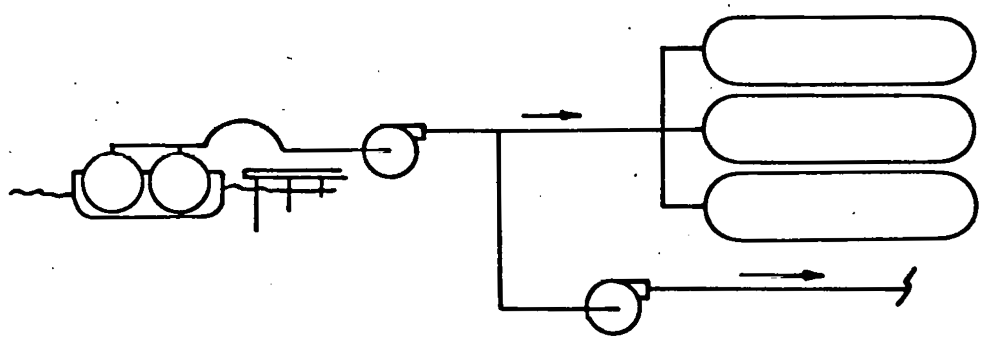
Figure S-3 shows a typical barge operation. LPG is transferred from the barge to storage tanks or a pipeline. The pipeline may later terminate at a storage cavern where it is held for eventual redistribution. The operations on a barge during transfer are reasonably simple. Figure S-4 shows a typical arrangement of the valves on an LPG barge. Barges seldom have pumps on board, and product transfer is usually accomplished by reducing barge tank pressure and/or pumping to load and increasing tank pressure to unload.

Transfer operations involving refrigerated cargoes are more complicated. Figure S-5 shows the kind of piping arrangement that might be found on a large LPG tanker. Transfer of cargo from ship to shore requires both the pumping of LPG from the tank and the return of vapor to the tank. The volumetric liquid transfer rate must be closely balanced with the volumetric vapor return rate because the ship's tanks cannot tolerate large pressure changes. If vapor is not available from the land operations, it can be provided by vaporizing a small amount of LPG in the ship's vaporizer.

Refrigerated LPG is usually pumped directly from the ship to a large storage tank that is operated at about the same pressure as the ship's tank, as shown in Figure S-6. In some cases, the LPG is pumped to underground storage caverns, pressurized storage tanks, or distribution pipelines. However these latter options may require the LPG to be warmed, so the transfer rates may be limited by heater capacity. Ship demurrage charges are high and operators prefer to transfer cargo rapidly to avoid high demurrage costs.



LPG LOADING TERMINAL



LPG RECEIVING TERMINAL

FIGURE S-3. TYPICAL LPG BARGE TRANSFER OPERATIONS.

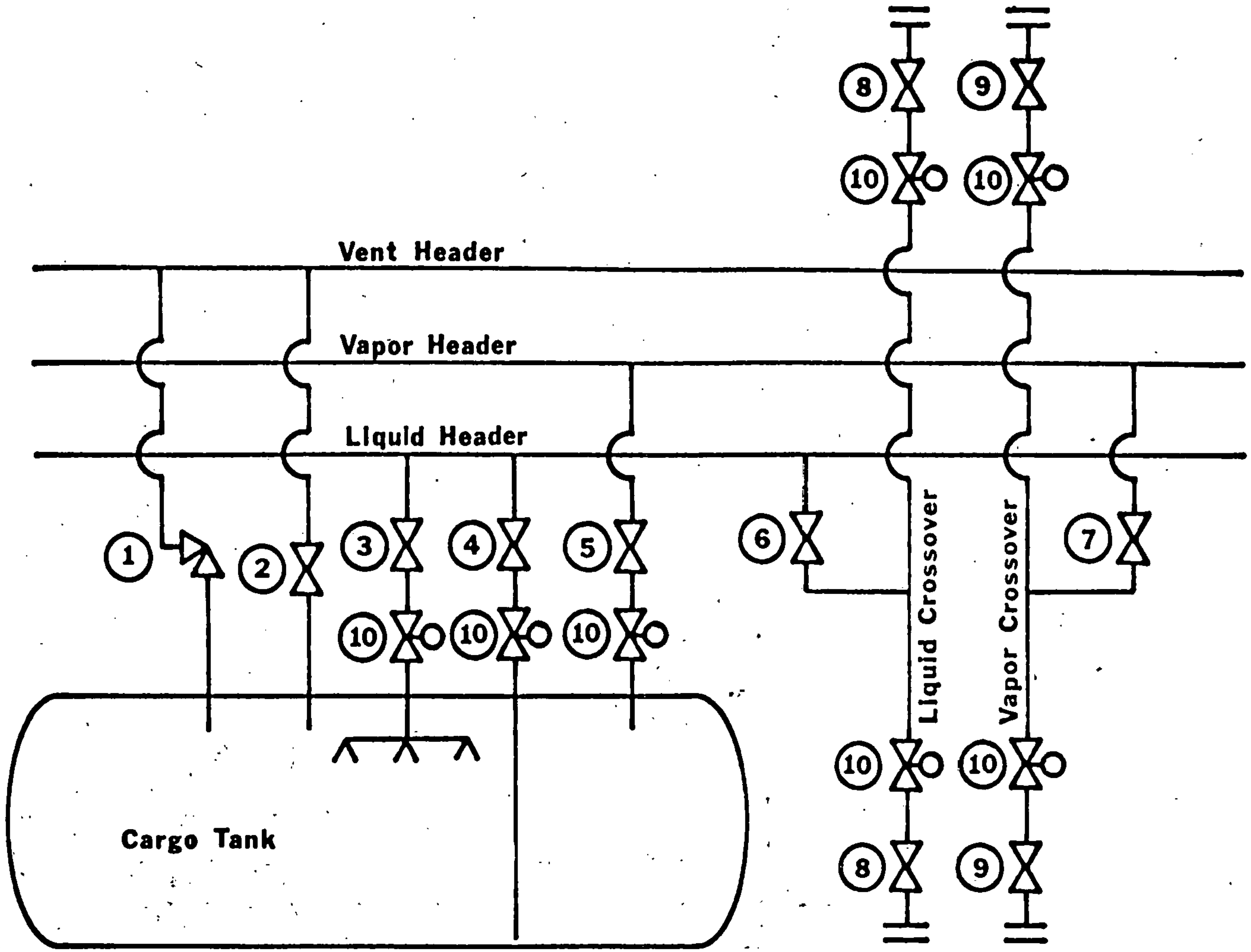


FIGURE S-4. TYPICAL ARRANGEMENT OF VALVES ON AN LPG BARGE.

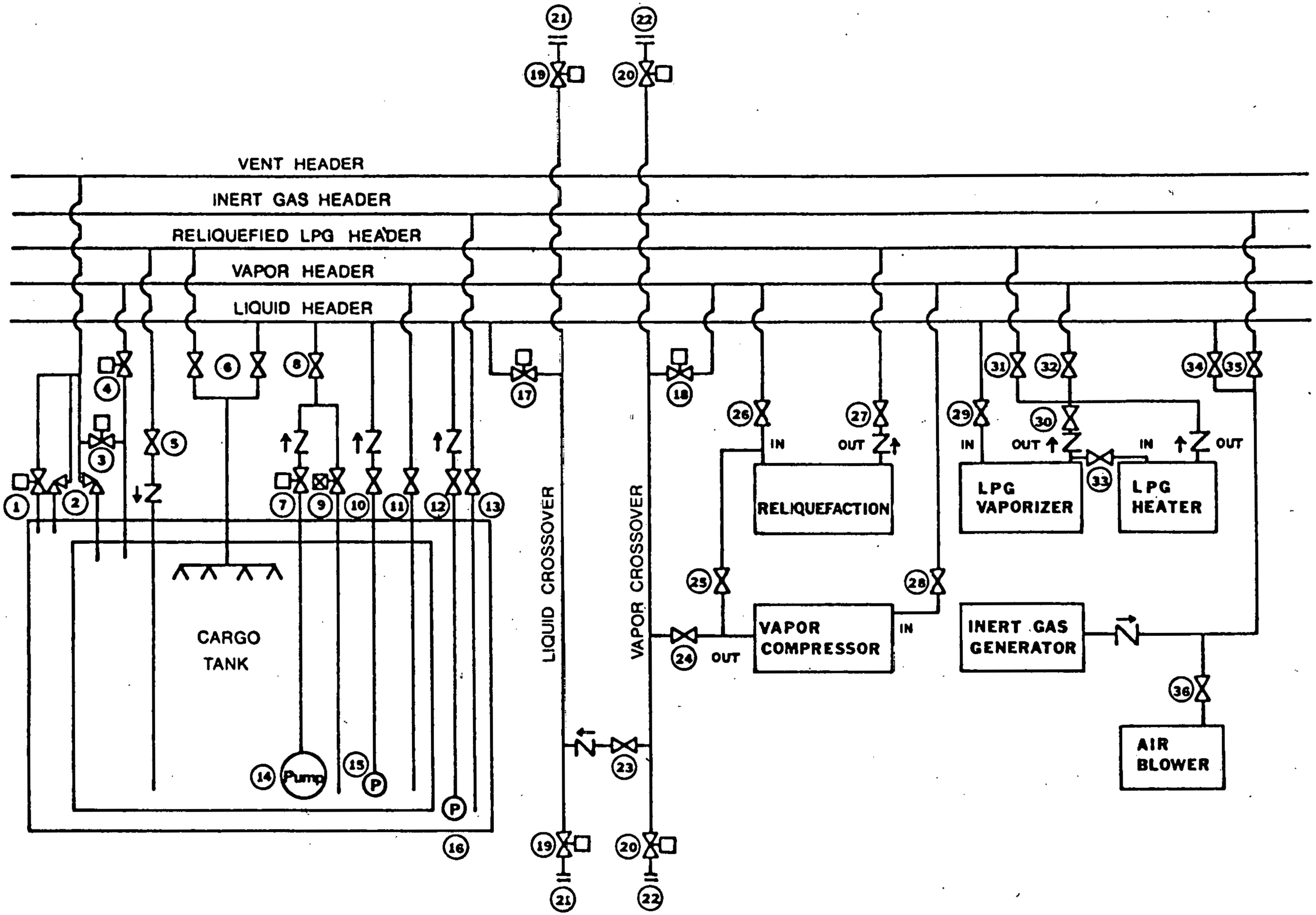


FIGURE S-5. PIPING AND CONTROL ARRANGEMENT FOR COMPOSITE LPG TANKER.

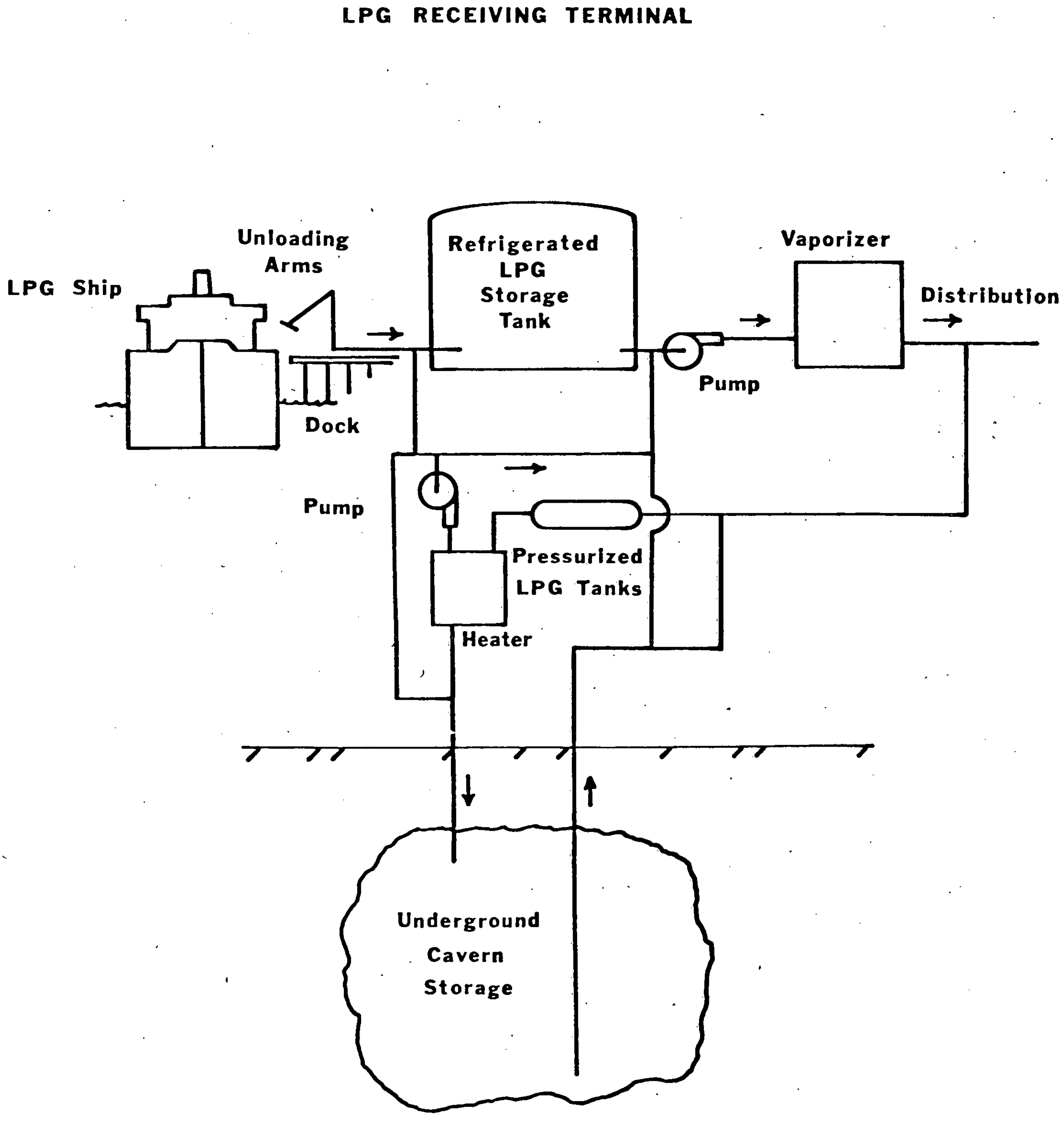


FIGURE S-6. POSSIBLE ARRANGEMENT FOR UNLOADING LPG FROM TANKERS.

The actual sequence of operations varies in detail from one facility to another. Since it is impractical to detail the specific operations for all LPG marine practice, a composite barge and a composite tanker were used in the analysis. These composite vessels result in the designs shown in Figures S-4 and S-5. Few vessels would have all piping, valves, and associated equipment shown in these two composites, but the composites incorporate all of the important equipment and operations encountered in marine transport of LPG in the United States.

In addition to the operations that are carried out while the vessel is docked, there may be special operating rules that apply to vessel movement. The large LPG tankers are usually boarded by Coast Guard personnel before they are allowed to enter U. S. ports. The Coast Guard inspection ascertains that the safety regulations are being followed before the port is entered. The inspection on the first voyage is more detailed because it also assures that the ship is constructed according to the various codes that apply. Once the inspection is complete, the vessel enters the port. Transit is usually restricted to daylight hours and a moving safety zone that prohibits other vessel traffic near the tanker may be provided. These restrictions are intended to prevent collisions during transit. Restrictions are relaxed when empty tankers leave the port.

Barge movements are not generally restricted to daylight hours. Barge traffic is required only to be towed at a safe speed and to have a tug with the barge unless the barge is tied up at the dock. The pressure vessel design for barge tanks is similar to that for railroad tanks, truck tanks, and pressurized land storage tanks, all of which have an excellent safety record. Barge transport of LPG also has a history of safe operation. Therefore the inspection and regulation of barge traffic is not subjected to the intense effort given to tankers. Barge operations are performed on a smaller scale than tanker operations, but at much higher frequencies. The systems are generally well-engineered and have good safety records.

Fire Protection

The fire protection philosophy for LPG ships includes fire prevention, limiting fire size, fire control and extinguishment, and damage potential reduction. Fire prevention includes the design and operation of vessels in a manner such that fires do not occur. The goal is sought through release prevention, inerting, and ignition source control. The basic design of facilities is arranged so that no product is released during normal operations either in the liquid or gas phase. Inerting of tank spaces is performed before cargo is transferred to any tank, either on the vessel or on land, and if a tank must be taken out of service, it is carefully purged to remove flammable materials before maintenance or repair work is performed. Potential ignition sources are eliminated in critical areas.

If, despite the precautions taken to prevent release and subsequent ignition, a fire occurs, the vessel and transfer system are designed to limit size (and thus the destructive potential) of the release. Fire sizes are minimized by minimizing the amount of cargo released, and, in the case of a liquid spill, limiting the area over which the cargo can spread. Rapid-acting, remote-controlled valves are usually provided so that product flow can be stopped quickly in an emergency. These valves are also designed to be fail-safe in the event of loss of control. Leak detection devices are used to monitor for leaks. Detection may include gas sensors for gas releases and low temperature detectors for liquid leaks. In addition to the sensors that are designed exclusively for emergency use, the instruments that monitor normal plant operations are watched to ensure that they are within normal operating limits. Transfer operations are under close supervision of both vessel and landside operators.

If a fire occurs, it may be extinguished, controlled, or allowed to burn out. Only small fires can be extinguished reliably, and the agent of choice for most situations is a dry chemical. Fires may be controlled using high expansion foam. These fire fighting methods are discussed in a report by Johnson, et al. (S1). Generally, LPG fires should be extinguished only if the spill is finished and flow of product is stopped. Otherwise reignition is possible, and, if reignition occurs, the fire fighting equipment may not have enough reserve capacity for a second attempt.

The potential damage from a fire can be minimized by both passive and active systems. Passive systems are designed for high fire resistance and provide protection to personnel and critical control systems. The most common active technique for damage reduction is application of water sprays for cooling. Water is not used directly on LPG fires because it increases the fire size by increasing boiloff rates.

Various codes require that minimum fire protection capabilities be provided on LPG tankers. The IMCO code is the basic standard for international trade, and all vessels bringing LPG into U. S. ports from foreign sources must comply with it. The IMCO code specifies minimum dry chemical capacity and minimum requirements for fire water distribution and spray systems. Non-cargo spaces are also required to have minimum fire protection capability, including special equipment for machinery spaces and locations where combustible liquids are stored.

Barges have smaller cargoes, are unmanned during transit, and have little or no operating machinery on board. Therefore, they have a much less rigorous set of requirements for fire protection. They are regulated under Title 46 of the Code of Federal Regulations.

Safety Analysis

LPG is very volatile because of its low boiling point and easily ignited if released from the closed transport, processing, and storage system. There are a variety of failures that can occur. Most of them are small and cause no damage.

However, there is always the potential for a small failure to either go unnoticed and propagate to a large failure or for the occurrence of a large failure per se.

One of the methods of estimating the probability that a failure will occur is through fault tree analysis. Such an analysis can be very complex and detailed, but in looking at LPG systems for only those failures that release product, significant simplifications can be made. The analysis was limited to those events that might cause product release because the goal was to estimate the probability of occurrence of events that might either endanger the public or operators or escalate to a larger event that could endanger the public or operators. In this context, danger to the public or operators was assumed to be possible only when the vessel was in port or traversing an inland waterway. Therefore, the major emphasis is on dockside operations because the cargo is then being transferred rather than in storage.

Figure S-7 is a fault tree diagram that summarizes the probabilities of various events during tank ship unloading and shows the pathways by which they might occur. The probabilities shown are for a single unloading sequence. Notice that the probability of a spill of less than 10 gallons is quite high, and can in fact be expected to occur on about three-quarters of the unloading operations. The reason the spill probability is so high is that in some operations the disconnect sequence requires draining a small quantity of LPG from the transfer arms. Small leaks from valve packing and gaskets are also expected to occur. While these leaks may not be corrected immediately, they are small enough that there is little chance that they will result in more than 100 gal being released over the unloading period. Larger spills are less likely to occur than smaller spills. In fact, for spills greater than 100,000 gal, the most likely cause of the spill is an external force such as a ship collision. The reason is that even at the highest transfer rates, the flow would be shut off following a failure before such a large spill could accumulate.

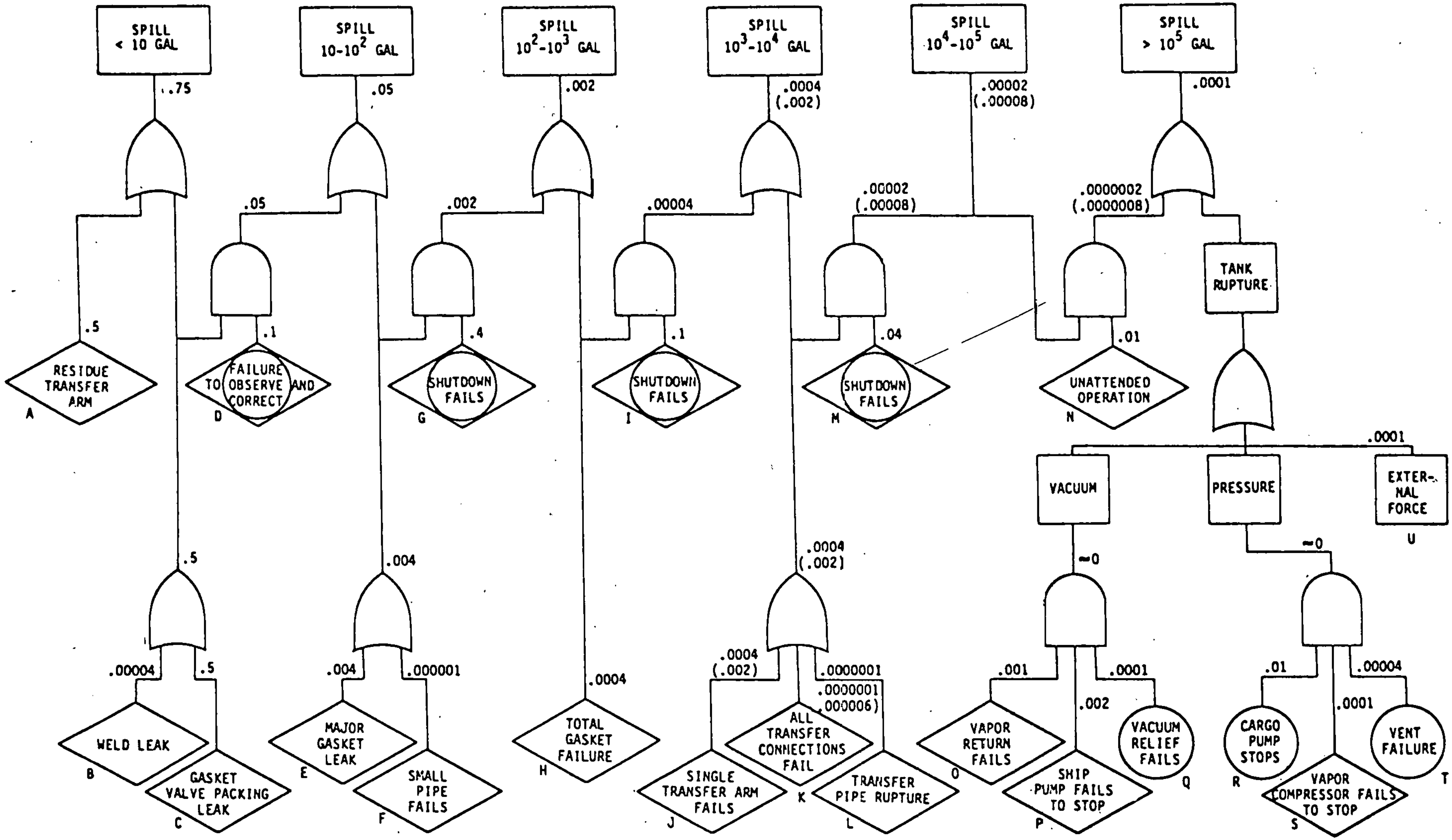


FIGURE S-7. FAULT TREE FOR LPG TANK SHIP UNLOADING.

Figure S-7 shows a set of probabilities enclosed in parentheses. These probabilities are for transfer from vessels at docks where rubber hoses are used for ship-to-shore connections rather than metal transfer arms. Transfer connection failure is more likely in operations using hoses than those using metal arms.

Figure S-8 is a graphical summary of the event probabilities from Figure S-7. The event probability has been plotted as a function of spill size, where the spill size is taken to be about the middle of the spill range on a logarithmic scale. The plot is shown as a broad range rather than a line to emphasize the approximate nature of the failure probabilities.

The spill probability shown in Figures S-7 and S-8 is based on an analysis of 16,000 voyages of liquefied gas ships, during which there has been no loss of the liquefied gas cargo as a direct result of a collision. (LPG loss on the Yuyo Maru was a result of fire burning naphtha in the wing tanks. Flammable liquids are forbidden in the wing and topside tanks in U. S. ports.) Table S-1 compares the resulting spill probability with similar estimates from other sources.

TABLE S-1. COMPARISON OF RISK PROBABILITIES

Source	Probability of Spill (per Cargo Delivery) Due to Ship Collision
Applied Technology Corp.	2×10^{-4}
FPC (S2)	1×10^{-3}
SAI (S3) for Los Angeles Harbor	1×10^{-4}
Cave and Kazarians (S4)	3×10^{-7}*
University Engineers (S5)	5×10^{-4}

*Probability given is for spills greater than 20,000 m^3.

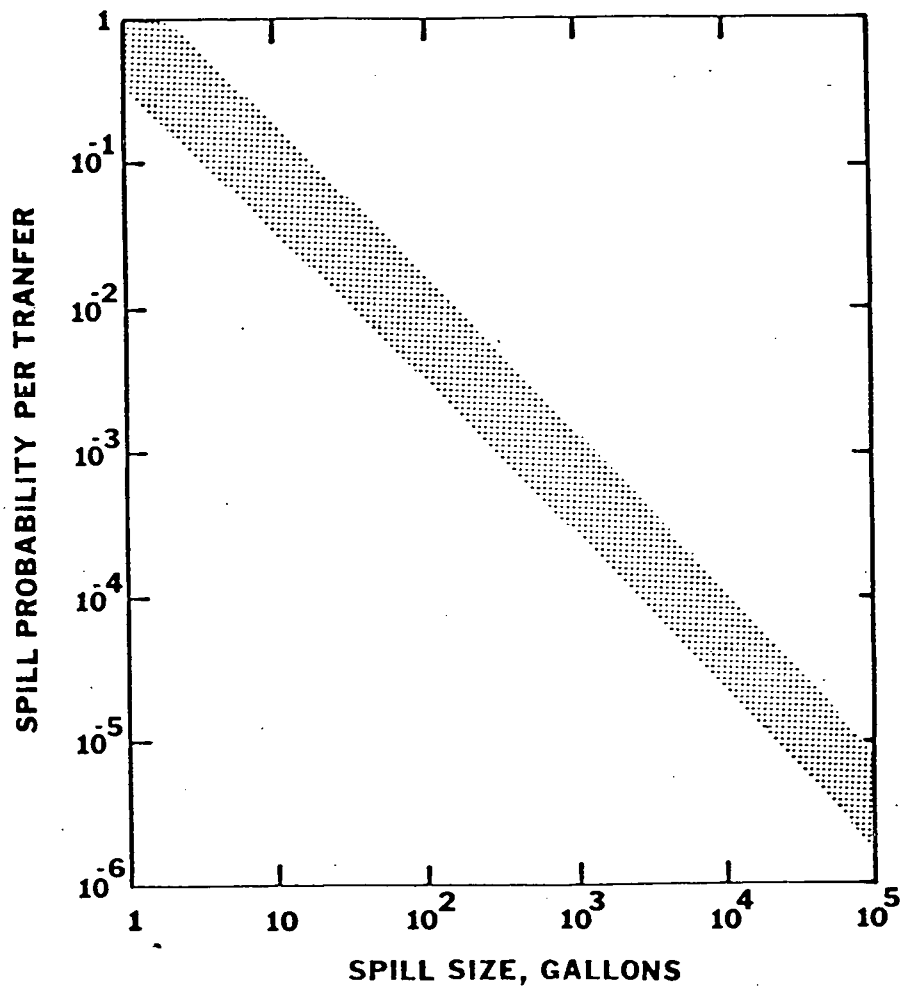


FIGURE S-8. SPILL PROBABILITIES FOR LPG TANKER TRANSFER OPERATIONS.

Figure S-9 shows a fault tree for loading or unloading LPG barges. The events that lead to spills are similar to those for LPG tankers, but the spill probabilities may be different because of differences in design, operating pressures, and transfer procedures. Figure S-10 shows a graphical summary of the spill probabilities for barges during transfer operations. Again the plot is shown as a broad line to emphasize the approximate nature of the spill probabilities.

It is interesting that the spill probabilities for barge and tanker operations are about the same. Intuitively, it might appear that barges would have more spills because of the pressurized cargo transfer and less sophisticated equipment and procedures. However, the transfer operations are simpler and the transfer time is shorter, so that the risk is reduced. Barge collisions causing spills are shown as being an order of magnitude less probable than ship collisions. The barge transport of LPG has a fairly long history and a much larger number of transfers than tanker transport, with only one known spill due to collisions. Collisions involving tankers may in fact have a much lower probability than shown, but there is not sufficient historical data to prove it. The comparison in Table S-1 illustrates the point. All the spill probabilities except that of Cave and Kazarians are based either on no spills for limited numbers of liquefied gas ships or other ships and for no vessel traffic control in the harbors. The results are roughly comparable, even though different data bases were used. Cave and Kazarians' study was specific for large spills in Boston Harbor, and included the provisions for traffic control and Coast Guard escort required for gas tankers in Boston Harbor. The special precautions obviously result in a higher level of safety by reducing the collision probability substantially.

Even though the spill probability may be large for some parts of the operation, it does not necessarily follow that the operation is especially dangerous. The primary danger from LPG spills, particularly those less than a few hundred gallons in volume, is from fire. The ignition probability depends on

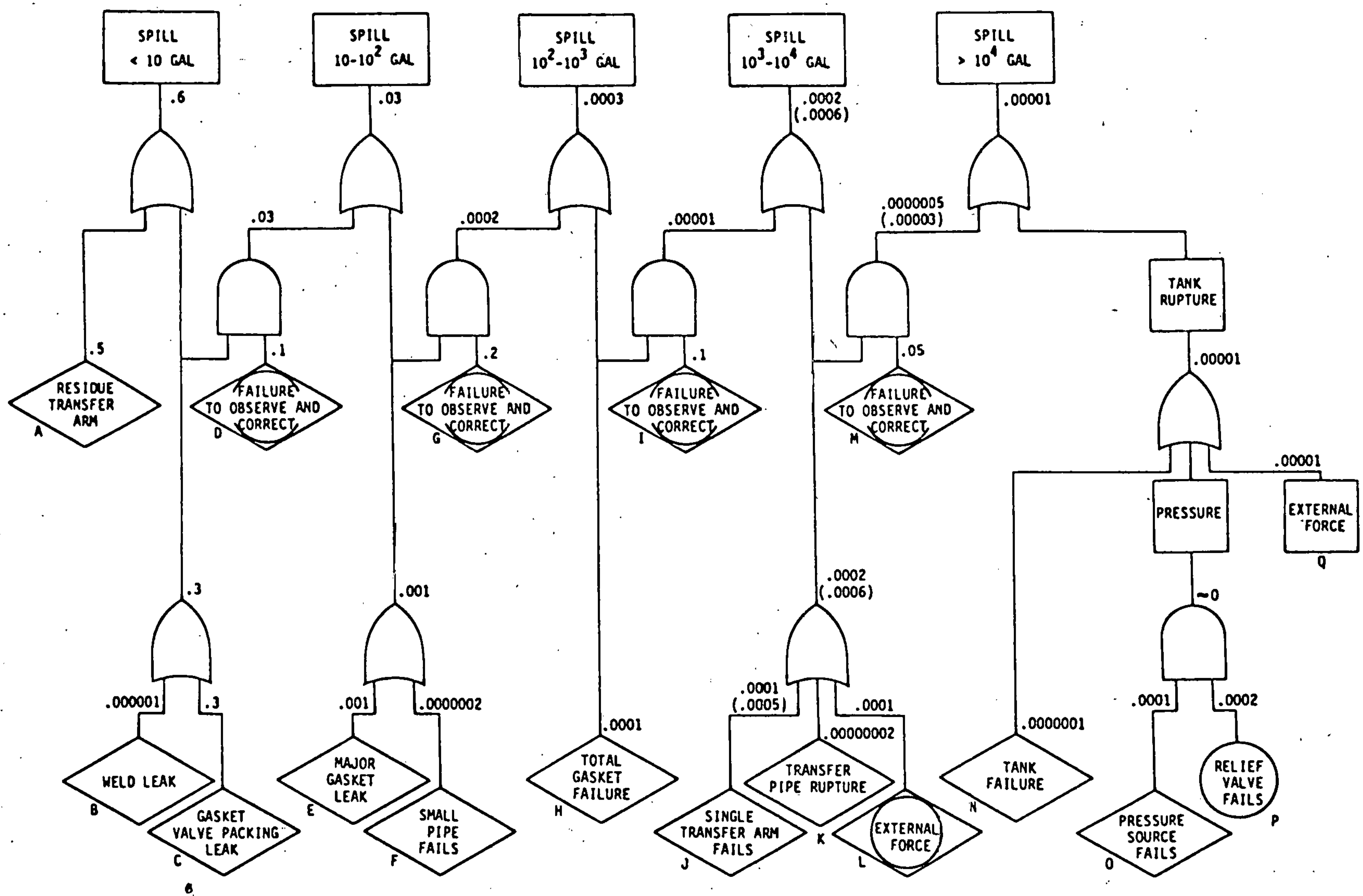


FIGURE S-9. FAULT TREE FOR LPG BARGE CARGO TRANSFER.

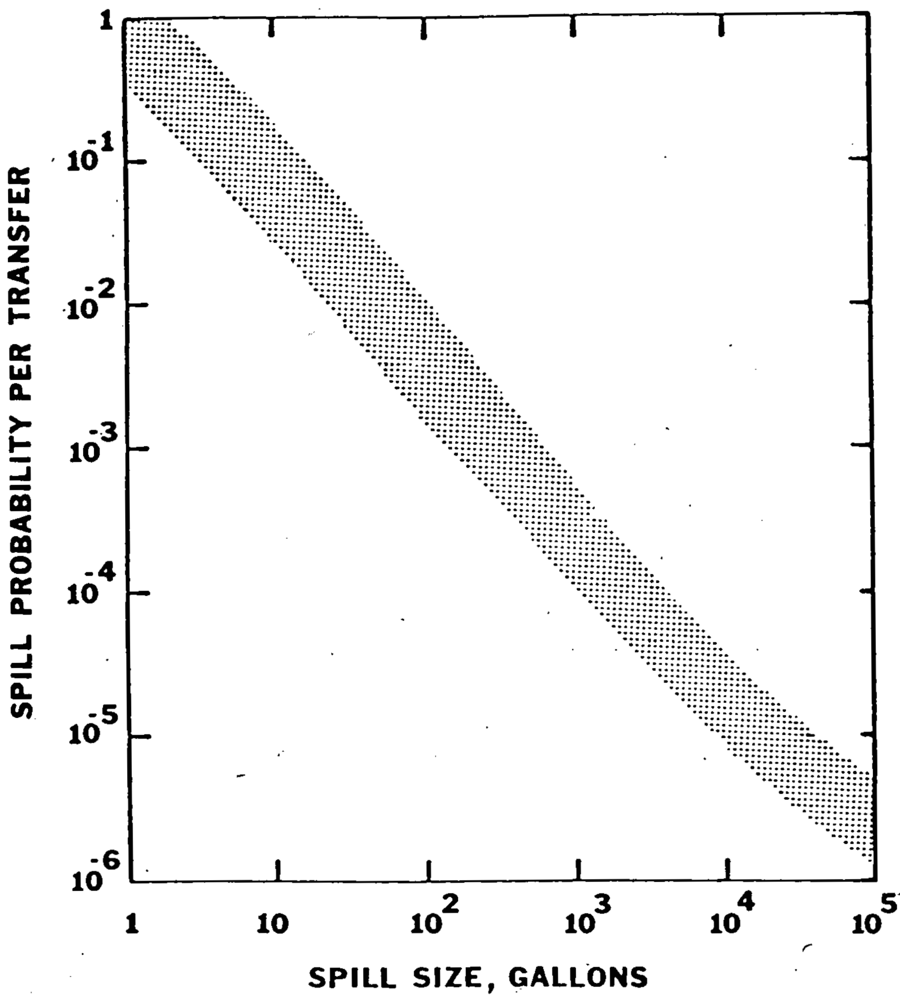


FIGURE S-10. SPILL PROBABILITIES FOR LPG BARGE CARGO TRANSFER OPERATIONS.

the spill size, with ignition more likely for larger spills. Small spills, less than 10 gal in size, which occur during more than half the transfers, must have very low ignition probabilities. Otherwise, fires would be common occurrences at LPG terminals. On the other hand, spills involving more than 100,000 gal of LPG at a high spill rate are practically certain to be ignited. The probability of fire occurring during transfer can be estimated if ignition probabilities are known. As an estimate, the following are used to approximate ignition probabilities:

Spill Size, gal	Ignition Probability
< 10 gal	0.001
100 gal	0.01
5000 gal	0.1
> 100,000 gal	1.0

These ignition probabilities are assumed to apply regardless of whether the spill occurs at a barge or tanker operation. If the ignition probabilities are applied to the spill probabilities from Figure S-8 and S-10, the result is the probability of occurrence of fire during a transfer operation. Figure S-11 shows the approximate fire probability for both barge and tanker operations for non-collision events.

The probability of a ship collision is estimated to be 0.0001 per transit based on historical data for gas carriers. However, the design of LPG ships will offer some protection from LPG spills (as the Yuyo Maru incident showed). Therefore, the spill frequency will be much less than shown in Figure S-7. The frequency will also be reduced substantially if traffic controls are instigated, as shown by Cave and Kazarians. It should also be recalled that the collision frequencies for gas carriers may be less than estimated from historical data because the number of collisions is so small that statistical analysis can be misleading. Figure S-11 omits the ship collision

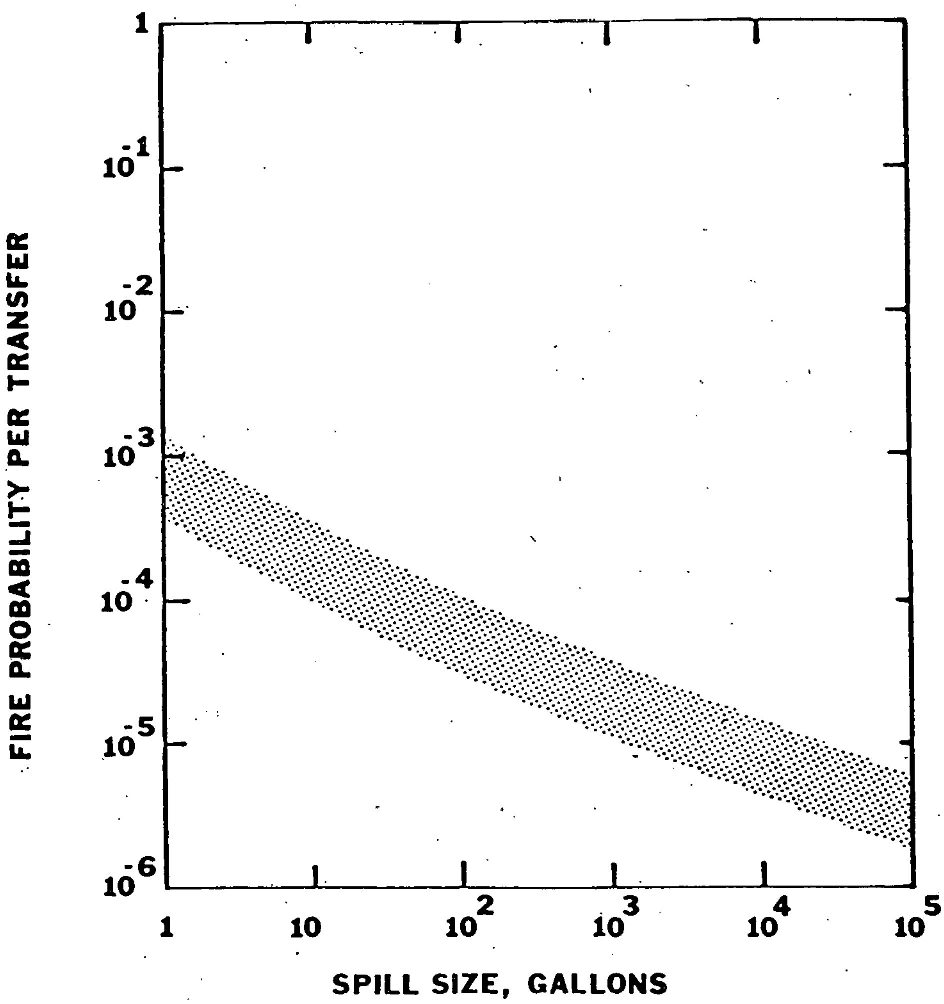


FIGURE S-11. FIRE PROBABILITIES FOR LPG TRANSFER OPERATIONS.

contribution to fire probability because it distorts the trend and makes the fire probabilities appear higher than they really are at the terminal.

Hazard Potential

Fire damage and personnel injuries are relative to fire size. Fires resulting from spills of less than 10 gallons are unlikely to cause substantial damage or result in fatalities, but fires involving thousands of gallons are nearly certain to cause substantial damage and are quite likely to result in fatalities or serious injuries as well. The overall probability of fatality from a spill during LPG transfer is therefore estimated to be in the range of 10^{-6} to 10^{-5} per transfer operation. This fatality probability is for operators near the transfer point and assumes continuous exposure during transfer. The fatality probability for the general public is much lower because of the greater separation from the transfer area.

LPG barge operations can result in a special hazard because the cargo is pressurized. If a cargo tank is heated by a fire, the internal pressure will rise and the emergency vent will open. As gas is vented, the vapor space in the top of the tank grows and the metal in the vapor space heats. At some point, the metal can weaken enough so that the tank ruptures. As the pressure is released, much of the liquid flashes to vapor and much is atomized by the force of the explosion. The fireball that results may be very large and cause a large amount of damage. This phenomenon is call a "boiling liquid expanding vapor explosion" (BLEVE) and has occurred following LPG tank car derailments. No fires at barge transfer facilities have been reported that resulted in BLEVE's.

BLEVE's cannot occur during operations for fully refrigerated LPG cargoes because the operations are all performed using liquids that are saturated near atmospheric pressure. The fraction of flash upon pressure release is therefore small and the liquid released from a storage tank is not disseminated explosively as it is from pressurized storage.

In general, refrigerated storage is used for larger quantities of LPG. If a spill occurs, a vapor cloud will form, and until it is dispersed by mixing with the atmosphere, it can easily be ignited. Under most circumstances, the result will be a vapor cloud fire, but a vapor cloud explosion is possible. In either case, primary damage will be confined to locations near or within the vapor cloud at the time of the fire or explosion. Secondary damage may also be caused if the fire spreads.

Conclusions

The safety record for marine LPG transportation in the United States is very good, probably because of fairly careful attention being paid to design, construction, and operation of facilities. Spills of small quantities of LPG (less than 10 gal) are quite frequent, but are not particularly dangerous.

Most of the small leaks are "planned" in the sense that they are part of normal operations. They occur on nearly every transfer at some facilities and very rarely at others because of differences in operations. The spill frequencies for very small spills could be reduced substantially for some facilities by changes in design and operational procedure. Whether such changes would improve safety is debatable.

The spill probabilities estimated in this report are based on generic designs and overall estimates of collision frequencies. Obviously, if similar calculations are made for a specific facility, the results may vary. Fatalities for barge and tanker terminals are estimated to have an occurrence probability of about 10^{-6} to 10^{-5} per transfer operation. Based on the assumption of weekly to monthly transfer operations, the annual fatality probability for an operator at a given facility would be in the range of 10^{-5} or lower. That is in the same general probability range as an average individual would accept by exposure to automobile accidents. The risk to the general public is substantially less.

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INTRODUCTION TO MARINE TRANSPORT OF LPG

Basic Forms of LPG Marine Transport

Marine transportation of LPG started approximately 30 years ago. Since then, three basic types of LPG ships have evolved. The earliest ships used pressure vessels for containing the LPG; the cargo was under pressure but at ambient temperature. This system, known as Fully Pressurized, is still used on barges and on very small ships.

The development of metals with improved low temperature toughness, better refrigeration techniques, and the desire for larger ships led to Partially Refrigerated ships in which a combination of sub-ambient temperature and above ambient pressure is used to keep the LPG liquefied. These ships are generally used for relatively short coastal or oceanic shipments and rarely exceed a capacity of 15,000 m^3.

The next evolution created the Fully Refrigerated ship. In this design the cargo is carried at its boiling point at atmospheric pressure. Ships of this type are well suited to long voyages and range up to 125,000 m^3 in capacity.

General Construction Details for LPG Ships and Barges

LPG Ships

Practically speaking, all liquefied gas ships built since 1976 must conform to the Inter-Governmental Maritime Consultative Organization Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMCO Code)(1). Before adoption of this code, all LPG tankers used in U.S. waters were to conform to the applicable portions of Title 46 CFR (2) and/or be approved by the U.S. Coast Guard through their Letter of Compliance program.

These codes prescribe the design and construction features of liquefied gas tankships and also the equipment that each ship is to carry in order to minimize the risk to the ship, the crew, and the environment. Due to certain requirements set forth in these codes, most of the LPG ships trading in U.S. ports are quite similar in overall layout. The biggest differences are in the design and construction of the cargo containment systems. Figure 1 shows a simplified representation of one type of fully refrigerated LPG ship. The cargo carrying section of the ship is segregated from other parts of the ship. The accommodation spaces are located aft of the cargo area and cannot be situated immediately above the cargo tanks. Below deck, the cargo area is separated from other areas (e.g. the engine room) by gas and liquid tight partitions. If the cargo temperature is below 14°F (-10°C) (as is the case for refrigerated LPG) the ship is required to have a double bottom. The area between the hull and the inner bottom is usually divided into several "double bottom tanks" which can be used for fuel oil for the engines or for ballast water. They also provide extra protection for the cargo tanks in case the ship runs aground. Wing (side) water ballast tanks are also present on many LPG ships. In addition, topside ballast tanks are often fitted above the cargo tanks. The wing and topside tanks cannot be used to transport flammable liquids or gases in U.S. ports. The separation distances between the cargo tanks and the hull are specified by the IMCO Code and depend to some extent on the type of cargo tanks used. The top of each refrigerated LPG cargo tank is joined to the deck of the ship to prevent air from entering any void spaces between the cargo tanks and the ballast tanks. On most LPG ships, these void spaces are filled with inert gas during normal operations so that, in the event of a cargo leak, no flammable gas/air mixture can occur below the main deck.

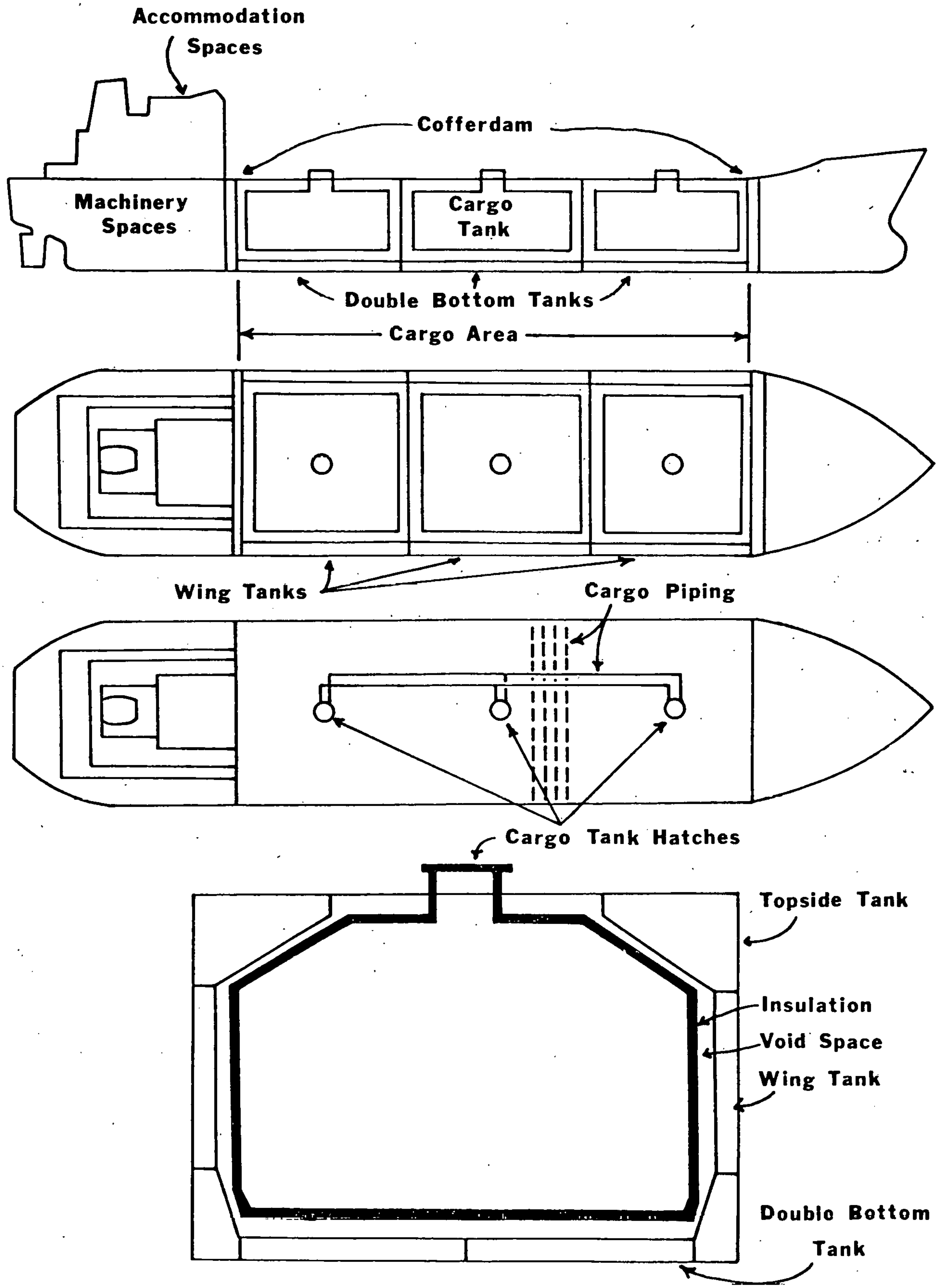


FIGURE 1. FULLY REFRIGERATED LPG SHIP

The piping connecting the cargo tanks to each other and to various pieces of LPG processing equipment is located above the weather deck. When loading or unloading cargo, the ship is moored parallel to the dock and cargo lines that run perpendicular to the length of the ship are connected to the shore-based piping system. This allows the ships to load/unload from either side.

LPG Barges

All LPG barges used in U.S. ports and waterways must conform to the applicable portions of Title 46 CFR (2) and must have a Certificate of Inspection from the U.S. Coast Guard. The requirements set forth in Title 46 concern design, construction, testing, inspection, fire protection, and operation of tank barges. Restrictions imposed by some of these requirements have caused all LPG barges to be basically similar in overall layout. Barge size, cargo tank size, and the number of cargo tanks will vary but the concept remains the same.

Figure 2 shows the main features of a typical LPG barge. Most of the barges are of the "open hopper" type as shown but some of the newer barges have a complete watertight weather deck. In either case, the hull must be constructed such that a loaded barge will remain afloat following all but the most severe accidents. A number of watertight compartments are built into the hull to provide the necessary buoyancy.

Cargo Containment Systems

General Requirements

Most LPG ships and barges are constructed with from two to six cargo tanks. Each tank is constructed of a metal

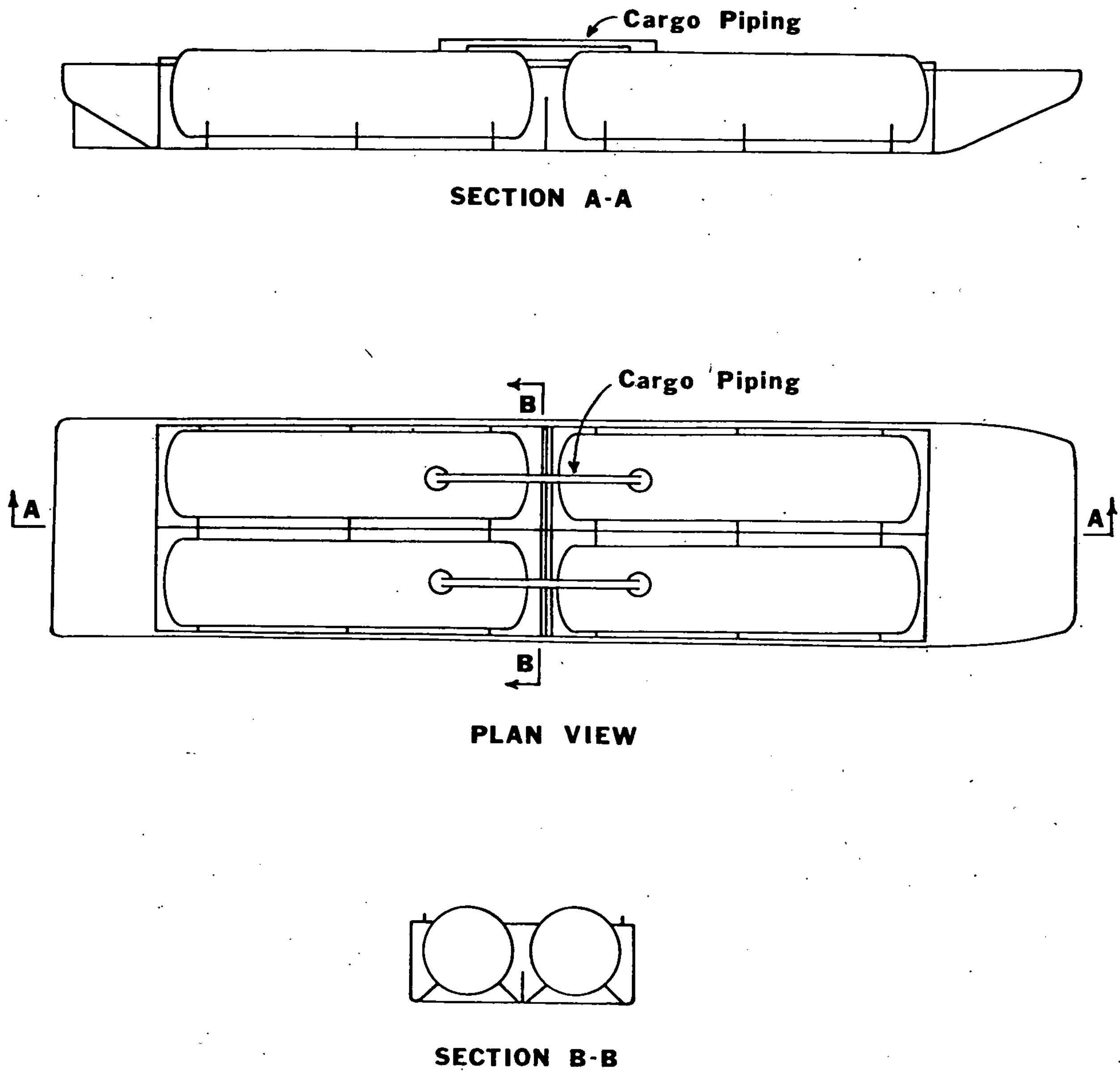


FIGURE 2. PRESSURIZED LPG BARGE.

alloy suitable for the lowest intended service temperature. The codes require that the tank be designed to withstand the rigors of marine transport without failing. For certain tank designs, mathematical analysis of the stresses involved is extremely difficult; in these cases an extra factor of safety is called for in the form of a "secondary barrier" (the tank itself being the "primary barrier"). This secondary barrier must also be constructed of materials with suitable low temperature properties and can, if desired, be a part of the ship's hull. The purpose of this barrier is to provide temporary containment of any LPG leaking from the main tank.

After construction, the tanks are inspected by x-ray radiography of the welds and by various other tests designed to determine if the tanks are gas and liquid tight. Visual inspection of at least one surface of both the primary and secondary barriers is required once every two years.

In those cases where the cargo temperature is less than 14°F (-10°C), suitable insulation must be provided to insure that the hull temperature does not fall below the minimum service temperature for the grade of steel used in the hull.

Fully Pressurized System

In the fully pressurized cargo containment system, the cargo is maintained as a liquid at ambient temperature strictly by the pressure of the system, no refrigeration being involved. The cargo tanks are either cylindrical or spherical pressure vessels with a design pressure in the region of 250 psig (176 kg/cm^2). This system allows the use of ordinary grades of steel for tank construction and no insulation or refrigeration machinery is necessary. However, the weight of the tanks is such that the design is generally economical only for ships or barges of less than 5,000 m^3 capacity.

Due to the safety record and the ease of calculating stresses in cylindrical and spherical tanks, no secondary cargo containment barrier is required for fully pressurized LPG ships/barges. The hold spaces surrounding the tanks do not have to be (and generally are not) inerted.

Fully Refrigerated System

In the fully refrigerated cargo containment system, the cargo is carried at its boiling point at (or very near) atmospheric pressure. Special metal alloys must be used in constructing the tanks in order to prevent brittle fracture. Although the tanks are heavily insulated to decrease heat leakage into the tanks, refrigeration equipment is installed on board the ship to reliquefy the boiloff gas.

The tanks in fully refrigerated ships are generally rectangular, prismatic, or spherical. Free-standing rectangular or prismatic tanks (i.e. those tanks capable of supporting their own weight and the weight of the contents without any external support) require a complete secondary cargo barrier. (If the tanks are designed with an increased safety factor, the secondary barrier can be deleted for upper portions of the tanks.) The secondary barrier is usually made of plywood, fiberglass reinforced polyester, or a suitable metal alloy. Spherical tanks are also free-standing but, since they are also classed as pressure vessels, they are required to have only partial secondary barriers located below the tanks. Membrane tanks are not free-standing, they therefore depend upon the hull of the ship to provide the rigidity and support. The stresses imposed upon the tanks are transmitted to the hull structure by means of the insulation. A full secondary barrier is required on all membrane tanks.

Fully refrigerated ships range in size from 5,000 to 125,000 m^3 and are generally used for trans-oceanic service.

Semi-Refrigerated System

In the semi-refrigerated cargo containment system, the cargo is carried at a temperature above its boiling point and a pressure greater than atmospheric. The cargo tanks are either cylindrical or spherical and are insulated. No secondary barrier is required and the hold need not be inerted. Ships using this type of cargo containment system range in size up to approximately 15,000 m^3. They are generally used in shorter trade routes than fully refrigerated ships and are rarely seen in U.S. ports.

BASIC OPERATING PROCEDURES FOR A REFRIGERATED LPG SHIP

Introduction

The basic operating procedures for the LPG plant on board a refrigerated LPG tankship will be discussed using a "composite tanker" that is typical of LPG ships currently in use and under construction but is not identical to any of them. A simplified diagram of the basic cargo handling system, including a cargo tank, LPG liquid and vapor piping and valves, reliquefaction facilities, inert gas generator and distribution piping, and related elements is shown in Figure 3. This schematic is limited to the basic cargo containment and piping system; duplicate, secondary (back-up), or alternate systems are not shown. Instrument air lines, working fluid piping, and electrical circuitry are not shown.

In order to consider all normal phases of cargo handling operations, assume that the ship is about to receive its first cargo (either newly built or returning to service from drydocking) and therefore the cargo tanks are filled with air and are at ambient temperature. The entire sequence from preparing the ship to receive cargo, loading and unloading, and on through taking the ship out of service for drydocking (or change of cargo) will be discussed.

Replacing Air With Inert Gas

Cargo Tanks

Cargo tanks containing air must be purged with inert gas before admitting any LPG in order to prevent a flammable mixture of LPG vapor and air being formed. In most cases,

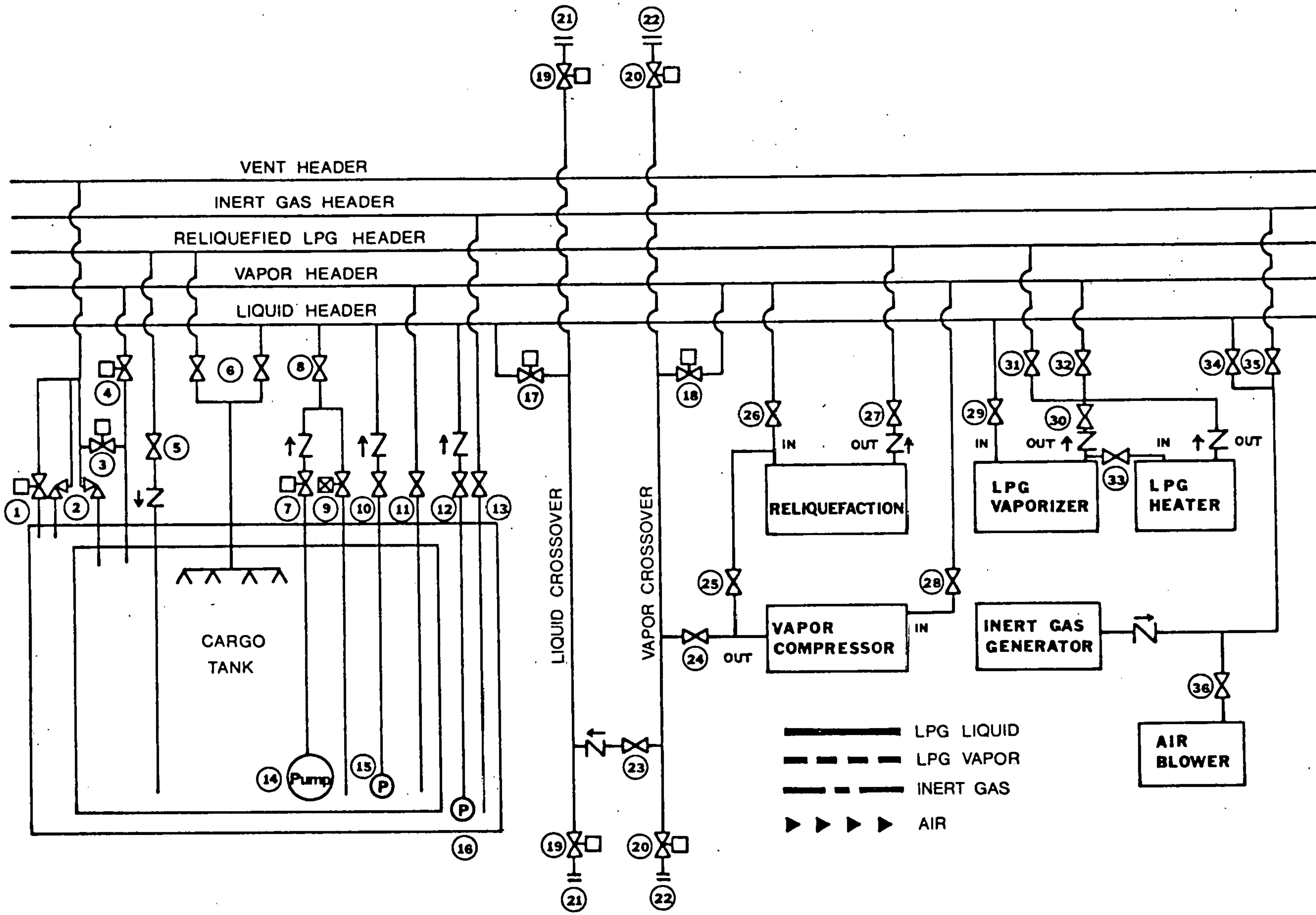


FIGURE 3. BASIC DIAGRAM OF LPG CARGO HANDLING SYSTEM ON BOARD A REFRIGERATED LPG SHIP.

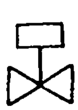
LEGEND

1. Discretionary relief valve for void space
2. Safety relief valves (void space anc cargo tank)
3. Discretionary relief valve for cargo tank
4. Vapor inlet/outlet valve, top
5. Reliquefied LPG return valve
6. Liquid spray cooling valves
7. Liquid pump outlet valve
8. Main liquid inlet/outlet valve
9. Liquid inlet valve
10. Emergency pump outlet valve
11. Vapor inlet/outlet valve, bottom
12. Void space liquid pump outlet valve
13. Inert gas inlet valve for void space
14. Main cargo pump
15. Auxiliary cargo pump
16. Void space emergency pump
17. Liquid header isolation valve
18. Vapor header isolation valve
19. Liquid crossover isolation valves
20. Vapor crossover isolation valves
21. Liquid cargo transfer arm connection
22. Vapor cargo transfer arm connection
23. Header interconnect valve
24. Vapor compressor outlet valve to vapor crossover
25. Vapor compressor outlet valve to reliquefaction unit
26. Uncompressed vapor inlet valve to reliquefaction unit
27. Reliquefied LPG outlet valve
28. Vapor inlet valve to vapor compressor
29. Liquid inlet valve to LPG vaporizer
30. Main outlet valve for cold LPG vapor
31. Vaporized LPG valve to reliquefied LPG header
32. Vaporized LPG valve to vapor header
33. Cold vapor inlet to LPG heater
34. Inert gas valve to liquid header
35. Inert gas valve to inert gas header
36. Air blower outlet valve

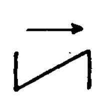
Local manual valve

Pressure relief valve

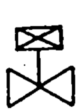
Local manual and remote manual valve



Check valve



Local manual, remote manual, and automatic (closing) valve



the inert gas is produced by burning fuel oil in an inert gas generator. The combustion products are passed through a set of dryers to remove the water vapor and filtered to remove particulate matter. The resulting inert gas is approximately 98% nitrogen and 2% carbon dioxide.

One method for inerting a cargo tank is shown in Figure 4. In this case, the inert gas (which is generated on the ship) is admitted to the bottom of the tank and air/inert gas is drawn off near the top of the tank and vented to the atmosphere. The piping is arranged so that it is also possible to admit inert gas near the top of the tank and remove it from near the bottom. In either case, the inerting procedure continues until the oxygen concentration of the gas being sent to the stack is below 5%. This inerting operation can also be carried out using inert gas from shore or by using nitrogen from the shore or ship if LN_2 storage and vaporization facilities are provided.

LPG Piping

All piping destined to carry LPG liquid or vapor must also be purged with inert gas. One method for accomplishing this is shown in Figure 5.

Void Spaces

The void space surrounding each cargo tank must also be inerted so that if a leak develops in a cargo tank, no flammable mixtures can be formed in the void space. This inerting is accomplished as shown in Figure 6. As before, the inert gas can be supplied by inert gas generators on ship or shore, or by vaporizing LN_2 on ship or shore.

Replacing Inert Gas With LPG Vapor

Once the oxygen content in the cargo tank has been reduced to an acceptable level by purging with inert gas,

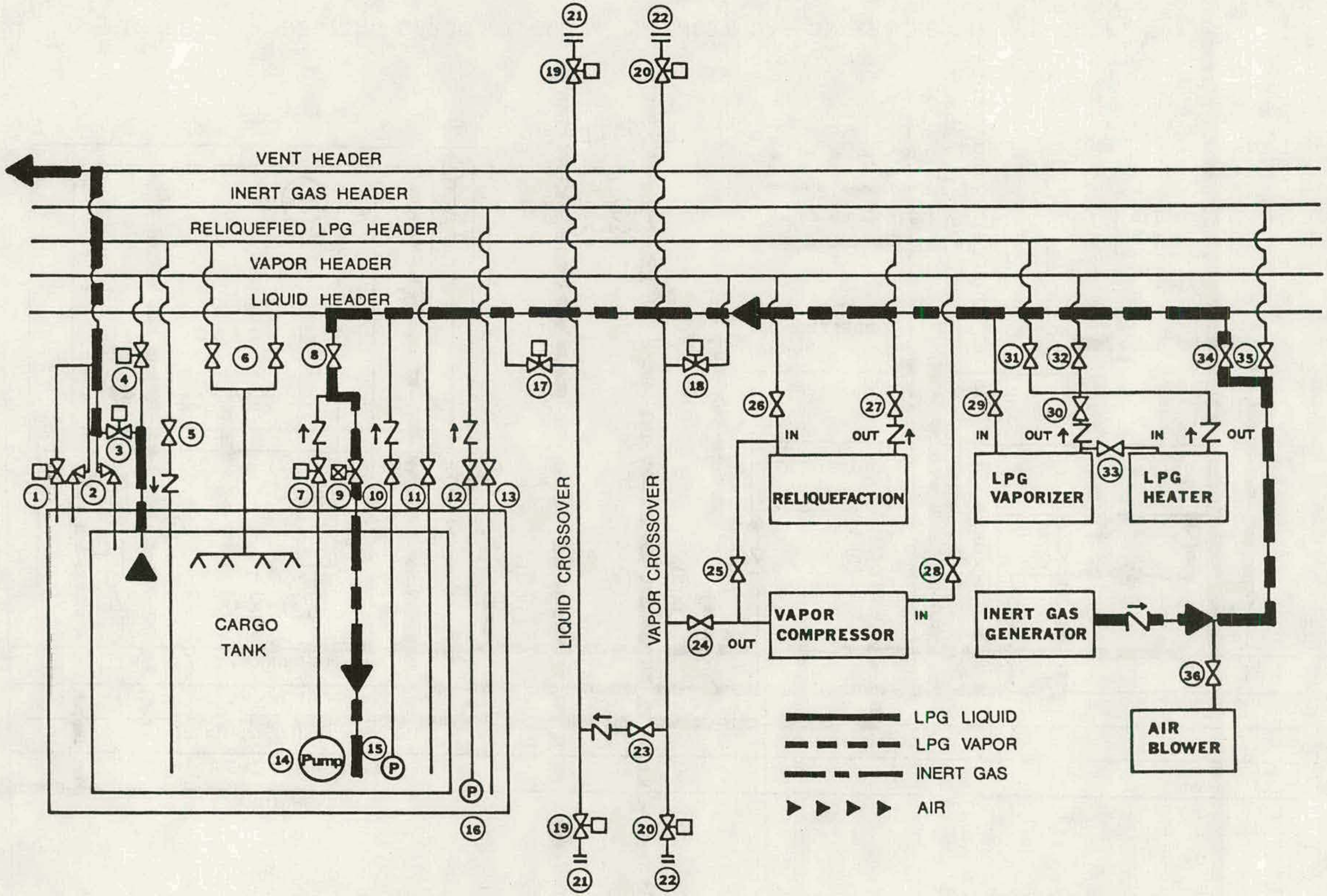


FIGURE 4. INERTING CARGO TANK WITH INERT GAS GENERATED ON THE SHIP.

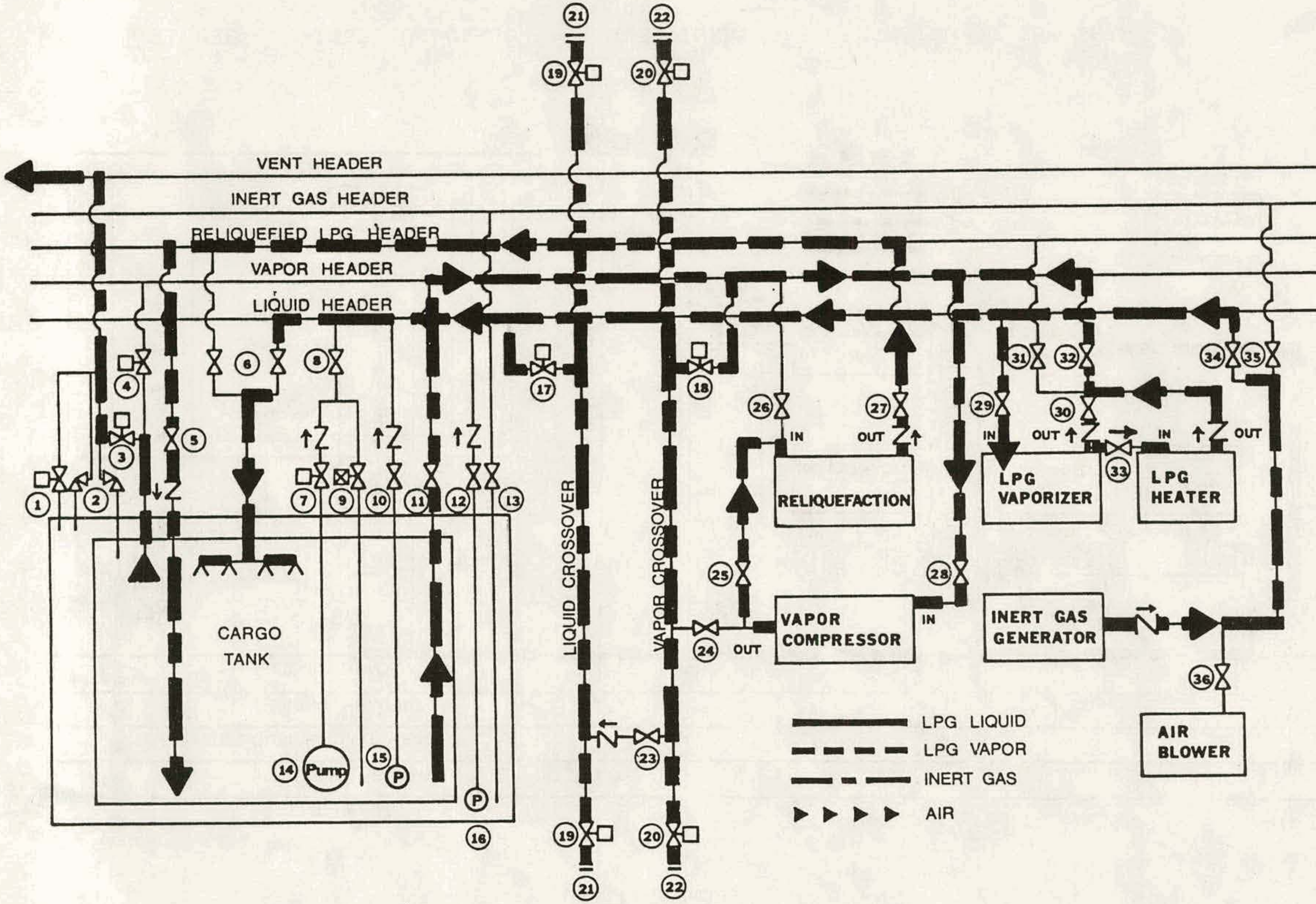


FIGURE 5. INERTING CARGO PIPING WITH INERT GAS GENERATED ON THE SHIP.

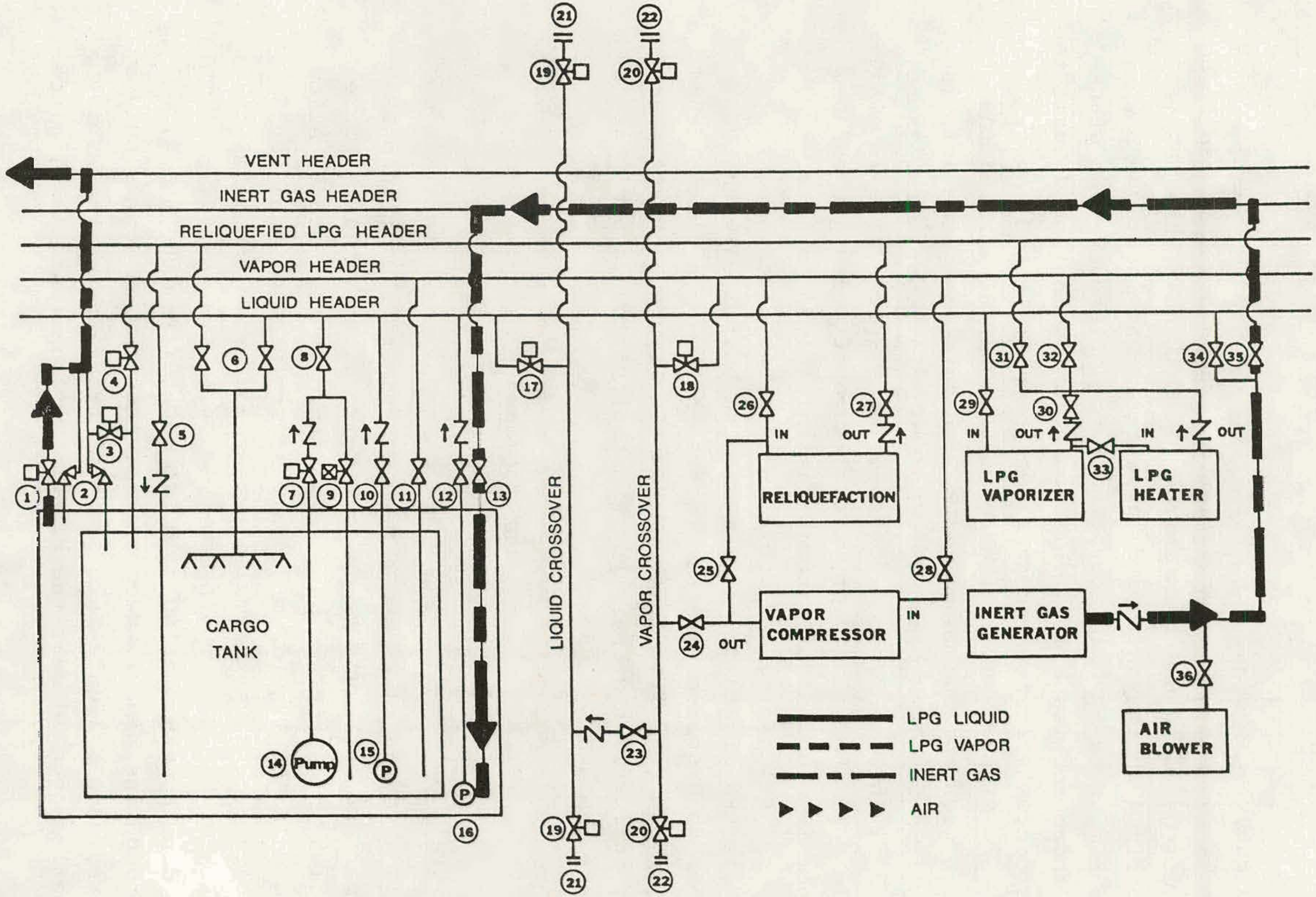


FIGURE 6. INERTING VOID SPACE WITH INERT GAS GENERATED ON THE SHIP.

the inerting process can be stopped and the inert gas can be displaced with LPG vapor. Figure 7 shows how this can be done by using liquid LPG from shore. In this case, the LPG is vaporized in the shipboard vaporizer. The inert gas/LPG vapor mixture is transferred back to a flare or vent stack on shore for disposal. This operation is continued until the gas content of the tank is almost completely LPG vapor.

Figure 8 shows another method for displacing the inert gas from the cargo tanks. In this case, the ship is supplied with LPG vapor (preferable cold vapor) from shore.

In some foreign ports no vapor return line is available. In that situation, the mixture of inert gas and LPG vapor is disposed of through the ship's vent stacks.

All piping and containers that are destined to handle LPG liquid or vapor must also be filled with LPG vapor to displace the inert gas. This can be accomplished in a manner similar to that shown in Figure 5 except that the inflow is now LPG vapor and the outflow is a mixture of inert gas and LPG vapor.

Tank Cooldown

Initial Cooldown

Cargo tanks and piping containing almost pure LPG vapor are still not ready to receive cargo until they are cooled to nearly the same temperature as the cargo. Allowing cold LPG liquid to contact a warm pipe or tank could create excessive thermal stresses and cause the metal to crack or buckle. The LPG piping is cooled down first. This is done by circulating cold LPG vapor (from the shore) through the pipes. Each tank is then cooled down slowly by spraying LPG liquid into the tank from a network of spray nozzles located near the top of the tank. At first, since

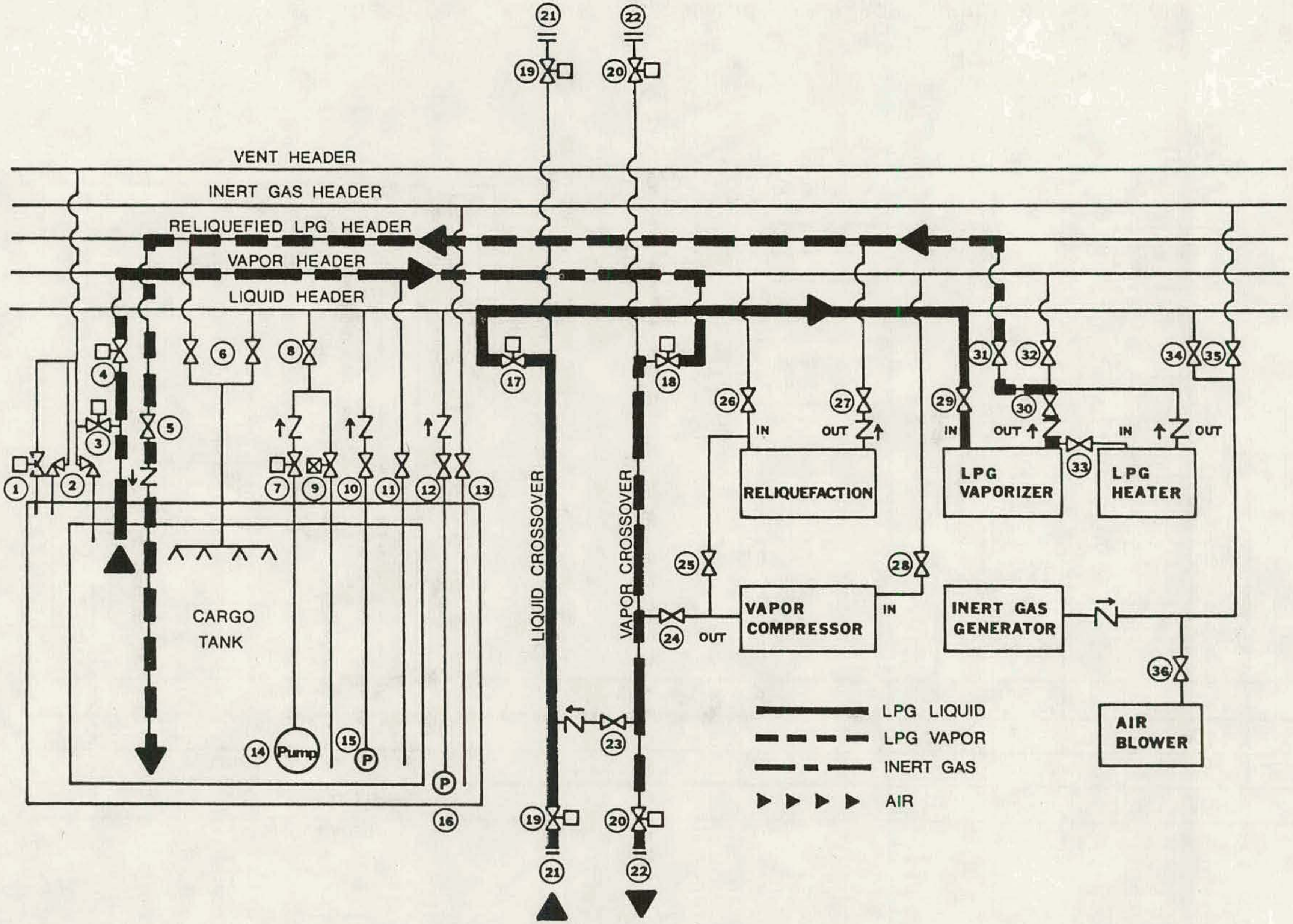


FIGURE 7. REPLACING INERT GAS IN CARGO TANK USING LPG LIQUID SUPPLIED FROM SHORE.

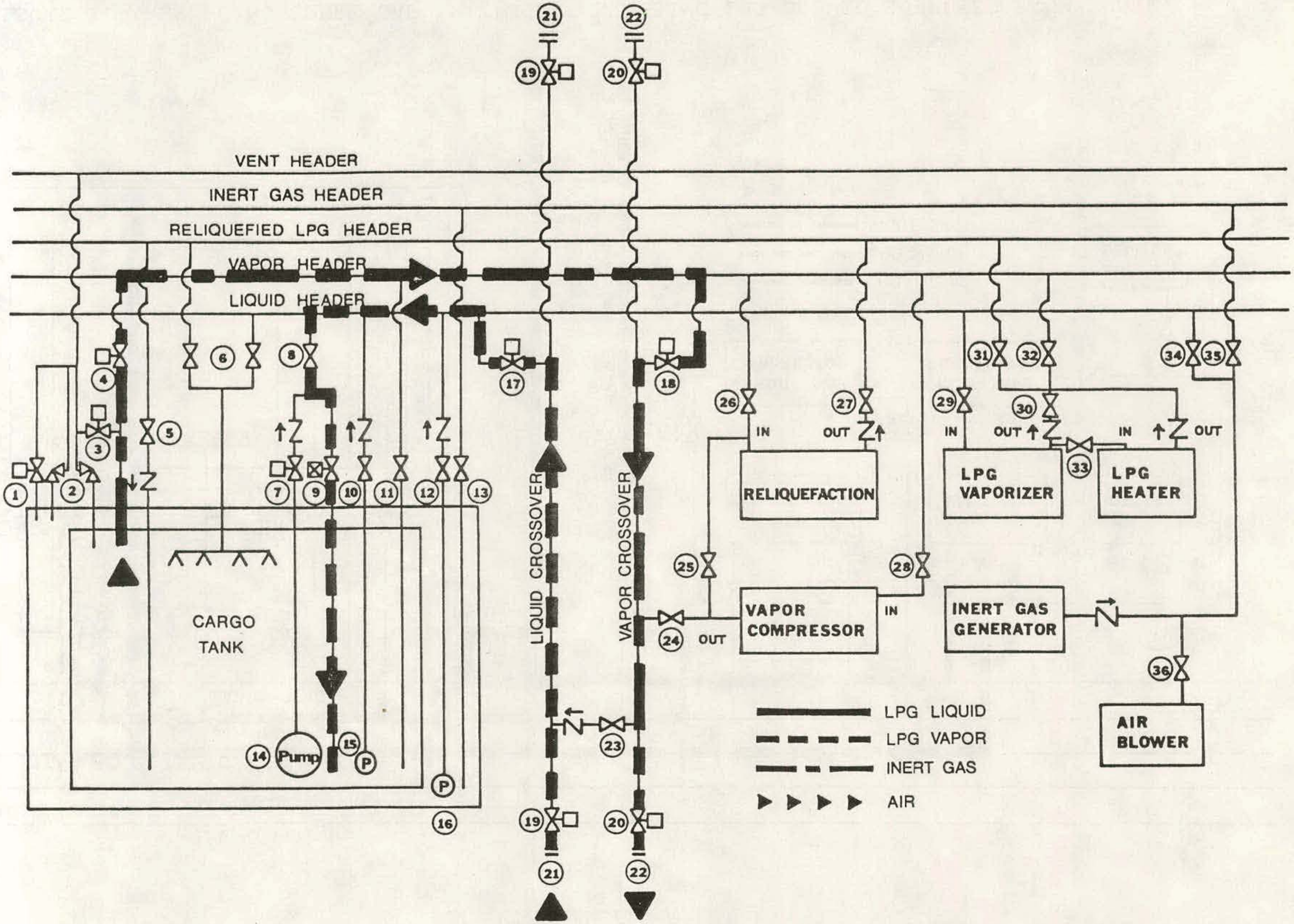


FIGURE 8. REPLACING INERT GAS IN CARGO TANK USING LPG VAPOR SUPPLIED FROM SHORE.

the LPG vapors in the tank and the tank itself are warm, all of the spray vaporizes to form LPG vapor. Later, when the tank and gas have cooled down somewhat, part of the spray will not vaporize and LPG liquid will start to accumulate in the tank.

Figure 9 shows one possible case of spray cooling. In this example the LPG liquid is supplied from the shore and the LPG vapor is sent back to shore. Figure 10 shows a similar configuration except that the LPG vapors are liquefied by using the ship's reliquefaction unit.

Cooldown at Sea

After an LPG cargo has been unloaded at a receiving terminal, only a small amount of LPG is present in each tank during the ballast voyage. This liquid is commonly referred to as the heel. During the ballast voyage the tanks warm up because the heat leak into the tanks is greater than the cooling effect provided by the vaporization of the cargo heel. Before reloading, the cargo tanks must be cooled again. This is done by withdrawing LPG liquid from one or more tanks and introducing this liquid back into the tanks through the spray cooling nozzles. Figure 11 shows one example of how this is done.

Loading

Loading With Vapor Return

The preferable method of loading is to use the vapor return line to transfer the LPG vapor displaced from ship's tanks by LPG liquid back to the shore tank to replace the volume of LPG liquid withdrawn. In this way it is possible to prevent overpressurizing the ship's tanks and prevent drawing a vacuum in the shore tank. This method is shown in Figure 12. In some cases, the returned vapor is flared or vented.

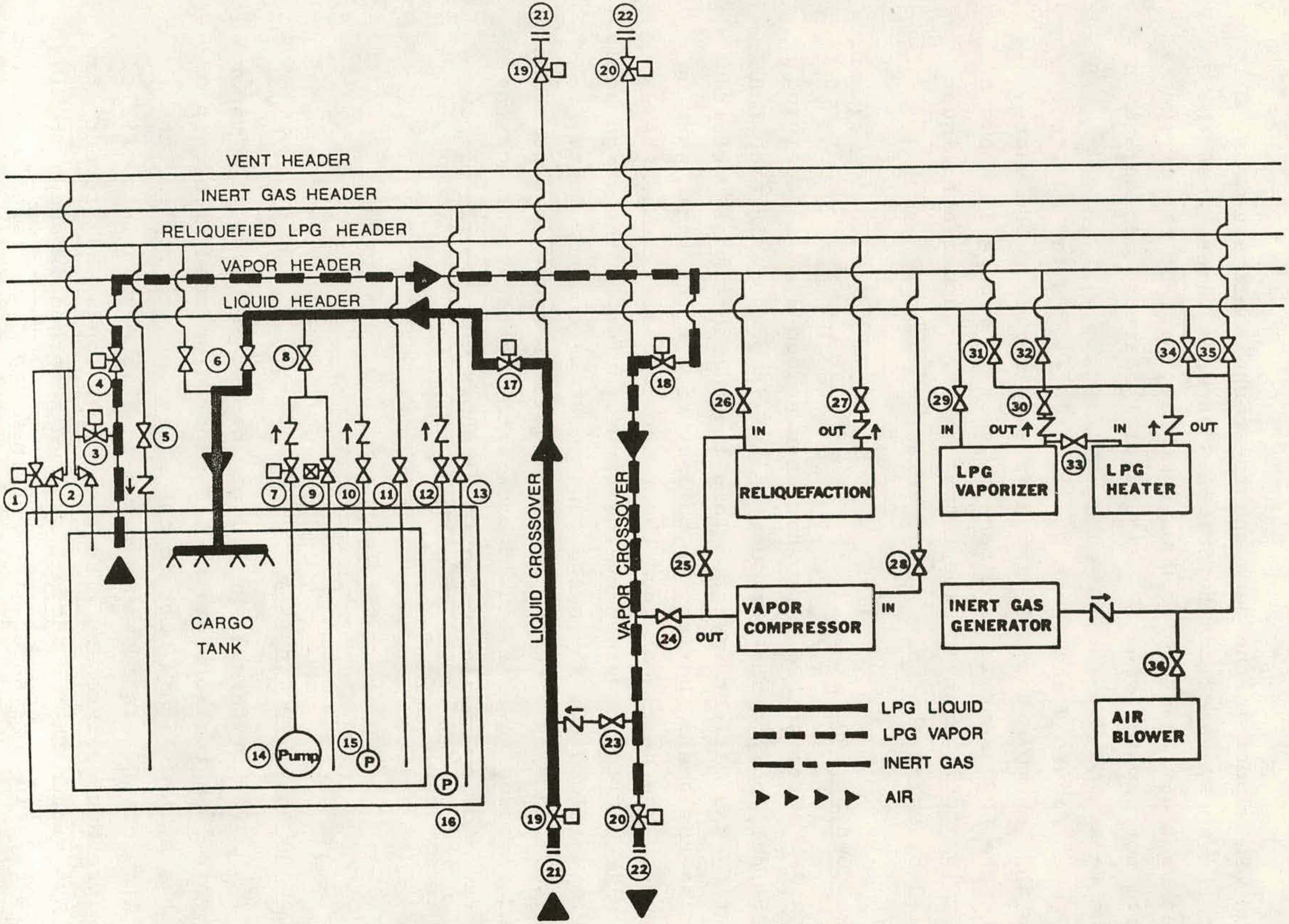


FIGURE 9. COOLDOWN OF CARGO TANK USING LPG SUPPLIED FROM SHORE, VAPOR RETURNED TO SHORE.

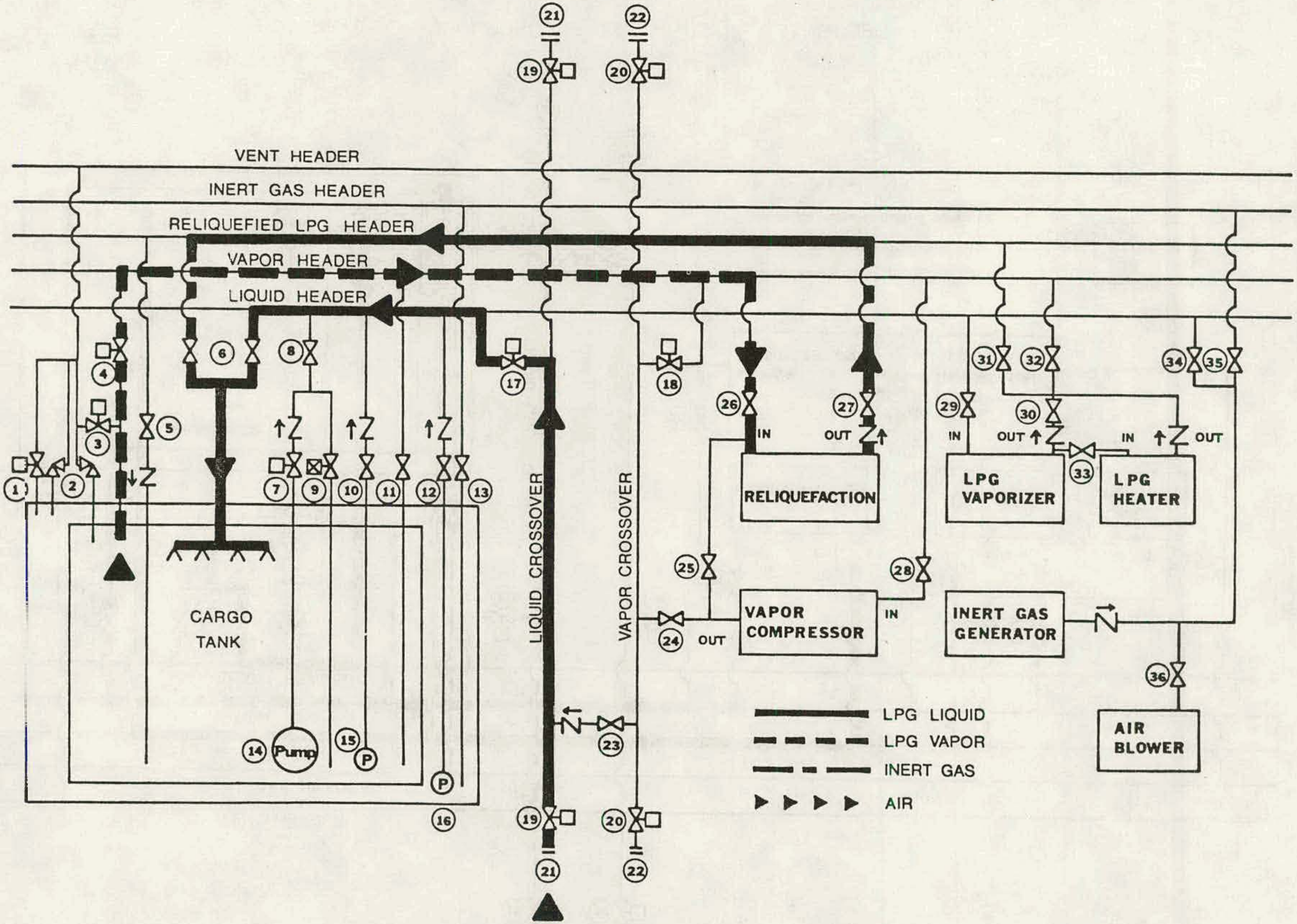


FIGURE 10. COOLDOWN OF CARGO TANK USING LPG SUPPLIED FROM SHORE, VAPOR RELIQUEFIED ON SHIP.

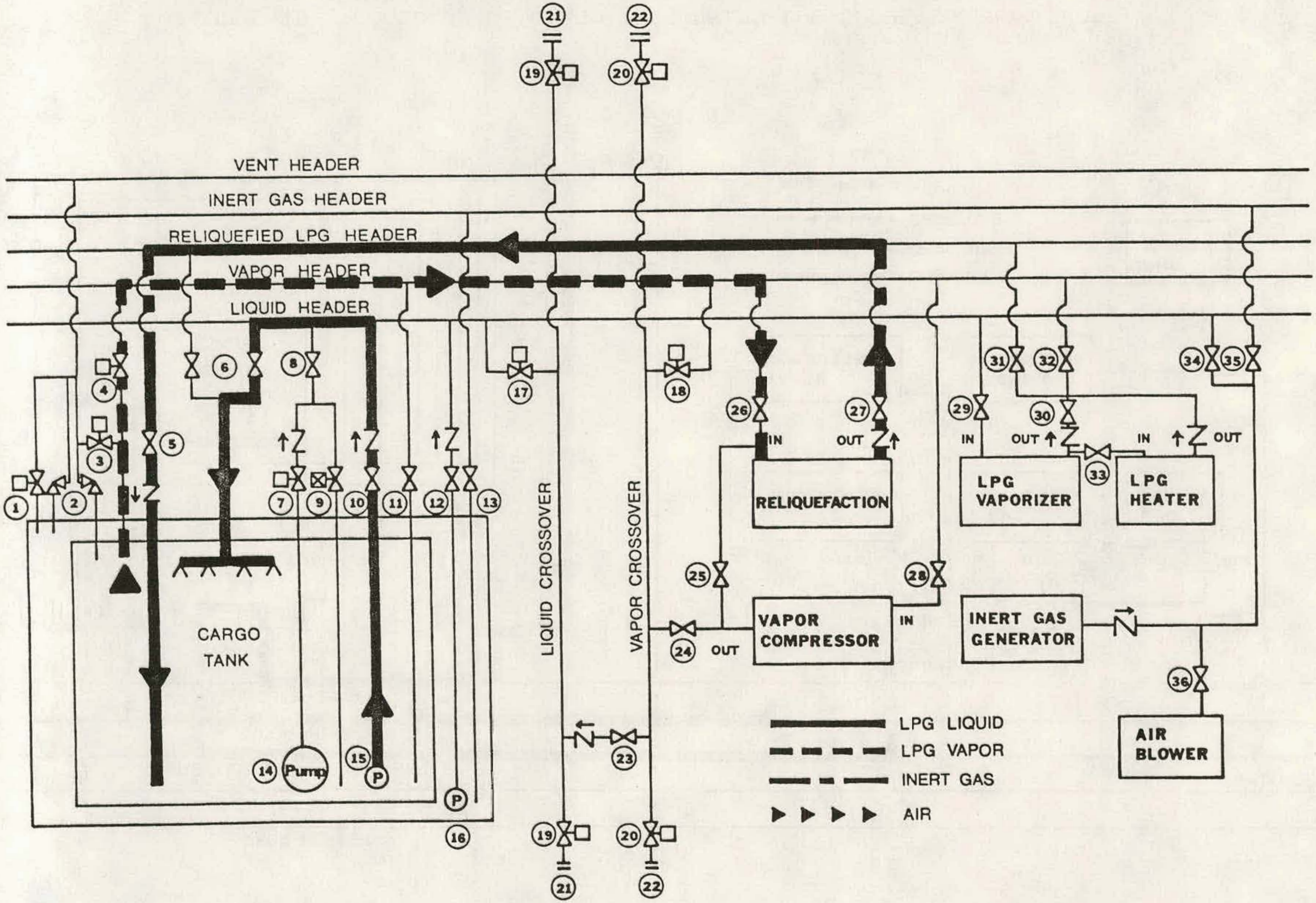


FIGURE 11. COOLDOWN OF CARGO TANK USING LPG HEEL.

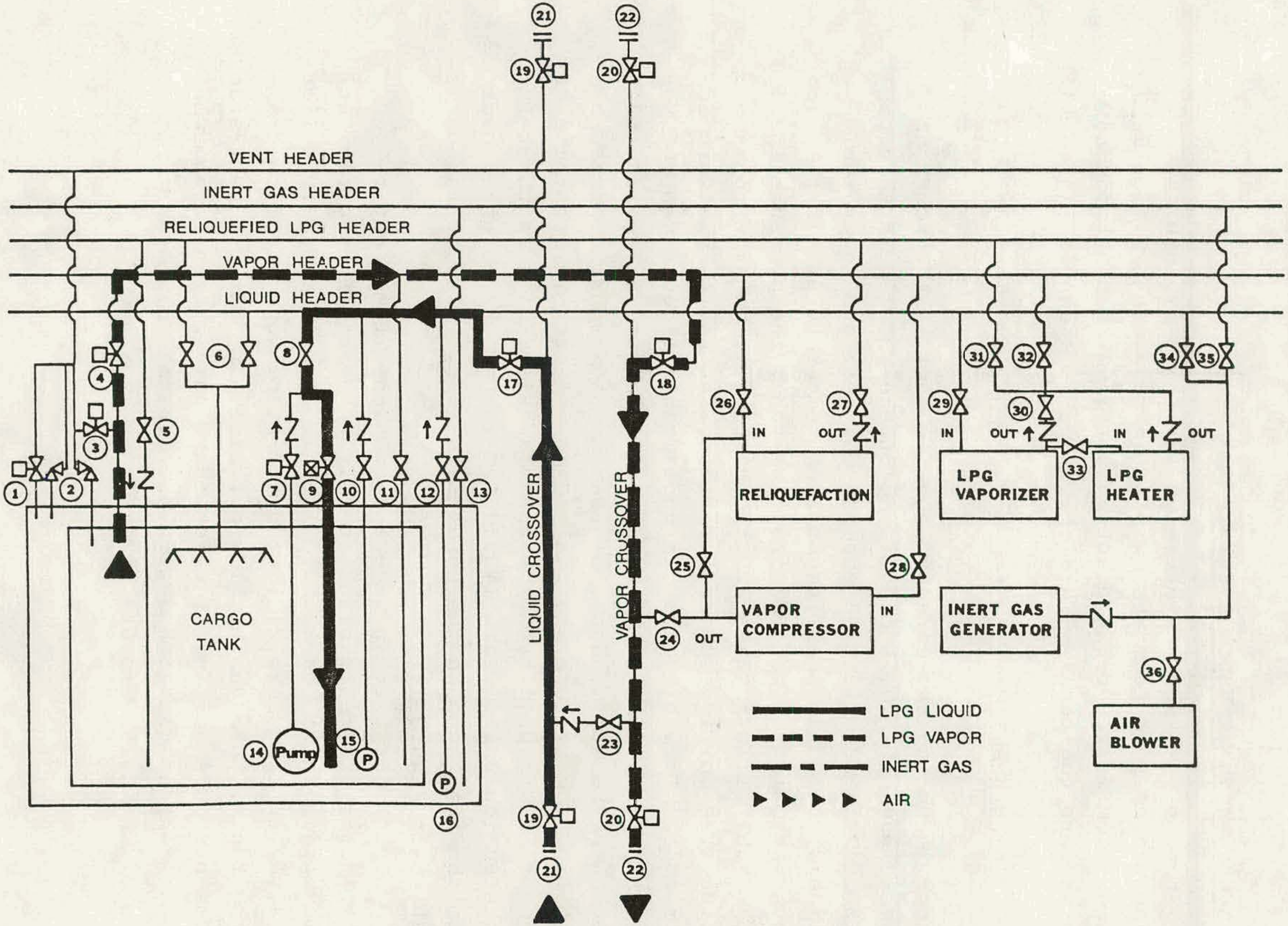


FIGURE 12. LOADING WITH VAPOR RETURN.

Loading Without Vapor Return

If no vapor return line is available then the LPG vapor displaced from the ship's tanks by the LPG liquid is liquefied in the reliquefaction unit and then introduced back into the tanks. This operation is shown in Figure 13.

Pressure and Temperature Maintenance in Cargo Tanks

During the cargo voyage the heat leak through the tank insulation will cause some of the LPG liquid to vaporize. This vaporization absorbs the heat and keeps the liquid cooled to near its boiling temperature. If the vapor generated is not removed from the tank, the pressure inside the tank will increase and the cargo will be able to warm up since the boiling temperature increases as the pressure increases. This situation is undesirable because many of the tanks can be damaged by even small pressure increases and because the cargo should be near its atmospheric pressure boiling temperature when unloading. Therefore, the boiloff vapor is stripped from the tanks and liquefied in the reliquefaction unit. This liquid LPG is then transferred back to the tank through the condensate line. This operation is shown in Figure 14.

Under certain severe conditions it may not be possible for the reliquefaction unit to maintain a sufficiently low pressure in the tanks. In this case, the safety relief valves on the tanks will open and allow vapor to flow from the tanks, through the blow-off line, and out the vent stacks. The pressure setting at which these valves open is somewhat dependent on the tank design but typical values are from 1.5 to 3.0 psig (0.1 to 0.2 kg/cm^2).

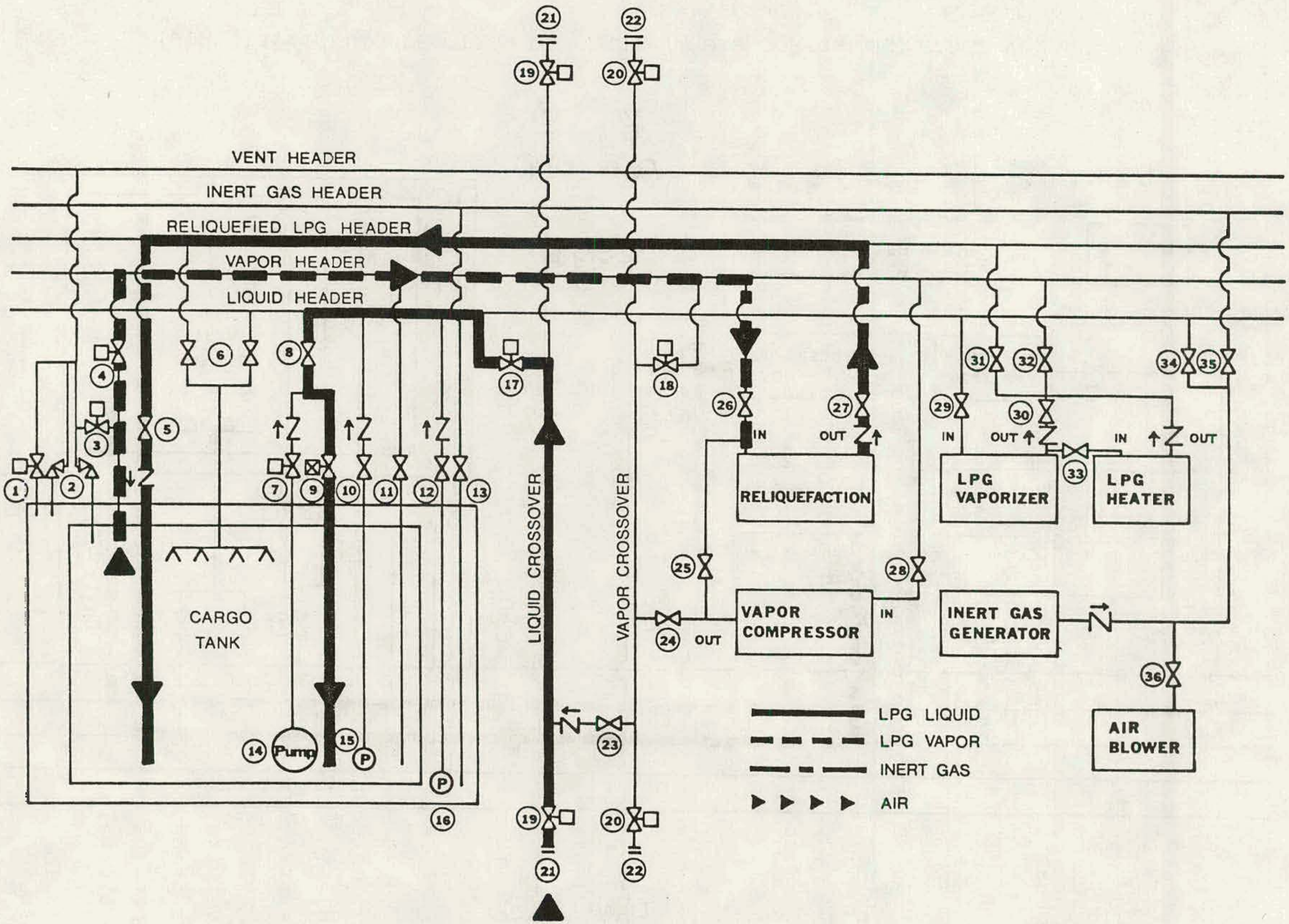


FIGURE 13. LOADING WITHOUT VAPOR RETURN.

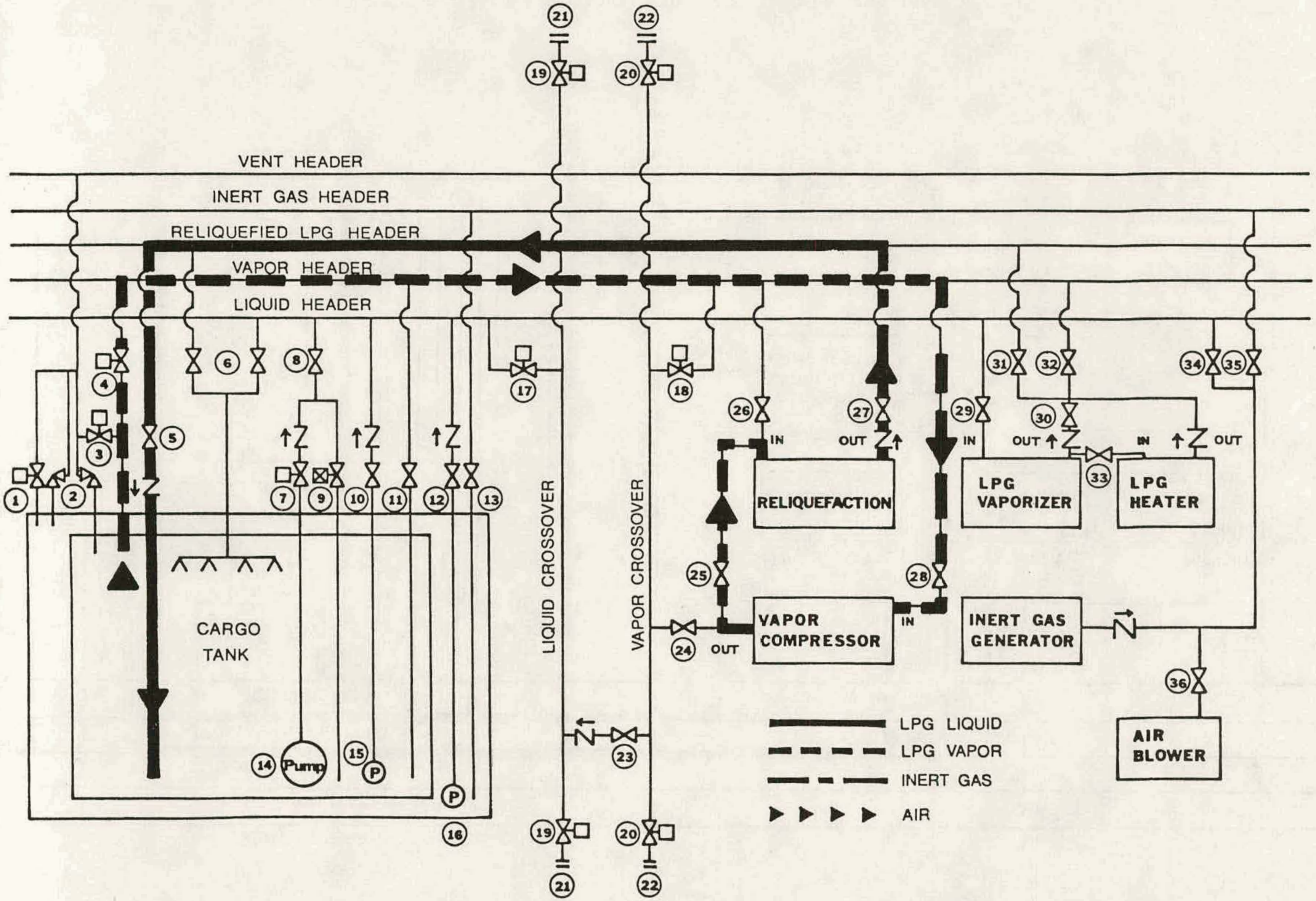


FIGURE 14. RELIQUEFACTION OF CARGO VAPORS DURING THE CARGO VOYACE.

Unloading

Terminal Storage Facilities

The types of storage facilities that are available at various U.S. LPG import terminals are shown in Figure 15 which is a schematic representation of a terminal receiving LPG from a refrigerated tank ship. At most U.S. terminals, the LPG is unloaded into large, refrigerated tanks. In some cases, the LPG is unloaded from the ship and placed in underground storage, or it can be heated and placed in pressurized storage. It is also possible to bypass the storage altogether, in which case the LPG goes directly from the ship to the shore based vaporizer.

Unloading With Vapor Return

As was the case with loading, it is preferable to simultaneously transfer both LPG liquid and vapor when unloading so that the shore based tanks are not overpressurized and so that a vacuum is not drawn on the ship's tanks. This operation is shown in Figure 16.

Unloading Without Vapor Return

If vapor return facilities are not available at the unloading facility, the vapor required to replace the volume of LPG liquid unloaded is provided by vaporizing some the ship's LPG cargo and returning the vapor to the tanks. Figure 17 shows one method for doing this.

Removing a Tank from Service

Liquid Freeing

In order to remove a tank from service for repairs or inspection, it is necessary to first remove all of the liquid

LPG RECEIVING TERMINAL

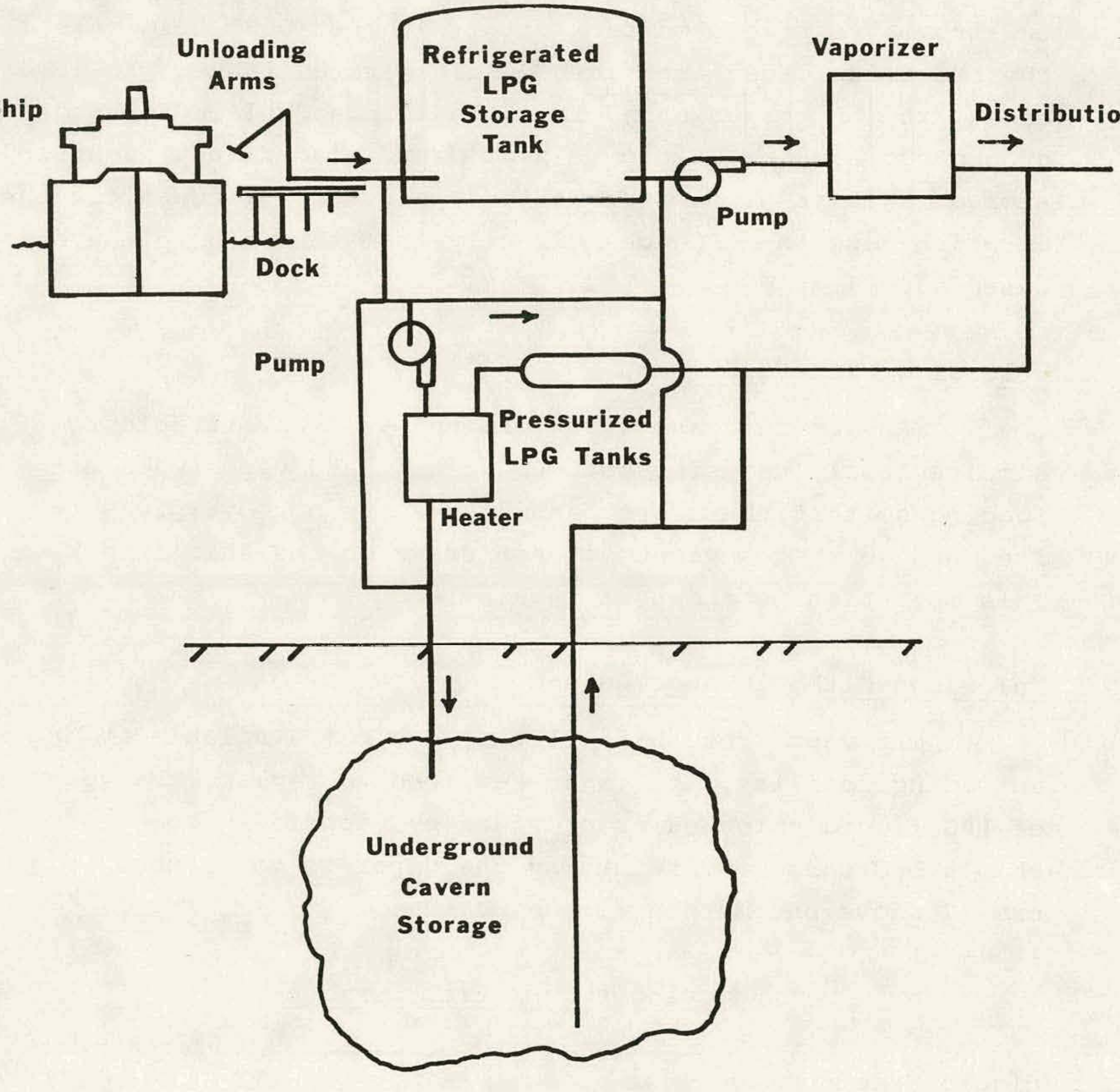


FIGURE 15. SCHEMATIC OF AN LPG TERMINAL RECEIVING REFRIGERATED LPG.

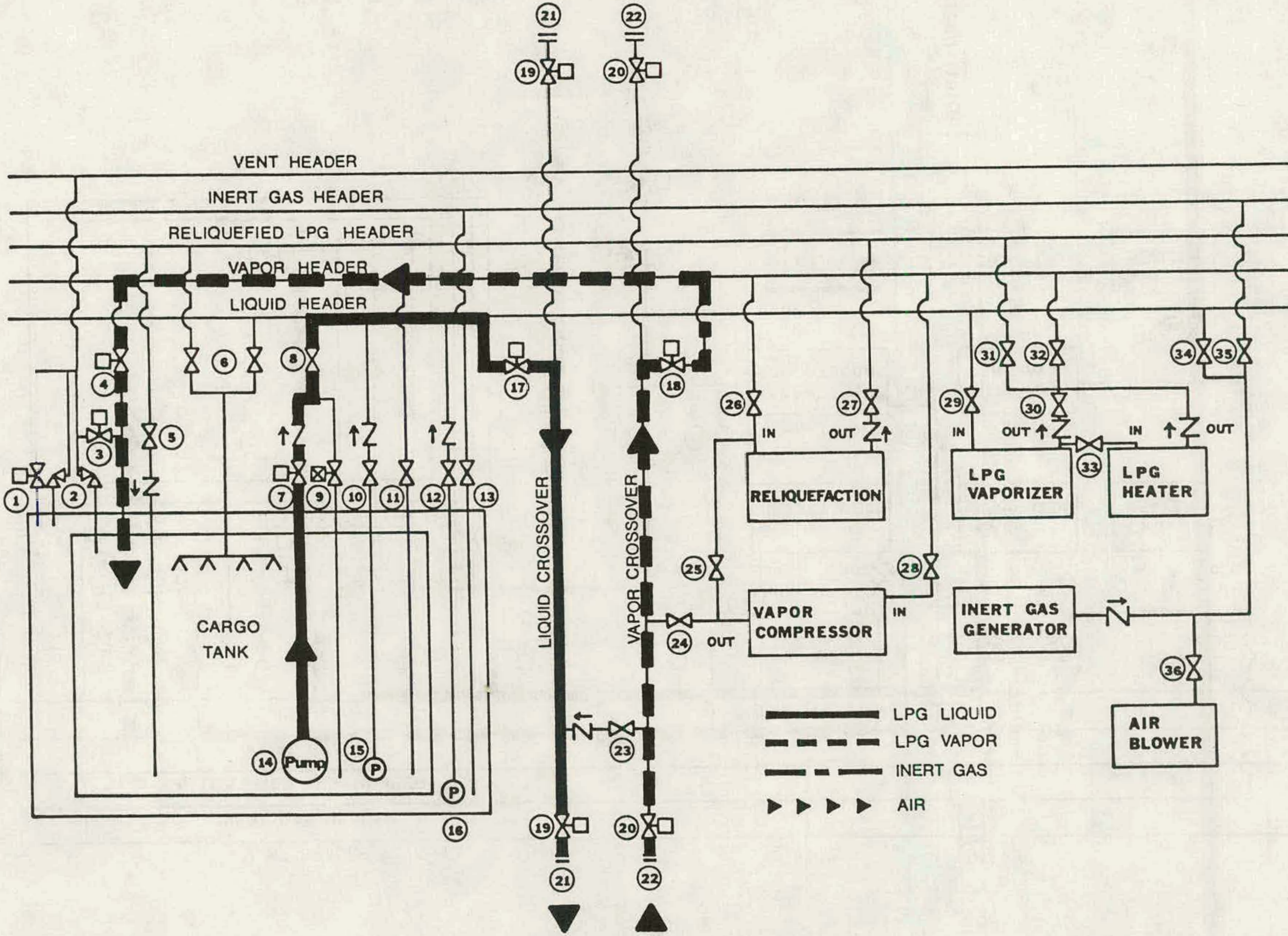


FIGURE 16. UNLOADING WITH VAPOR RETURN.

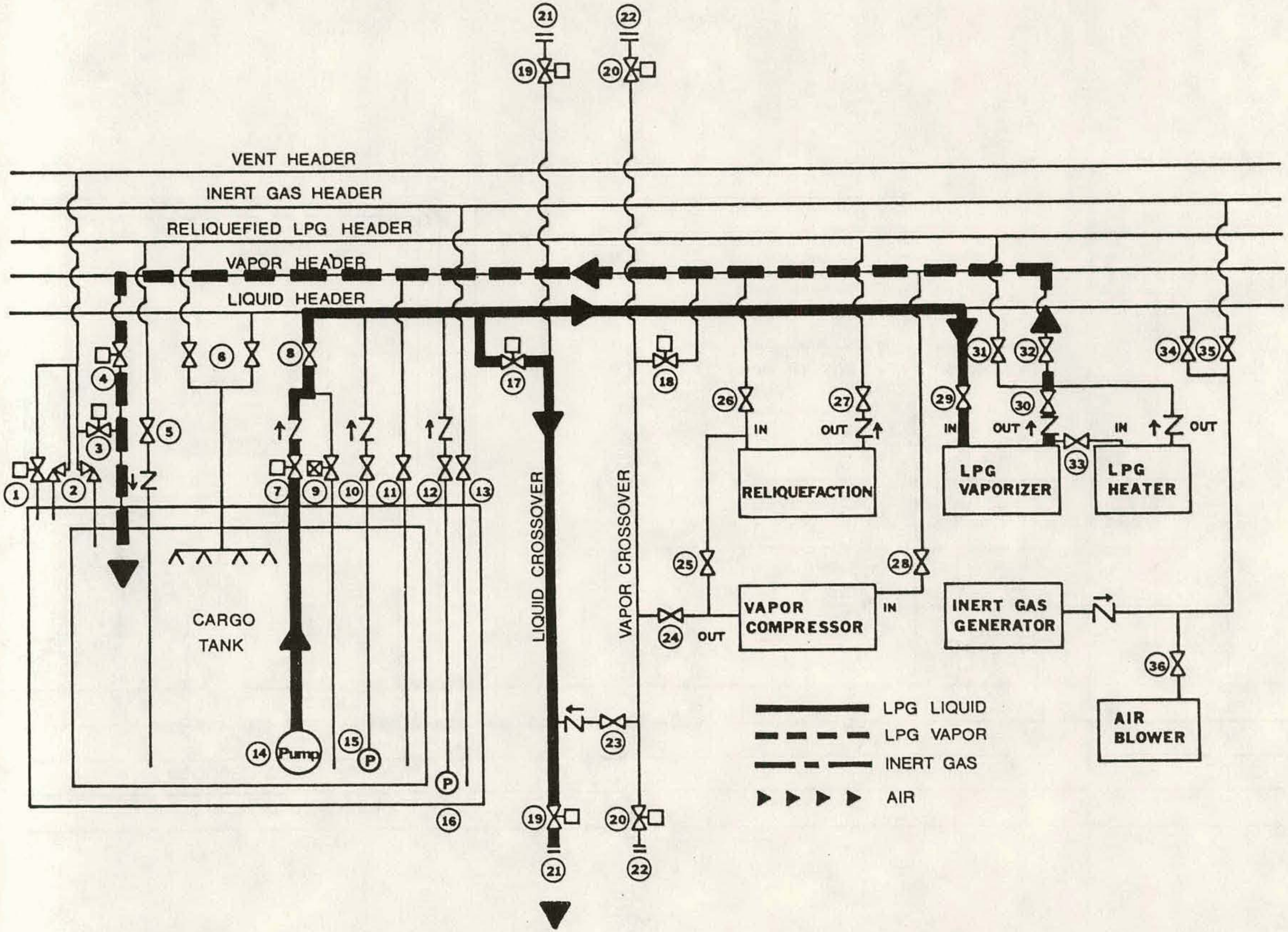


FIGURE 17. UNLOADING WITHOUT VAPOR RETURN.

LPG. First the ship is trimmed so that the cargo pumps can discharge as much LPG as possible. The LPG that cannot be pumped out is then vaporized by drawing some LPG from one of the other tanks, vaporizing it in the LPG vaporizer, heating it, and injecting it into the tank near the remaining liquid. This operation is shown in Figure 18. The last tank to be removed from service must obviously receive its warm LPG vapor from some other source. This vapor can come from shore or LPG vapor can be withdrawn from the tank, heated, and reinjected into the same tank.

Gas Freeing

The second stage in removing a tank from service is gas freeing the tank by using inert gas to displace the LPG vapors. This can be done by using the ship's inert gas generator, as shown in Figure 19, or inert gas from a shore based generator can be used.

Aeration

The third stage is cargo tank aeration, that is, the displacing of the inert gas with air. This stage is not required when merely changing the tank over to hold a different cargo or if the inspection or repairs can be made in an inert atmosphere. Figure 20 shows one method of aerating the tanks using a shipboard blower and discharging of the inert gas/air mixture out the vent stacks. This operation is continued until the oxygen concentration in the tanks is greater than 20%.

Void Space Aeration

Void spaces must also be aerated before entry unless personnel are equipped with appropriate breathing apparatus.

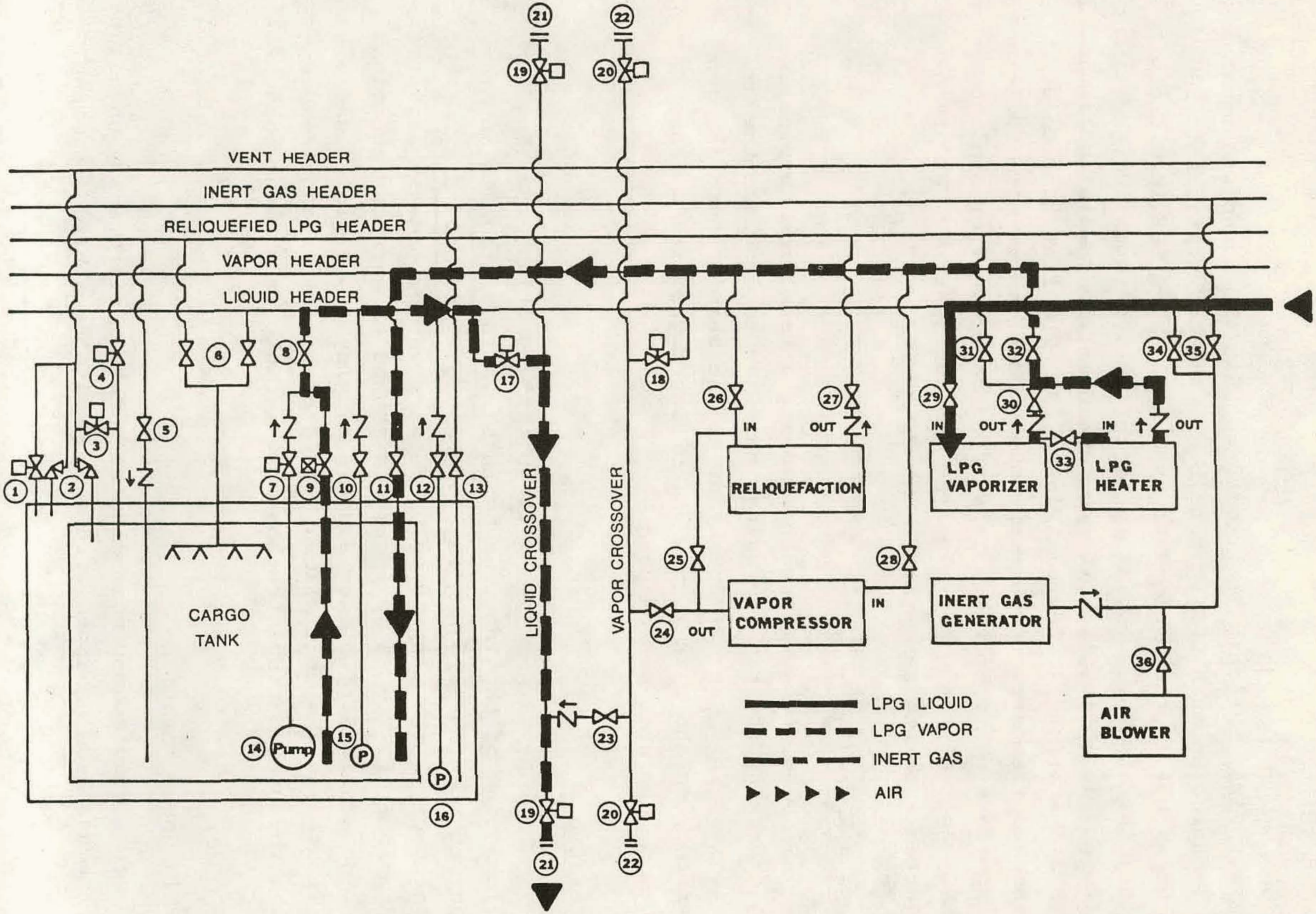


FIGURE 18. LIQUID FREEING USING WARM LPG VAPOR FROM THE SHIP.

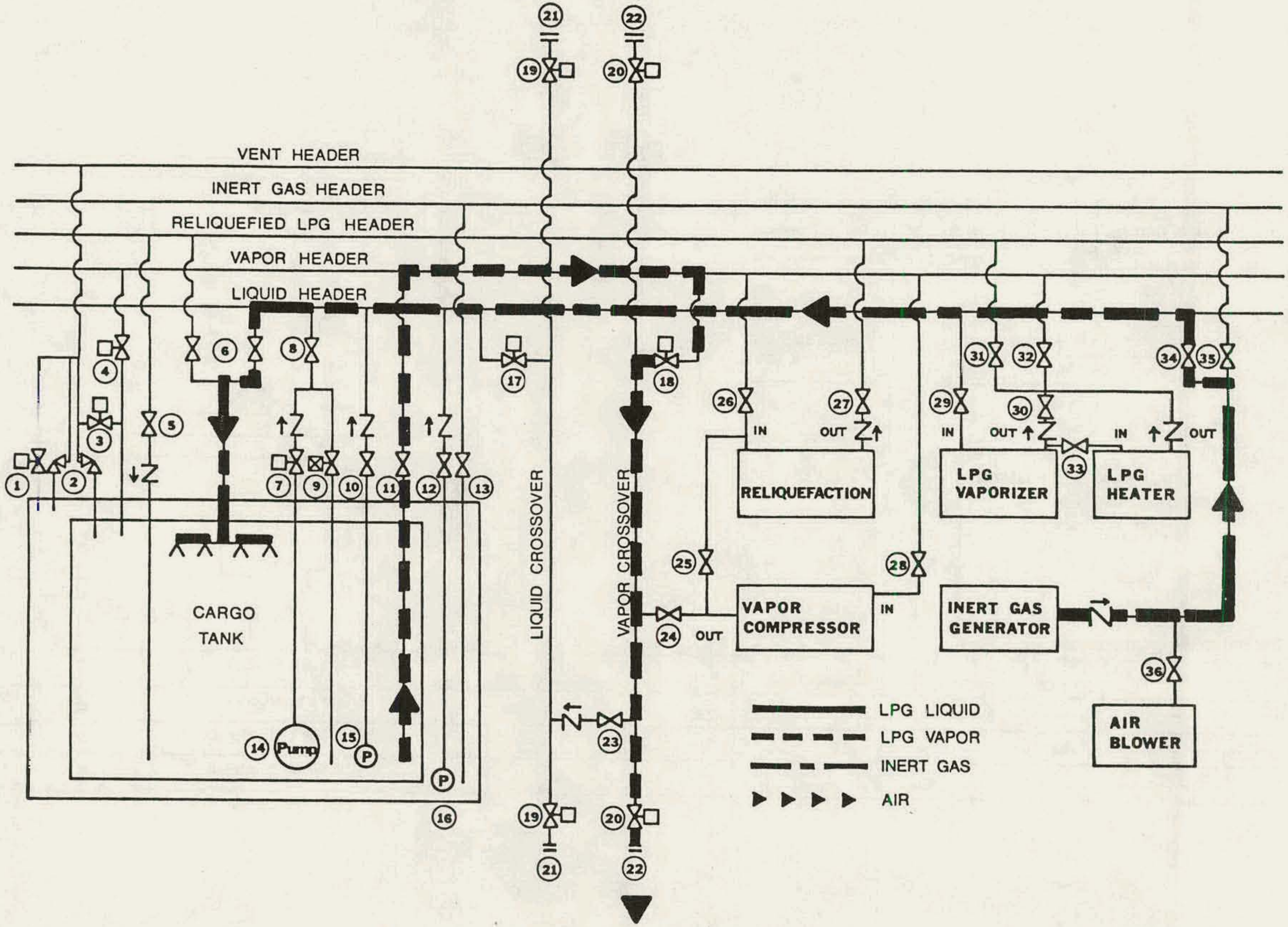


FIGURE 19. GAS FREEING USING INERT GAS GENERATED ON THE SHIP.

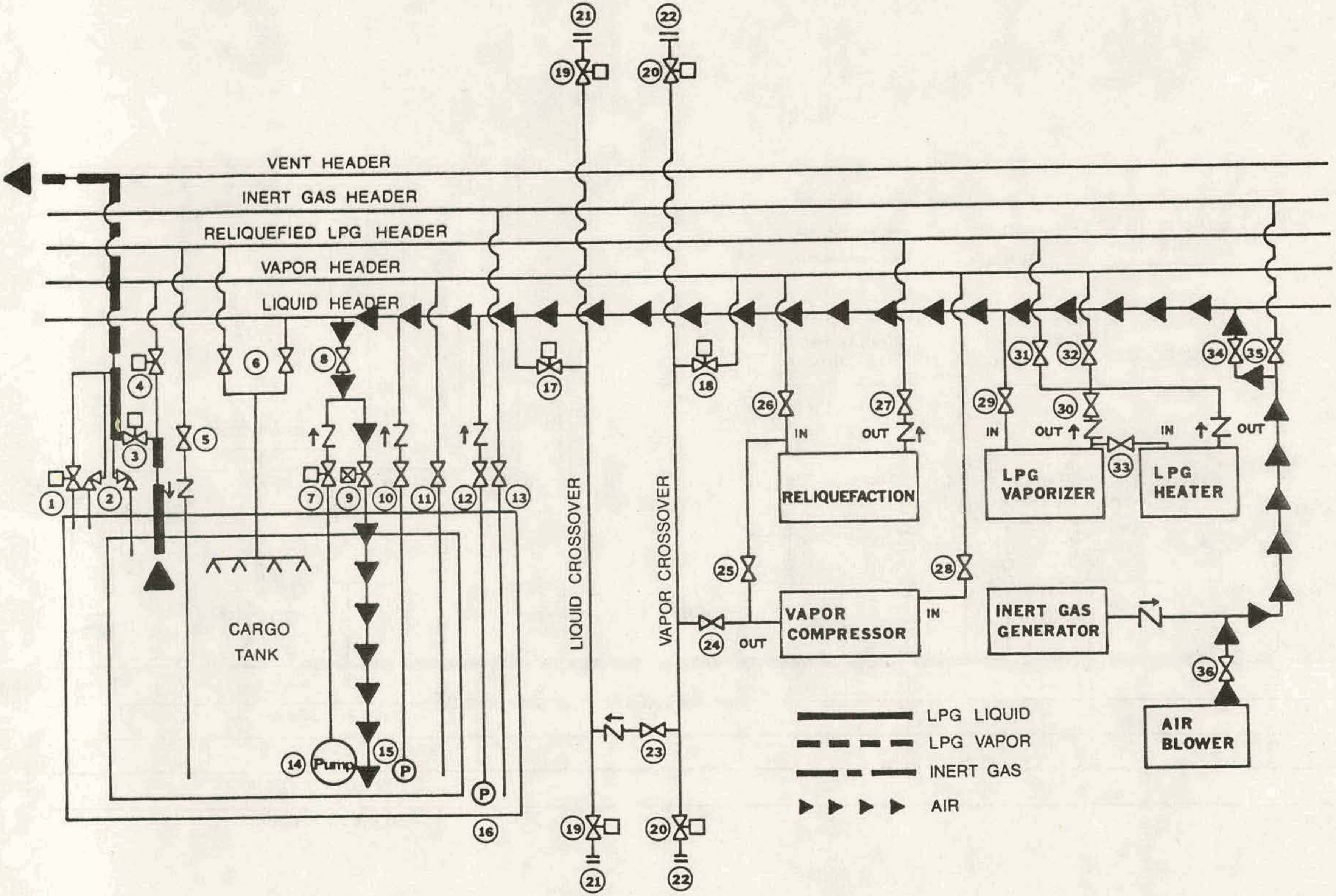


FIGURE 2·0. AERATING A CARGO TANK.

The shipboard blower is used to blow air into the void spaces. The inert gas can be blown out the vent stack or the entry hatches can be opened to the atmosphere to allow the inert gas to escape.

Emergency Cargo Handling

Primary Pump Failure

If the primary LPG pump fails to operate in a given tank, the LPG can be removed from the tank by using the auxiliary pump as shown in Figure 21. In some cases the auxiliary pump is an electrically driven submersible pump. In other cases the "auxiliary pump" is really an eductor driven by LPG pumped from another tank. Ships equipped with spherical or cylindrical tanks can often transfer the LPG by pressurizing the tank with LPG vapor from the vaporizer as shown in Figure 22. This option is available because the cylindrical and spherical tanks can withstand greater internal pressure than other common tank designs.

The LPG being discharged from the tank can either be transferred to another tank or, in some cases, it can be jettisoned overboard.

LPG in Void Space

Small amounts of cargo that have leaked into the void space can be removed by vaporizing the LPG with inert gas and venting the LPG vapor/inert gas mixture as shown in Figure 23.

Larger spills can be handled by using a small submersible pump (or eductor) to transfer the LPG as shown in Figure 24. On some ships these pumps (or eductors) are permanently installed while on other ships, a portable model is used.

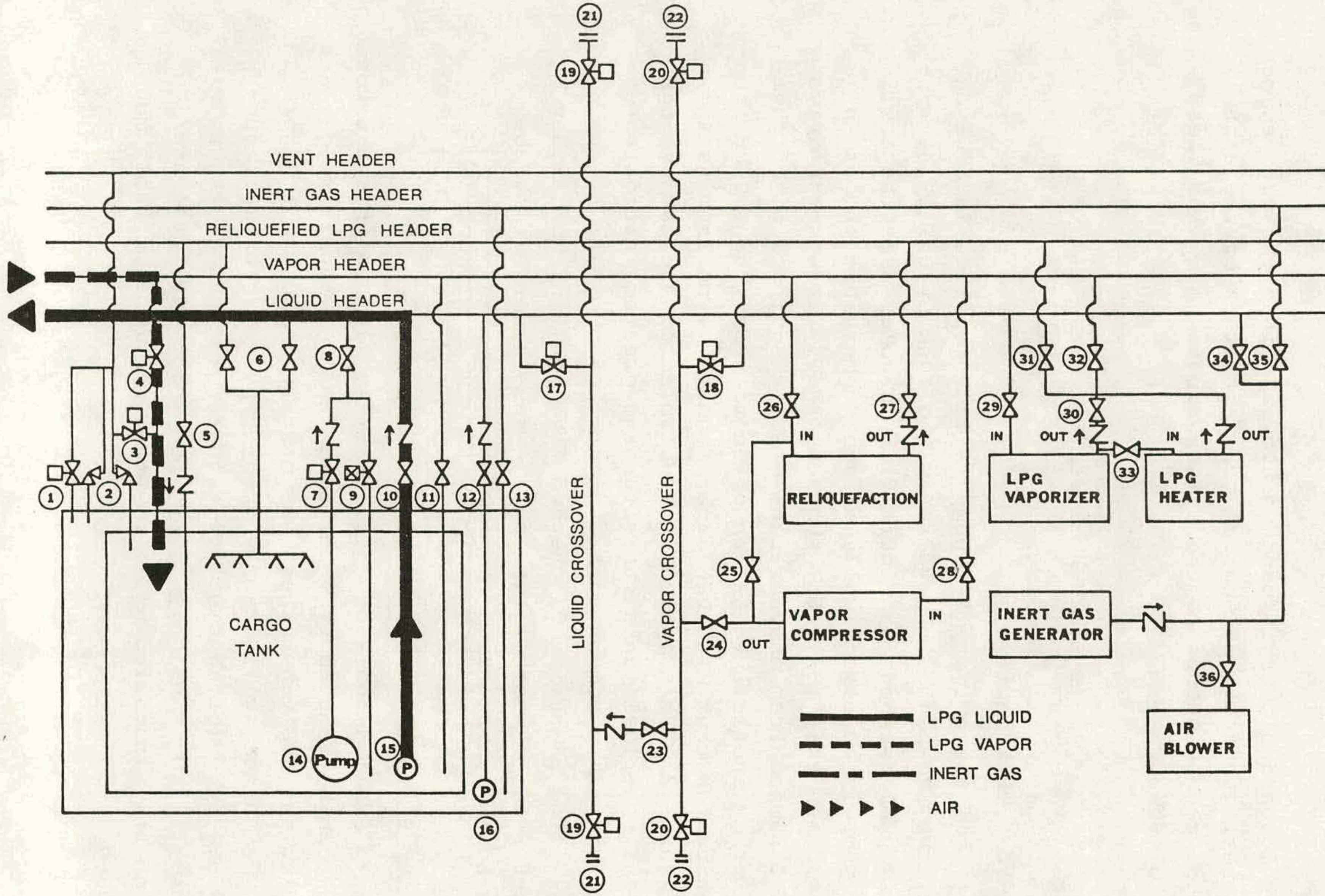


FIGURE 21. CARGO TRANSFER USING AN AUXILIARY CARGO PUMP.

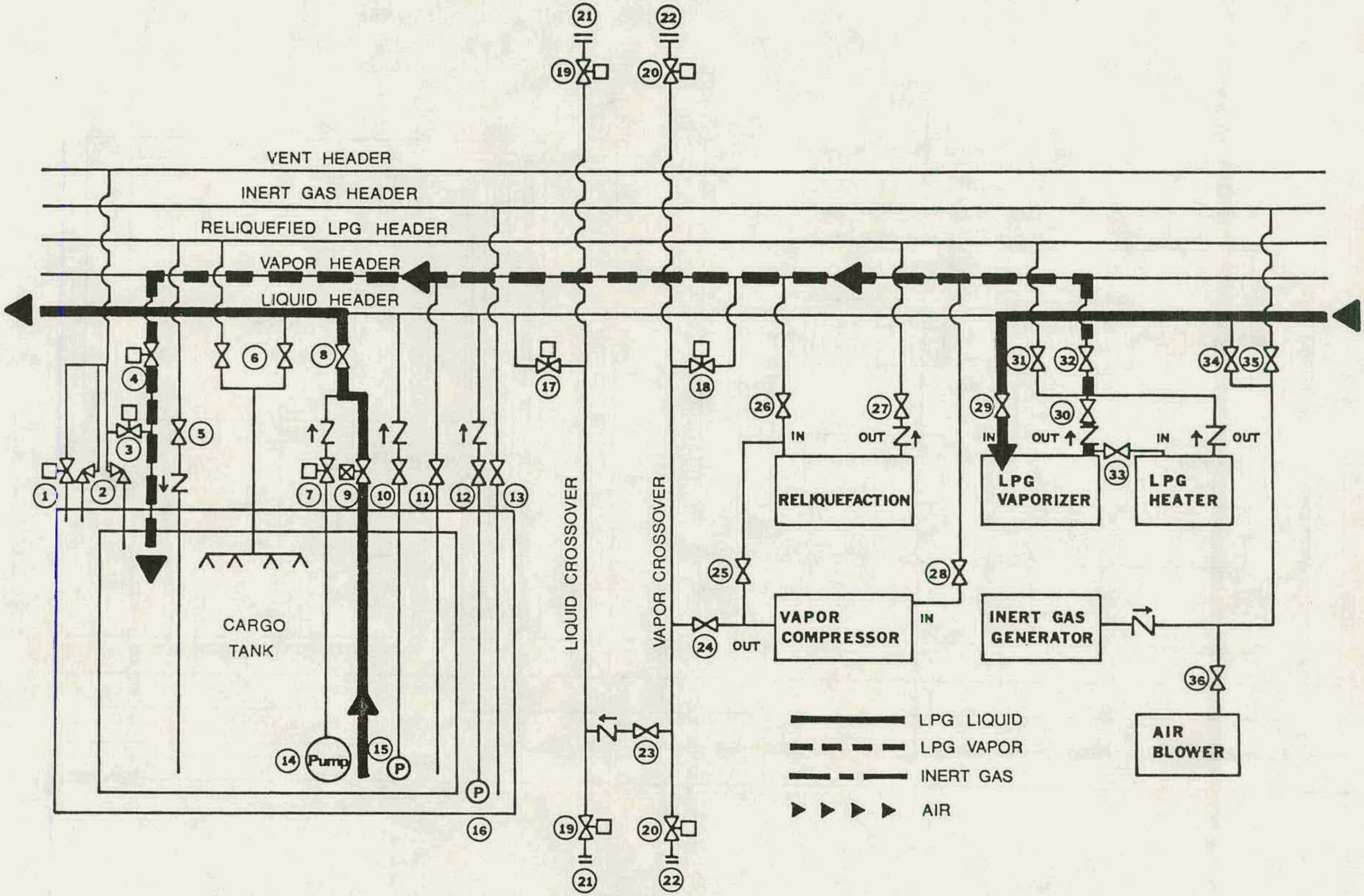


FIGURE 22. CARGO TRANSFER USING PRESSURIZED LPG VAPOR.

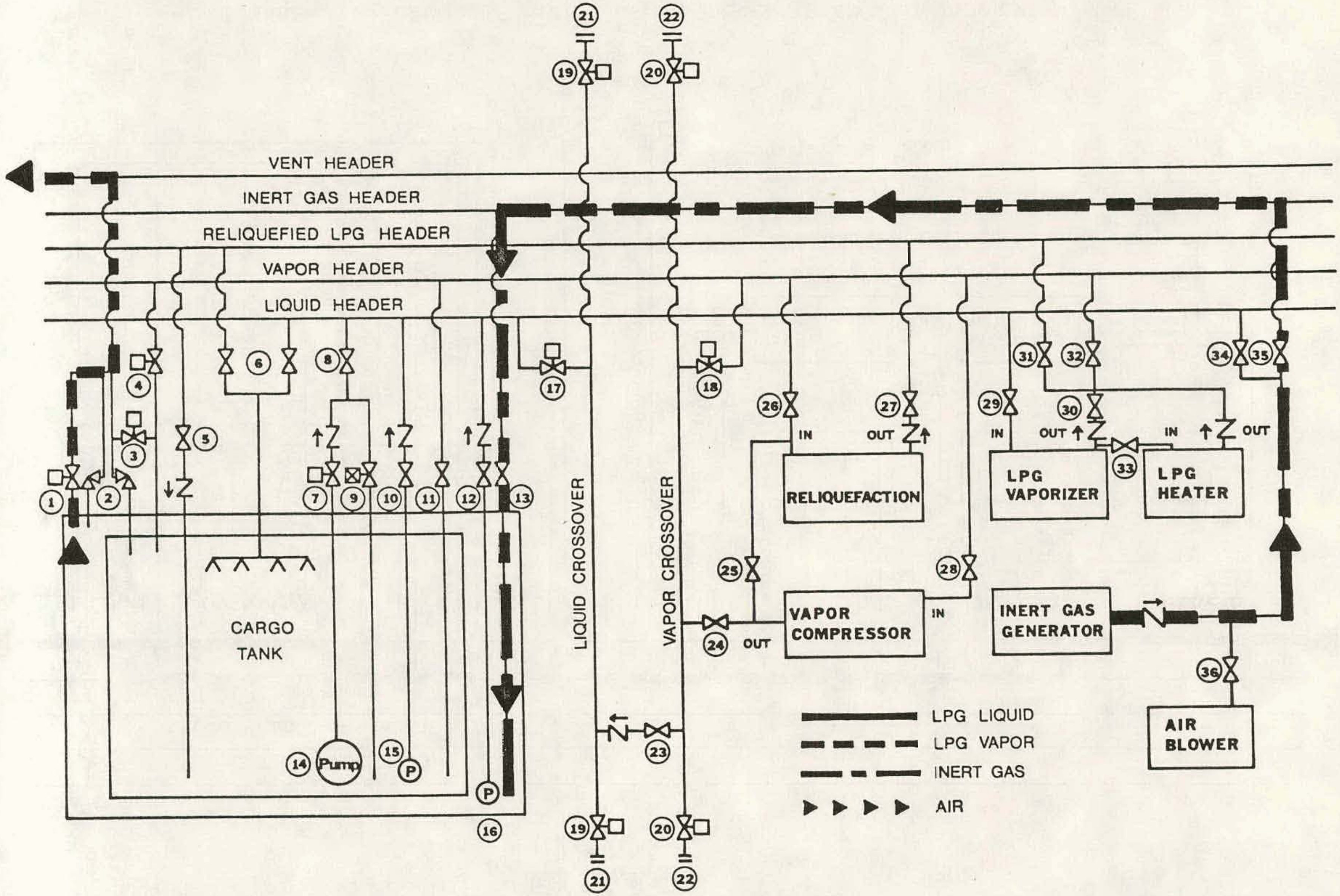


FIGURE 23. REMOVAL OF LEAKED CARGO FROM VOID SPACE USING INERT GAS.

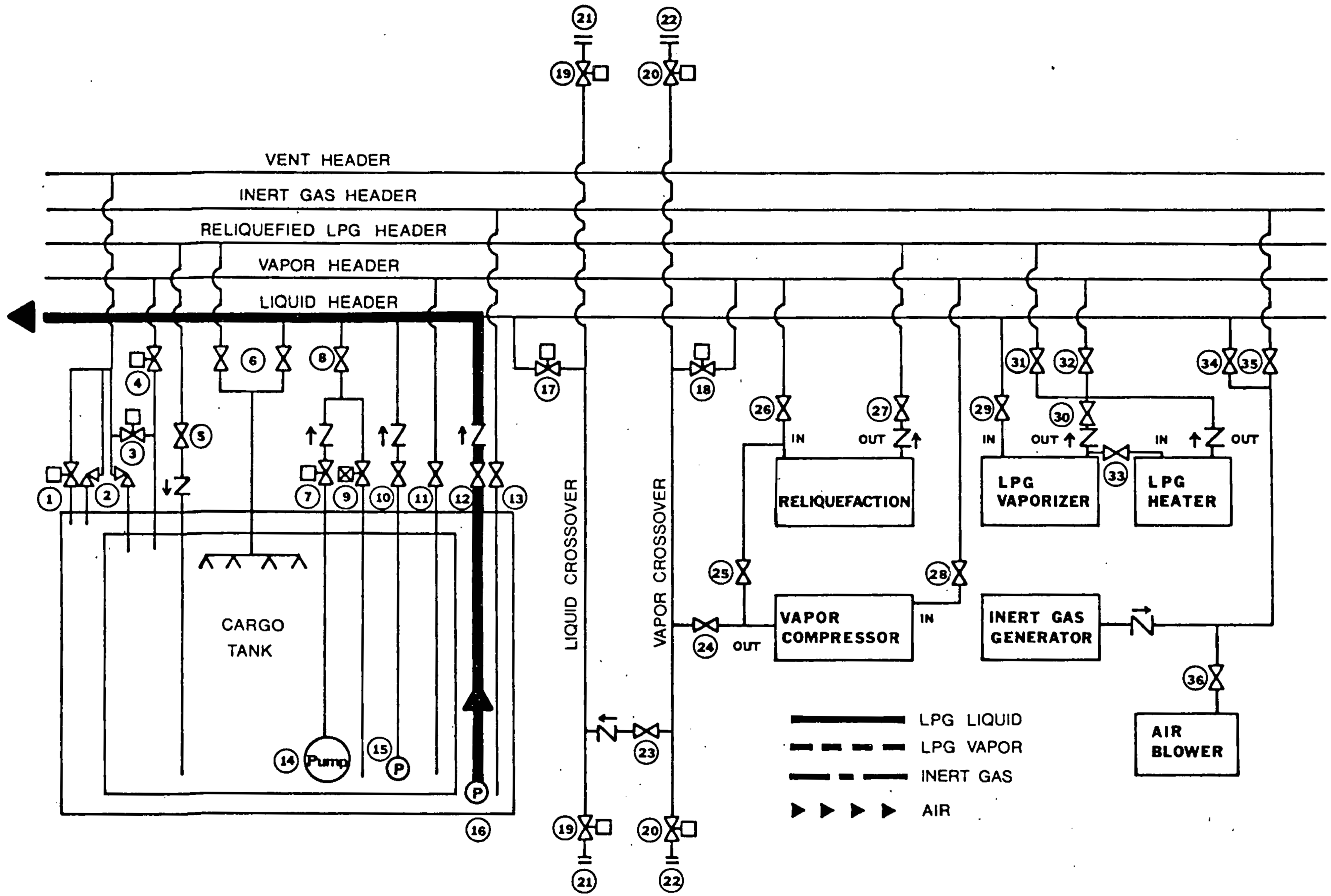


FIGURE 24. REMOVAL OF LEAKED CARGO FROM VOID SPACE USING EMERGENCY PUMP.

Very large quantities of LPG in the void space indicate that serious problems exist with the integrity of the cargo tank. In this case, the tank must be emptied before draining the void space.

Typical Unloading Scenario

The most common cargo handling operation within U.S. ports is unloading. Therefore, a "typical" unloading operation will be described in detail. This "typical" operation may vary slightly from one port to another due to local restrictions imposed by the USCG Captain of the Port and/or due to certain operating procedures of the receiving terminal. However, the main points are applicable to all U.S. ports.

Prior to entering the port, each LPG ship is boarded by U.S. Coast Guard personnel who inspect the ship to determine if all safety regulations are being followed. If it is the ship's first voyage into a U.S. port, the inspection is more detailed and is carried out even farther away from the port. Once the ship has passed the inspection it is escorted to its berth at the receiving terminal dock. During this ship movement, all ships two miles ahead of and one mile in back of the LPG ship are required to remain stationary. In addition, this movement can take place only during daylight hours, never at night or in dense fog.

Once the ship has been berthed at the dock, various electrical and piping connections must be made between the dock and the ship. The first connection to be made is a grounding cable. This is to equalize the electric potential of the ship and the dock. It also prevents static electricity build-up during cargo transfer from ship to shore.

The LPG liquid and vapor pipes on the dock are then connected to the corresponding pipes on the ship. The lines used to connect the dock cargo pipes with those on the ship must be flexible enough to allow for some relative movement between the ship and the dock. Flexible rubber hoses or articulated metal loading arms can be used. In general, larger facilities have larger sizes of transfer piping and therefore prefer to use articulated metal arms. The physical connection between the transfer hose or arm and the ship's piping is made by quick-disconnect couplings (for small sizes) or by bolted flanges (for larger sizes).

During this time the dock and ship personnel confer regarding the unloading procedure to be followed (i.e. number of pumps to be used, desired flow rate, etc.) This is also the time that the tanks are gauged to determine the quantity of LPG in each tank. Gauging is usually done by an independent firm in order to reduce arguments between the shipper and the receiver concerning how much LPG was transferred. Simultaneously the Coast Guard observer is inspecting the cargo transfer arms connections, checking that two fire hoses are laid out on the ship's deck, etc. Once he is satisfied that it is safe to transfer cargo he gives written permission to the dock personnel to begin the unloading.

At least two persons are required to be on duty during the entire unloading operation; the USCG representative and a qualified cryogenics supervisor on the ship. The receiving terminal will also have at least one operator on duty but he will not necessarily be at the dock. (The Port of Boston LNG-LPG USCG Operation/Emergency Plan (3) calls for 5 people on the ship; 2 officers fully qualified for cargo transfer, 2 deck hands, and one watch officer; and 2 people at the terminal; one on board the ship and one in the terminal control room.)

Coordination between terminal and ship personnel is critical during the unloading since the two LPG plants are interconnected but the instrumentation for the two plants are usually kept separated. Thus the information that the terminal operator has concerning conditions on the ship is limited to what the ship's personnel communicate to him and vice versa.

The LPG liquid lines on ship and on shore are cooled down prior to the beginning of cargo transfer. These lines are usually not kept cool continuously, but are cooled down a day or two prior to the unloading. This is done by circulating LPG through the appropriate pipes. In some cases, the LPG vapor lines are also pre-cooled using cold LPG vapor circulation. Failure to cool the LPG liquid lines slowly could cause structural problems due to the thermal contraction of the pipes.

Before starting the submerged LPG pumps, it is common practice on many ships to inject methanol into the pumps. The methanol dissolves any ice that has formed within the pumps, thereby helping to prevent pump damage. In some cases the methanol is stored on deck in 55 gallon (208 ℓ) drums and is injected with manual pumps. In other cases a more sophisticated system is used.

Once the LPG pumps are started and cargo transfer has begun, the unloading operation consists mainly of balancing the liquid and vapor flow rates to achieve the quickest possible transfer of cargo without over or under-pressurizing the cargo tanks on ship or shore. The cargo transfer rate is usually fairly low at the beginning of the unloading operation: so that the operators can determine that all systems are working properly, to prevent sudden changes in tank pressures due to transient imbalances between vapor and liquid flow rates, and to allow the cargo transfer arms to cool down slowly. The unloading rate is reduced gradually near the end of the operation to allow an orderly shutdown of the pumps and to prevent pump cavitation.

In order to discharge the maximum percentage of the cargo it is usually necessary to adjust the trim of the ship so that the remaining liquid is accessible to the cargo pumps. It is not usually necessary or desirable to discharge 100 percent of the cargo since some of it is needed as heel during the ballast voyage for cooling the tanks.

Before disconnecting the unloading arms, it is desirable to drain the LPG liquid lines so that the amount of LPG spilled during the disconnect is minimized. When articulated transfer arms of rigid pipe are used, the lines are generally drained by injecting gaseous nitrogen near the highest point in the transfer arms. In this manner part of the LPG is drained into the ship's tanks and part of it returns to the shore tanks. At this time the tanks are gauged again so that the quantity of LPG transferred can be determined.

The rules governing the ship leaving the port are similar to those imposed when entering; daylight hours only and USCG escort, if the ship is still partially loaded. Restrictions are relaxed if the LPG ship is essentially empty.

BASIC OPERATING PROCEDURES FOR A PRESSURIZED LPG BARGE

Introduction

The basic operating procedures for an LNG barge will be discussed using a "composite barge" that is typical of barges currently in use and under construction but is not identical to any of them. A somewhat simplified diagram of one cargo tank and the associated piping is shown in Figure 25. (This diagram and the following discussion also apply to pressurized LPG ships, but, for simplicity, we have used "barge" to imply pressurized cargo tanks and "ship" to imply refrigerated cargo tanks.) Only the primary system is shown; duplicate, secondary (back-up), or alternate systems are not shown. Instrumentation and air or hydraulic systems are not shown.

The relative simplicity of the LPG barge with respect to a refrigerated LPG ship is apparent when one compares Figure 3 and 25. The typical barge has no electrically powered equipment on board (i.e., no pumps, compressors, etc.), no inerted areas, and need not be constructed of low temperature materials. The cargo handling system is much simpler since the cargo is carried under pressure at ambient temperature, thus eliminating reliquefaction, spray cooling, etc.

All phases of cargo handling will be discussed. However, due to similarities in cargo handling between ships and barges, only the major differences will be noted here.

Replacing Air With Inert Gas

This operation is basically similar to that used on LPG ships except that the source of the inert gas is located on shore. Figure 26 shows one possible inerting scheme.

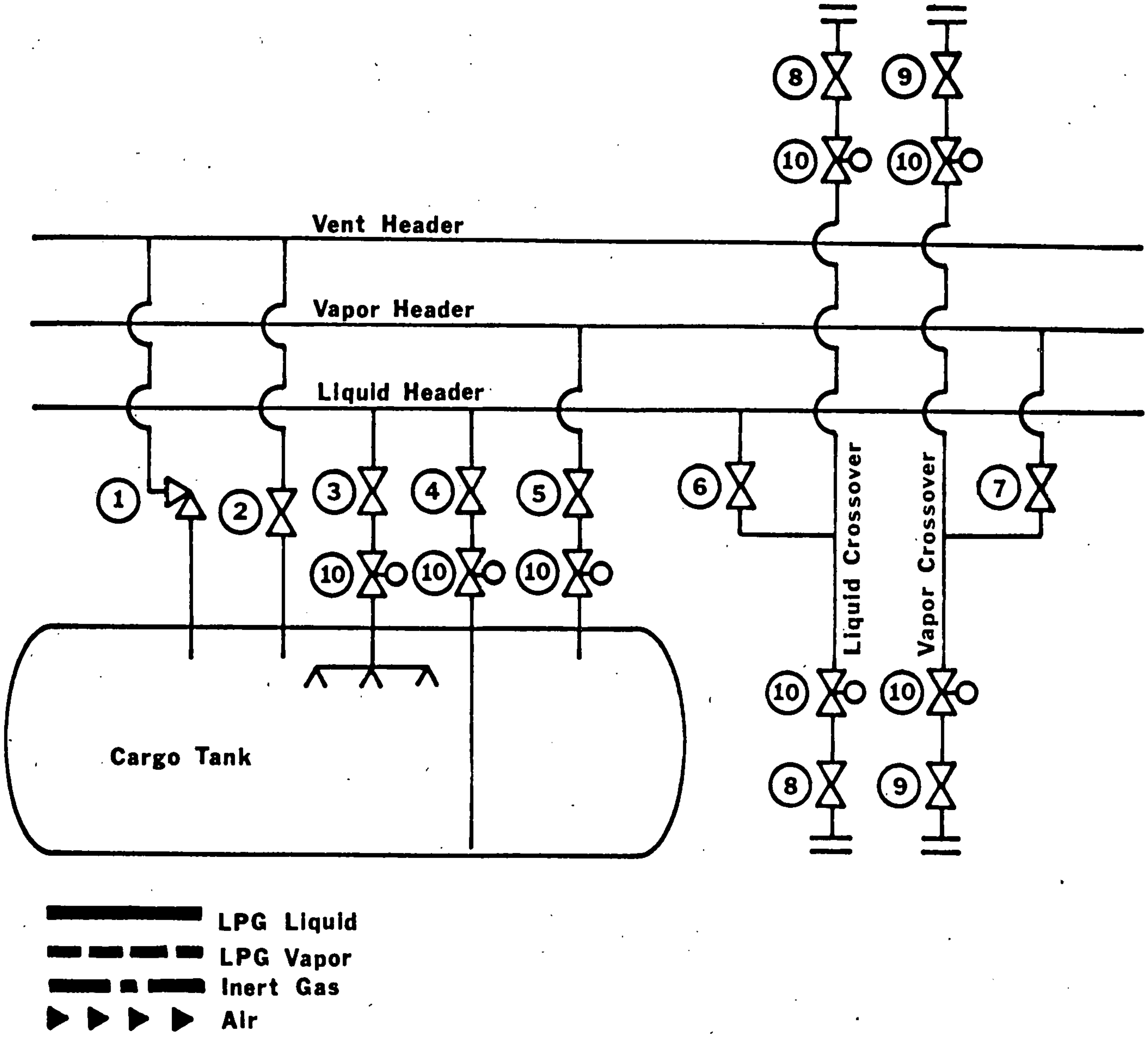


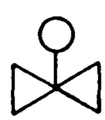
FIGURE 25. BASIC DIAGRAM OF LPG CARGO HANDLING SYSTEM ON BOARD A PRESSURIZED LPG BARGE.

LEGEND

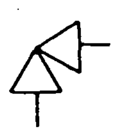
1. Pressure relief valve
2. Discretionary pressure relief valve
3. Liquid spray valve
4. Liquid inlet/outlet valve
5. Vapor inlet/outlet valve
6. Liquid header isolation valve
7. Vapor header isolation valve
8. Liquid crossover isolation valves, manual
9. Vapor crossover isolation valves, manual
10. Remote controlled quick-closing valves (fail-closed)

Local manual valve

Remote controlled quick-closing valve (fail-closed)



Pressure relief valve



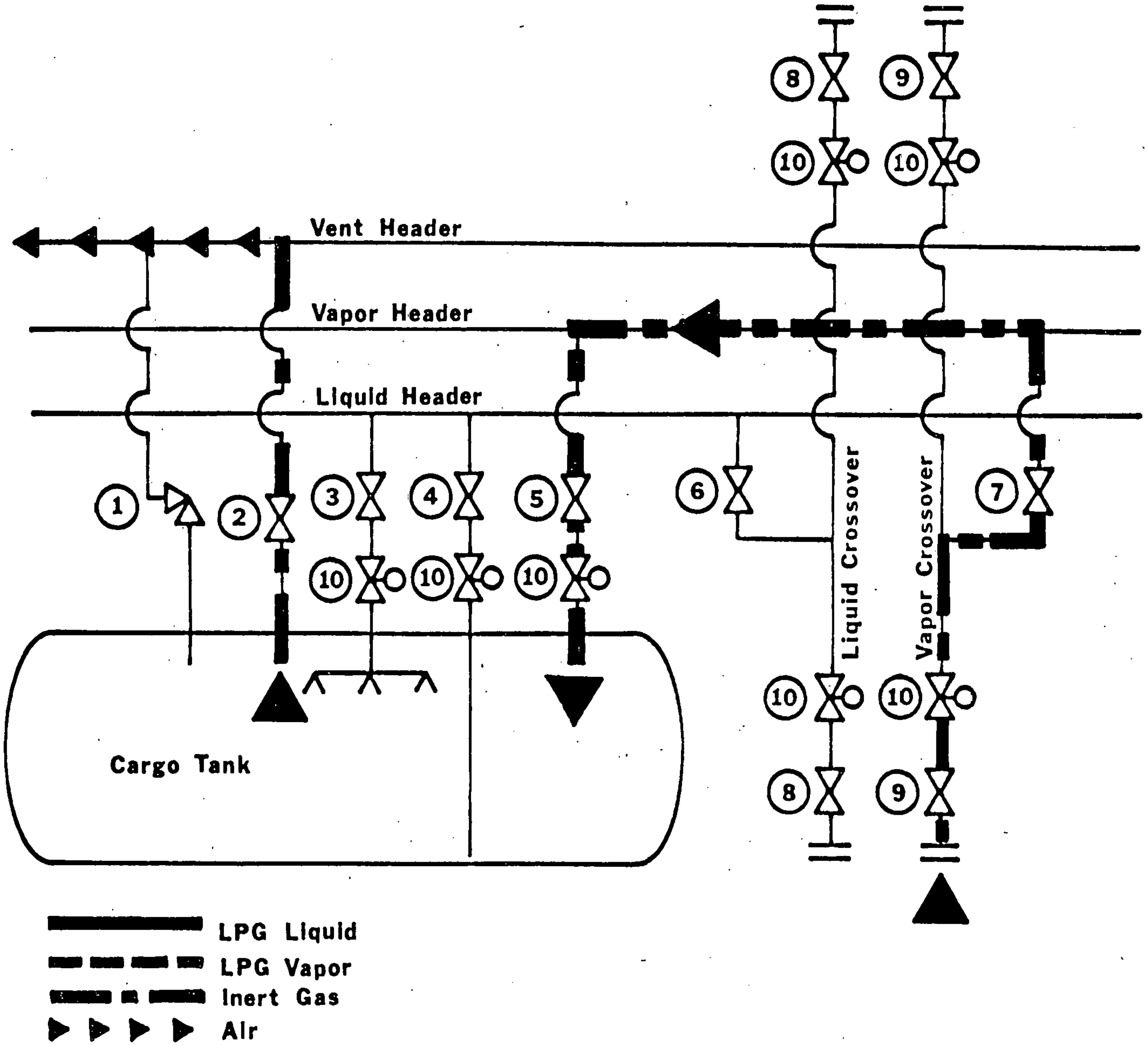


FIGURE 26. INERTING OF CARGO TANKS.

Replacing Inert Gas With LPG Vapor

This operation, shown in Figure 27, is also similar to that used on LPG ships (see Figure 8) with ambient temperature LPG vapor being supplied from shore.

Loading

The barge is generally loaded from pressurized LPG storage tanks or directly from an LPG pipeline as shown in Figure 28. Figure 29 shows the loading sequence with a vapor return line. By using a vapor return line and filling through the top spray arrangement, the pressure within the tanks can be regulated so that no pumps are needed to load the cargo (although they are sometimes used). Flexible rubber hoses are normally used to connect the barge piping to the dock piping, although the trend is toward articulated metal transfer arms.

Pressure and Temperature Maintenance in Cargo Tanks

During the cargo voyage, the temperature of the cargo is allowed to fluctuate in response to changes in the ambient temperature. The pressure inside the cargo tank fluctuates in response to the temperature of the LPG; the pressure being equal to the vapor pressure of the liquid LPG. Redundant pressure relief valves are fitted on each tank and are set to open around 250 psig (17.6 kg/cm^2). In some cases, the vapor flows from the pressure relief valves to a vent stack.

Unloading

The LPG is generally unloaded into pressurized storage tanks or sometimes directly into an LPG pipeline as shown in Figure 28. Unloading is usually accomplished by pressurizing the tanks to expel the liquid. Vapor is supplied from shore to maintain pressure in the tanks. This vapor is usually LPG

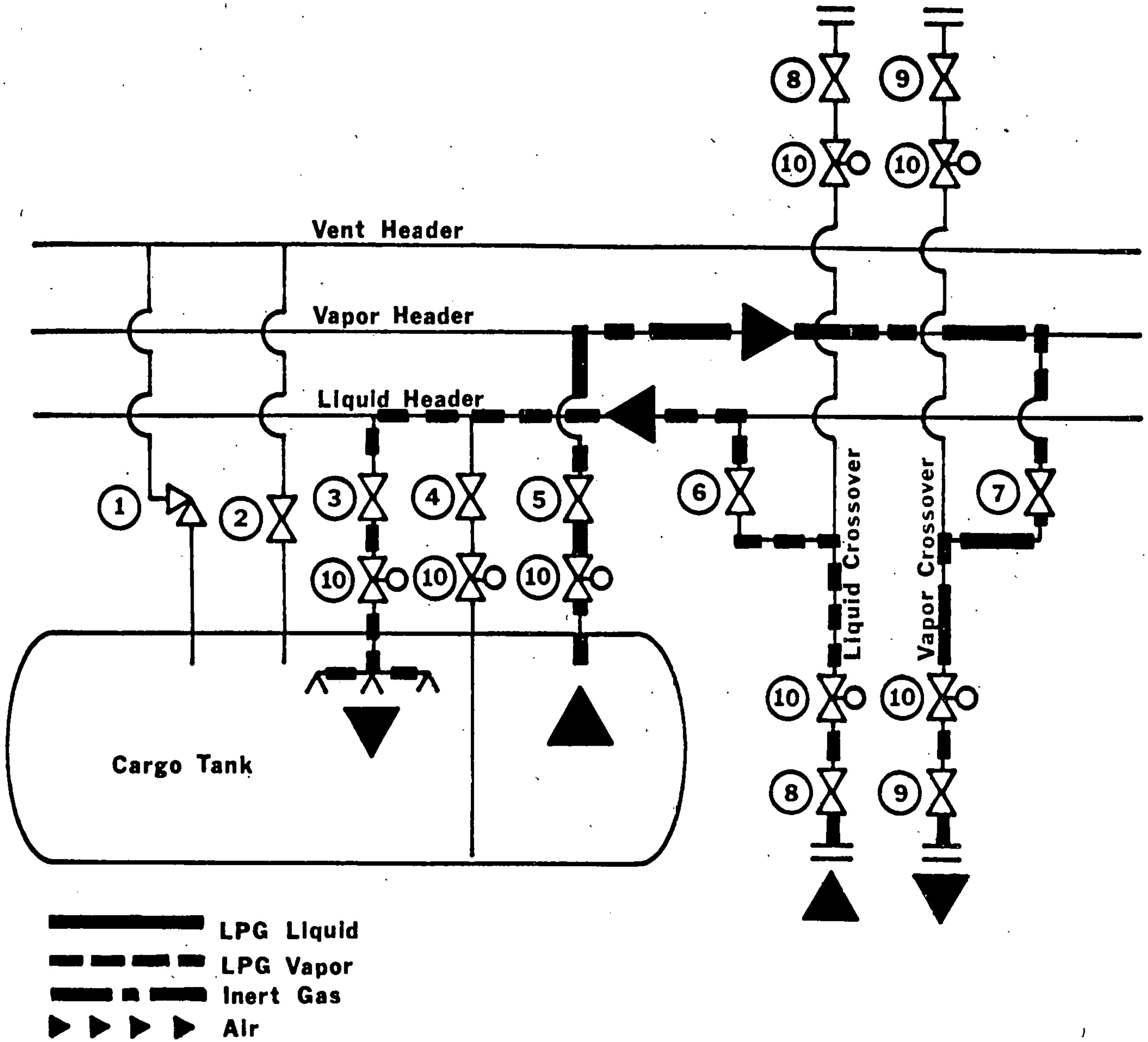
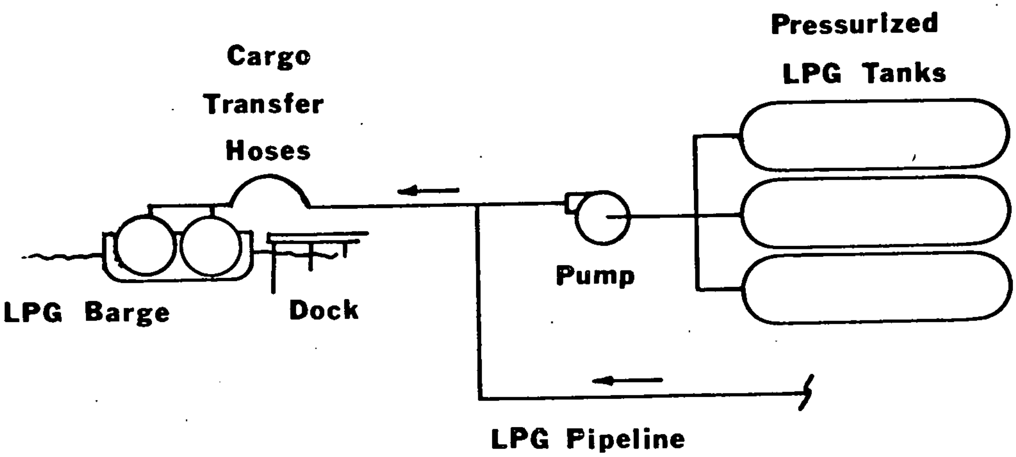
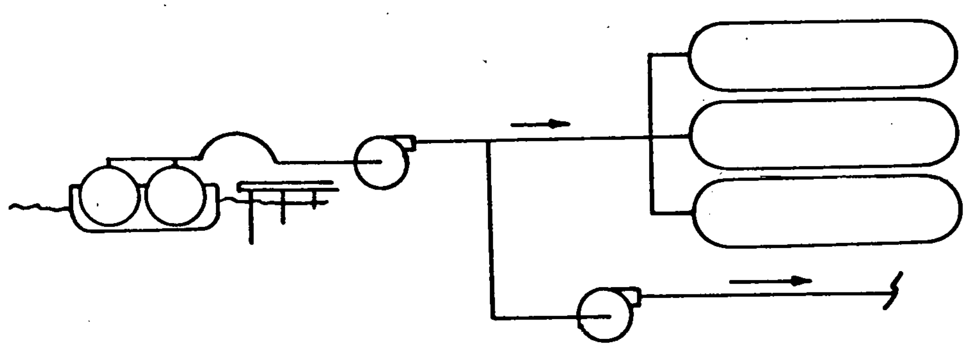


FIGURE 27. REPLACING INERT GAS IN CARGO TANKS WITH LPG VAPOR.



LPG LOADING TERMINAL



LPG RECEIVING TERMINAL

FIGURE 28. SCHEMATIC OF LPG BARGE AND TERMINAL DURING LOADING AND UNLOADING.

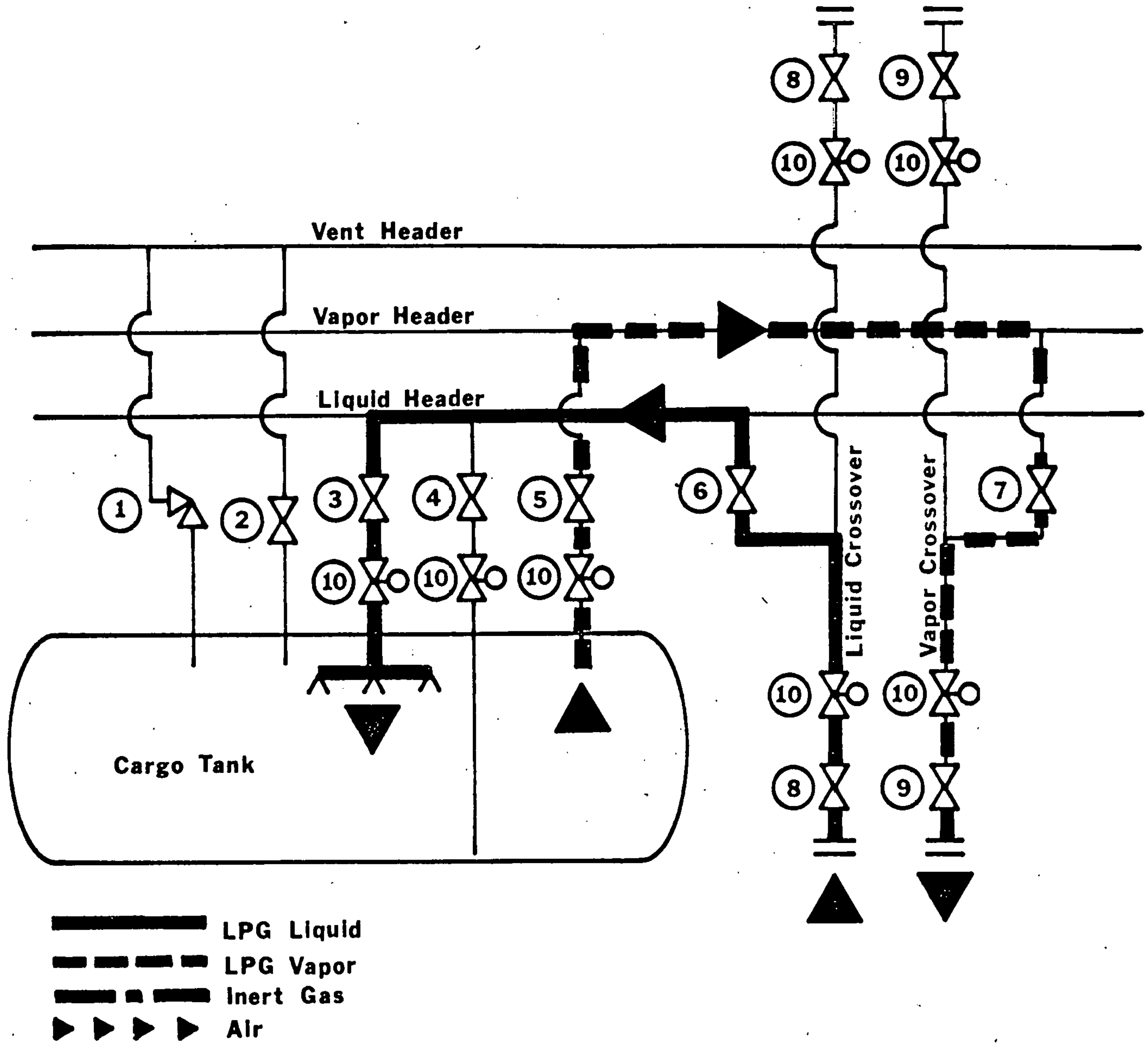


FIGURE 29. LOADING CARGO TANKS, WITH VAPOR RETURN.

vapor but an inert gas or methane, etc. can also be used. If sufficient gas pressure is not available, pumps may be required to aid in unloading. As in loading, rubber hoses are generally used to connect the barge piping to the dock piping. Figure 30 shows the unloading operation with LPG vapor supply from shore.

Removing a Tank from Service

All the liquid LPG can be removed from a tank by drawing the vapor off through the vapor or liquid line. This reduces the pressure in the tank so that the remaining liquid will vaporize. Inert gas is then circulated through the tank to remove the LPG vapor. Finally, air is circulated through the tank to remove the inert gas. The inert gas and air are supplied from shore as shown in Figure 31.

Emergency Cargo Handling

Emergency cargo handling should be necessary only in the case of a leaking tank. If such an event should occur, the tank contents could be transferred to another tank (if that tank can hold the extra volume of liquid) or can be jettisoned overboard (if allowed by local authorities).

Typical Loading/Unloading Scenario

Unlike refrigerated LPG ships which generally only unload in U.S. ports, LPG barges typically spend all of their time in U.S. waters and load and unload in U.S. ports. Therefore, both loading and unloading of LPG barges (and pressurized LPG ships) will be described. As before, this "typical" operation may vary somewhat from one port to another.

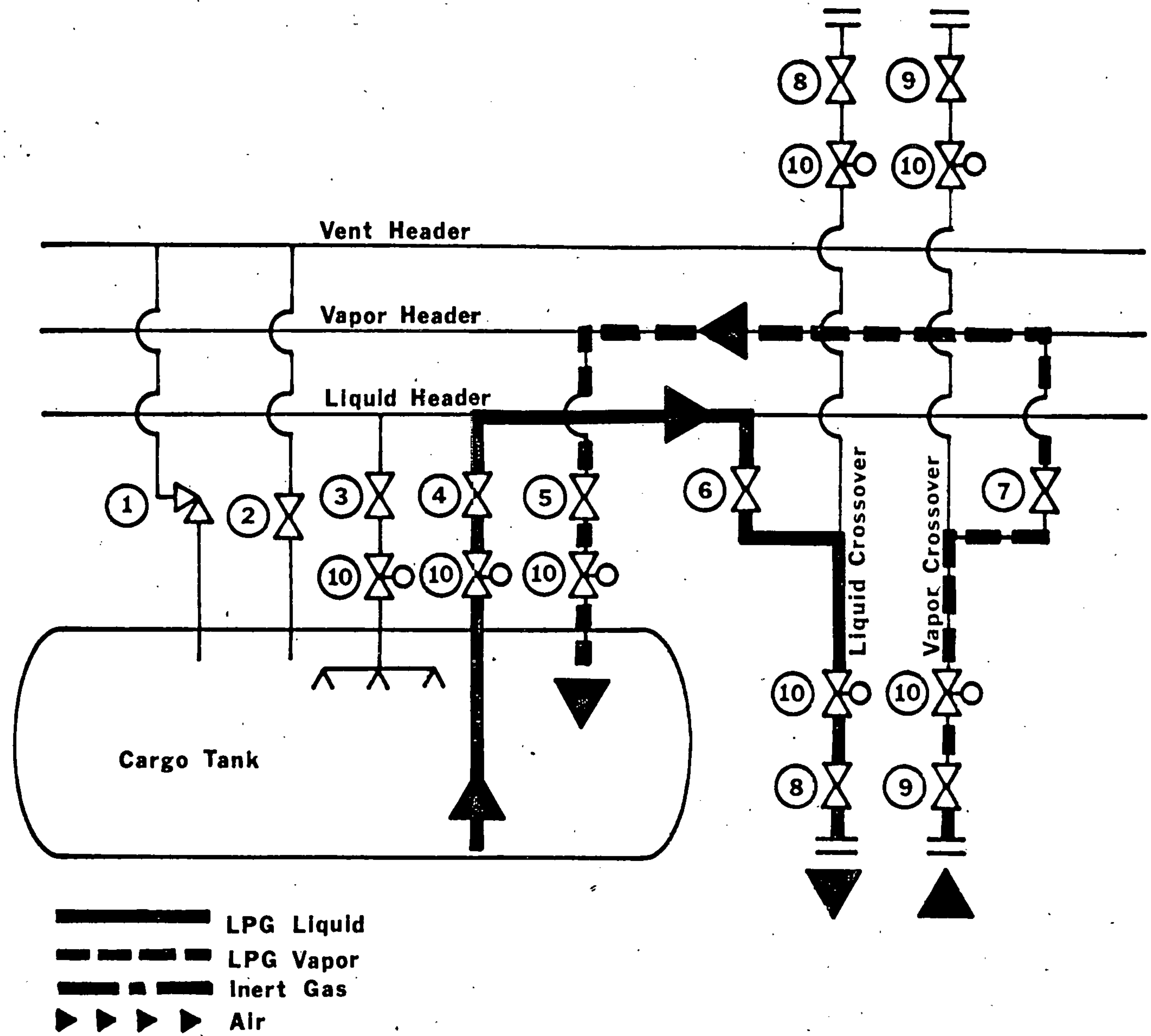


FIGURE 30. UNLOADING WITH LPG VAPOR RETURN

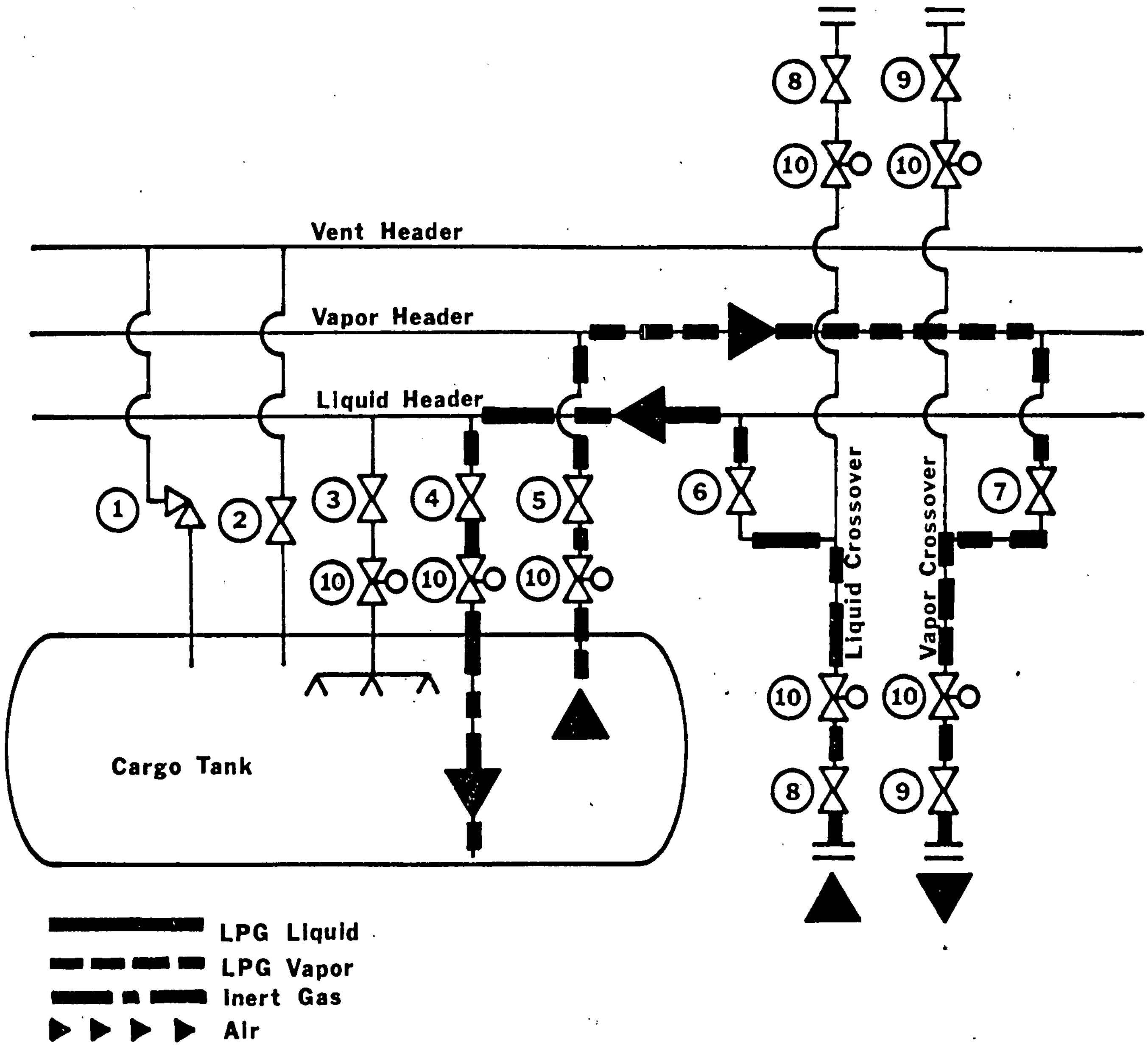


FIGURE 31. REPLACING LPG VAPOR WITH INERT GAS.

LPG barges are not normally boarded by the U.S. Coast Guard for inspection upon entering the port; spot-checks of barges are frequently conducted but the cargo transfer operation is often completed without a USCG boarding. Prior to entering LPG service, each barge must be certified by the USCG.

Barge movements in a port are not restricted to daylight hours. Practically speaking, the only restrictions imposed are that the tug must stay with the barge until it is docked and that the barge must be pushed (or towed) at a safe speed.

Once the barge is docked, the operation begins in much the same manner as for the ship; grounding strap, liquid and vapor transfer connections (usually hoses but some terminals have articulated metal arms), and tank gauging by an independent firm. During these preliminary operations, the tankerman (supplied by the barge company) and the dock personnel (usually one man) confer on the load/unload procedure to be followed. A third person, located in the terminal control room, is also necessary because the dock usually has no cargo transfer controls.

When all connections have been made and all personnel are ready, the cargo transfer is begun; no pre-cooling of pipes being required since the cargo is not refrigerated. Loading can take place with or without a vapor return (by filling the tanks through a top spray line, it is possible to load without vapor return and without venting). Shore-based pumps can be used, if necessary, to supply the LPG at the required pressure. Unloading is accomplished by using a pressurized gas supply (LPG vapor, natural gas, nitrogen, etc.) to expel the LPG from the tanks. Shore-based pumps may be required to boost the pressure in order to transfer the cargo into the shore-based storage tanks (or pipeline).

The cargo transfer is begun slowly so that the personnel can check to be sure that everything is operating properly. During the transfer operation, the tankerman will periodically check the tanks to determine the liquid level. As the liquid approaches the desired level (empty or full), the cargo transfer rate is slowed to allow an orderly shutdown.

Before disconnecting the transfer lines, many terminals blow out the lines with pressurized gas to eliminate (or decrease) the spillage of LPG when disconnecting. The tanks are also gauged again so that the quantity of LPG transferred can be determined.

In comparison to the cargo transfer operations involving a refrigerated LPG ship, the barges have far less instrumentation, most operations must be done manually rather than remotely, no cooldown is necessary, restrictions on vessel movements are less severe, USCG inspections are much less frequent, and automatic shutdown equipment is limited.

LPG SHIP FIRE PROTECTION

Fire Protection Philosophy

The fire protection philosophy that the code writing bodies have chosen for LPG ship cargo fires has four basic elements.

1. Fire prevention by excluding at least one of the three components required for an LPG fire: fuel, oxygen, and a source of ignition.
2. Limiting fire size by using containment areas, spill and fire detection systems, and the emergency shutdown system.
3. Fire extinguishment using dry chemical extinguishing agents.
4. Reducing the potential damage caused by the heat of the fire by using water sprays for cooling and by using suitable construction materials for critical areas.

Fire Prevention

In order for any LPG spill to develop into a spill fire, oxygen must be present in the surrounding atmosphere and a source of ignition must be present to provide the energy needed to initiate the combustion process. Fire prevention on LPG ships is based on preventing all three of these components from coexisting in any one place at any given time.

Fuel Exclusion

The design, construction, and testing of the LPG cargo handling and containment system are all directed toward preventing LPG spills. These aspects have been discussed previously in the report and will not be repeated here. One other technique that is used to exclude the presence of fuel in certain areas is to keep the air pressure in gas-safe spaces (e.g. the control room) slightly above atmospheric pressure so that LPG vapors will not be drawn in.

Oxygen Exclusion

Inert atmospheres are maintained in the void areas around the LPG cargo tanks as previously discussed. Inert gases are also used to prevent combustible mixtures in the tanks and piping when placing the ship in service initially, after dry docking, and when taking the tanks out of service. Some ships also have inerting capability in their cargo venting systems to prevent vent stack fires.

Ignition Source Exclusion

All electrical equipment located in gas-dangerous spaces (e.g. the cargo tanks and piping, cargo pump and compressor room, the weather deck above the cargo area, non-inerted hold areas, etc.) are either in flame-proof or pressurized enclosures or are of an intrinsically safe type. Electrical motors driving cargo pumps and compressors are separated from the pumps and compressors by a gas-tight bulkhead or deck. For electrical equipment in gas-dangerous spaces, the switches must be located in gas-free spaces.

LPG liquid flow through a metal pipe will create static electricity. To prevent a static charge from building up, a grounding cable is used between the ship and the dock.

Limiting Fire Size

Two basic methods are employed to limit the size of a cargo fire.

1. Limiting the amount of cargo spilled.
2. Limiting the area over which the cargo can spread.

Limiting the Spill Volume

Spill detection systems and emergency shutdown systems are installed on LPG ships so that cargo leaks can be detected quickly and, in the case of cargo pipe leaks, be stopped quickly, thereby limiting the volume of the spill.

All LPG ships are equipped with a number of devices designed to detect a leak or spill of liquid LPG or LPG vapor. These devices can be monitored in the control room so that the operator can determine not only that a leak or spill has occurred but can also determine the general location of the problem. It is also possible to tie certain detection devices into the automatic emergency shutdown system.

All refrigerated LPG ships are required to incorporate a system of flammable gas detectors. In some cases they must be capable of measuring the full concentration range (0-100%) of the gasified cargo. In other cases, the detection range need only be 0-30% of the lower flammable limit (LFL). Many types of gas detectors are available but LPG ships generally use either an infrared (IR) detector or a gas chromatograph (GC). Both of these types of detector systems use the same general piping and sampling system and can detect the full concentration range of the cargo, even when mixed with inert gas. The detector itself is located in a central location, usually the control room. A vacuum pump and sequential sampling valve are used to draw samples from various locations throughout the ship. These locations include the tank void spaces, LPG pump room, reliquefaction room, engine room, control room, etc. (Additional points in the cargo tanks, vent stacks, etc. can also be monitored but this is only done during inerting, gas freeing, etc.) The time required to sample one point is approximately 30 seconds. Therefore, on a ship with 40 sampling points, each point is monitored only once every 20 minutes.

Thermocouples are the most common type of temperature measuring devices used for spill detection on LPG ships. The temperatures at various locations in tank void spaces are monitored so that a spill of cold LPG into the void space can be detected.

Another method of detecting cargo leaks into the tank void space is to monitor the pressure in this space. Any leaking cargo will vaporize and cause an increase in pressure. Obviously small leaks will cause only a very small pressure rise and will therefore be difficult to detect by this method.

The pressure within each cargo tank is monitored continuously so that corrective action (e.g. venting) can be taken if the pressure becomes too great or if the tank is about to be subjected to a vacuum.

The cargo level in each tank is also monitored, particularly during loading and unloading. Each tank generally contains at least two different types of level measuring devices. In addition, most ships are required to have a separate device for alarming when the cargo level approached the maximum allowable (usually 98% of the tank volume). This device, or another independent sensor, is also required to automatically shut-off the flow of cargo into the tank to prevent overfilling.

The cargo pumps are monitored, when they are operating, for motor amperage and outlet pressure. If a major piping leak develops during unloading, the pump outlet pressure and the pump motor amperage both decrease, thereby indicating the possiblility of a spill.

One vital safety element incorporated in the LPG handling and storage system aboard ship is an emergency shutdown system (ESS). The IMCO codes for ships carrying liquefied gases in bulk (1, 4) set the minimum requirements for the ESS. As of October 31, 1978, all refrigerated LPG ships are required to have one or more remotely controllable quick-closing shutoff valves of fail-closed type for shutting down liquid and vapor cargo transfer between ship and shore. Ships constructed after October 31, 1976 are required to have one such valve at each cargo transfer hose or arm connection in use. Cargo pumps and compressors are also to be arranged to shutdown automatically if the required quick-closing shutoff valves are closed by the ESS. ESS switches must be available in at least two separate locations, one of which is to be cargo control room or cargo loading station. The ESS must also be provided with fusible elements designed to melt between 208 and 220°F (98-104°C) which will cause the quick-closing valves to close and stop the cargo pumps and compressors in case of fire. Locations for the fusible elements should include the tank domes and loading stations (i.e. the area where the crossover pipes are connected to the cargo transfer hoses or arms).

In addition to the above requirements, ships built after October 31, 1976 must have an independent high liquid level alarm for each cargo tank. This device is to give an audible and visual warning and should automatically actuate the shutoff of the flow of cargo to the tank. Ships built prior to Ocotber 31, 1976 must comply with this regulation by October 31, 1982.

During cargo loading and unloading operations, the ship's piping and tanks are directly connected to the shore-based tanks and piping and the ship-based and shore-based cargo handling operations must be well coordinated with one another. It is therefore desirable to have the ship-based and shore-based ESS's not only be compatible but also interconnected so that operation of the ESS on the ship will also cause appropriate measures to be taken on shore, and vice versa. For example, assume that while loading the ship the ESS is called upon due to overfilling a tank. The liquid crossover isolation valve (or its equivalent) would be closed automatically. It would also be desirable for the shore based isolation valves to be closed and the LPG pumps stopped. Such interconnected events must be carefully coordinated to prevent damaging part of the system. For example, all valves controlled by the ESS should close at approximately the same rate to avoid possible damage due to hydraulic hammer. Such coordination can be difficult to obtain unless the ship always loads and unloads at the same two docks.

By detecting the spill and shutting down the cargo handling system, the spill volume can be limited to the spill rate multiplied by the sum of the detection and shutdown times. In some cases, the volume of the pipe between shut-off valves will also have to be included.

Limiting the Spill Area

Most LPG ships are constructed with drip pans below the LPG loading/unloading manifolds. These pans serve two purposes; they protect the deck from contact with cold LPG which could cause low temperature embrittlement and subsequent fracture; and they limit the area over which an LPG spill from the manifold area can spread.

Fire Extinguishment

The preferred agents for extinguishing deck fires of LPG are the dry chemical fire extinguishing agents. The IMCO Code (1, 4) is quite specific in its dry chemical system requirements. The main provisions are:

1. At least two independent dry chemical systems should be available to fight deck fires in the cargo area.
2. The system should be capable of delivering dry chemical to every point on the deck above the cargo area from at least two handlines or a monitor/handline combination.
3. The cargo loading/unloading manifold is to be protected by a monitor nozzle capable of remote or local activation.

4. Dry chemical units must be capable of delivering powder to all attached monitors and handlines simultaneously at their rated capacities ($\geq$ 22 lb/sec (10 kg/sec) for monitor nozzles and $\geq$ 7.7 lb/sec (3.5 kg/sec) for handlines) for a minimum of 45 sec.
5. Handlines cannot exceed 108 ft (33 m) in length and shall be operable by one man.
6. Coverage from monitors shall be:

33 ft for 22 lb/sec	(10 m for 10 kg/sec)
98 ft for 55 lb/sec	(30 m for 25 kg/sec)
131 ft for 99 lb/sec	(40 m for 45 kg/sec)

7. The effective range of a handline is considered to be the hose length (no credit given for nozzle range).
8. Ships constructed prior to October 31, 1976 have until October 31, 1982 to comply with these rules. In the interim, at least 220 lb (100 kg) of dry chemical must be available on deck in portable extinguishers.

Most of the LPG ships that call on U.S. ports are in substantial agreement with the IMCO Code (1) for new ships. In general, older ships provide somewhat less dry chemical equipment. The primary area of difference is that older ships have not yet added monitor nozzles for the loading/unloading manifolds.

Two different equipment layouts are used to comply with the code requirements. In some cases, multiple, independent dry chemical units are located on the weather deck. Each unit has its own combination of hose reels and/or monitor nozzle. Other ships use two very large dry chemical units located in a dry powder room aft of the cargo area. These units supply multiple hose reel and monitor nozzle locations on the weather deck.

Damage Reduction

The heat produced by an LPG deck fire could cause failure of certain structural components, cargo piping, tank domes, etc. and could pose a threat to ship's personnel. Two primary methods are used to reduce the amount of damage that could be caused by a fire.

1. Head resistant and insulating materials are used to provide protection from the heat of the fire. These are known as passive systems (i.e. no action is required to operate the system).
2. Water is used extensively to provide a cooling action on objects exposed to the heating effects of the fire.

Passive Systems

The major passive system is the front wall of the accommodation space. The Safety of Life at Sea (SOLAS) Conferences of 1960 (5) and 1974 (6) require this wall to withstand a fire for one hour without transmitting large amounts of heat into the accommodation spaces (average temperature of the unexposed side of wall not to increase more than 250°F (139°C) above the initial temperature). This same provision also applies to any other deckhouses (e.g. the control room) and to bulkheads between the cargo area and engine or boiler rooms. This is to insure that these critical areas will be safe for human occupancy for a least one hour of fire exposure. These requirements have been adopted as part of the IMCO Code (1) for new ships.

Fire Water System

Although water is not used directly in fighting an LPG fire, a sizable fire water system is required on LPG ships. The main purposes of the system are to extinguish fires of ordinary combustible materials (class A fires), to provide cooling for vital equipment in case of an LPG deck fire, and to provide protection for personnel near a fire.

Water sprayed into an LPG fire will not extinguish the fire but will instead have the effect of increasing the burning rate of the LPG by causing it to boil off faster due to the heat input supplied by the water. It can, therefore, be used to decrease the time that an LPG fire or unignited LPG pool exists.

Water sprayed onto equipment or structures near an LPG fire can provide a substantial cooling effect, thereby reducing the damage potential of the fire. As long as a surface is wet with water, the surface temperature cannot exceed 212°F (100°C). Water fogs are also useful for protecting exposed personnel during fire-fighting or evacuation.

The IMCO Code requirements (1, 4) for a fire water system are based on SOLAS 60 (5) and SOLAS 74 (6) and summarized as follows:

1. A looped fire water main shall be provided in the cargo area.
2. Two independently driven pumps are required (one main pump and one standby) and each shall be capable of maintaining a pressure of 71 psig (5 kg/cm^2) in the main.
3. Fire hydrants and hoses should be located so that at least two jets of water can reach any part of the cargo area deck.
4. A water spray system must be installed to cover:
   a. Exposed cargo tank domes and any exposed parts of cargo tanks.
   b. Exposed on-deck storage vessels for flammable or toxic products.
   c. Cargo liquid and vapor loading/unloading manifolds, their control valves, and any other critical control valves.
   d. Boundaries of superstructures, deckhouses, and cargo control room facing the cargo area.
5. The water spray application rate is to be at least 0.245 gal/ft^2-min (10 l/m^2-min) for vertical surfaces.
6. Ships constructed before October 31, 1976 have until October 31, 1982 to comply with most of these rules.

Requirements 2 and 3 are very similar to those called for by 46 CFR, Part 34 (2). Therefore, all LPG ships calling on U.S. ports will be in general compliance with these two regulations. Water spray systems for some of the older ships are limited to protecting on-deck tanks used for storing refrigerants. Some of the newer ships provide spray systems in excess of IMCO rules and protect all of the cargo piping. Some have also provided water sprays for the ship's hull in the vicinity of the loading/unloading manifolds to prevent possible brittle fracture of the hull steel in case of an LPG spill in this area.

Protection of Non-Cargo Spaces

The accommodation spaces are generally equipped with water hydrants and portable CO_2, dry powder, and water extinguishers to fight fires of ordinary combustible materials (class A) and small flammable liquid (class B) and electrical fires (class C).

Machinery spaces such as engine rooms, pump rooms, and compressor rooms and rooms where paint, oil, or other combustible liquids are stored are required by 46 CFR, Part 34 (2) to be equipped with fixed fire protection systems. These include inert gas systems (CO_2, nitrogen, or halon) for smothering fires and inerting enclosed spaces; steam smothering systems; and, in a few cases, low expansion foam systems for class B fires. The IMCO Codes (1, 4) call for a fixed inerting/fire smothering installation in all enclosed spaces that are normally entered where flammable liquid or vapor leakage may occur. It specifically calls out cargo compressor and pump rooms and recommends that CO_2 or steam be avoided unless "due consideration is given to the danger of static electricity."

LPG BARGE FIRE PROTECTION

LPG barges are subject to a much less rigorous set of rules concerning fire safety in comparison with the requirements for LPG ships. The fire protection philosophy for LPG barges is different mainly because the barges are unmanned, have very limited quantities of flammable materials on board (other than the LPG cargo), have little or no operating machinery on board to act as ignition sources, the cargo tanks are pressure vessels, and, unless loading or unloading, all cargo remains in the storage tanks (i.e., no spray cooling, reliquefaction, etc.)

Title 46 CFR Subpart 38.10 (2) requires that, except for safety relief valves and liquid level gauging devices, all LPG liquid and vapor lines connected to the cargo tanks must be equipped with manual shutoff valves located as close to the tank as possible. In addition, all of these lines except the filling and discharge connections must have automatic excess flow valves or remotely controlled quick closing shutoff valves. The fill and discharge lines are required to have remotely controlled quick closing shutoff valves of the fail-closed type. All of these remotely controlled valves are also to be provided with fusible elements designed to melt between 208 and 220°F (98-104°C), which will cause these valves to close in case of a fire. Compliance with this requirement usually constitutes the only emergency shutdown system on LPG barges.

Fire fighting equipment requirements for LPG barges are minimal. Part 34 of 46 CFR (2) requires that an unmanned LPG barge be equipped with one portable fire extinguisher either a 2.5 gal (8.2 l) foam, 15 lb (6.8 kg) CO_2, or 10 lb (4.5 kg) dry chemical, in the cargo tank area during loading and unloading. This of course is a minimum requirement and most barges have more than one portable extinguisher available during cargo transfer. The main source of fire extinguishing capability is usually whatever is available on the loading/unloading docks. This also holds true for water sprays for exposure protection.

SAFETY ANALYSIS

Introduction

A safety analysis of a given system can aid in determining the likelihood of the system failing and help evaluate the risks caused by system failures. In the case of marine transportation of LPG, this analysis should include the probability of LPG spills of various sizes; fire potential associated with LPG spills; damage potential of LPG fires; and the probability of successfully controlling LPG spills and fires. Such an analysis should also discover the primary causes of failures, thus pointing out those areas where significant increases in overall safety can possibly be achieved.

In this report, the safety analysis of marine transportation of LPG is limited to on board systems for storing, handling, and processing LPG and to the hazard warning and control systems which apply strictly to the LPG cargo. Thus engine room fires, fires in accommodation spaces, etc. are not included in the analysis but ship collisions are included because they can affect the whole LPG system.

A further limitation is imposed by restricting the safety analysis to only those events that occur when the ship or barge is in a U.S. port or inland waterway. The major emphasis is on dockside operations because the cargo is then in transfer rather than storage. Incidents outside of U.S. ports or inland waterways do not generally endanger the public and are therefore not included.

In order to adequately perform a system safety analysis for an LPG ship or barge, a number of discrete systems must be analyzed separately; the results of these analysis are then combined to form the overall safety analysis. The analysis of each discrete system requires the completion of a series of interrelated tasks:

1. Identify and define the system.
2. Identify all potential failure modes for each component.
3. Determine the probability of failure for individual components in the system, considering all failure modes that could lead to system failure.
4. Determine the probability of system failure.
5. Estimate the hazards associated with system failure.

In this report, all of the LPG storage, handling, and process equipment involved in the transfer of LPG from marine vessels to shore-based terminals (and vice versa) will be considered as one system. In some cases, certain shore-based components will be included in this system since, when cargo is being transferred, the two LPG plants are interconnected and a failure on shore could lead to a failure on the ship/barge.

After all of the various components that constitute a given system have been identified, the types of failures that can occur with each component must be determined. The only failure modes that are of interest are those that involve critical functions of the component (i.e. those failures that cause the system to fail in such a way so as to constitute a hazard). As an example, in a given system a valve might fail by refusing to open, by refusing to shut, by leaking past the stem packing, or by rupturing, but, for the purpose of safety analysis, valve opening might not be a critical function, in which case failure to open would not constitute a safety hazard but only an impediment to the desired flow of cargo.

The probability of a given component failing by a given failure mode can be arrived at from failure rate data for similar components in similar plants or systems; from the operating experience of the ships and barges; and from failure rate data and operating experience of components and systems that are only loosely analogous to the marine components and systems. Unfortunately the reporting of safety related failures on board LPG ships or barges is so limited that very little failure rate data can be generated from this source. Failure rate data from land based LPG plants is also very limited. Therefore, the probability of component failure must be based largely on failure rate data for generic classes of components used in a wide variety of systems. Probabilities generated from such data are compared to operating experience wherever possible and, in any case, are adjusted for the harsh environment imposed on components aboard marine vessels.

The cause and effect relationships among the various components are determined by use of fault trees (i.e. Boolean logic diagrams) showing the logical progression of events leading from component failures to system failure, and including the probability of occurrence of each event based on the probabilities of the preceeding causative events. The end result of such an analysis is the determination of the probability of a system failure.

The magnitude of the hazard (i.e. risk) associated with a system failure can, in some cases, be determined rather accurately (e.g. radiative heating effects from an LPG spill fire of known size); in other cases, estimates will have to be made based on past experience and engineering judgment (e.g. the magnitude of an LPG vapor cloud following a collision). No attempt is made to define the risk to the general public in terms of the probability of fatalities since such an analysis is site specific (i.e. requires population density data, weather data, etc.) and is beyond the scope of this report.

Probability of Failure

Hardware Failures

The probability of failure, P_f, of a component during a given time interval, Δt, can be computed if the failure rate, λ, of the component is known.

$$P_f = 1 - e^{-(\lambda \Delta t)} \qquad \text{Eq. 1}$$

If the failure rate (i.e. failures per unit time) of a component does not change with the "age" of the component, then the probability of failure of the component is only dependent on the time interval of interest. However, most components have a higher rate of failure when new and when approaching the end of their normal useful life span as shown in Figure 32. The high rate when new can be ascribed to fabrication and assembly defects. Components do not have infinite lifetimes and must, at some point, wear out due to normal causes. This leads to the increase in failure rate as the component wears out.

For purposes of this report, it will be assumed that the run-in failures will be corrected during testing and sea trials and that preventive maintenance programs will replace components before they wear out. Between run-in and wear-out, the failures are assumed to be random and Equation 1 can be used to determine the probability of component failure. Because the failure rate is constant during this period, the probability of failure depends on the time interval chosen, probability obviously increasing as the time interval increases. For this report, the time interval (known as the time at risk) will generally be chosen as the number of hours per voyage that the component is in use while the ship or barge is docked in a U.S. port. The largest LPG receiving terminals in the U.S. have a maximum transfer rate of 7,000 gpm (26.5 m^3/min).

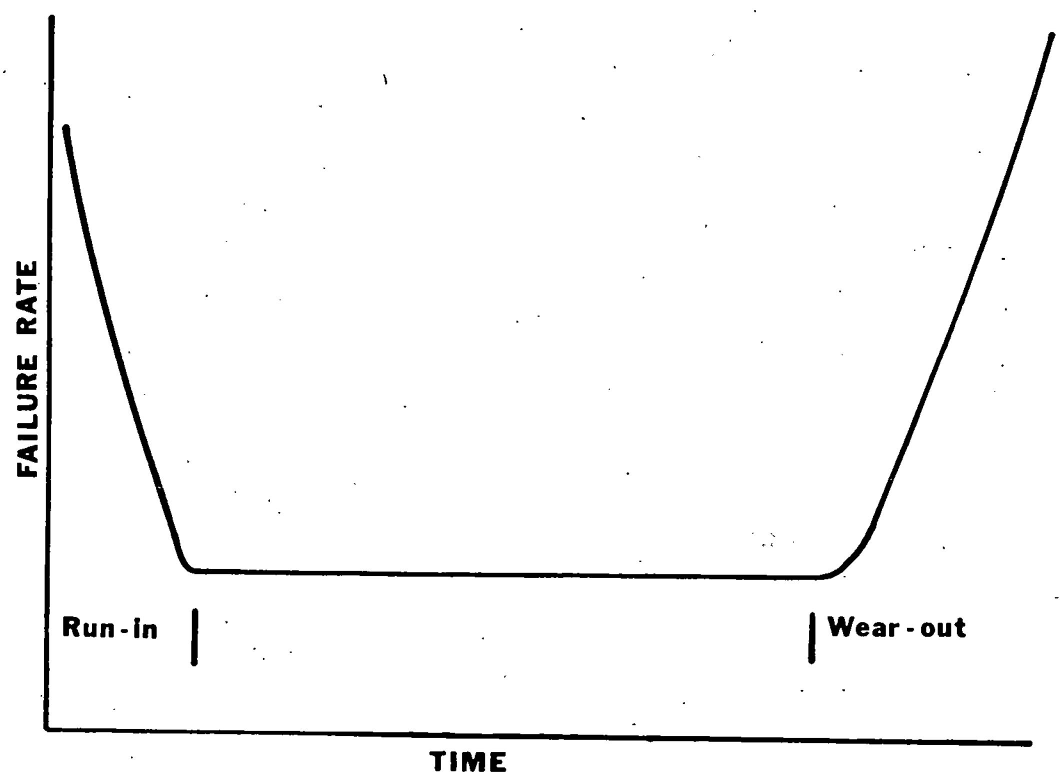


FIGURE 32. RELIABILITY PROFILE OF PROCESS EQUIPMENT.

At this rate a 40,000 m^3 ship could be unloaded in 25 hours. Allowing for start-up and shutdown, the transfer time was assumed to be 30 hours. Thus the time at risk for components such as LPG unloading pumps is 30 hours per voyage.

Many components have more than one critical failure mode. In order to determine the overall probability of failure for such a component it is necessary to first obtain an overall failure rate by summing all the individual failure rates.

$$\lambda = \lambda_a + \lambda_b + \lambda_c + \ldots \qquad \text{Eq. 2}$$

If the failure modes are not totally independent of one another, a more complicated analysis is required. The types of critical failures that are of interest in the safety analysis are generally independent, thus allowing Equation 2 to be applied.

Once the overall failure rate for a given single component is known, then the overall probability of a critical failure for that component can be calculated by using Equation 1. However, because most of the failure rate data are collected from general purpose land-based facilities, the failure rate should first be adjusted to reflect the component's environment. Table 1 lists the service factors, f, for various environments. The probability of failure is now calculated using Equation 3.

$$P_f = 1 - e^{-(f\lambda\Delta t)} \qquad \text{Eq. 3}$$

Now consider a system that has multiple components of a given type where, if one component fails, the system fails (e.g. a failure of any one of several gaskets can result in an LPG leak). In such a case, the failure rate of the group of identical components is equal to the failure rate for a single component multiplied by the number of components, n.

TABLE 1. COMPONENT ENVIRONMENTAL SERVICE FACTORS (7)

General Environmental Condition	f
Ideal, static conditions	0.1
Vibration free, controlled environment	0.5
General-purpose ground-based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0

$$\lambda_g = n\lambda_i \qquad \text{Eq. 4}$$

$$P_f = 1 - e^{-(f\lambda_g \Delta t)} \qquad \text{Eq. 5}$$

In many systems, redundant components are included so that a single component failure will not cause system failure (e.g. two safety relief valves, each of which is capable of venting at the maximum anticipated rate). If all of these components must fail in order to cause failure of the system, then the failure rate, λ_g, of this group of components is equal to the individual failure rate, λ_i, raised to the n power, when n is the number of components.

$$\lambda_g = (\lambda_i)^n \qquad \text{Eq. 6}$$

$$P_f = 1 - e^{-(f\lambda_g \Delta t)} \qquad \text{Eq. 7}$$

Some components are obviously not used continuously but most operate only at certain specific times (e.g. a momentary contact electrical switch that controls a relay). The probability of failure for such a component is equal to the relative frequency of failure of the component. For example, consider a switch that fails to function once in every one thousand demands (on the average). The relative frequency of failure is then 0.001 (i.e., 1 ÷ 1000) which is also the probability of failure "per demand". This is merely an application of the Porportionate Law of Probability (8). It is applicable to demand failures, but not to time based failures because, in the demand case, both failures and non-failures can be counted: non-failures cannot be quantified for time based failures.

The probability of component failure per demand, P_d, is thus equal to the number of observed failures, N_f, divided by the total number of trials, N_t.

$$P_d = \frac{N_f}{N_t} \qquad \text{Eq. 8}$$

This is also how the demand "failure rates" listed in various literature sources are calculated. However, P_d should not be confused with λ which is the failure rate for time based failures.

Since P_d is the probability of failure per demand, $1 - P_d$ must be the probability of success per demand. Using this fact and Bernoulli's Binomial Formula (8) allows computation of the probability of one or more failures occurring in a given number of demands. The first term of the binomial formula is the probability that all of the trials will be successes and is equal to the probability of success per demand, $1 - P_d$, raised to the m power where m is the number of trials (demands). This quantity, $(1 - P_d)^m$, represents the probability of zero failures, thus $1 - (1 - P_d)^m$ must represent the probability of one or more failures occurring in m trials.

The probability of failure of a component in a standby system (i.e. one that is used only intermittently, such as a fire fighting system) can be calculated if the proper failure rate for the component is available. Failure rate data for most components are taken from systems that operate more or less continuously; to apply these failure rates to components in standby service is suspect. To assume that unused hoses that are wound on hose reels will fail with the same frequency as hoses constantly in use carrying water at 125 psi (8.75 kg/cm^2) is unrealistic. There is, of course, a finite probability of component failure even when it is not being used (e.g. a hose can fail from weather induced degradation, etc.) and this probability can be calculated using Equation 9 if the standby failure rate, λ_s, is known.

$$P_f = 1 - e^{-(f\lambda_s \Delta t)} \qquad \text{Eq. 9}$$

If we assume that any failures during a standby period go undetected and uncorrected, then the probability that a component will be in the failed state when finally called upon to operate will be given by Equation 10 where the time increment is now the time between uses, Δt_s.

$$P_f = 1 - e^{-(f\lambda_s \Delta t_s)} \qquad \text{Eq. 10}$$

From the previous discussion it can be seen that some components actually have three failure probabilities of interest. Consider a valve in a standby system. There is a probability that it can split, crack, rupture, etc. even when not in use (Equation 10). There is also a probability that when called upon to operate (i.e. open or close) it will not perform properly (Equation 8). Finally there is the probability that during a period of actual use it will crack, split, rupture, plug, etc. (Equation 3).

Human Reliability

One essential "component" in most of the operating and safety systems on board an LPG ship is the human operator. The operators are called upon frequently to make decisions that could affect the safety of the ship. The human "component" can fail to make the proper decision, thereby causing the system to fail. Although the operator may be on the job continuously, he is called upon only at certain times to provide an input, thus the human failures are demand failures and the probability of human failure is a demand probability.

Human failure rate data is very limited; however, some data do exist on the reliability of human judgment (summarized in WASH-1400 (9)). The data demonstrate that the reliability of human judgment is greatly influenced by the stress level that accompanies the decision making process. At very low stress levels the probability of human failure is high because the operator may be bored and inattentive. At very high stress levels the probability of failure is also high because fear and anxiety interfere with the operator's judgment. Human failure rates are lowest when the task is sufficiently interesting to keep the operator alert and when the operator does not perceive himself to be in any danger. This is shown qualitatively in Figure 33 (10).

Although Figure 33 is only qualitative, judgments have been made for human failure probabilities for various situations (9). These are summarized in Table 2. Passive, walk-around type inspections that are dull and unchallenging (e.g. passive monitoring) have an assumed human failure probability of 0.5. For very high stress levels where the operator perceives himself to be in immediate physical danger, the probability of failure is assumed to be as high as 0.9 to 1.0. For interesting, standardized, moderate stress level tasks, the probability of human failure is probably no better than 0.0001.

It should also be noted that some human reliability experts (9, 11) believe that once a human has committed an error (and realizes it), the probability that his next action will also be an error is higher than the probability of committing the previous error. The theory is that for time-critical tasks the stress level increases once an error has been made, thereby increasing the likelihood of subsequent errors.

Effect of Inspections and Tests

The value of periodic inspections and/or tests of a system, in terms of improving system reliability, is somewhat hazy. It is perhaps only natural to think that frequent inspections must improve the reliability of a system. Let us examine this assumption more closely by considering various inspection intervals for a single component, e.g., a valve, during a one year period. If the valve is inspected

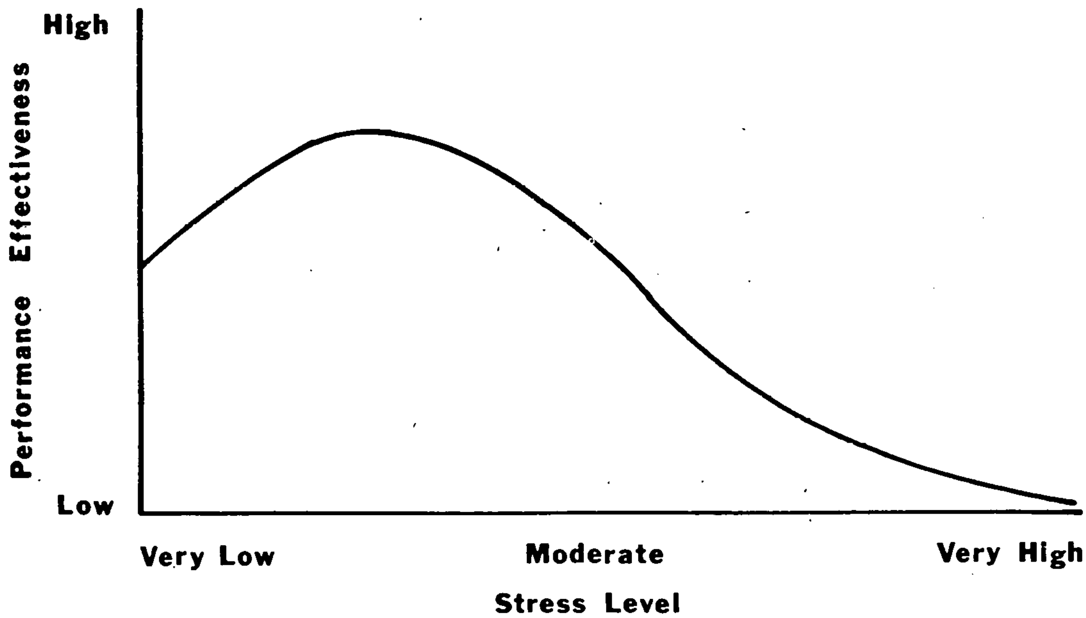


FIGURE 33. HYPOTHETICAL RELATIONSHIP BETWEEN PERFORMANCE AND STRESS (10).

TABLE 2. ESTIMATED HUMAN ERROR RATES (9)

Estimated Rate (per demand)	Activity
∿ 1.0	Operator fails to act correctly in the first 60 seconds after the onset of an extremely high stress condition.
0.9	Operator fails to act correctly after the first 5 minutes after the onset of an extremely high stress condition.
0.1	Operator fails to act correctly after the first 30 minutes in an extreme stress condition.
$2^{(n - 1)} x$	Given severe time stress, as in trying to compensate for an error made in an emergency situation, the initial error rate, x, for an activity doubles for each attempt, n, after a previous incorrect attempt, until the limiting condition of an error rate of 1.0 is reached or until time runs out. This limiting condition corresponds to an individual's becoming completely disorganized or ineffective.
∿ 1.0	If an operator fails to operate correctly one of two closely coupled valves or switches in a procedural step, he also fails to correctly operate the other valve.
0.1	Monitor or inspector fails to recognize initial error by operator. Note: With continuing feed-back of the error on the annunciator panel, this high error rate would not apply.
0.5	Monitor fails to detect undesired position of valves, etc., during general walk-around inspections, assuming no check list is used.
0.2 - 0.3	General error rate given very high stress levels where dangerous activities are occurring rapidly.
0.001	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch.

TABLE 2--Continued.

Estimated Rate (per demand)	Activity
0.003	General human error of commission, e.g., misreading label and therefore selecting wrong switch.
0.01	General human error of omission where there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance.

yearly (i.e., once every 8760 hours) then the probability of failure between inspections is given by:

$$P_a = 1 - e^{-(\lambda \Delta t)} \approx 8760(\lambda) \qquad \text{Eq. 11}$$

If the valve is inspected monthly, (i.e., once every 730 hours) then the probability of failure between inspections is given by:

$$P_m = 1 - e^{-(\lambda \Delta t)} \approx 730(\lambda) \qquad \text{Eq. 12}$$

The probability of failure during 12 successive one-month periods is approximately 12 P_m (i.e. ≈ 8760 (λ)).

Obviously the probability of failure between inspections is lower when inspections are more frequent, however, the probability of failure during a given time interval, e.g. one year, is the same regardless of inspection rate unless the failure rate, λ, is altered. If an inspection reveals that the valve is in a failed state, this does not change the failure rate. If an inspection reveals that the valve is close to failure (e.g., the presence of excess corrosion, a small crack, etc.) then the failure rate can be affected by replacing the valve.

Now consider how the inspections have affected the reliability of the system. If the inspection reveals no failures or imminent failures, the system reliability is the same as it would have been if not inspected. If the inspection reveals a failed component in a continuously operating system, the reliability of the system has already been affected, only the source of the problem has been determined. Finding a failed component in a standby system leads to improved system reliability by being able to replace the component before it is needed. If the inspection reveals an imminent failure of a component, the system reliability is improved by being able to replace the component before it actually fails.

Bush (12) has examined a statistical model for nuclear pressure vessel failure and predicts that the failure probability for catastrophic failures, assuming no inspections or repairs, is 20 to 60 times greater than the failure probability if periodic inspections and repairs are performed. Before concluding that it would be beneficial to require more frequent and/or more extensive inspections for LPG ships and barges, it would be advisable to examine this claim more closely. The model assumes that small defects will be found and repaired before they can cause catastrophic failure. Thus if all failures (defects) are counted, regardless of their size or damage potential, the failure rate will not be greatly altered by periodic inspections; only the probability of a catastrophic failure is affected. In order to achieve this substantial reduction in failure probability, the recommended inspections are quite extensive and include visual examinations of both sides of the pressure vessel, acoustic emission, ultrasonic testing, and pressure testing for leaks.

It should not be assumed from the preceding discussion that more frequent and more thorough inspections will always lead to large reductions in failure probability; nor should it be assumed that inspections are not beneficial. The point to be made is that properly conducted inspections can be of benefit for certain components, particularly those in continuous operating systems, but are of little value in other cases. Furthermore, the failure rate data used in this report were compiled on systems already subject to periodic inspection, as are the systems aboard LPG ships and barges.

Actual tests of systems will affect system reliability in much the same manner as inspections. However, in contrast to inspections, tests are more likely to reveal actual failures (especially in standby systems) and less likely to reveal imminent failures. The main value of a test is to demonstrate that, at the time of the test, the system is working properly. When calculating the probability of component failure in such a system, the time at risk starts at the time of the test. Thus if one expects that a standby system might be needed soon, a test of the system now can be beneficial by demonstrating that the system is in working order or it can show that certain components have failed and allow time for them to be replaced before the system is needed. In either case, system reliability is increased by reducing the time at risk, Δt, to the time interval between the time of the test and the time when the system might be needed. Such a result is important in LPG shipping because of the greater potential for hazard at certain times, such as during transfer operations.

In certain instances, it is possible for tests to be counter-productive and actually increase the likelihood of system failure. For example, a test of the cargo piping system on an LPG ship requires the piping system to undergo a cooldown/warmup cycle that causes the piping to contract and expand, thus stressing the pipe, gaskets, valve seals, etc. In addition, the cargo pumps must be started. These submerged pumps may be damaged when starting due to the presence of ice crystals in the pumps (unless certain procedures are followed). Therefore it is probably preferable not to test such a system but rather operate it only when needed and to supervise it closely when it is used.

For components that are subject to demand type failures, it is doubtful if inspections or tests can improve the component reliability. Consider, for example, a sealed electrical relay. It would be almost impossible for an inspection to determine whether or not it would work properly the next time needed. Similarly a test of the relay, whether it passes the test or not, is not necessarily indicative of whether or not it will function properly when called upon again.

Inspections and tests can be of value in improving system reliability. Inspections that reveal failures in standby components, imminent failures of continuous use components, or the presence of components that are nearing the end of their normal useful life are beneficial. The main benefit associated with testing is that a test of a standby system reduces the effective time at risk for the system, thus reducing the probability of system failure when it is needed.

Fault Tree Analysis

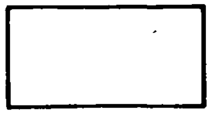
A fault tree analysis begins by defining the undesired event (e.g. an LPG spill). Beginning with this top event as the starting point, the analysis looks backward in time to discover all possible circumstances which could have caused the undesired event. These causative circumstances (component failures or human errors) are connected to one another and to the top event through the appropriate Boolean algebraic expressions since the entire fault tree is merely a graphic representation of the logical progression from component failure(s) to system failure.

The symbols used in fault tree construction are shown in Figure 34. Because the various events are connected by Boolean algebraic logic operations (gates), it is possible to obtain the overall probability of occurrence of the top event from the probabilities of the causative events. Figure 35 illustrates the construction of a simple fault tree and the methods for calculating probabilities of events when AND and OR gates are involved.

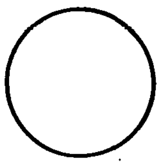
Emergency Shutdown System Fault Trees

Figures 36, 37, and 38 illustrate the fault tree for a manually activated Emergency Shutdown System (ESS). In the manual system, detection of cargo leaks or spills can be accomplished by direct visual observation of the actual spill and/or by visual observation of instrumentation readouts which indicate a spill. The detection instruments include liquid level gauges, low temperature sensors, pressure sensors, pump amperage gauges, gas detectors, etc. The emergency shutdown devices that actually isolate the problem area consist of remotely operable valves, pump and compressor motors, etc. The desired chain of events, once a spill has occurred, is that the spill is detected, the operator makes the proper

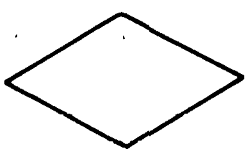
EVENT REPRESENTATIONS



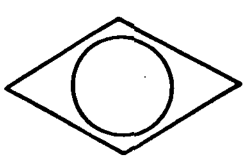
The rectangle identifies an event that results from the combination of fault events through the input logic gate.



The circle describes a basic fault event that requires no further development. Frequency and mode of failure of items so identified are derived from empirical data.

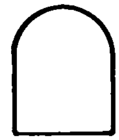


The diamond describes a fault event that is considered basic in a given fault tree. The possible causes of the event are not developed whether because the event is of insufficient consequence or the necessary information is unavailable.

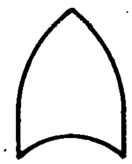


The circle within a diamond indicates a subtree exists, but that subtree was evaluated separately and the quantitative results inserted as though a component.

LOGIC OPERATIONS



AND gate describes the logical operations whereby the coexistence of all input events is required to produce the output event.



OR gate defines the situation whereby the output event will exist if one or more of the input events exists.

FIGURE 34. FAULT TREE SYMBOLS

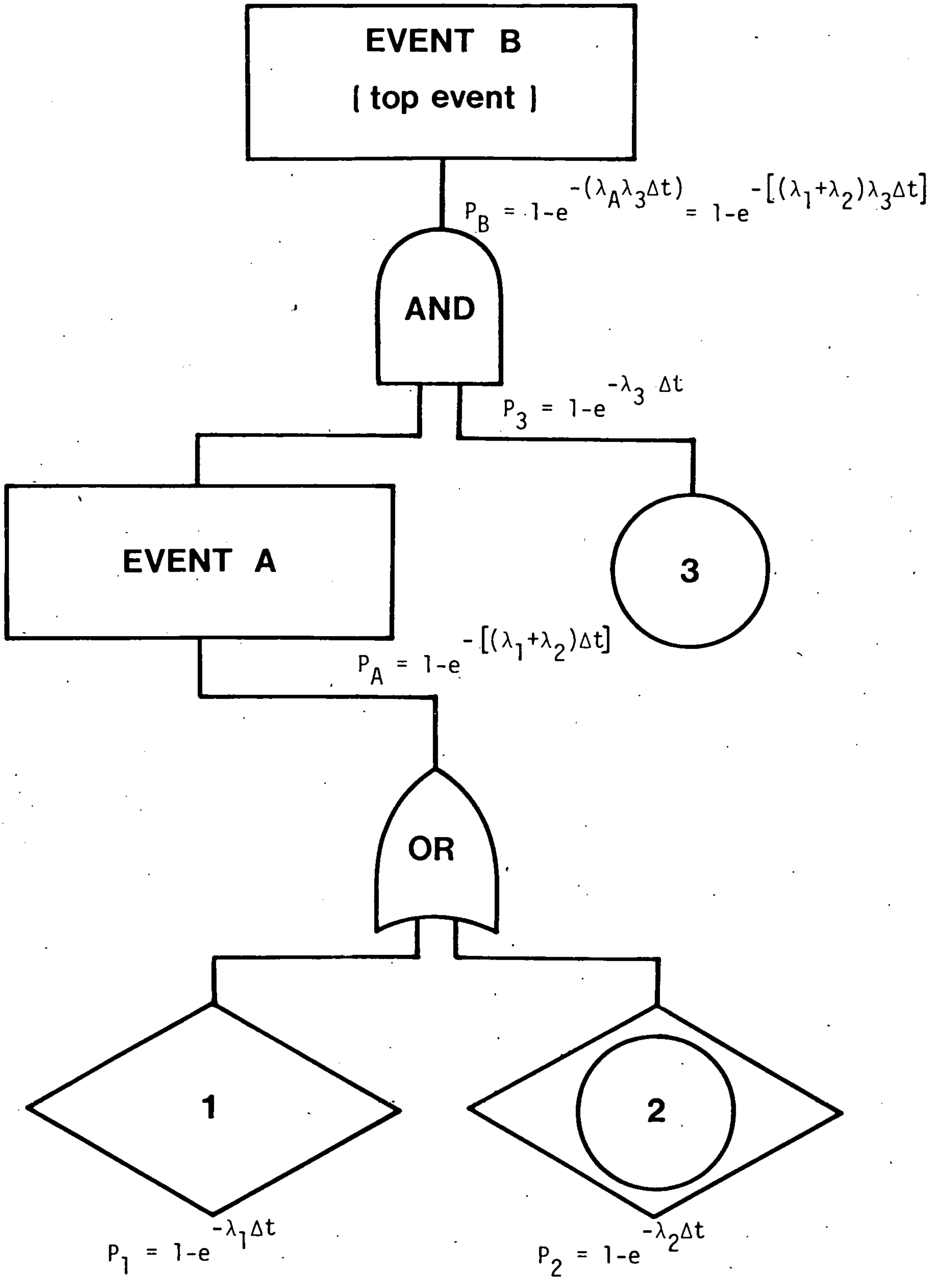


FIGURE 35. TYPICAL FAULT TREE ILLUSTRATING COMPONENT PROBABILITY RELATIONSHIPS.

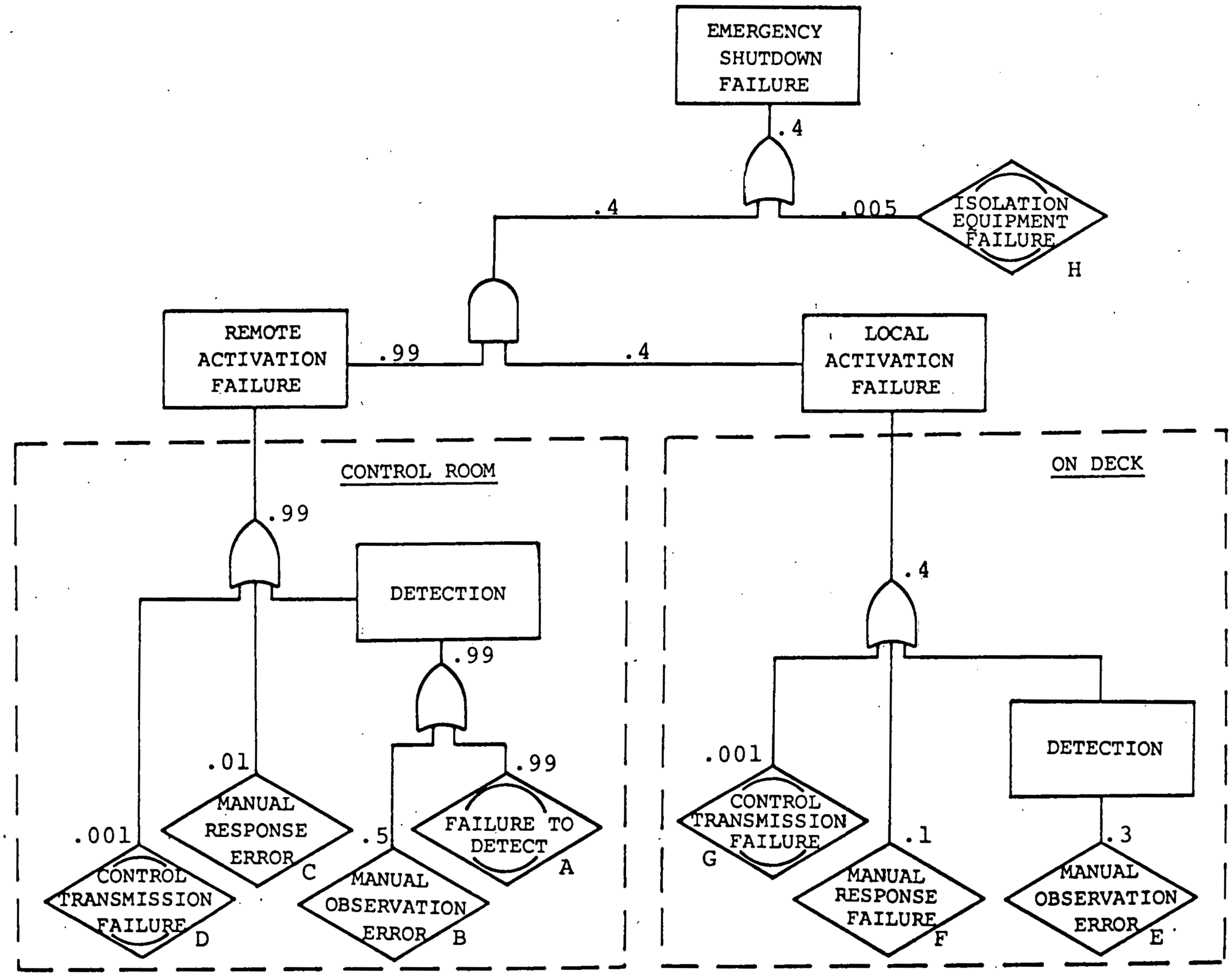


FIGURE 36. FAULT TREE FOR MANUALLY ACTIVATED EMERGENCY SHUTDOWN SYSTEM: SPILL SIZE < 100 GAL.

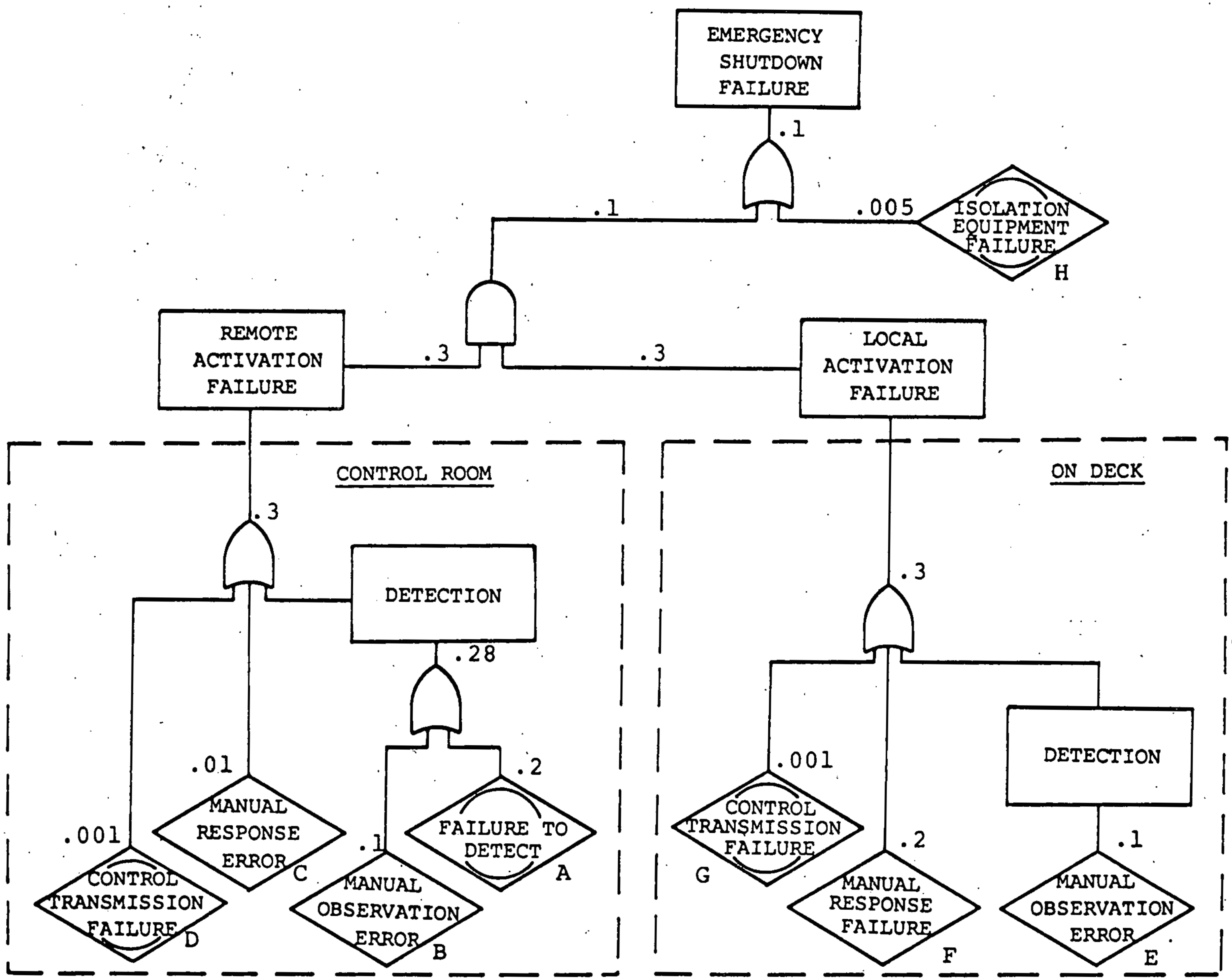


FIGURE 37. FAULT TREE FOR MANUALLY ACTIVATED EMERGENCY SHUTDOWN SYSTEM: SPILL SIZE 100 - 1000 GAL.

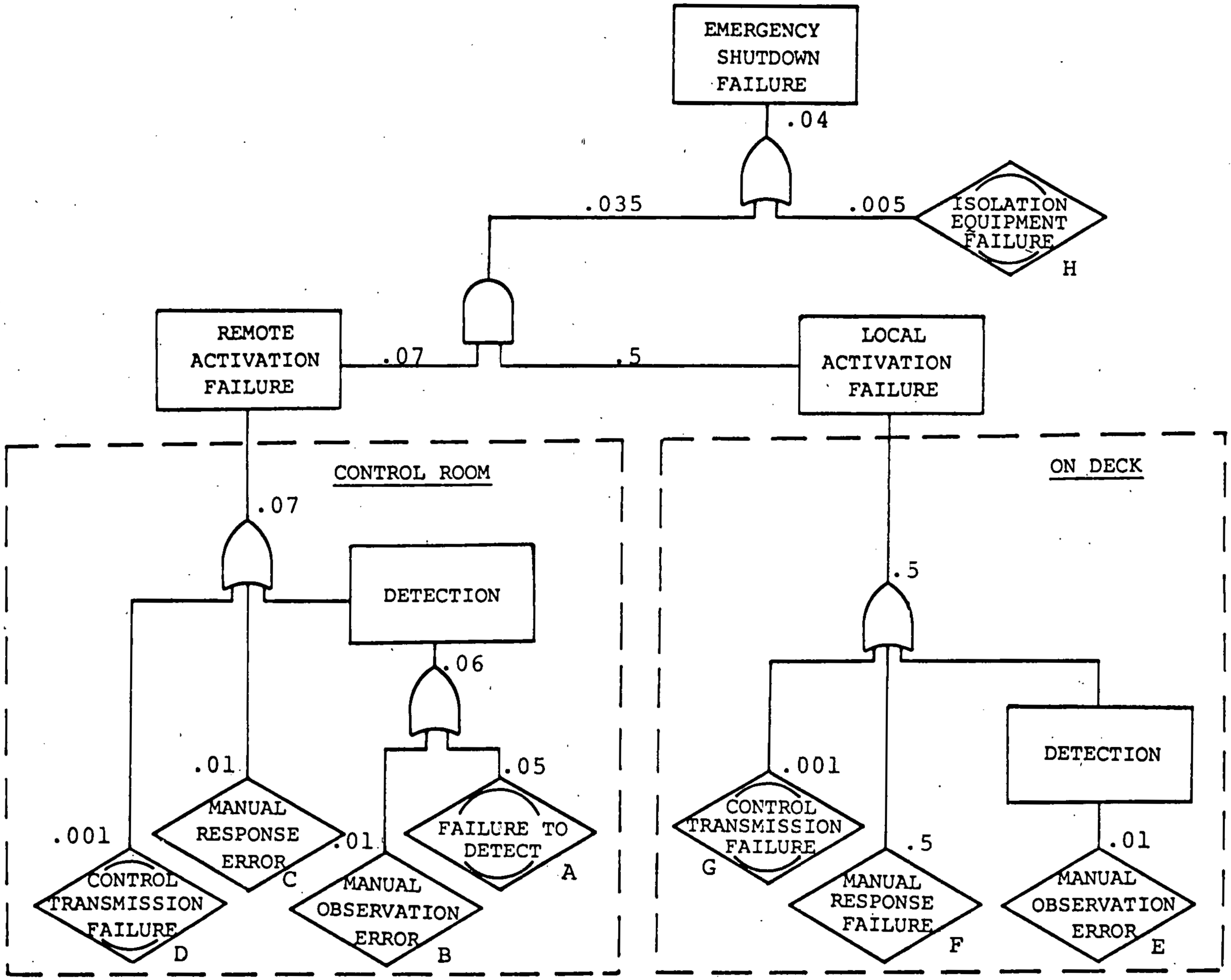


FIGURE 38. FAULT TREE FOR MANUALLY ACTIVATED EMERGENCY SHUTDOWN SYSTEM: SPILL SIZE > 1000 GAL.

decision concerning how to best stop the leak, the electrical (or pneumatic or hydraulic) signal initiated by the operator is sent to the proper emergency shutdown devices which also operate properly, thus isolating the leak and limiting the spill.

The fault trees illustrate how these various events are connected and include the probability of failure for each event. The probabilities of failures are based primarily on engineering judgement and are calculated on a per demand basis. Each separate event will now be examined.

A. Failure to Detect - Failure of the gauges, alarms, etc. within the cargo control room to adequately indicate that a spill has occurred. This failure can have many causes; failure of the sensing element; failure of the signal from the sensing element to reach the control room; or failure of the indicating device in the control room. Spill size has a definite effect on the probability of detecting a spill. Small spills are most difficult to detect because they would normally cause only slight changes in indicated readings of pressure, temperature, level, etc.

B. Manual Observation Error - Failure of control room personnel to properly interpret the instrumentation readouts that indicate a spill. Spill size has an effect here too. The slight change in indicated readings of pressure, temperature, level, etc. caused by small spills will be difficult to interpret. Larger spills will cause larger changes in readings and, in some cases, will set-off visible and audible alarms that are difficult to ignore.

C. Manual Response Error - Failure of control room personnel to take the proper action once a spill is detected. The probability of this event is not dependent on spill size since the operator should, in most cases, feel sufficiently isolated from the leak so that he does not perceive himself to be in any immediate danger.

D. Control and Transmission Failure - Failure of the shutdown signal (electric, pneumatic, or hydraulic) to reach the required shutdown devices. This could be caused by open circuits, short circuits, faulty switches, etc.

E. Manual Observation Error - Failure of deck personnel to visually observe a leak or spill. For small spills, there is a high probability of failure to observe. Large spills would be hard to miss if anyone is on deck, therefore the probability is much lower for large spills.

F. Manual Response Error - Failure of deck personnel to take proper action once a spill has been visually observed. This probability is very dependent on the spill size. In the case of a large spill, the observer might perceive himself to be in immediate danger. The resulting high anxiety level of the observer makes it difficult for him to take the proper action.

G. Control and Transmission Failure - Same as D except that the initiating device will probably be on deck rather than in the control room and part, or all, of the transmission system will be different.

H. Isolation Equipment Failure - Failure of the required shutdown devices to operate properly once they have received the signal to shut down.

The manually activated ESS, as just described, is found on many LPG tankships and on almost all LPG barges. More sophisticated systems that can be activated either manually or automatically (in response to sensor readouts) are more likely to be found on newer LPG ships. The overall probability of failure of such a system is expected to be less than that for the manually activated system because the totally automatic portion of the newer system provides redundancy for the "response" events. However, one of the controlling events is still the Failure to Detect and its probability is the same for both the manually activated and the automatically activated systems if the same number and type of sensors are used in both systems. Therefore, it is likely that the overall probability of failure for an automatically activated system will be less than one order of magnitude (i.e. a factor of ten) lower than the probability of failure of the manually activated system (for a given spill size).

LPG Ship Unloading Fault Tree

Before beginning any fault tree analysis, the system that is to be analyzed must be defined. The system to be considered during the LPG unloading operation includes all parts of the ship-based and shore-based LPG plants that are actually involved in the transfer of cargo and vapor. However, the only spills that are considered are those that occur on the ship, on the dock, or onto the water. Rather than limiting the analysis to a specific ship and terminal, the system was defined in terms of a "typical" LPG ship. Some of the parameters chosen for this ship are listed in Table 3. The "typical" ship concept was also used in determining the number of various individual components involved.

The fault tree for accidental releases of LPG onto the deck of the ship during ship unloading is shown in Figure 39. The top event (i.e. an LPG spill) has been broken into a number of similar events, each one differing by the quantity of LPG spilled. Thus the system is analyzed by a series of fault trees, each one leading to a spill of a certain size. Events that allow spills to increase in size are shown as connecting events among the various fault trees.

Whenever possible, the probability of failure for each component was calculated from the median value of the failure rate for that generic class of component as listed in WASH-1400 (9). In a few cases, generic failure rate data from other sources were used. Table 4 lists the various

TABLE 3. SELECTED PARAMETERS FOR "TYPICAL" LPG SHIP

Total cargo capacity	250,000 bbl (40,000m^3)
Number of cargo tanks	4
Number of cargo pumps per tank	2
Number of pressure/vacuum relief valves per tank	2
Number of liquid transfer arm connections	2
Size of liquid transfer arm connections	12 inch (30.5 cm)
Number of vapor transfer arm connections	1
Size of vapor transfer arm connection	8 inch (20.3 cm)
Maximum cargo transfer rate	7000 gpm (26.5 m^3/min)
Average unloading time	30 hours

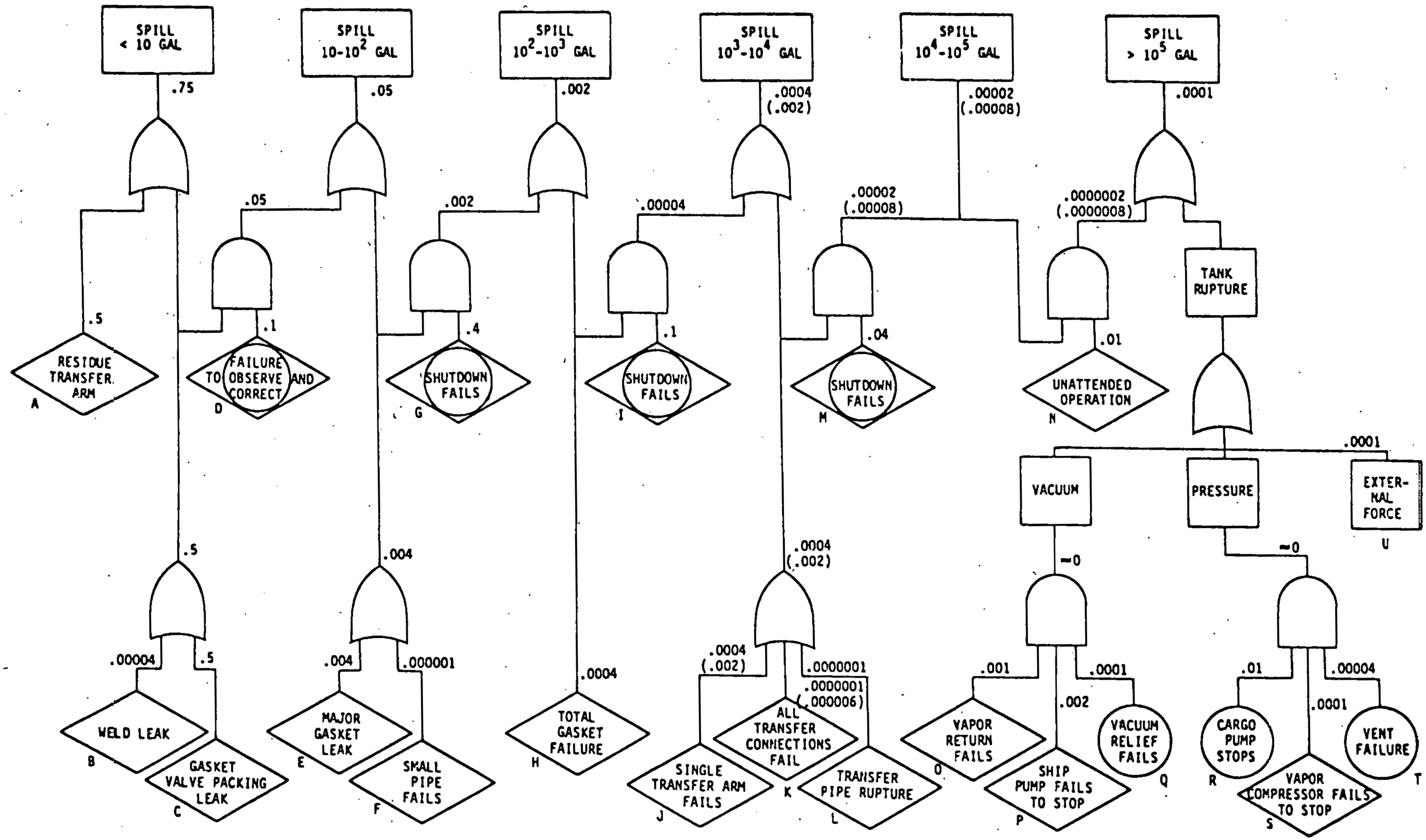


FIGURE 39. FAULT TREE: LPG SHIP UNLOADING OPERATION SHOWING PROBABILITIES OF EVENTS LEADING TO SPILLS OF VARIOUS SIZES.

TABLE 4. FAILURE PROBABILITY PARAMETERS FOR LPG SHIP OFFLOADING FAULT TREE

Component (or Subsystem)	Failure Mode	Median Failure Rate(a)	Service Factor	Number of Failures Required	Number of Components(b)	Time at Risk	Failure Probability Per Transfer
Transfer Arm	Liquid Residue	0.5/D †	N/A	1	2	N/A	0.5 †
Weld	Leak	3×10^{-9}/hr	2	1	200	30 hr	0.00004
Gasket or Valve Packing	Leak	---	2	1	30	30 hr	0.5 †
Operator	Fail to Observe and Correct	0.1/D *	N/A	1	N/A	N/A	0.1/D
Gasket	Major Leak	3×10^{-6}/hr	2	1	20	30 hr	0.004
Small Pipe	Leak or Rupture	1×10^{-9}/hr ∇	2	1	15	30 hr	0.000001
ESS	Fails	0.4/D *	N/A	1	N/A	N/A	0.4/D
Gasket	Total Failure	3×10^{-7}/hr	2	1	20	30 hr	0.0004
ESS	Fails	0.1/D *	N/A	1	N/A	N/A	0.1/D
Transfer Arm	Leak or Rupture	3×10^{-6}/hr	2	1	2	30 hr	0.0004
Transfer Arm	Leak or Rupture	3×10^{-6}/hr	2	2	2	30 hr	0.0000001
Transfer Piping	Leak or Rupture	1×10^{-10}/hr∇	2	1	15	30 hr	0.0000001
ESS	Fails	0.04/D *	N/A	1	N/A	N/A	0.04/D
Operator	Unattended Operation	0.01/D *	N/A	1	N/A	N/A	0.01/D
Vapor Return Compressor	Stops	3×10^{-5}/hr	1	1	1	30 hr	0.001
Cargo Pump	Fails to Stop	1×10^{-4}/D	2	1	8	N/A	0.002/D

TABLE 4--Continued.

Component (or Subsystem)	Failure Mode	Median Failure Rate(a)	Service Factor	Number of Failures Required	Number of Components(b)	Time at Risk	Failure Probability Per Transfer
Vacuum Relief Valve	Fails to Open	3×10^{-5}/D	2	1	2	N/A	0.0001/D
Cargo Pump	Stops	3×10^{-5}/hr	2	1	8	30 hr	0.01
Vapor Return Compressor	Fails to Stop	1×10^{-4}/D	1	1	1	N/A	0.0001/D
Pressure Relief Valve	Fails to Open	1×10^{-5}/D	2	1	2	N/A	0.00004/D
External Force	Collision, etc.	---	N/A	1	N/A	N/A	0.0001 *
Transfer Hose	Leak or Rupture	2×10^{-5}/hr §	2	1	2	30 hr	0.002
Transfer Hose	Leak or Rupture	2×10^{-5}/hr §	2	2	2	30 hr	0.000006

(a) Failure rates taken from WASH-1400 (9) unless otherwise noted. In some cases, failure rates for specific components or subsystems were not available so engineering judgment was used in applying failure rates for roughly similar items. Although the offloading system is essentially a standby system (used intermittently), the failure rates shown are generally for continuous systems since standby failure rates are not available in many cases.

(b) Total number of components is based on the "typical" LPG ship concept which is in turn based on various actual LPG ships.

† Failure rates and/or probabilities based on ship and terminal experience.

∇ Failure rate given is "per section" of pipe.

* See text for source of failure rate or failure probability.

§ Failure rate taken from "Reliability Technology." (7)

N/A = Not Applicable

components, the median failure rate, source of data, etc. for all the initiating events. Each separate event will now be examined.

A. Residue Transfer Arm - Failure to clear all LPG liquid from the transfer arms before disconnecting them. After talking to several LPG plant and ship operators, it was estimated that, on the average, an LPG spill could be expected from this source on about one-half of the possible occasions ($P_d \approx 0.5$). It is perhaps questionable whether or not this event should be considered in a fault tree because some LPG terminal and ship operators said that such spills occur on almost every unloading due to their particular operational sequence; other operators said that it has never happened because they completely purge all lines prior to disconnecting. Note that the spill from the transfer arms does not connect to the next fault tree (10 - 100 gal spill) because the quantity of liquid in the arms is small, and, since no LPG is flowing, cannot increase.

B. Weld Leak - Failure of a weld on any of the cargo transfer piping to remain liquid-tight. As can be seen in Table 4, the median failure rate was 3×10^{-9}/hr. Combining this with a service factor of 2, an assumed total of 200 welds on the transfer piping (based on cargo piping drawings for various LPG ships), and at risk time of 30 hours per trip gives a probability of 0.00004 that one of these welds will fail during an unloading operation.

C. Gasket, Valve Packing Leak - Failure of a gasketed piping joint or valve packing to remain liquid-tight. As Table 4 shows, no applicable failure rate could be found in the literature for this generic class of components. However, discussions with LPG terminal and ship operators indicated that such leaks were rather common. Therefore, a probability of 0.5 was selected for this event. These failures generally occur during the cooling down of the transfer piping due to thermal expansion/contraction imbalances.

D. Failure to Observe and Correct - Failure of the shipboard personnel to observe that LPG is leaking and failing to take proper corrective action to stop the leak. Weld, gasket, and valve packing leaks will generally occur when the cargo transfer piping is being cooled down or at the very start of the transfer operation. During this time, the shipboard personnel are especially watchful for such leaks. Therefore, most of these leaks are observed before much LPG has been spilled. Leaks at gaskets or valve packings can often be stopped by tightening the flange bolts or valve packing gland nut without any need for stopping the cargo transfer process. Other possible control methods include re-routing the LPG flow, or placing a drip bucket beneath the leak to confine the spilled LPG.

The probability of failure to observe and correct such leaks was judged to be 0.1. Note that because this event leads into an AND gate and because this event will never occur unless a leak has already occurred, its failure probability must be on a 'per demand' basis.

E. Major Gasket Leak - Failure of a gasket to maintain its integrity. Cracks, splits, tears, etc. of a gasket will allow LPG to spill at a higher rate than the leaks covered under event C. Using the data contained in Table 4, the probability of a leak from this source, during the 30 hour "at risk" period, is 0.004.

F. Small Pipe Fails - Failure of a cargo handling pipe smaller than 3 inches (7.5 cm) in diameter to maintain its structural integrity. Splits, cracks, or ruptures in small diameter pipes occur at a median rate of 1×10^{-9} per hour per section of pipe, according to WASH - 1400 (9). Note that this is per section of pipe; each section being defined as the length of pipe between two discontinuities such as pumps, valves, etc; welds and flanges are not considered as discontinuities. Assuming 15 small pipe sections, the probability of failure is 0.000001.

G. Shutdown Fails - Failure of the emergency shutdown system to detect or isolate the spill. This has been discussed in another section of this report and will not be repeated here. However, it must be noted that the probability of 0.4 is on a 'per demand' basis.

H. Total Gasket Failure - Failure of a gasket to remain in its required location (e.g. the loss of all gasket material between two or more bolts on a flanged connection). This type of gasket failure will result in leaks with flow rates higher than gasket failures C or E. Assuming 20 gaskets, the probability of failure is 0.0004.

I. Shutdown Fails - Failure of the emergency shutdown system to detect or isolate the spill. The probability of 0.1 per demand was arrived at previously.

J. Single Transfer Arm Fails - Failure of a metal or rubber LPG liquid transfer arm to retain its structural integrity. This includes cuts, splits, ruptures, etc. Rubber cargo transfer hoses have failure rates approximately five times greater than metal arms (7). Assuming two liquid transfer arms, the probability of failure is 0.0004 for metal arms and 0.002 for rubber.

K. All Transfer Connections Fail - Simultaneous failure of all LPG liquid transfer arms. Assuming two transfer connections for liquid, the probability of both failing simultaneously is $p = 1 - e^{-(\lambda^2 \Delta t)}$ (i.e. 0.0000001 for metal arms, 0.000006 for rubber hoses).

L. Transfer Pipe Rupture - Failure of a cargo transfer pipe to remain liquid tight. As was the case for event F, the failure rate is based on a pipe "section". Assuming 15 pipe sections, the probability of pipe failure is 0.0000001.

M. Shutdown Fails - Failure of the emergency shutdown system to detect and isolate a spill. For these larger spills the probability of failure is 0.04, as discussed previously.

N. Unattended Operation - Failure to have an operator on board the ship to take corrective action. Although unattended operation is contrary to the codes adopted by the governing bodies, it is still a possibility. The choice of 0.01 per demand for the probability of unattended operation is based on judgment and on-site observation.

O. Vapor Return Fails - Failure of the shore-based vapor compressor to deliver adequate LPG vapor to the ship's tanks. If no corrective action is taken (either manually or automatically), this could cause tank rupture by pulling a vacuum on the tank (liquid volume out being greater than the vapor volume going in). The same situation could arise if the vapor is not being returned from shore but is instead being generated by the ship's vaporizer. However, the probability, 0.001 is calculated for shore-based compressors.

P. Ship Pump Fails to Stop - Failure of the cargo pump to stop in response to a loss of vapor return. If the cargo pumps are stopped when the vapor return is stopped, the problem of pulling a vacuum in the tank can be avoided. Assuming that there are 2 cargo pumps in each tank, 4 tanks per ship, and that failure of any one pump to stop will cause a vacuum to be created, then the probability of this event is about 0.002 per demand. This is on a demand basis since no hazard exists for failure of a cargo pump to stop as long as the vapor return is working.

Q. Vacuum Relief Fails - Failure of the vacuum relief valves to open and allow air into the cargo tank. All LPG cargo tanks must be fitted with vacuum relief valves that will allow air to enter the tank when the tank is in danger of structural damage due to an internal vacuum. If the vapor return stops and a cargo pump fails to stop, then the vacuum relief valves will be needed. Assuming that there are 2 valves per tank and that both valves on the tank with the operating cargo pump must operate properly, then the probability of failure is about 0.0001 per demand. This number is probably conservative because failure of both vacuum relief valves would probably be required before structural damage would occur.

R. Cargo Pump Stops - Failure of cargo pump to continue to run during unloading. If corrective action is not taken, the failure of a cargo pump could lead to cargo tank damage due to overpressurization. Assuming that 8 cargo pumps are in use (2 per tank, 4 tanks) and that a failure of any one cargo pump is critical, then the probability of this event is about 0.01. This is probably conservative because it is doubtful if the loss of just one pump in a tank is critical.

S. Vapor Compressor Fails to Stop - Failure of the shore-based vapor compressor to stop when a cargo pump stops. Vapor return without simultaneous offloading of cargo will lead to a pressure build-up in the tank(s) involved. In some cases, the pressure could be sufficient to cause tank failure. The probability that the vapor compressor will fail to stop on demand is 0.0001.

T. Vent Failure - Failure of the pressure relief valves to open and allow excess vapor to escape to the vent stack. If a cargo pump stops and the vapor return fails to stop, then the pressure relief valves must work in order to prevent structural damage to the cargo tank due to overpressurization. Making the same assumptions as were made for vacuum relief valves (i.e., 2 valves per tank, and one failure is critical), gives a probability of about 0.00004 per demand, which, as before, is probably conservative since both valves would probably have to fail in order to have a critical venting failure.

U. External Force - Failure of a cargo tank to retain its structural integrity following a collision with another ship. Failure rate data for this event is nearly non-existent because the total number of LPG ship voyages is not very great. Therefore, others have tried to use the casualty record for all tank ships with adjustments to account for the improved collision resistance of LPG tankers (e.g. double bottom, void spaces, etc.). This approach was used by the Federal Power Commission (13) when preparing the environmental impact statement for the Alaska liquefied natural gas transportation system and by Cave and Kazarians (14). A more detailed method has been tried by Science Applications, Inc. (15) in which harbor traffic patterns, ship speeds, and ship displacements are used to predict the probability of ship collisions in specific harbors. Although this approach is technically elegant, it still relies on actual ship collision data to modify the results of the analysis. A third, and more straightforward method is to take the available casualty data for liquefied gas ships and develop spill probabilities based on this previous experience. Historical data for liquefied gas ship casualties during the period 1964-1979 is available and can be used for such an analysis.

These data on liquefied gas ship casualties were compiled by Poten and Partners (16), mainly from insurance claims and loss reports to the U. S. Coast Guard and other governing bodies. Undoubtedly some spills have occurred that were not reported. However, there is little chance that a spill due to collision would go unreported due to the serious nature of the accident. In the period 1964-1979 there were 19,000 liquefied gas cargo deliveries world-wide and no record of an LPG cargo spill due to collision. (See Appendix A for a discussion of the accident involving the LPG ship "Yuyo Maru.")

In order to determine the probability of a cargo spill due to collision, varying numbers of spills can be assumed to have occurred. Table 5 shows the probability of fewer than n events occurring given that m events have previously occurred. For example, if we assume that one spill due to collision had occurred in the 19,000 voyages, then the

TABLE 5. EVENT PROBABILITY BASED ON NUMBER OF PREVIOUS EVENTS, ASSUMING POISSON DISTRIBUTION (17)

Observed Number of Events (m)	Probability of n or Fewer Events Occurring in the Same Time Interval as m Observed Events					
	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6
1	.72	.91	.98	.996	.999	
2	.40	.68	.85	.95	.98	.995
3	.20	.42	.65	.81	.91	.97
4	.10	.24	.43	.62	.80	.90

probability of no more than 3 spills occurring in the next 19,000 voyages is about 98%. Using 3 spills per 19,000 voyages yields a probability of a spill due to collision of approximately 2×10^{-4} per cargo delivery (3 ÷ 19,000). Table 6 compares this with the probabilities developed by other techniques (probabilities adjusted to correspond to the conditions imposed in our analysis where necessary).

Using this probability of spill due to collision of 0.0002 per cargo delivery in our unloading fault tree would be overly conservative when estimating the probability of large spills. This is because the 0.0002 probability is based on all of the time that the ship is in the water during one complete voyage. Casualty data for all spills indicate that the chances of a collision occurring are much lower when at sea than when in port. Let us assume that no collisions occur at sea so that all 3 assumed collisions must occur in port. On the average, each ship voyage that includes a stop in a U. S. port will also include a stop in a foreign port. Thus the probability of a spill due to collision in a U. S. port can be approximated as 0.0001 (i.e. 0.0002 ÷ 2). Implicit in this analysis is the assumption that the collision frequencies in U. S. and foreign ports are not greatly different.

When examining the construction of the fault tree it is important to remember that considerable detail has been omitted. Certainly the list of causative events is not complete; damage due to "acts of God", sabotage, miscellaneous human errors such as opening the wrong valves, etc. have been omitted. This simplification is justified due to the very small probability of certain events (e.g. damage due to "acts of God") and the futility of trying to apply failure rate analysis to certain human acts (e.g. sabotage).

In order to present the various events in a fault tree of manageable size and detail it has been necessary to

TABLE 6. COMPARISON OF RISK PROBABILITIES

Source	Probability of Spill (per Cargo Delivery) Due to Ship Collision
Applied Technology Corp.	2×10^{-4}
FPC (13)	1×10^{-3}
SAI (15) for Los Angeles Harbor	1×10^{-4}
Cave and Kazarians (14)	3×10^{-7}*
University Engineers (18)	5×10^{-4}

*Probability given is for spills greater than 20,000 m^3.

make certain simplifications. For example, consider the Total Gasket Failure (event H). Depending on the diameter of the pipe and the pressure of the LPG flowing within the pipe, the spill caused by a total gasket failure could be only a few gallons, if detected and isolated quickly; or, going to the other extreme, could lead to a spill equivalent to a whole cargo tank if it is never detected and isolated. Thus each event that leads to a spill of a given size should also be thought of as being a possible cause of smaller spills. Similarly, each event can lead to even larger spills if undetected. Realistically the Shutdown Fails events must be considered as having a certain time element involved. This time element is the time that is required for a spill of one size to escalate to the next larger spill size. For example, assume that one of the liquid cargo transfer arms ruptures, thereby allowing LPG to be spilled at a rate of approximately 7000 gpm (26.5 m^3/min). The probability of the Shutdown Fails event in this case is 0.04. As was noted previously, this probability is controlled mainly by the Manual Response Error, i.e. the failure of ship's personnel to take the proper corrective action. It stretches the imagination to conceive of this high rate spill going undetected and unisolated until the entire contents of the tank ($\sim$2,500,000 gallons (10,000 m^3)) have been spilled. Even if the operator makes the wrong decision initially and any automatic shutdown systems fail, surely someone will eventually make the proper decision and stop any further cargo discharge. The Shutdown Fails event is therefore to be thought of in terms of failure to detect and isolate a spill within one or two minutes from the inception of the spill.

Fire Water System

The main operating components of a typical LPG ship fire water system are shown in Figure 40. This is a simplified schematic diagram and only includes those components that would be used for fire protection on the deck of the ship.

The fire water pump (1) draws seawater into the pump inlet and supplies this water, at pressure, through the main block valve (2) to the fire water distribution system piping (3). Opening the appropriate isolation valves (4) allows the water to be dispensed through the desired combination of monitor nozzles (5), hand-held hoselines (6), and fixed nozzle spray systems (7). An international shore connection (8) is also provided so that the ship can be supplied with fire water from the shore and vice-versa.

LPG ships are required to have two or more independently driven fire water pumps. These are generally located in the machinery spaces fore or aft of the cargo area. The pumps need not be dedicated to fire water service; often the primary pump is also used for ballast or bilge pumping and the back-up or emergency pump is dedicated to fire water service. The pumps are normally electric or diesel powered.

On some ships, the fire water distribution piping is arranged in a loop with numerous isolation valves (9) strategically placed such that a failure in one part of the piping can be isolated so that the fire fighting capability is not impaired. The hoselines are usually preconnected to the hydrants and are stored on hose reels or in hose cabinets. The hoses are generally interchangeable so a failed hose can be easily replaced.

An analysis of the fire water system shows that no single component failure, other then a human failure, can cause a total system failure (i.e. both pumps must fail to

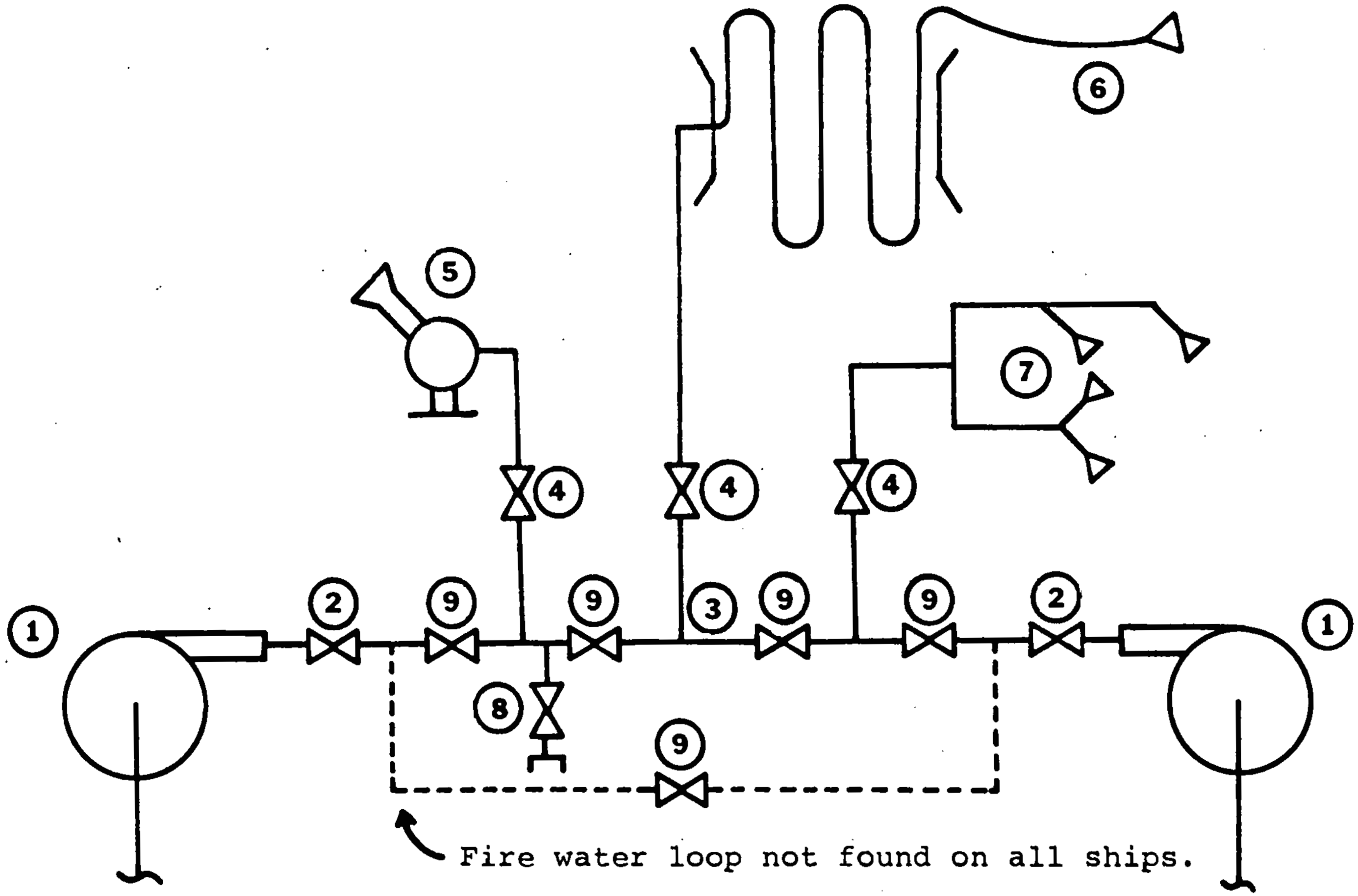


FIGURE 40. SCHEMATIC OF FIRE WATER SYSTEM FOR CARGO AREA FIRES.

start or fail to continue to run, the piping must break in two locations, two valves must fail to open or close, etc.). Combining this point with the frequent tests of the system (once each week) leads to the conclusion that a total failure of the system due to component failures is very small indeed. For example, using the failure probabilities for the components as listed in Table 7, the failure of both pumps to start has a probability of about 1×10^{-5} per demand. Most of the other multiple failure events that could cause total system failure have even smaller probabilities.

On the other hand, partial failures of the system due to hardware failures (ruptured hoses, valves that fail to open, etc.) can be expected to occur much more often. Many of these failures can be circumvented by replacing the component, re-routing the water flow, etc. Also, hoses and monitors can act as at least partial back-ups for one another and for the fixed nozzle spray system. This flexibility further reduces the system failure probability due to hardware failures.

The fire water systems on board most LPG ships are manually activated systems (fire detectors may be installed but they are rarely used to activate fire water systems in the cargo area of the ship). Therefore the operators must play a large role in the proper operation of the fire water system; the fire must be detected, the pump turned on, valves opened, etc. As was the case for manually activated emergency shutdown systems, the reliability of the human operator is related to his perceived stress level. For small fires, the probability of operator failure might be as low as 0.01; for large deck fires the probability might be 0.5 or even more if the operator perceives himself to be in great physical danger. However, if the operator takes the wrong action (or no action) it is likely that his error can be corrected within a few minutes, either by himself or by other personnel.

TABLE 7. FAILURE PROBABILITY PARAMETERS FOR THE FIRE WATER SYSTEM

Component Type	Failure Mode	Median Failure Rate	Service Factor	Number of Failures Required	Number of Components	Time at Risk	Failure Probability
Diesel Pump	Fails to Start	3×10^{-3}/D	2	1	1	N/A	6×10^{-3}
Electric Pump	Fails to Start	1×10^{-3}/D	2	1	1	N/A	2×10^{-3}
Valve	Fails to Open	1×10^{-4}/D	2	1	2	N/A	4×10^{-4}
Nozzle	Fails to Open	1×10^{-4}/D	2	1	1	N/A	2×10^{-4}
Piping	Leak or Rupture	1×10^{-9}/hr/Section	2	1	40	168 hrs†	1×10^{-5}
Hose	Leak or Rupture	2×10^{-5}/hr*	2	1	1	168 hrs	7×10^{-3}
Valve	Rupture	1×10^{-8}/hr	2	1	20	168 hrs	7×10^{-5}
Operator	Improper Action						0.01 - 0.5

*Continuous use failure rate used in the absence of data for standby use.

†168 hours (one week) between tests.

N/A = Not Applicable

Failure rates taken from WASH-1400 (9) unless otherwise noted. In some cases, failure rates for specific components or subsystems were not available so engineering judgment was used in applying failure rates for roughly similar items.

Thus human errors, and some hardware failures, are correctable and should only cause delays in fire fighting rather than long-term, total system failures.

In addition to human errors at the time of the emergency, the possibility exists for human errors to be committed during standby time so that the system is rendered in operative when needed. In a report on the effectiveness of fire fighting systems, Miller (19) states that the closing of valves that should be left open is a major problem in fire water systems and that the system reliability is influenced most heavily by human errors.

The foregoing discussion assumes that during the emergency the operating personnel will be able to reach the necessary equipment and that the equipment has not been damaged. A collision or fire in certain areas could damage the fire water system and hinder personnel movements. No attempt has been made to quantify the probability of such an occurrence but qualitatively it appears that the more severe the fire is, the greater the need for the fire water system and the higher the probability of system failure due to fire or external damage and/or inaccessibility of the equipment.

Dry Chemical Fire Extinguishing System

The main operating components of a large dry chemical fire extinguishing system are shown in Figure 41. The dry chemical storage unit (1) is used to store the dry chemical extinguishing agent and also functions as the mixing chamber for the dry chemical and the propellant gas (usually nitrogen). High pressure cylinders (2) supply nitrogen gas to fluidize the dry chemical and to propel it. Various types of high pressure valve arrangements (3) can be used to release the nitrogen. Regulators (4) drop the pressure from the storage pressure (2200 - 2700 psi (155 - 190 kg/cm^2)) to the operating pressure (usually 250 psi (17.6 kg/cm^2)). A check

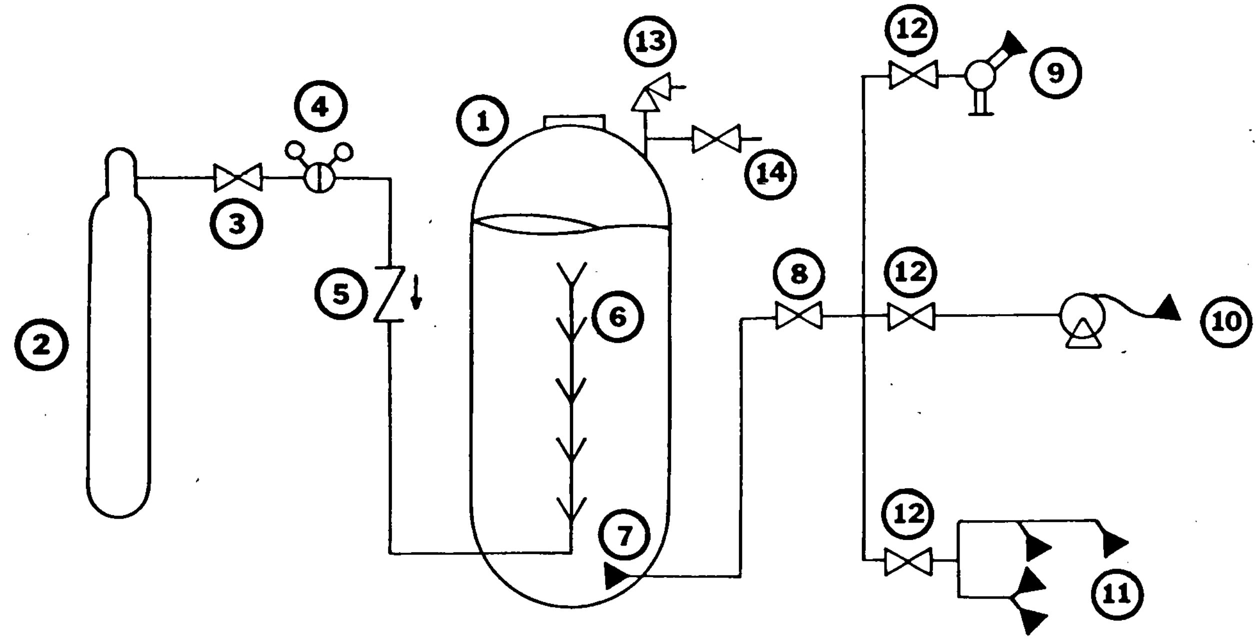


FIGURE 41. SCHEMATIC OF A DRY CHEMICAL FIRE EXTINGUISHING SYSTEM.

valve (5) is included in the line to prevent dry chemical powder from entering the regulators and high pressure cylinders. The regulated nitrogen gas enters the dry chemical storage unit through a series of holes in the fluidizing tube (6). The nitrogen breaks up the packed dry chemical so that it will flow more easily. Simultaneously, the pressure in the storage tank is increasing. The nitrogen/dry chemical mixture leaves the tank through the pick-up tube (7) when the main release valve (8) is opened and is then dispensed through monitor nozzles (9), handheld hoselines (10), or fixed nozzle systems (11). Isolation valves (12) are included so that only the desired dispensing systems will be pressurized. A pressure relief valve (13) is provided on the dry chemical storage tank to prevent overpressurization. Pressure relief valves are also incorporated in all pressure regulators and are found on some high pressure cylinder valves. A blow-off valve (14) is included so that any pressurized nitrogen in the storage tank can be easily released after the system has been used. It can also be arranged to blow nitrogen through the various dispensing devices in order to clear the distribution lines of residual dry chemical.

Table 8 lists the various components and subsystems found in a manually operated dry chemical system (i.e. it must be manually activated at the location of the unit). The failure rates used in the analysis are for components in continuous use rather than for standby use since standby failure rates are not available. The time at risk was chosen to be 50 hours which should correspond to the average time from USCG inspection (when entering the port) to the time the ship has transferred its cargo and has left the dock. This combination of continuous use failure rates and 50 hour time at risk should result in conservative estimates of failure probability (e.g. the dry chemical hose is in standby service until the dry chemical unit is pressurized and it is then in use for only a few minutes at most).

TABLE 8. FAILURE PROBABILITY PARAMETERS FOR DRY CHEMICAL SYSTEMS

Component Type	Failure Mode	Median Failure Rate*	Service Factor	Number of Failures Required	Number of Components	Time at Risk§	Failure Probability
Nitrogen Cylinders	Leak or Rupture	1×10^{-9}/hr ∇	2	1	3	50 hr	∿ 0
Cylinder Valves	Fails to Open	1×10^{-4}/D	2	1	3	N/A	0.0006
High Pressure Manifold	Leak or Rupture	2×10^{-5}/hr	2	1	3	50 hr	0.006
Pressure Regulators	Fails to Regulate	1×10^{-3}/D †	2	1	3	N/A	0.0006
Storage Tank	Leak or Rupture	1×10^{-9}/hr ∇	2	1	1	50 hr	∿ 0
Pressure Relief Valve	Opens Prematurely	1×10^{-5}/hr	2	1	1	50 hr	0.001
Distribution Piping	Leak or Rupture	1×10^{-9}/hr/Section	2	1	10	50 hr	∿ 0
Hose	Leak or Rupture	2×10^{-5}/hr	2	1	1	50 hr	0.002
Hose	Plugs	1×10^{-3}/D	1	1	1	N/A	0.001
Nozzle	Fails to Open	1×10^{-4}/D	2	1	1	N/A	0.0002

* Continuous use failure rates used because standby rates not available.

† Based on experience with large dry chemical systems.

§ Time at risk taken as 50 hours to approximate the time between USCG inspection and the end of cargo transfer operations.

∇ Data from Bush (12).

N/A = Not Applicable

Failure rates taken from WASH-1400 (9) unless otherwise noted. In some cases, failure rates for specific components or subsystems were not available so engineering judgment was used in applying failure rates for roughly similar items.

The failure probabilities are calculated on the basis that the entire system is in proper working order after the USCG inspection is completed. It is possible of course for certain failures to be overlooked by the inspector; it is after all only an inspection, not a test. The system is required to be tested once each year. The test is intended to check the system for leaks, proper valve operation, etc. by pressurizing the piping system, however, no dry chemical is discharged.

Many of the dry chemical units on board LPG ships are remotely operable and therefore include pneumatic or electric actuators, pressure or solenoid operated valves, and various other "refinements". These additions do not generally provide any redundancy to the system but do add additional components that can fail, thus the probability of system failure due to hardware failure increases. Most of the failures associated with these additional components can be overidden by local manual activation of the system.

As was the case for fire water systems, the operator of the system must play a large role in the proper operation of the dry chemical system. The operator must first decide whether or not he thinks he can extinguish the fire. If he decides that he can, he must then follow the proper sequence to activate the dry chemical system. Finally he must attack the fire in the proper manner in order to extinguish the fire. This discussion assumes that the equipment will be accessible during the fire and that the operator can approach the fire without encountering major obstacles.

In order to extinguish the fire, the equipment must work properly, the dry chemical flow rate must be sufficiently high (depends on fire size), and the operator must attack the fire properly. The subjects of flow rate versus fire size and the effectiveness of manual fire extinguishment will be dealt with in detail later.

LPG Barge Loading/Unloading Fault Tree

The fault tree analysis for an LPG barge is similar to that for refrigerated LPG ships; only spills onto the barge, the dock, or the water are considered. The analysis is also based on a "typical" LPG barge. Some of the parameters chosen for this barge are listed in Table 9. The "typical" barge concept was also used in determining the number of individual components used.

The fault tree for accidental release of LPG during barge loading/unloading is shown in Figure 42. The top event (i.e., and LPG spill) has been broken into a number of similar events, each one differing by the quantity of LPG spilled. Thus the system is analyzed by a series of fault trees, each one leading to a spill of a certain size. Events that allow spills to increase in size are shown as connecting events among the various fault trees.

As expected, many of the causative events are similar to those in the fault tree analysis of ship unloading. The spill sizes that can result from certain specific events are also similar. This is perhaps unexpected since the cargo transfer rate for the barge is significantly less than that for a large ship (1250 vs 7000 gpm (4.7 vs 26.5 m^3/min)). However, the pressures involved in the two cases are also quite different; the higher pressure of the barge operation leading to higher leak rates for a given size crack, rupture, etc. Also, the difference in the number of personnel involved in the transfer, their locations, and the relative lack of automatic shutdown equipment must be considered. The unloading of an LPG ship will typically be observed by four to six persons in the ship/dock area with at least two of these being on the ship. During the loading or unloading of a barge, only two persons are normally present in the barge/dock area and for most of the transfer they are both on the dock since the barge usually has no enclosed control room. Therefore,

TABLE 9. SELECTED PARAMETERS FOR "TYPICAL" LPG BARGE

Total cargo capacity	16,000 bbl (2500 m^3)
Number of cargo tanks	4
Number of pressure relief valves per tank	2
Number of liquid transfer arm connections	1
Size of liquid transfer arm connections	6 inch (15.2 cm)
Number of vapor transfer arm connections	1
Size of vapor transfer connections	4 inch (10.2 cm)
Maximum cargo transfer rate	1250 gpm (4.7 m^3/min)
Average load or unload time	12 hours

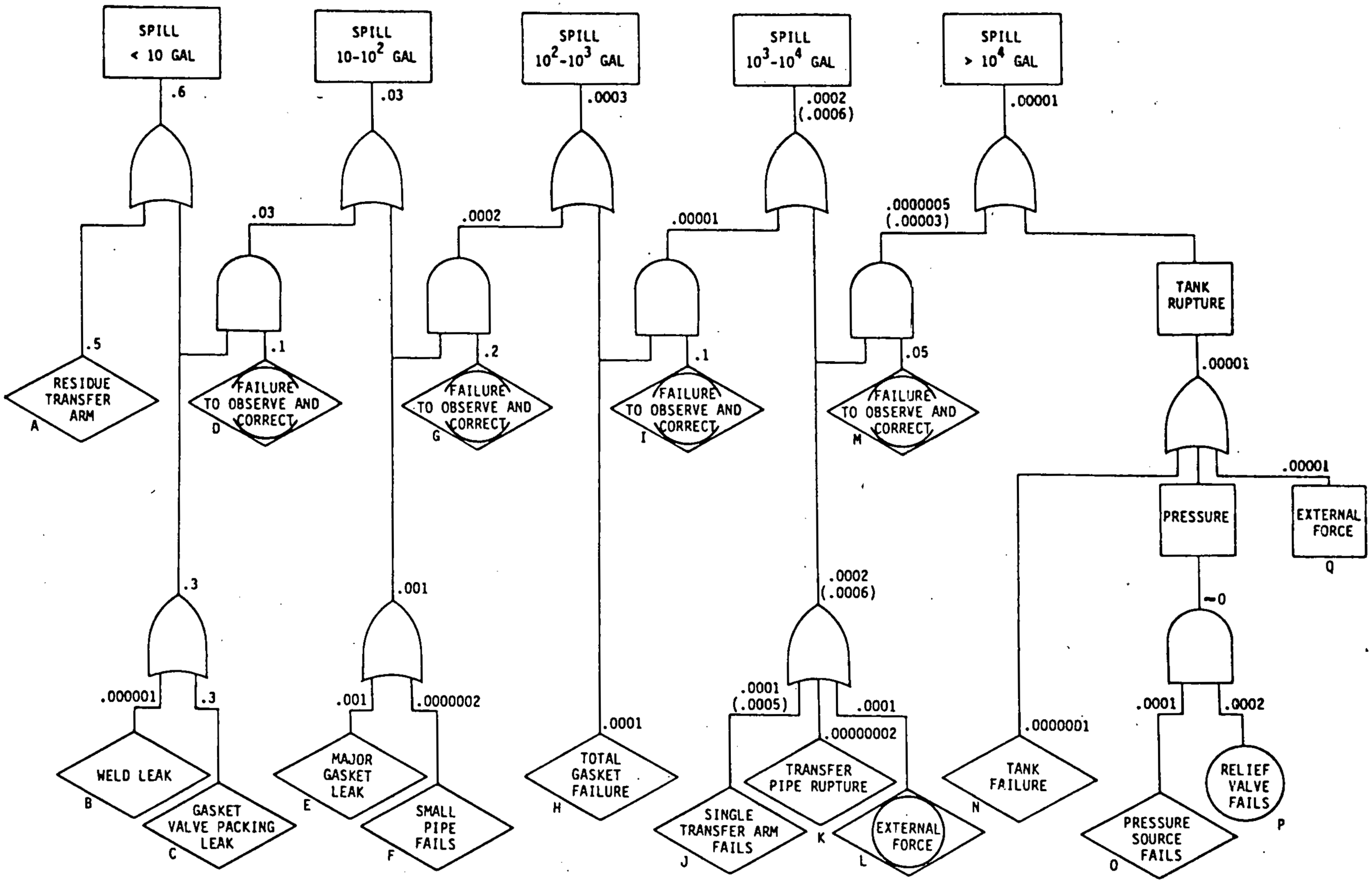


FIGURE 42. FAULT TREE: LPG BARGE LOADING/UNLOADING OPERATION SHOWING PROBABILITIES OF VARIOUS EVENTS LEADING TO SPILLS OF VARIOUS SIZES.

it would probably take longer for a given size of spill to be detected by the barge/dock personnel than it would in the case of a ship. The relative lack of spill detection and alarm equipment and the reliance on mostly manual shutdown valves also tends to increase the time required to detect a spill and stop the flow of cargo.

Whenever possible, the probability of failure for each component was calculated from the median value of the failure rate for the generic class of component as listed in WASH-1400 (9). In a few cases, generic failure rate data from other sources were used. Table 10 lists the various components, the median failure rate, source of data, etc. for all the initiating events. Each separate event will now be examined.

A. Residue Transfer Arm - Failure to clear all LPG liquid from the transfer arms before disconnecting them. After talking to several LPG plant and barge operators, it was estimated that, on the average, an LPG spill could be expected from this source on about one-half of the possible occasions ($P_d \approx 0.5$). It is perhaps questionable whether or not this event should be considered in a fault tree because some LPG terminal and barge operators said that such spills occur on almost every unloading due to their particular operational sequence; other operators said that it has never happened because they completely purge all lines prior to disconnecting. Note that the spill from the transfer arms does not connect to the next fault tree (10 - 100 gal spill) because the quantity of liquid in the arms is small, and, since no LPG is flowing, cannot increase.

Perhaps it should also be pointed out here that most barges use slip-tube gauging devices that release small quantities of LPG vapor and/or liquid every time that the liquid level in a tank is measured. The flow rate from such a device is so small that it is not considered hazardous.

TABLE 10. FAILURE PROBABILITY PARAMETERS FOR LPG BARGE LOADING/UNLOADING FAULT TREE

Component (or Subsystem)	Failure Mode	Median Failure Rate (a)	Service Factor	Number of Failures Required	Number of Components (b)	Time at Risk	Failure Probability Per Transfer
Transfer Arm	Liquid Residue	0.5/D †	N/A	1	1	N/A	0.5 †
Weld	Leak	3×10^{-9}/hr	2	1	100	12 hr	0.000001
Gasket or Valve Packing	Leak	---	2	1	20	12 hr	0.3 †
Operator	Fail to Observe and Correct	0.1/D *	N/A	1	N/A	N/A	0.1/D
Gasket	Major Leak	3×10^{-6}/hr	2	1	10	12 hr	0.001
Small Pipe	Leak or Rupture	1×10^{-9}/hr ∇	2	1	10	12 hr	0.0000002
Operator	Fail to Observe and Correct	0.2/D *	N/A	1	N/A	N/A	0.2/D
Gasket	Total Failure	3×10^{-7}/hr	2	1	10	12 hr	0.0001
Operator	Fail to Observe and Correct	0.1/D *	N/A	1	N/A	N/A	0.1/D
Transfer Arm	Leak or Rupture	3×10^{-6}/hr	2	1	1	12 hr	0.0001
Transfer Piping	Leak or Rupture	1×10^{-10}/hr ∇	2	1	10	12 hr	0.00000002
External Force	Pipe Leak or Rupture	---	N/A	1	N/A	N/A	0.0001
Operator	Fail to Observe and Correct	0.05/D *	N/A	1	N/A	N/A	0.05/D
Cargo Tank	Leak or Rupture	1×10^{-9}/hr **	2	1	4	12 hr	0.0000001

TABLE 10--Continued.

Component (or Subsystem)	Failure Mode	Median Failure Rate(a)	Service Factor	Number of Failures Required	Number of Components(b)	Time at Risk	Failure Probability Per Transfer
Pressure Source	Fails to Stop	1×10^{-4}/D	1	1	1	N/A	0.0001/D
Pressure Relief Valve	Fails to Open	1×10^{-5}/D	2	1	8	N/A	0.0002/D
External Force	Collision, etc.	---	N/A	1	N/A	N/A	0.0001 *
Transfer Hose	Leak or Rupture	2×10^{-5}/hr §	2	1	1	12 hr	0.0005

(a) Failure rates taken from WASH-1400 (9) unless otherwise noted. In some cases, failure rates for specific components or subsystems were not available so engineering judgment was used in applying failure rates for roughly similar items. Although the cargo transfer system is essentially a standby system (used intermittently), the failure rates shown are generally for continuous systems since standby failure rates are not available in many cases.

(b) Total number of components is based on the "typical" LPG barge concept which is in turn based on various actual LPG barges.

† Failure rates and/or probabilities based on barge and terminal experience.

∇ Failure rate given is "per section" of pipe.

* See text for source of failure rate or failure probability.

§ Failure rate taken from "Reliability Technology." (7)

** Failure rate taken from Bush (12).

N/A = Not Applicable.

B. Weld Leak - Failure of a weld on any of the cargo transfer piping to remain liquid-tight. As can be seen in Table 9, the median failure rate was 3×10^{-9}/hr. Combining this with a service factor of 2, an assumed total of 100 welds on the transfer piping (based on cargo piping drawings for various LPG barges), and at risk time of 12 hours per transfer operation.

C. Gasket, Valve Packing Leak - Failure of a gasketed piping joint or valve packing to remain liquid-tight. As Table 9 shows, no applicable failure rate could be found in the literature for this generic class of components. However, discussions with LPG terminal and barge operators indicated that such leaks were rather common. Therefore, a probability of 0.3 was selected for this event.

D. Failure to Observe and Correct - Failure of the barge/dock personnel to observe that LPG is leaking and failing to take proper corrective action to stop the leak. Weld, gasket, and valve packing leaks will generally occur when the cargo transfer piping is being pressurized at the very start of the transfer operation. During this time, the barge/dock personnel are especially watchful for such leaks. Therefore, most of these leaks are observed before much LPG has been spilled.

The probability of failure to observe and correct such leaks was judged to be 0.1. Note that because this event leads into an AND gate, and because this event will never occur unless a leak has already occurred, its failure probability must be on a 'per demand' basis.

E. Major Gasket Leak - Failure of a gasket to maintain its integrity. Cracks, splits, tears, etc. of a gasket will allow LPG to spill at a higher rate than the leaks covered under event C. Using the data contained in Table 9, the probability of a leak from this source, during the 12 hour "at risk" period, is 0.001.

F. Small Pipe Fails - Failure of a cargo handling pipe smaller than 3 inches (7.5 cm) in diameter to maintain its structural integrity. Splits, cracks or ruptures in small diameter pipes occur at a median rate of 1×10^{-9} per hour per section of pipe, according to WASH - 1400 (9). Note that this is per section of pipe, each section being defined as the length of pipe between two discontinuities such as pumps, valves, etc.; welds and flanges are not considered as discontinuities. Assuming 10 small pipe sections, the probability of failure is 0.0000002.

G. Failure to Observe and Correct - Failure of the barge/dock personnel to observe that LPG is leaking and failing to take proper corrective action to stop the leak. This event is the equivalent of the ESS failure event on the ship fault tree, the difference being that in the case of the barge the observation and shutdown are totally dependent on the operators. Spill detection instrumentation is normally not provided and, although the barge has a manually activated ESS, it is likely that shutdown will be accomplished by manually closing shore-based valves rather than boarding the barge (where the leak is located) to operate the ESS. The probability of this event, chosen as 0.2, is less than that for the corresponding event on the ship fault tree for three reasons: 1. The cargo is odorized so leaks are easier for the personnel to detect. 2. The cargo is under pressure so leaks may be more visible due to jetting or spraying. 3. The operators are usually somewhat removed from the barge (usually on the deck) and therefore should not perceive themselves to be in danger, thus their decision making should not be impaired. As was the case for the ESS failure on the ship fault tree, this event has an associated time limit (e.g. 10 minutes) since it is inconceivable that the leak could go unnoticed forever.

H. Total Gasket Failure - Failure of a gasket to remain in its required location (e.g. the loss of all gasket material between two or more bolts on a flanged connection). This type of gasket failure will result in leaks with flow rates higher than gasket failures C or E. Assuming 10 gaskets, the probability of failure is 0.0001.

I. Failure to Observe and Correct - Failure of the barge/dock personnel to observe that LPG is leaking and failing to take proper corrective action to stop the leak. The reasoning is the same as for G, however, the probability is only 0.1 since the larger spill rate is easier to detect.

J. Single Transfer Arm Fails - Failure of a metal or rubber LPG liquid transfer arm to retain its structural integrity. This includes cuts, splits, ruptures, etc. Rubber cargo transfer hoses have failure rates approximately five times greater than metal arms (7). Assuming one liquid transfer arm, the probability of failure is 0.0001 for a metal arm and 0.0005 for rubber.

K. Transfer Pipe Rupture - Failure of a cargo transfer pipe to remain liquid tight. As was the case for event F, the failure rate is based on a pipe "section". Assuming 10 pipe sections, the probability of pipe failure is 0.00000002.

L. External Force - Failure of the cargo transfer arm due to overextension caused by waves, winds, or the wake of a passing ship. In conversations with barge and dock personnel, it was determined that on rare occasions the wake from a passing ship has caused a barge to be torn loose from its moorings, subsequently causing rupture of the cargo transfer arms. Conceivably, wind or waves could also cause such a failure, however, under severe weather conditions, cargo transfer is often postponed. The probability of 0.0001 is based on limited data and is probably conservative.

M. Failure to Observe and Correct - Failure of the barge/dock personnel to observe that LPG is leaking and failing to take proper corrective action to stop the leak. The reasoning is the same as for G and I except that, due to the higher spill rate, the terminal control room operator might also detect the spill.

N. Tank Failure - Failure of a cargo tank to maintain its structural integrity. The design and construction of pressurized LPG cargo tanks are in accordance with Section VIII of the ASME Code for Pressure Vessels (20) which requires hydrostatic testing of the finished tank and incorporates a safety factor when determining the working pressure. Due to these factors, "spontaneous" failure of a cargo tank is very unlikely.

O. Pressure Source Fails - Failure of the source of pressure (pump, pressurized gas, etc.), used to move the cargo, to stop when desired. The cargo tanks are under pressure whenever they have any LPG in them; during cargo transfer, this pressure is increased due to the load/unload procedure. If the source of this excess pressure does not stop when desired (e.g. when the tank is nearly filled) the pressure in the tanks will increase even further. The probability of this event is very low, 0.0001, based on failure of a pump to stop on demand. In some cases, the pressurized gas source used for moving the cargo is at a pressure below the working pressure of the tank, thus the probability of this event is very small.

P. Relief Valve Fails - Failure of the pressure relief valves to open and allow excess vapor (or liquid) to escape. If the source of excess pressure cannot be stopped, then the relief valves must function to prevent failure of the tank. Assuming 2 valves per tank, 4 tanks, any one failure is critical gives a probability of about 0.0002 per demand. This number is probably conservative because it is likely that both relief valves on a given tank would have to fail to allow overpressurization.

Q. External Force - Failure of a cargo tank to retain its structural integrity following a collision with another barge or a ship. Only one failure of this type could be found (see Appendix B for a description of the accident). Unfortunately, no record of the number of LPG barge loadings and unloadings is available so it is difficult to determine an accident frequency rate based on historical data. The same type of reasoning as used for estimating accident frequencies for LPG ships can be applied to LPG barges with modifications to account for the much larger number of cargo transfer operations for barges (see Appendix C); the extra strength of the barge cargo tanks in comparison to the tanks on refrigerated LPG ships; and that the barges load and unload in U. S. waters. The probability of a cargo release from an LPG barge caused by impact from another barge or ship is thus estimated to be 0.00001 per cargo transfer, which is an order of magnitude less than that computed for LPG ships.

HAZARD POTENTIAL

The NFPA (21) defines LPG (liquefied petroleum gases) as "... any material having a vapor pressure not exceeding that allowed for commercial propane which is composed predominantly of any of the following hydrocarbons, or mixtures of them: propane, propylene, butanes (normal butane and isobutane), and butylenes". Thus the composition limits are extremely broad and the physical characteristics of LPG can vary widely. On the other hand, most of the LPG safety research and test programs have used commercially available LPG (predominantly propane) or commercial purity propane. Since much of the hazard potential analysis is based on these studies, the LPG will be considered to be predominantly propane, or, in certain cases, nearly pure propane.

LPG, when gasified, is an odorless, colorless, nonpoisonous mixture of flammable gases. (Odorant is generally added to LPG when pressurized but not when refrigerated). As with any gas, other than oxygen, high concentrations of LPG vapors can cause suffocation due to lack of oxygen. Skin contact with LPG can easily result in severe frostbite. (Refrigerated LPG is stored at its boiling point, approximately -43°F, (-42°C), and pressurized LPG, when released from pressure, quickly undergoes an adiabatic flash wherein some of the liquid vaporizes and the remaining liquid is chilled to approximately the boiling point). Contact of cold LPG and metals not suited for low temperature service might also be a problem because the sudden temperature change (thermal shock) might cause the metal to crack. Contact between LPG and water results in an initial period of "violent boiling" (22) followed by relatively rapid vaporization of the LPG; however, unless the water temperature is above 127°F (53°C) there will be no flameless vapor explosion (23) like those documented for LNG (liquefied natural gas) (24).

Thus if one is sufficiently distant from an LPG spill to prevent contact with the liquid and to prevent breathing high percentages of the vapor, the main hazards are presented by the flammable and explosive characteristics of the liquid and vapor. There are many different types of fires and explosions that must be considered:

1. LPG pool fire
2. Pressure LPG torch fire
3. Confined LPG vapor explosion
4. Burn-back of LPG vapor cloud
5. Unconfined LPG vapor cloud deflagration
6. Unconfined LPG vapor cloud detonation
7. BLEVE (Boiling Liquid Expanding Vapor Explosion) of pressurized LPG tanks

Each of these fires or explosions presents one or more of the following types of damage potential:

1. Direct flame contact
2. Radiative heat transfer to object outside the flame
3. Overpressures from deflagrations and detonations
4. Flying shrapnel from exploding pressure vessels

LPG Pool Fires

An LPG pool fire is a possibility whenever a sufficient quantity of LPG liquid is spilled to create an accumulation of the liquid on the ship's deck, on the water, or on the dock. As the liquid vaporizes the resulting vapor is dispersed into the air. If ignited, the vapor plume will burn back to the liquid and a pool fire will result. Unless this ignition takes place rather quickly, the burning (possibly an explosion) of the vapor cloud will present a hazard greater than that posed by the resulting pool fire.

Before, the hazards presented by an LPG pool fire can be estimated, the size of the pool must be determined. For refrigerated LPG, the main parameters that determine the pool size are the rate of release of LPG, the rate of vaporization of the accumulated LPG, the total volume of released LPG, and the rate at which the LPG spreads on the surface on which it is spilled.

In the case of pressurized LPG at ambient temperature, an additional parameter must be considered. Because the LPG is maintained as a liquid above its normal boiling point by the application of pressure, some of the LPG will "flash" to vapor immediately upon release of the pressure. The escaping LPG that does not flash will be cooled to its boiling point. Thus, in comparison to a spill of the same quantity of refrigerated LPG, less LPG is available to accumulate in the pool. Figure 43 shows the percentage of escaping propane that will flash (adiabatically) to vapor as a function of the storage temperature. It is likely for any real spill that the flashing will also cause agitation and droplet formation which will lead to increased vapor production, thereby resulting in less liquid accumulation. Consider, for example, two 100 gpm (378 ℓ/min) spills of propane; one from refrigerated storage at -43°F (-42°C) and one from pressurized storage at 70°F (21°C). Figure 43 shows that approximately 36 percent of the leaking propane from pressurized storage will flash to vapor (adiabatic flash). Thus it is likely that the liquid pool will spread not like a 100 (378 ℓ/min) spill but more like a 50 to 60 gpm (190 or 227 ℓ/min) spill of refrigerated LPG.

The spreading and boiloff rates of LPG on steel plates (e.g. a ship's deck) have not been experimentally determined. The LPG boiloff rate on water has been measured for very small area (29.6 in^2 (191 cm^2)), confined "spills" (22). However, applicability of this data to the case of larger, unconfined spills is somewhat doubtful. In addition, the usefulness of such information with respect to pool fires on the deck of a ship is limited since the ship's deck will likely not be level at the time of the spill; obstructions to the spreading pool

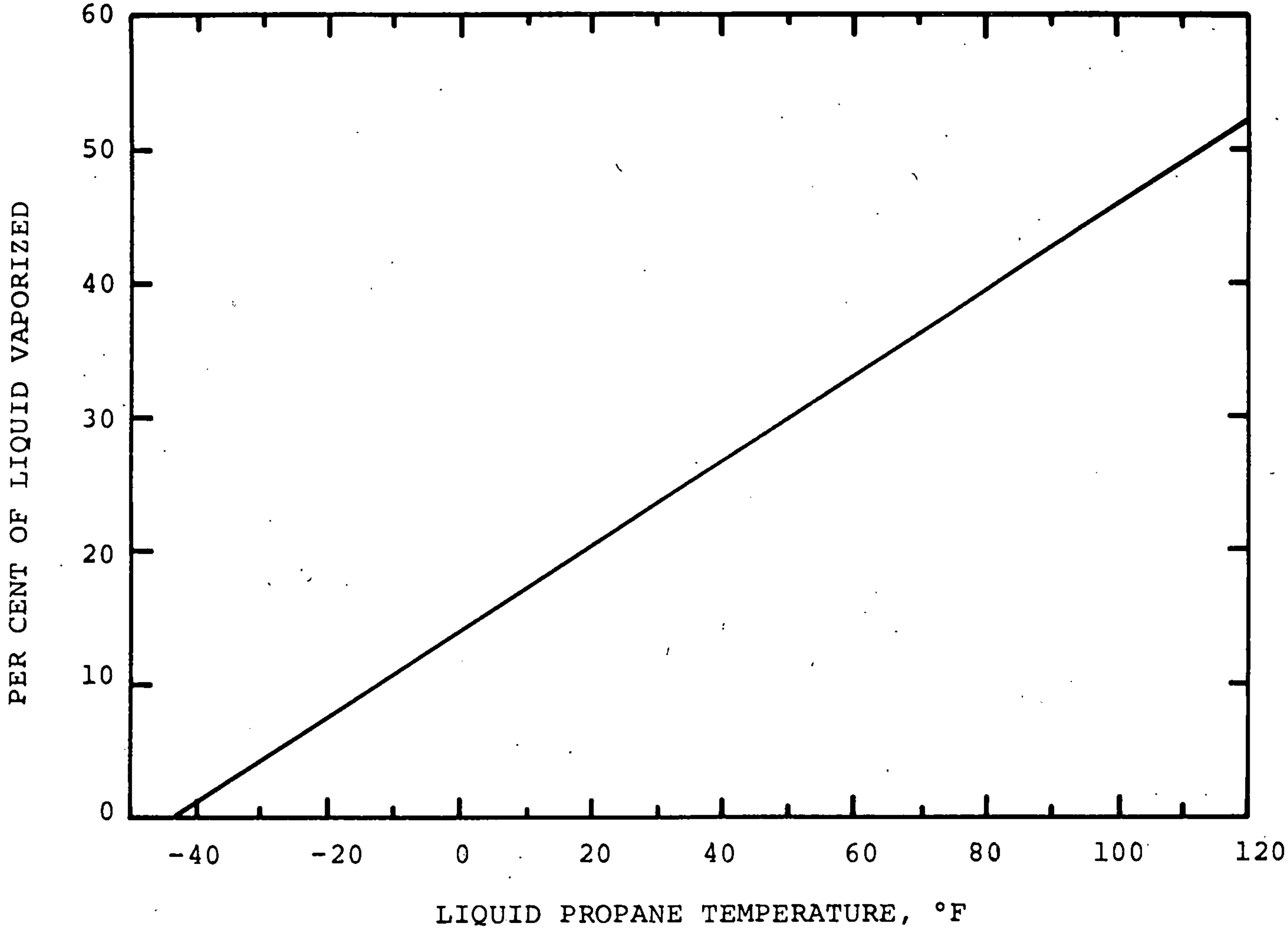


FIGURE 43. PER CENT OF LIQUID PROPANE THAT WILL FLASH (ADIABATICALLY) TO VAPOR WHEN RELEASED TO THE ATMOSPHERE (25).

are present (especially on ships with spherical tanks); the radiant heating power of large fires is not well known; and the dry chemical flow rates required to extinguish LPG pool fires have not been determined. These problems are being studied at present but results are not yet final.

The main hazard presented by an LPG pool fire is that the heating effect of the fire can cause personnel injuries and/or cause further failure of equipment, tanks, etc. Water sprays can be useful in protecting equipment, tanks, piping, etc. that are exposed to the thermal effects of a pool fire. Dry chemical fire extinguishing systems can be used to extinguish pool fires if personnel who have received some fire-fighting training can reach the dry chemical units. However, in some cases it may be preferable to allow the pool to burn, stop the leak, and protect exposures with water sprays rather than to extinguish the fire and risk a vapor cloud fire/explosion which could have greater destructive power. (A present peril of known magnitude may be preferable to a future peril of unknown, but possibly greater, magnitude).

Ignition of an LPG spill may occur simultaneously with the start of the spill or it may be delayed for some time. For a given spill rate and duration, the smallest pool fire results if the spill is ignited immediately. This fire also exists for the longest possible time (essentially equal to the spill duration if unconfined). Delayed ignition results in a larger pool fire of shorter duration. Confinement of the spill, such as in drip pans placed beneath the cargo transfer arm connections on many ships, will result in smaller fires of longer duration. The hazardous zone for a pool fire is thus affected by initial temperature of the LPG, duration and rate of spill, confinement (if any), and time of ignition, because they all effect the size and duration of the fire.

Pressurized LPG Torch Fires

The break in a pressurized LPG vapor or liquid line can result in a "torch fire", if ignited, since the fuel will be escaping at a relatively high velocity. The size of the fire is a function of the flow rate which in turn is controlled by the size of the break and the operating pressure of the pipe. If the leak occurs in the ullage space of a pressurized tank (i.e. the part of the tank that is not occupied by liquid) or a vapor line, the escaping LPG will be in the form of vapor. Due to the pressure in the tank, the flow rate will be quite high at first (limited by sonic velocity of the vapor through the opening) but will decrease with time as the vaporization of LPG within the tank results in cooling of the remaining liquid. If the leak is in the liquid filled portion of the tank or a liquid line, the release will be a mixture of vapor and liquid and the flow rate will remain high until the contents are all gone or until the liquid level is below the failed area.

For purposes of this analysis we shall assume that the 6 inch (15.2 cm) liquid withdrawal line has been broken. Using the method of Hardee and Lee (26) the flow rate through the broken pipe could be as high as 2000 gpm (7.6 m^3/min) or, expressing it as vapor since the assumed fire will be burning all of the released LPG, about 1400 ft^3/sec (40 m^3/sec). The approximate flame size can be calculated using the equations developed by Guise (27).

$$h = 18\ Q^{1/3} \qquad \text{Eq. 13}$$

$$d = 2.5\ Q^{1/3} \qquad \text{Eq. 14}$$

where: h = height of flame, ft

d = diameter of flame, ft

Q = gas flow rate, ft^3/sec

The calculated flame is thus about 200 ft (61 m) in length and 30 ft (9 m) in diameter.

The radiant heating power of LPG torch fires has not been determined; however, torch fires are known to have higher surface fluxes than pool fires due to the extra turbulence. Certainly the radiant heat from such a large fire could produce considerable damage. One of the worst possible situations that might occur is that the torch fire might impinge on one of the pressurized tanks, ultimately leading to an "explosion" of the tank (BLEVE).

Fortunately, the probability of a large torch fire is very small since the probability of a transfer pipe rupture or tank failure is less the 1×10^{-7} per cargo transfer. Also, the cargo transfer pipes are protected by shutoff valves that close if the temperature increases markedly and they can also be closed remotely if personnel can reach the location of the remote controls.

The fire extinguishers required to be on hand during cargo transfer on a barge are not nearly large enough to extinguish a fire of this size; however, it is doubtful if it would be desirable to extinguish it since the vapor cloud could pose a greater hazard than the torch fire. Water sprays can be of great benefit in combatting the effects of a torch fire. If the fire is impinging on another tank, the water sprays must be set up quickly because BLEVE's have been known to occur in less than 15 minutes.

The method for handling torch fires usually consists of allowing the fire to burn (not attempting extinguishment) until the flow of gas can be stopped, using water fogs and sprays to protect exposures and personnel, and evacuation of noncritical personnel from the area. By following this plan, fatalities should be preventable unless they occur immediately following the ignition or during the initial fire fighting period.

Confined LPG Vapor Explosions

If the vapors from an LPG release are allowed to accumulate within an enclosed space (e.g. control room, house, etc.), an explosion of the confined vapors becomes a possibility if the vapor concentration is within the explosive limits and if ignition sources are present within the enclosure. The strength of such an explosion is certainly great enough to cause serious damages to ordinary structures and to cause death to the inhabitants.

The enclosed areas on board ship and, in certain cases, in the terminal are provided with ventilation systems and gas detection equipment that are designed to prevent the entry of flammable vapors. In addition, the electrical systems are intrinsically safe or explosion-proof. Beyond the plant boundaries these precautions are not required.

Burn-Back of LPG Vapor Clouds

Whenever LPG is released from its containment system, the liquid starts to vaporize and the resulting vapor mixes with the air and forms a vapor cloud or plume. Portions of the vapor cloud will be flammable. For propane, the flammable limits are 2.1 to 9.5 volume percent. The size of the flammable portion of the vapor cloud is dependent on the vaporization rate, the density of the vapors, the local atmospheric conditions, and the area of the spill.

Although many vapor dispersion models have been developed for predicting the size of the flammable plume that results from a release of liquid or vapor, most of the models are based on Pasquill (28) type dispersion formulas that assume a Gaussian distribution of the dispersed vapor and do not take into account that LPG vapors are denser than air. This deficiency was highlighted by experiments conducted in the Netherlands in which the dispersion of dense gases from liquid spills was studied (29, 30). The tests showed that spreading of the cloud due to density differences with respect to the air (i.e. gravity spreading) is important and causes increased horizontal spread of the plume and decreased vertical spread. Once these differences are accounted for, the normal Gaussian distribution can be assumed and the standard dispersion formulas can be applied. It is interesting to note that increased horizontal spreading should aid dispersion and decreased vertical spreading should hamper dispersion; the end result being that, at least for relatively small spills, the distance (calculated) that the flammable plume extends downwind might not be greatly different whether the vapor density is or is not considered (30).

Predictions of the extent of flammable plumes resulting from propane spills (liquid and vapor releases), can be found in papers by Burgess and Zabetakis (31), Burgess, et al. (32), Sutton and McCauley (33), and Hardee and Lee (26). These predictions cover a range of spill rates and atmospheric conditions as shown in Table 11. Also included in Table 11 are flammable cloud sizes given by Davenport (34) for some actual vapor cloud incidents involving various liquid and vapor releases including LPG. The survey of actual vapor cloud incidents (34) includes two very large releases; a 30,000 gal (115 m^3) isobutane spill (from a railroad tank car) that created a cloud estimated to be 0.5 by 0.75 miles (800 by 1200 m) that was ignited 8 to 10 minutes after the spill; and a large release of butane, caused by overfilling an underground storage cavern, that created a cloud 1.25 miles (2 km) in diameter. Most of the other spills were ignited before the vapors had spread beyond 1000 ft (305 m).

It is apparent that the extent of the hazard presented by a flammable vapor cloud is a complex function of spill rate and quantity, spill location, atmospheric conditions, ignition delay time, and location of ignition. The influence of each of these variables can be predicted; higher spill rates can create larger clouds; longer spill times increase the time at risk; low wind speeds and stable atmospheric conditions increase the extent of the flammable plume; delayed ignition, due either to time or distance, increases the size of the resulting fire. However, in light of the controversies regarding dispersion calculations for large LNG spills, we feel that calculations of flammable plumes for LPG spills would

TABLE 11. PREDICTED EXTENT OF FLAMMABLE PLUMES RESULTING FROM LPG RELEASES

Commodity Released	Spill Size	Spill Time (min)	Wind Speed mph (m/sec)	Atmospheric Stability (Brookhaven)	Dimensions of Flammable Cloud ft (m)
LPG (Liquid)	31,500 gal (119,200 ℓ)	24	5.5 (2.4)	F	1500 ft long x 1000 ft wide (457 x 31 m)
Propane (Vapor)	370 ft^3/sec (10.4 m^3/sec)	---	12 (5.4)	B_1	72 ft long x 23 ft wide (22 x 7 m)
Propane (Liquid)	60 gal/min (227 ℓ/min)	---	12 (5.4)	B_1	250 ft long x 70 ft wide (77 x 21 m)
Propane (Liquid)	8,000 gal (30,280 ℓ)	1.3	---	---	388 ft diameter hemisphere (118 m)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	4.5 (2.0)	D	2200 ft long (671 m)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	24 (10.7)	C	180 ft long (55 m)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	16 (7.0)	B_1	118 ft long (36 m)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	8 (3.7)	B_2	115 ft long (35 m)
Isobutane (Liquid)	30,000 gal (113,550 ℓ)	---	---	---	3940 ft long x 2625 ft wide (1200 x 800 m)
Butane (Liquid)	---	---	---	---	6600 ft long (2000 m)
LPG (Liquid)	6,876 gal (26,025 ℓ)	---	---	---	400-600 ft diameter x 80 ft wide (120-180 x 24 m)

be only an academic exercise since there is no experimental data to compare the results to as there is for LNG. Perhaps it is sufficient to note that under certain conditions, the area covered by the flammable plume can be extensive.

The hazard presented to life by the burn-back of an LPG vapor cloud is related to the area covered by the cloud at the time of ignition and to the population density since it can probably be assumed that anyone caught in the burning plume will be killed. Due to the relatively short lived nature of the fire, there is little threat of fatality to persons outside the flammable cloud. The average number of fatalities due to such a fire can thus be quantized as the population density (people per unit area) times the area of the plume at the time of ignition. However, it is too simplistic to assume that the predicted number of fatalities increases linearly with population density since the area of the plume is also related to population density since, as the population density increases so does the number of possible ignition sources; more ignition sources should lead to earlier ignition thus reducing the area of the plume at the time of ignition. Simmons (35) has attempted to quantize this interrelationship between population density, ignition potential, and flammable plume area (e.g. based on the historical record for LPG accidents (mainly trucks), he has proposed that over half of the spills are ignited essentially instantaneously).

There is of course a possibility that the plume will not be ignited. In one case listed by Davenport (34), 9,500 gal (36 m^3) of butane was released from a broken transfer pipe without ignition. In another case it is known that a 6 inch (15.2 cm) transfer connection broke while loading a barge with butadiene and, although the liquid spread over a wide area on the water, no ignition occurred. In general, the probability of ignition increases as the spill size and population density increases.

Unconfined LPG Vapor Cloud Deflagrations

A deflagration is considered to be one type of explosion that can occur in an unconfined vapor cloud. The deflagration can begin with a simple, low energy ignition of the cloud. The resultant flame heats the surrounding vapor/air mixture; the flame travels faster in the preheated mixture; the result being that the flame front tends to travel even faster (but never greater than sonic velocity) as the flame propagates. The burning is accompanied by an increase in pressure due to the temperature rise and the increase in the number of moles of gas. This overpressure can be thought of in terms of a strong wind.

There is thought to be a possibility that an unconfined propane/air vapor cloud containing from 2.1 to 9.5 percent propane (by volume) could deflagrate if ignited. Experiments using plastic film hemispheres of 32.8 ft (10 m) radius to simulate unconfined propane/air clouds have failed to produce any acceleration of the flame front (36); however, the presence of obstructions or surface irregularities outdoors might create a sufficient increase in flame turbulence to cause the acceleration of the flame front. In certain cases where some degree of confinement is present (e.g. burning inside a long pipe) the flame speed can accelerate sufficiently to make a transition to a detonation.

Strehlow and Baker (17) have gathered damage data on a number of unconfined vapor cloud explosions and have concluded that "... detonative combustion must always occur before a destructive blast is produced". However, in an earlier paper, Strehlow (38) states "... deflagration velocities are commonly observed to be quite high and extensive blast wave damage can occur even for this type of vapor cloud combustion...". Obviously some uncertainty exists concerning the destructive effects of deflagrations of unconfined vapor clouds. For the purposes of this report, the damage potential of a deflagration is considered to be intermediate between the simple burn-back of the vapor cloud and detonation of the vapor cloud; i.e. the damage area is assumed to be only slightly larger than the area covered by the portion of the vapor cloud richer than the lower flammable limit and damages are restricted to those caused by fire and small overpressures.

Unconfined LPG Vapor Cloud Detonations

A detonation of an unconfined vapor cloud is similar in some respects to a deflagration in that both involve fast moving flame fronts and both produce overpressures. They differ in that a detonation propagates at supersonic speed and generates a shock wave. The blast pressures from detonation can be as much as one thousand times greater than those caused by deflagrations but are usually only from five to ten times as great (39).

The possible destructive effects of a detonation are certainly greater than those due to burn-back or deflagration of the flammable plume. However, the probability of an unconfined vapor cloud detonation is much less than that for a burn-back or deflagration due to the restricted conditions under which a detonation can occur.

The flammable limits for propane in air, measured at atmospheric pressure and ambient temperature, are 2.1 and 9.5 volume percent. Mixtures of propane and air that fall between these limits will burn if ignited; however, not all mixtures within this range will detonate. The detonable range for propane/air mixtures contained in large plastic bags (to stimulate unconfined conditions) was determined to be approximately 3 to 7 volume percent (using 800 grams of high explosive as the initiator) (40).

In addition to the narrower composition limits for detonability, the ignition energy required for detonating a propane/air cloud is much greater than that required for simple burning of the cloud. In general, it is believed a simple flame ignition source will not cause detonation of an unconfined propane/air cloud (39). A shock wave generated by detonating high explosives, by explosions of confined vapors, by the impact of flying objects, etc. can trigger a detonation if of sufficinet strength. Benedick, Kennedy, and Morrison (40) experimentally determined that the minimum amount of high explosive needed to cause an unconfined, stoichiometric propane/air cloud to detonate is 0.33 lb (0.15 kg). The amount of high explosive required increases as the deviation from stoichiometric increases. The detonation of the propane/air cloud following the break of a propane pipeline at Port Hudson, Missouri, is believed to have been caused by the explosion of a building within the cloud (31). The strength of such an explosion that is required in order to cause detonation of an unconfined cloud is not known but it is probably similar to the equivalent amount of high explosives required since both methods trigger detonation by means of a shock wave. Brown (39) has reported that the impact of an 8 inch (20.3 cm) diameter, 0.25 inch (0.64 cm) thick steel plate traveling at 7500 ft/sec (2286 m/sec) is sufficient to detonate a propane/air cloud.

The possibility of direct initiation of propane/air detonations (i.e. a detonation caused not by a precursor detonation but rather by flame acceleration) has been hypothesized. However, experiments by Lind and Whitson (36), which were designed to optimize conditions for such detonations, have not yet resulted in any propane/air detonations.

Attempts at predicting the possible damages that might be caused by an unconfined vapor cloud explosion have been made by various authors (31, 32, 33, 34, 41). The method used usually consists of postulating a spill of a certain rate and quantity under certain atmospheric conditions; calculating the extent of the flammable cloud that corresponds to these conditions; calculating the quantity of fuel contained within the cloud; making an assumption as to the percentage of fuel that contributes to the explosion; calculating a TNT equivalent for the explosion; and finally predicting damages based on a damage vs scaled distance plot shown in Figure 44.

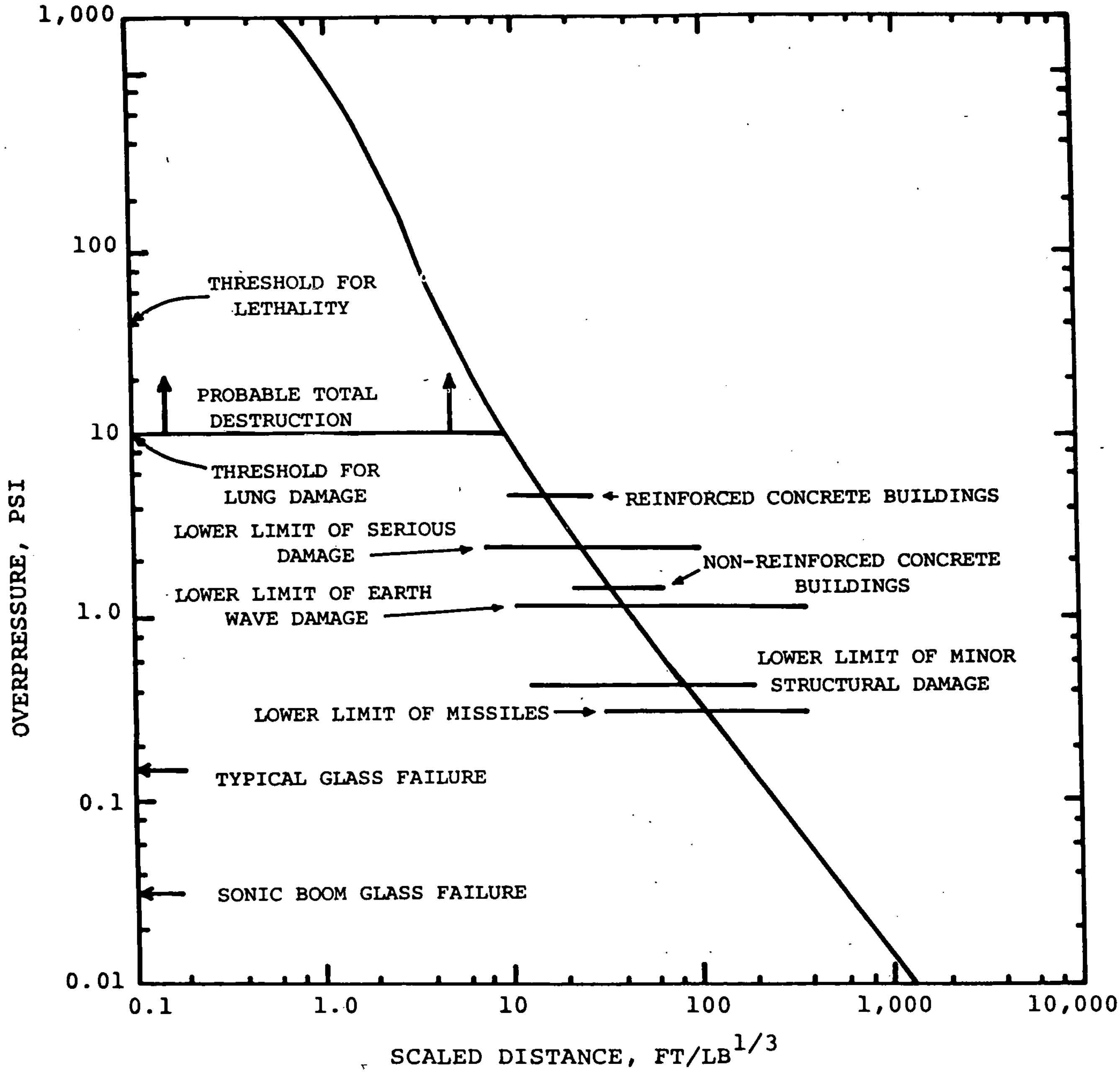


FIGURE 44. OVERPRESSURE VS. SCALED DISTANCE PLOT SHOWING TYPICAL LEVELS FOR BLAST DAMAGE TO OBJECTS (41, 43) AND HUMANS (44).

Some of the uncertainties involved in calculating flammable plume sizes have been discussed previously. Obviously if calculation of the distance to the leading edge of the flammable plume is uncertain, calculating the volume of the plume and the quantity of flammable vapor within the plume is subject to even greater error. Estimates have been made that for a continuous fuel release the maximum quantity of fuel that is within the flammable vapor cloud at any given time is never more than 10 percent.

The fuel conversion ratio (i.e. the percentage of fuel within the flammable plume that is assumed to contribute to the explosion) is also uncertain. Numbers as low as 10 percent have been postulated for rapid (nearly instantaneous) release (42). For longer term spills, 100 percent conversion is usually assumed (33, 41).

The equivalent amount of TNT is computed on the basis of 1 lb (454 gm) of TNT releasing about 2000 Btu/lb (1110 cal/gm) and 1 lb of propane releasing about 17,000 Btu/lb (9400 cal/gm), (31), (Sutton and McCauley (33) use 22,000 Btu/lb (12,160 cal/gm) for propane). This conversion to TNT is subject to error since large vapor cloud explosions exhibit non-ideal behavior (37), because the fuel is distributed over a wide area rather than being concentrated at one point as is the case for high explosives.

Once the TNT equivalent has been calculated, potential damage zones can be established by using the overpressure vs scaled distance curve shown in Figure 44.

Applying this method to the propane vapor clouds calculated by Burgess and Zabetakis (31), Burgess, et al. (32), Hardee and Lee (26), and Sutton and McCauley (41) leads to some interesting findings as shown in Table 12. Using a value of 40 psi (2.8 kg/cm^2) overpressure as the threshold value for fatalities, very few deaths would be caused to persons outside the flammable cloud due strictly to overpressure effects. The overpressures outside the cloud could of course slam the person into an object or cause failure of

TABLE 12. CALCULATED DAMAGE POTENTIALS FOR UNCONFINED LPG PLUME DETONATIONS

Commodity Released	Spill Size	Spill Time (min)	Wind Speed mph (m/sec)	Atmospheric Stability (Brookhaven)	Dimensions of Flammable Cloud ft (m)	Volume of Flammable Cloud ft^3 (m^3)	Volume of Propane in Cloud ft^3 (m^3)	Conversion (%)	TNT Equivalent lb (kg)	Distance to Overpressure 40 psi ft (m)	Distance to Overpressure 10 psi ft (m)
LPG (Liquid)	31,500 gal (119,200 ℓ)	24	5.5 (2.4)	F	1500 ft long x 100 ft wide (457 x 31 m)	1,100,000 (31,150)	53,900 (1525)	100	50,000 (22,730)	185 (57)	330 (101)
Propane (Liquid)	30,000 gal (113,550 ℓ)	0	---	---	---	---	1,077,000 (30,509)	10	139,500 (63,410)	260 (79)	470 (143)
Propane (Vapor)	370 ft^3/sec (10.4 m^3/sec)	---	12 (5.4)	B_1	72 ft long x 23 ft wide (22 x 7 m)	9,420 (267)	570 (16)	100	737 (335)	45 (14)	80 (25)
Propane (Liquid)	60 gal/min (227 ℓ/min)	---	12	B_1	250 ft long x 70 ft wide (77 x 21 m)	273,700 (7,750)	16,560 (469)	100	21,444 (9747)	140 (43)	250 (76)
Propane (Liquid)	8,000 gal (30,280 ℓ)	1.3	---	---	38 ft diameter hemisphere (118 m)	15,000,000 (424,800)	330,000 (9350)	10	31,200 (14,180)	160 (49)	280 (85)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	4.5 (2.0)	D	2200 ft long (671 m)	3,037,000 (86,000)	93,600 (2650)	100	90,000 (40,910)	225 (69)	400 (122)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	24 (10.7)	C	180 ft long (55 m)	44,850 (1,270)	1410 (40)	100	1360 (620)	55 (17)	100 (31)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	16 (7.0)	B_1	118 ft long (36 m)	43,800 (1,240)	1380 (39)	100 100	1325 (600)	55 (17)	100 (31)
Propane (Vapor)	883 ft^3/sec (25 m^3/sec)	---	8 (3.7)	B_2	115 ft long (35 m)	79,100 (2,240)	2470 (70)	100	2380 (1080)	70 (21)	120 (37)

a structure, either of which could cause death. Whether or not persons within the plume would be killed by blast overpressures is a moot point since anyone in the flammable plume at the time of ignition would probably be killed by the fire.

Boiling Liquid-Expanding Vapor Explosion

A BLEVE (Boiling Liquid-Expanding Vapor Explosion) is the name given to the violent rupturing of a pressure vessel that can occur when a pressure vessel that is partially filled with liquid is exposed to a fire. The accident scenario generally is:

a) A pressure vessel, partially filled with liquid, is subjected to high heat flux from a fire.

b) The temperature of the liquid starts to increase, the pressure in the tank increases due to the increased vaporization rate until the safety relief valve pressure setting is reached, at which time the relief valve opens and starts to vent vapor (or liquid) to the outside.

c) Simultaneous with the previous step, the temperature of that portion of the tank shell that is not in contact with the liquid (i.e. the ullage space) increases dramatically.

d) The heat weakens the tank shell around the ullage space and thermally induced stresses are created in the tank shell near the vapor/liquid interface (45).

e) The thermally induced stresses, heat weakened tank, and high internal pressure combine to cause a sudden, violent rupture of the tank.

f) Fragments of the tank are propelled away from the tank location with great force.

g) Some of the remaining liquid vaporizes extremely rapidly due to the pressure release and some atomizes to small drops

due to the force of the explosion.
A fireball is created by the vapor
and liquid.

A BLEVE cannot occur because of a failure of a very large cargo tank on refrigerated LPG ships because the tanks would generally fail at a fairly low pressure (except for spherical or cylindrical tanks), water spray systems are available (not on all ships) to spray exposed portions of the tanks, and the insulation helps to prevent heat-up of the cargo tanks and cargo. In some cases, pressure vessels are provided on the deck of a ship to hold refrigerants or small quantities of LPG. These could undergo a BLEVE if exposed to a pool fire burning below them or if a torch fire impinged on them. Most LPG ships have water spray systems to protect such tanks.

LPG barges present an altogether different possibility of a BLEVE; the cargo tanks are pressure vessels, the cargo is already substantially above its boiling point, no insulation or water spray is available, and, due to the open hopper style of construction, any liquid LPG that leaks from a tank will be contained so that any resultant fire will certainly contact one or more of the storage tanks. The hazard posed by the pieces of the metal tank that are scattered when the tank ruptures is difficult to quantify. A calculation can be made that will estimate the amount of energy released when the rupture occurs, however, the blast wave created by the rupture presents only a minor hazard compared to flying fragments and the fireball. Uncertainties concerning how much of this energy is transmitted to the metal tank pieces, size and weight of fragments, etc. are of such a magnitude that one can have little confidence in the prediction of hazards due to flying fragments. Actual data gathered on the distances that tank fragments have been hurled by BLEVE's of LPG railroad tank cars are available (46). They show that fragments as large as one-half of a 33,500 gal (112 m^3) tank car tank can be hurled 1500 ft (457 m) or more from the site of the car. Smaller fragments, still large enough to cause severe injury or death, have been thrown several thousand feet.

The other hazard presented by the BLEVE of an LPG tank is the fireball created by combustion of the mixture of vapor and liquid that is explosively dispersed by the sudden rupture of the tank. The sudden expansion of the compressed vapor and the large quantities of vapor suddenly produced by liquid flashing combine to create a large ball of liquid and vapor. The heat created by the burning of the dispersed LPG causes a powerful thermal updraft which interacts with the burning LPG to create a constantly rising, toroidal shaped "ball of fire". The size and duration of the fireball can be estimated by using the empirical relationships developed by High (47) as modified by Strehlow and Baker (37).

$$d = 9.73\ W^{1/3} \qquad \text{Eq. 15}$$

$$t = 0.23\ W^{1/3} \qquad \text{Eq. 16}$$

where: d = diameter of fireball, ft

t = duration of fireball, sec

W = weight of combustibles, lb

If we assume that 40,000 gal (151 m^3) are involved (this accounts for some loss by venting before the BLEVE occurs), the fireball is approximately 565 ft (172 m) in diameter and lasts about 13 sec. For 25,000 gal (95 m^3), the results are 480 ft (146 m) and 11 sec (see Figure 45).

The effect of radiant heat from the fireball on objects at grade level is difficult to predict with accuracy since, although the diameter and duration of the fireball can be calculated, the distance between the fire and the object is constantly increasing; thus the heat flux to the object is not constant but decreases with time. In most cases, the area directly beneath the fireball will be subjected

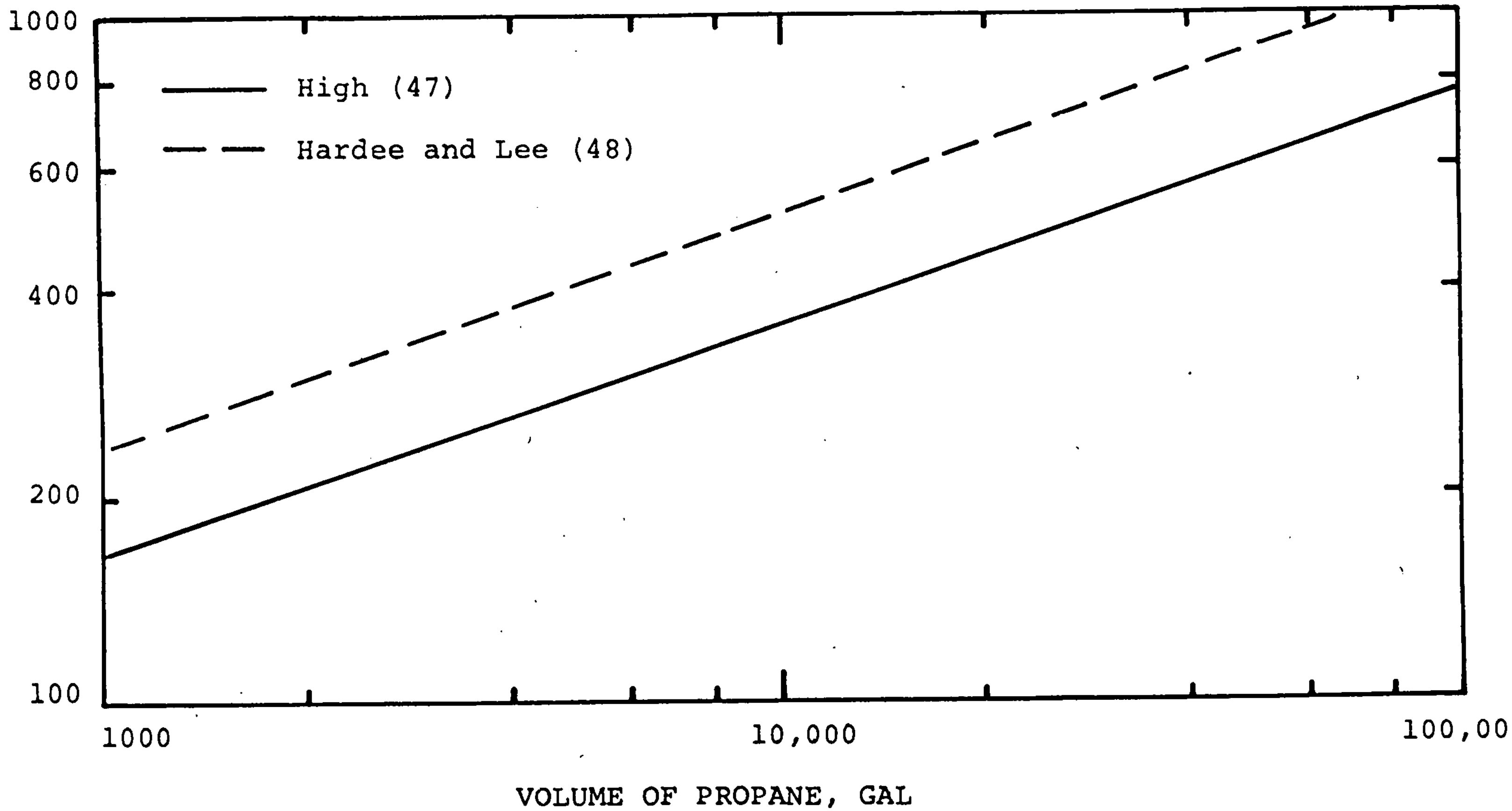


FIGURE 45. DIAMETER OF FIREBALL FORMED FOLLOWING CATASTROPHIC FAILURE OF A PRESSURIZED PROPANE TANK.

to sufficient flame contact with the fireball in its early stages (ground flash) to cause ignition of ordinary combustibles. Structural damage to noncombustible objects would be expected to be minimal because the fireball lasts for only a few seconds.

Hardee and Lee (48) have developed a model for determining the thermal hazard associated with propane fireballs. Using our previous assumption of some cargo loss before the BLEVE occurs, a maximum of about 200,000 lb (140,000 kg) of propane could be involved in the fireball. According to their analysis, this would create a fireball approximately 820 ft (250 m) in diameter (i.e. about 45 percent larger than calculated by the previous method) that could cause ignition of ordinary class A combustible materials (wood, paper, etc.) at a distance of about 820 ft (250 m) from tank and third degree skin burns at a distance of 1200 ft (366 m). These should be considered the absolute maximum distances because the analysis is based on worst case, idealized conditions (e.g. stoichiometric propane/air mixture) and the calculations of fireball sizes are based on extrapolations from fairly small tests.

Siewart (49) analysed the location of tank fragments following explosions of liquid propellant vessels and recommends that all persons within a 2,000 ft radius of the tank be evacuated. His analysis showed that only 5% of the fragments traveled more than this distance. He also calculated that if the area within a 2,000 ft radius is evacuated, the probability of a fatality is one in 100 such accidents.

The NFPA (Handling Hazardous Materials Transportation Emergencies) (50) recommends an evacuation distance of 2,500 ft from railroad tank cars to protect the public from flying debris due to a BLEVE. The potential burn areas due to the ground flash and fireball from a railroad tank car BLEVE is given as up to 1,000 ft. The time in which corrective action and evacuation must take place is given as between 10 and 30 minutes. This is the time between flame contact with the vessel and the BLEVE. Although these figures apply to railroad tank cars, it is reasonable to expect similar behavior for LPG tank barge cargo tanks; the main difference being that the barge cargo tanks are generally of larger capacity than railroad tank cars, thus the potential for larger fireballs and increased travel of tank fragments exists.

DISCUSSION

The probabilities of cargo spills of various sizes occurring during the unloading of LPG ships and during the loading and unloading of LPG barges have been estimated by the technique of fault tree analysis. The analysis was limited to those events that might cause cargo release because the goal was to estimate the probability of occurrence of events that might either endanger the public or operators, or escalate to a larger event that could endanger the public or operators. In this context, danger to the public or operators was considered only when the vessel was in port or traversing an inland eaterway. The major emphasis was on dockside operations because the cargo is then being transferred rather than in storage.

The fault tree diagram shown in Figure 39 summarizes the probabilities of cargo spills of various sizes occurring during any single unloading of an LPG ship. Figure 46 is a graphical summary of the event (i.e. cargo spill) probabilities from Figure 39. The event probability has been plotted as a function of spill size, where the spill size is taken to be about the middle of the spill range on a logarithmic scale. The plot is shown as a broad range rather than a line to empha= size the approximate nature of the failure probabilities.

Figure 42 shows a fault tree for loading or unloading LPG barges. The events that lead to spills are similar to those for LPG tankers, but the spill probabilities may be different because of differences in design, operating pressures, and transfer procedures. Figure 47 shows a graphical summary of the event probabilities from Figure 42. Again the plot is shown as a broad line to emphasize the approximate nature of the spill probabilities.

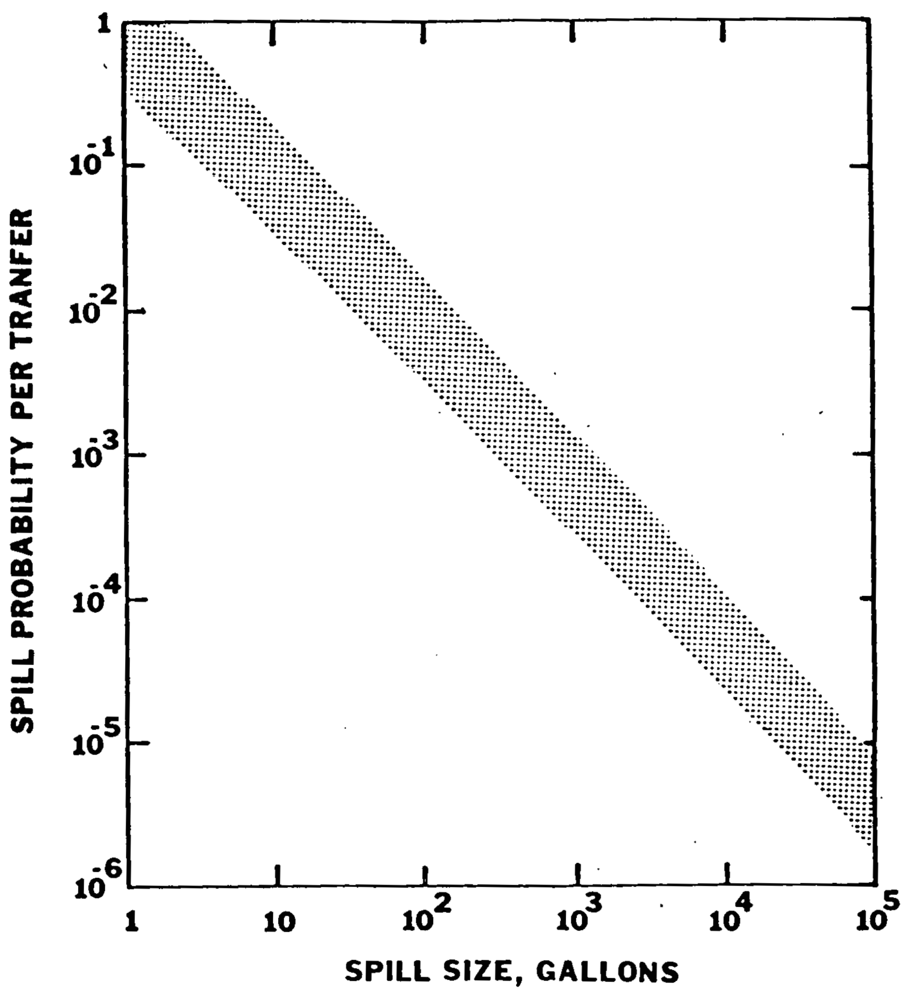


FIGURE 46. SPILL PROBABILITIES FOR LPG TANKER TRANSFER OPERATIONS.

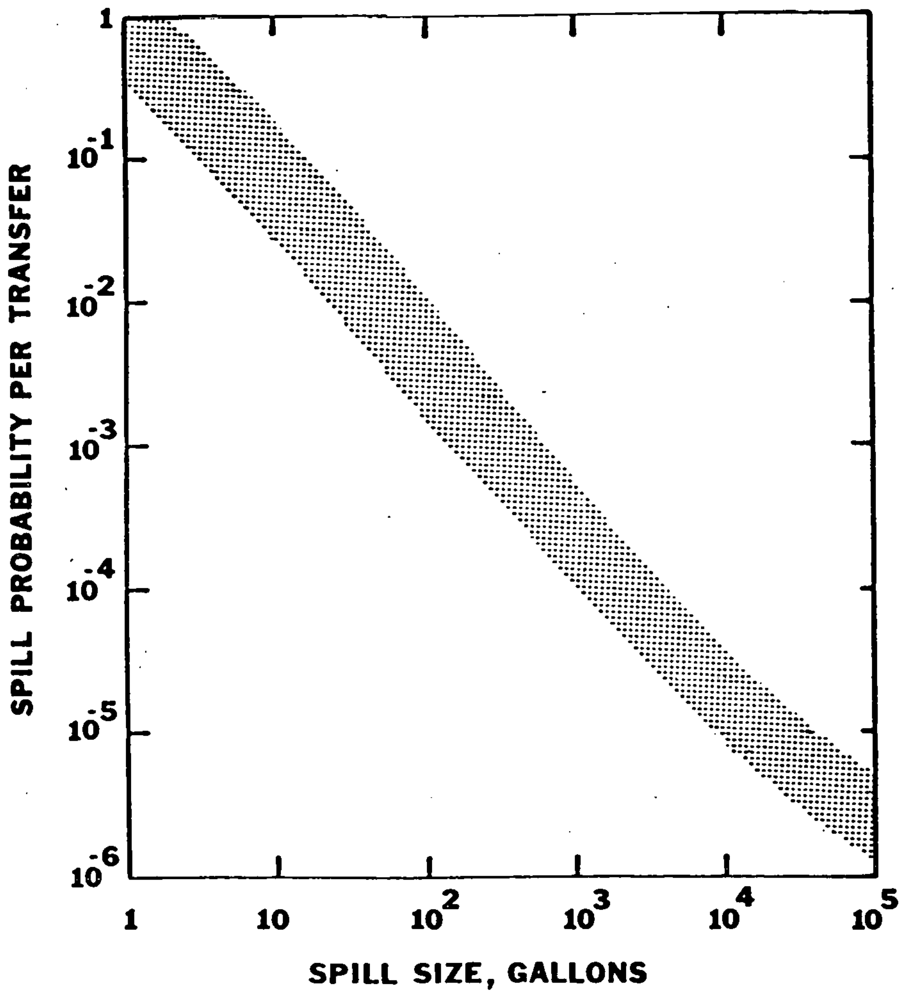


FIGURE 47. SPILL PROBABILITIES FOR LPG BARGE CARGO TRANSFER OPERATIONS.

It is interesting that the spill probabilities for barge and tanker operations are about the same. Intuitively, it might appear that barges would have more spills because of the pressurized cargo transfer and less sophisticated equipment and procedures. However, the transfer operations are simpler and the transfer time is shorter, so that the risk is reduced. Barge collisions causing spills are shown as being an order of magnitude less probable than ship collisions. The barge transport of LPG has a fairly long history and a much larger number of transfers than tanker transport, with only one known spill due to collisions. Collisions involving tankers may in fact have a much lower probability than shown, but there is not sufficient historical data to prove it. Notice that for both ships and barges the probability of a spill of less than 10 gallons is quite high, and can in fact be expected to occur on more than half of the loading or unloading operations. The reason that the spill probability is so high is that in some operations the disconnect sequence requires draining a small quantity of LPG from the transfer arms. Small leaks from valve packing and gaskets are also expected to occur. While these leaks may not be corrected immediately, they are small enough that there is little chance that they will result in more than 100 gals being released over the unloading period. Larger spills are less likely to occur than smaller spills. In fact, for spills greater than 100,000 gals, the most likely cause of the spill is an external force such as a ship collision. The reason is that even at the highest transfer rates, the flow would be shut off following a failure before such a large spill could accumulate.

Even though the spill probability may be large for some parts of the cargo transfer operation, it does not necessarily follow that the operation is especially dangerous. The primary danger from LPG spills, particularly those less than a few hundred gallons in volume, is from fire. The ignition probability depends on the spill size, with ignition more likely for larger spills. Small spills, less than 10 gal in size, which occur during more than half the transfers, must have very low ignition probabilities. Otherwise, fires would be common occurrences at LPG terminals. On the other hand, spills involving more than 100,000 gal of LPG at a high spill rate are practically certain to be ignited, although the compilation of liquefied gas ship incidents (16) includes one spill of "hundreds of tons of butane" (100,000 gal ≈ 250 tons) during the unloading of an LPG ship in France that did not ignite. The probability of fire occurring during transfer can be estimated if ignition probabilities are known. As an estimate, the following are used to approximate ignition probabilities:

Spill Size, gal	Ignition Probability
<10 gal	0.001
100 gal	0.01
5000 gal	0.1
>100,000 gal	1.0

These ignition probabilities are assumed to apply regardless of whether the spill occurs at a barge or tanker operation. If the ignition probabilities are applied to the spill probabilities from Figures 46 and 47, the result is the probability of occurrence of fire during a transfer operation. Figure 48 shows the approximate fire probability for both barge and tanker operations for non-collision events.

The probability of a ship collision is estimated to be 0.0001 per transit based on historical data for gas carriers. However, the design of LPG ships will offer some protection from LPG spills (as the Yuyo Maru incident showed). Therefore, the spill frequency will be much less than shown in Figure 39. The frequency will also be reduced substantially if traffic controls are instigated, as shown by Cave and Kazarians (14). It should also be recalled that the collision frequencies

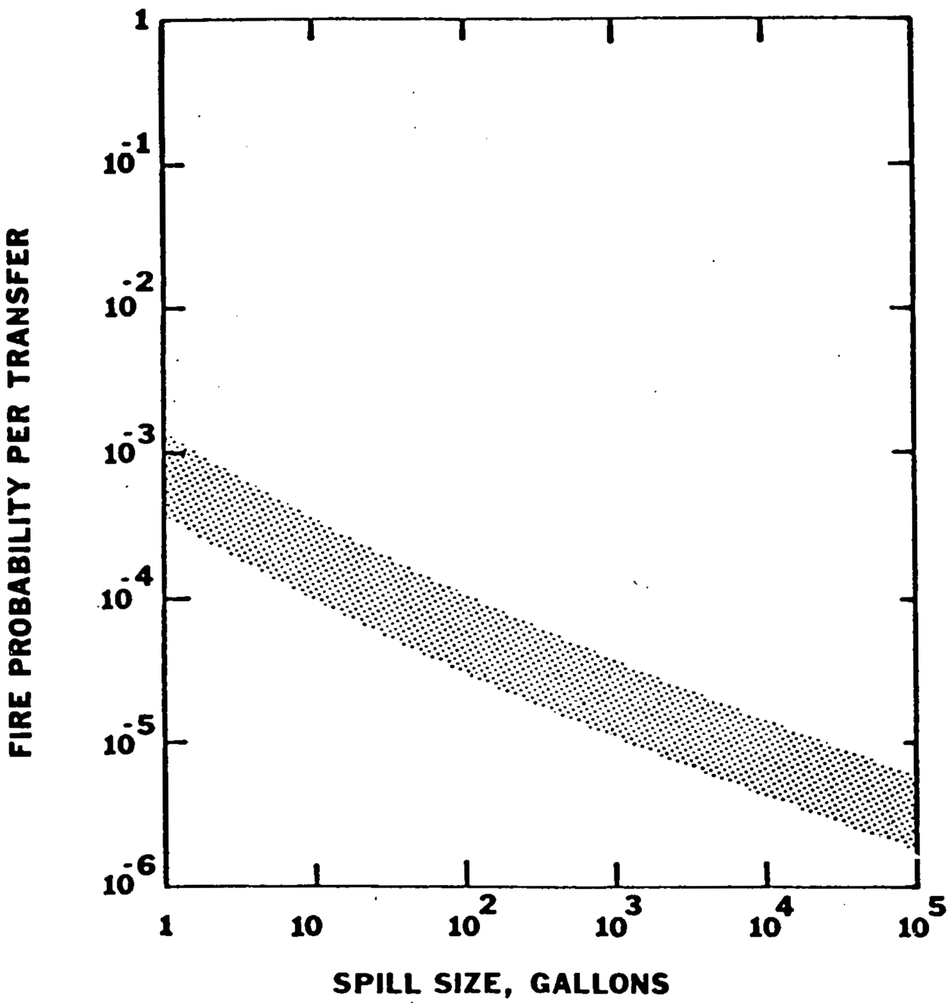


FIGURE 48. FIRE PROBABILITIES FOR LPG TRANSFER OPERATIONS.

for gas carriers may be less than estimated from historical data because the number of collisions is so small that statistical analysis can be misleading. Figure 48 omits the ship collision contribution to fire probability because it distorts the trend and makes the fire probabilities appear higher than they really are at the terminal.

Fire damage and personnel injuries are relative to fire size. Fires resulting from spills of less than 10 gallons are unlikely to cause substantial damage or result in fatalities, but fires involving thousands of gallons are nearly certain to cause substantial damage and are quite likely to result in fatalities or serious injuries as well. The overall probability of fatality from a spill during LPG transfer is therefore estimated to be in the range of 10^{-6} to 10^{-5} per transfer operation. This fatality probability is for operators near the transfer point and assumes continuous exposure during transfer. The fatality probability for the general public is much lower because of the greater separation from the transfer area.

LPG barge operations can result in a special hazard because the cargo is pressurized. If a cargo tank is heated by a fire, the internal pressure will rise and the emergency vent will open. As gas is vented, the vapor space in the top of the tank grows and the metal in the vapor space heats. At some point, the metal can weaken enough so that the tank ruptures. As the pressure is released, much of the liquid flashes to vapor and much is atomized by the force of the explosion. The fireball that results may be very large and cause a large amount of damage. This phenomenon is called a "boiling liquid expanding vapor explosion" (BLEVE) and has occurred following LPG tank car derailments. No fires at barge transfer facilities have been reported that resulted in BLEVE's.

BLEVE's cannot occur during operations for fully refrigerated LPG cargoes because the operations are all performed using liquids that are saturated near atmospheric pressure. The fraction of flash upon pressure release is therefore small and the liquid released from a storage tank is not disseminated explosively as it is from pressurized storage.

In general, refrigerated storage is used for larger quantities of LPG. If a spill occurs, a vapor cloud will form, and until it is dispersed by mixing with the atmosphere, it can easily be ignited. Under most circumstances, the result will be a vapor cloud fire, but a vapor cloud explosion is possible. In either case, primary damage will be confined to locations near or within the vapor cloud at the time of the fire or explosion. Secondary damage may be caused if the fire spreads.

CONCLUSIONS

In conclusion, the safety record for marine LPG transportation in the United States is very good, probably because careful attention is paid to design, construction, and operation of facilities. Spills of small quantities of LPG (less than 10 gal) are quite frequent, but are not particularly dangerous. The spill frequencies for very small spills could be reduced substantially for some facilities by changes in design and operation procedures. Whether changes would improve safety is debatable.

Due to the safety procedures, hazard warning systems, emergency shutdown systems, etc., the probability of a spill greater than 10,000 gal occurring from equipment failure during loading or unloading is estimated to be about 10^{-5} per transfer operation. The event that has the highest probability for causing a very large spill is a collision with another ship or barge. The probability of this event can be reduced by traffic control procedures in the port and by judicious selection of the site for the docking facility.

If a cargo release does occur, the probability that it will be ignited depends on the flow rate and duration of the spill. Those spills that produce the largest quantity of vapor in a given time are the most likely to be ignited. If ignition does occur, the most probable result will be a simple burn-back of the vapor cloud, with immediate damages limited to the area covered by the cloud, although secondary fires may result in a larger damage area. Explosions of unconfined clouds of LPG are very rare, but are possible. Similarly, a BLEVE of a pressurized cargo tank on a barge is a possibility, but none are known to have occurred.

In the event of a cargo spill fire, dry chemical fire extinguishers may be useful for extinguishing small to moderate spill fires, but they cannot extinguish really large fires or prevent reignition of the spilled cargo. Water sprays can be used to keep equipment, structures, piping, etc. from being heavily damaged even in the case of a large LPG spill fire, if sufficient water spraying capability is provided.

The probability of human error being the proximate cause of a cargo spill is estimated to be fairly small except for very small spills (e.g., leaks from poorly assembled flanged connections) or very large spills (e.g., collision with another vessel due to pilot error). In the middle range of spill sizes, equipment failures are the most likely cause of spills. However, the operator, in some cases at least, is being relied upon to prevent relatively small spills from escalating to even larger spills. Because human error rates are often quite high, it is imperative that operators be carefully trained to make the proper decision in a time of crisis.

The spill probabilities estimated in this report are based on generic designs and overall estimates of collision frequencies. Obviously, if similar calculations are made for a specific facility, the results may vary. Fatalities for barge and tanker terminals are estimated to have an occurrence probability of about 10^{-6} to 10^{-5} per transfer operation. Based on the assumption of weekly to monthly transfer operations, the annual fatality probability for an operator at a given facility would be in the range of 10^{-5} or lower. That is in the same general probability range an average individual would accept by exposure to automobile accidents. The risk to the general public from LPG ship or barge operations is substantially less.

While the accidental release rates and human casualty rates are quite low (and apparently acceptable to employee, employer, and regulating agencies), further reductions could be made. Some changes in hardware and practices would be required to reduce the spill frequencies for the middle ranges of spill sizes. Spill frequencies for the very small and very large spills might be reduced through improvements in operations and training with some modifications in hardware. These changes could only be made on an individual terminal, port, or waterway following analysis of individual problems. There appear to be no generic changes required in LPG marine transport systems.

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APPENDIX A

DISCUSSION OF THE "YUYO MARU" ACCIDENT

The following discussion is based on the report compiled by the Japanese Maritime Safety Agency, Tokyo, Japan and private communications with the U. S. Coast Guard.

> On November 9, 1974, in Tokyo Bay, Japan, the Japanese LPG tanker "Yuyo Maru No. 10," carrying refrigerated LPG in her cargo tanks and naptha in her wing tanks and forward reserve cargo oil tank, was struck approximately at a right angle on her starboard bow by the bow of the Liberian cargo vessel "Pacific Ares." As a result of the collision, the outer plating of the forward reserve cargo oil tank and the #1 starboard wing tank (both containing naptha) was broken. This allowed a large amount of naptha to flow out onto the Pacific Ares and onto the water. The naptha caught fire, killing 5 of the Yuyo Maru crew members and 28 on the Pacific Ares.
>
> Fire fighting efforts began about an hour after the collision. About 2 hours later, all external fires aboard the Pacific Ares were extinguished. The fire aboard the Yuyo Maru was attacked with fire fighting foam but, in spite of these efforts, the fire continued to spread to more of the naptha tanks. The heat from the fire caused the LPG tanks to vent and reportedly melted one relief valve and gasket and packing materials at joints in several vent and gage lines leading to the LPG tanks, resulting

in a series of small fires where the LPG vented from the tanks. Eventually all naptha fires on the Yuyo Maru were extinguished; only the LPG venting from the relief valves and heat damaged piping continued to burn. For the most part, these were small, localized fires with an occasional larger flare-up.

Five days after the accident, the decision was made to tow the Yuyo Maru out of the bay. During the towing operation, naptha was spilled and fire again broke out. Towing was suspended at this time; the ship now being about 23 nautical miles from the shoreline. The ship was subsequently towed further out to sea and was then sunk by the Japanese Defense Agency.

Because this is the largest and most dramatic incident involving fire aboard an LPG ship, it has often been cited as an example of the hazards posed by such ships. There is another side to this discussion that should also be stated. The tanks that contained the naptha onboard the Yuyo Maru cannot be used to carry flammable liquids when the ship is in a U. S. port. Since the collision did not damage any of the LPG cargo tanks, it is very likely that no fire would have occurred if the naptha tanks had been empty or were filled with ballast water. The fire was essentially a naptha fire. The only part of the LPG cargo that was involved was the portion that vented and fed the small fires around the cargo tank hatch areas; the naptha fire never breached the integrity of the cargo tanks but only damaged relief valves, packing, gaskets, etc. on the cargo piping system. And, as a final note, the relative integrity and stability of the LPG ship was demonstrated by the fact that the Japanese Defense Agency was able to sink the ship only with great difficulty using shells, bombs, and torpedoes.

APPENDIX B

DISCUSSION OF LPG BARGE "PANAMA CITY" INCIDENT

The following discussion is based on private communications with the U. S. Coast Guard and on the NTSB Hazardous Materials Accident Spill Maps NTSB-HZM Map-80-1. The full National Transportation Safety Board report has not yet been completed or released, therefore certain aspects of the accident are not yet available for publication.

On August 30, 1979, the LPG barge "Panama City" was docked on the lower Mississippi River near Good Hope, Louisiana. It had been loaded with about 283,500 gal of butane in its six cylindrical pressure vessel cargo tanks. No cargo was being transferred when it was struck by the Peruvian freighter "Inca Tupac Yupanqui" which had lost its steering. The collision severed the barge into two pieces and ruptured at least one of the cargo tanks. The LPG vapor escaping from the ruptured tank created a vapor cloud that engulfed the freighter. This vapor cloud was ignited almost immediately by an unknown source. A fireball formed which was hundreds of feet high and lasted less than one minute. The cloud did not detonate and none of the tanks underwent a BLEVE. The fireball ignited combustibles on the dock, the shoreline, the freighter, and a towboat, and burned several people in the immediate vicinity.

The forward half of the barge hull and the most severely damaged tank both quickly sank.

The aft portion of the hull, containing three tanks, and two tanks from the forward half all floated downstream with all tanks releasing burning LPG from cracks, broken pipes, and/or relief valves. The two separate tanks and the aft portion of the barge were beached at various locations downstream of the dock. The fires were allowed to burn out over the next 24 hours, during which time the Coast Guard closed that section of the river and some local residents were evacuated. Once beached, the burning tanks did no further damage.

A total of 34 people were hospitalized for burns, 9 died. Three others died from drowning. Ten of the victims were from the freighter, two were from a towboat that was standing by to move the barge. All of the people that were injured were in the immediate vicinity (i.e. on the freighter, barge, dock, or towboat). No one from the general public was injured.

APPENDIX C

DATA ON MARINE TERMINALS AND LPG SHIP AND BARGE FLEETS

In the world-wide fleet of ships, there are approximately 170 that are rated for carrying LPG cargoes. These are broken down by capacity and cargo containment system type in Table C-1. Of these ships, only a relatively small number are involved in importing of LPG to the U.S. Many of the ships are not certified by the U.S. Coast Guard (no letter of Compliance). The smaller ships, especially the pressurized type, are generally not an economical method for transporting LPG over long distances. The very large ships that do not have reliquefaction equipment installed are mainly designed and used for transporting LNG.

The U.S. has only 16 terminals that are generally recognized as LPG import terminals. These are listed in Table C-2 and their locations are given in Figure C-1. Other terminals that are not listed here may be capable of receiving imported LPG if necessary, but they are not now doing so and do not plan to in the near future.

The world market price of propane and butane in the recent past has risen sharply due to heavy demand by Europe and Japan. This has caused those U.S. importers that resell the LPG for use as a fuel gas (e.g. home heating, etc.) to curtail the amount they import, relying instead on domestic supplies. Those U.S. importers that use the LPG for other purposes (e.g. petrochemical refineries) have not curtailed their demand for LPG to such an extent.

In calendar year 1979, the U.S. import terminals received fewer than 100 shipments of imported LPG. Due to the economic conditions discussed previously, the projection for 1980 is for even fewer shipments.

TABLE C-1. WORLD-WIDE LPG SHIP FLEET

Capacity (m^3)	Portion of Total Fleet* (%)	Breakdown of Group by Type of Cargo Containment System† (%) P	S§	R	I
≤ 1,999	9	30	70		
2,000 - 4,999	22	10	80	10	
5,000 - 9,999	12		95	5	
10,000 - 19,999	17		40	60	
20,000 - 39,999	11			90	10
40,000 - 79,999	23			95	5
≥ 80,000	6			90	10

*Based on a fleet of approximately 170 ships.

†P = Pressurized; no insulation, no reliquefaction equipment

S = Semi-Refrigerated; might or might not be insulated, might or might not have reliquefaction equipment

R = Refrigerated; insulated, reliquefaction equipment

I = Insulated; insulated, no reliquefaction equipment

§Implies that the ship is capable of carrying cargo in a semi-refrigerated state, i.e. at a pressure greater than atmospheric and a temperature above the boiling point; does not imply that the cargo must be semi-refrigerated, e.g. some of these ships can be used just like pressurized ships and others can be used just like refrigerated ships.

TABLE C-2. U. S. LPG IMPORT TERMINALS

ID#	Terminal Facilities Company - Location	Maximum Unloading Rate (gpm)	Storage Capacity (1000's of Barrels)
1	Atlantic Energy, Inc. --Norfolk, VA	8,400	420
2	California Liq. Gas Corp. --Ferndale, WA	7,000	350
3	Cities Service Co. --Lake Charles, LA	7,000	2,000
4	Coastal St. Crude Gathering --Corpus Christi, TX	3,150	9,260
5	Dorchester Sea-3 Prod., Inc. --Portsmouth, NH	8,750	400
6	Exxon Co., U.S.A. --Everett, MA	7,000	400
7	Gulf Oil Corp. --New Orleans, LA	2,800	242
8	Gulf Oil Corp. --Philadelphia, PA	1,050	200
9	Petrolane, Inc. --Los Angeles, CA	7,000	600
10	Petrolane, Inc. --Providence, RI	5,250	400
11	Petro-Tex Chemical Corp. --Houston, TX	1,400	No Limit
12	Phillips Petroleum Co. --Houston, TX	3,500	No Limit
13	Sun Gas Co. --Marcus, PA	12,600	1,570
14	Tropigas, Inc. of Florida --Port Everglades, FL	580	10
15	Warren Petroleum Co. --Houston, TX	10,500	No Limit
16	Warren Petroleum Co. --Port Everglades, FL	1,100	38

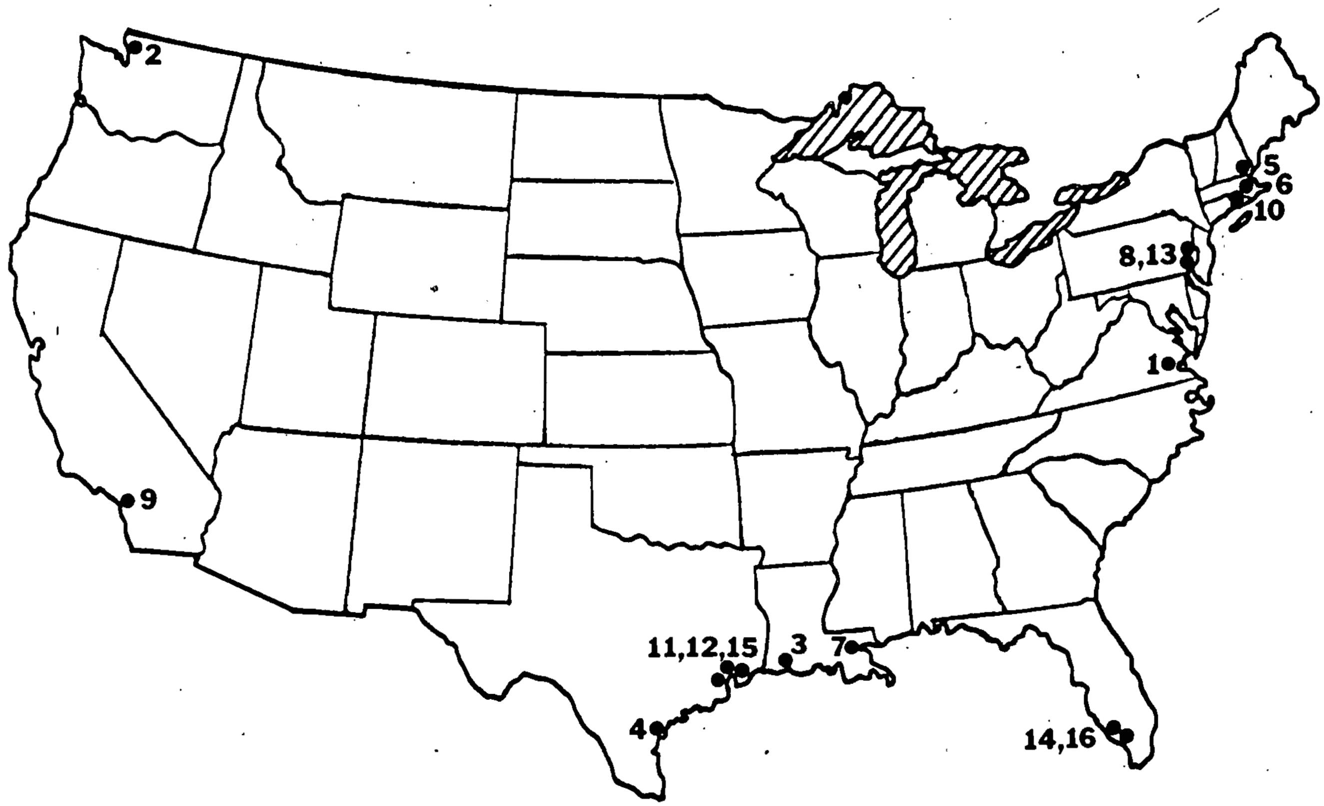

FIGURE C-1. LOCATIONS OF U. S. LPG IMPORT TERMINALS.

The U. S. barge fleet consists of approximately 60 barges. These are broken down by capacity in Table C-3. The vast majority (>75%) of the barges are in use in the Gulf Coast area of Texas and Louisiana, including the Intercoastal Waterway, and on the Mississippi.

The number of terminals that can load or unload LPG barges is much greater than the number of import terminals. Statistics for the number of cargo transfers for barges are very difficult to obtain since most government agencies' records indicate only the total tons of LPG transported in a given port each year. These records would tend to indicate that the annual total for loadings and unloadings would be in the range of 2000 to 4000.

(Much of the information on LPG import terminals contained in this Appendix is based on "United States LP-Gas Import Terminals-1977," published by the Gas Processors Association, Tulsa, OK. LPG ship and barge fleet data were based on current editions of "The Tanker Register," published by H. Clarkson & Co., Ltd., London, England, and "List of Inspected Tank Barges and Tank Ships" published by the Dept. of Transportation (USCG), Washington, DC. The data were checked and updated wherever possible.)

TABLE C-3. U. S. LPG BARGE FLEET

Capacity (m^3)	Portion of Total Fleet* (%)
≤ 999	6.5
1,000 - 1,999	23
2,000 - 2,999	27
3,000 - 3,999	25
4,000 - 5,100	17
5,100 - 15,000	0
≥ 15,000	1.5

*Based on a fleet of approximately 60 barges.

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