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ABSTRACT

This unit was designed to develop mathematical applications in relation to a community resource issue. It should both motivate mathematics learning and provide meaningful problems for reinforcing understanding of mathematics content and skills, including ratios and percentages, linear equations, exponential functions, graphing, and the reading and interpretation of graphs and tables. A discussion section is intended to give the teacher a good understanding of the issues, present available important data, and elicit mathematics problems. The mathematics is introduced implicitly with diagrams, tables, and graphs embodied in the discussion. The second section contains real-life mathematics problems involving natural gas. Appendices present equivalent measures, additional information on pricing gas, and problem solutions. (MNS)

MATHEMATICS EDUCATION TRUST

LIQUEFIED NATURAL GAS

A Potential for an Abundant Energy Supply or a Potential for Danger

Joseph Fishman
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1985

established by the National Council of Teachers of Mathematics, Reston, Virginia 22091

Liquefied Natural Gas (LNG): A Potential for an Abundant Energy Supply or a Potential for Danger

The purpose of this unit is to develop mathematics applications in relation to a community issue in which the mathematics might contribute to furthering discussion, understanding and involvement. The work developed here should both motivate mathematics learning and provide more meaningful problems for reinforcing understanding of mathematics content and skills. The unit is divided into two parts: a discussion section and a mathematics problems section.

The discussion is intended to give the teacher a good understanding of the issues, make available important data and elicit mathematics problems. The mathematics is first introduced in an implicit way with diagrams, tables and graphs embodied in the discussion. There is a good deal of potential mathematics in this section of the unit: ratios and percentages, linear equations, exponential functions, graphing, the reading and interpretation of graphs and tables.*

The discussion of the importation and use of liquefied natural gas raises some important questions which are relevant to basic aspects of modern economic development; How are decisions made to invest tremendous outlays of capital in projects which may or may not be of lasting value and which ultimately may be a financial burden on present and future generations? Who should bear the costs of poor managerial decisions? How can we balance the need to protect the environment and the safety of people and the needs of economic growth? To what extent should residents be informed of the potential hazards of facilities and materials used in their communities? Hopefully, the reader will accept a relatively lengthy discussion in order to acquire a basic understanding of the issues raised in this unit.

*The data in this unit are presented in metric units. See appendix 1 for volume, length, price and energy equivalences to non-metric measure.

Following the discussion section are several mathematics problems dealing with geometric relationships to be found in the storage and shipping facilities of LNG. There are also problems dealing with the potential danger of LNG.

Discussion

Introduction

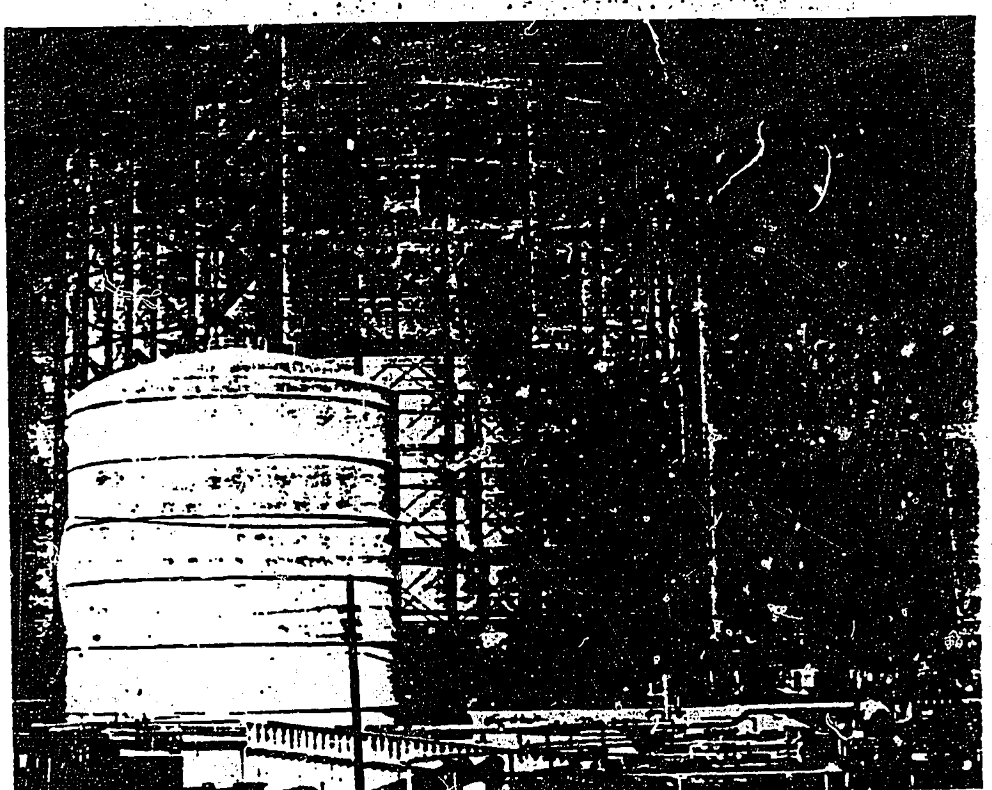
The present abundance of energy supplies provides the background for changing perspectives with respect to energy projects embarked upon in the 1970's during the time of the so-called energy crisis. Interested in the energy debates of the 1970's and the transition of these debates into the 1980's, I have investigated one energy source, natural gas, expecting that it would be a rich source of mathematics applications for high school and college teaching.

Approximately one-third of total U.S. energy consumption and one-half of industry and commercial energy consumption depends on natural gas. Most of the gas consumed in the United States is produced domestically; some 5 percent is imported by pipelines from Mexico and Canada, and less than 1 percent is imported by ship from Algeria, in the form of liquefied natural gas. Since liquefied natural gas (or LNG) has been a relatively insignificant factor in our energy economy I did not give it much attention, until I became aware that on Staten Island liquefied gas had become an important and controversial issue.

On February 10, 1973, in the community of Bloomfield, Staten Island, an explosion inside an empty 95 000 cubic meter liquefied natural gas tank killed 40 workers of a repair crew. At about the same time, in the community of Rossville, Staten Island, the construction of two of the world's largest LNG storage tanks, 14 stories high, each capable of holding 143 000 cubic meters of LNG, had been completed. These tanks were to be part of an import-terminal complex receiving imported gas from Arzew, Algeria. Although the gas companies had received Federal approval, the local community with the support of city and state representatives was determined to prevent these tanks from being filled because of its fear of the potential danger not only to Staten Island but to the whole harbor area of New York and New Jersey. There began a long process of community challenges of safety procedures and hearings before the Federal Energy Regulatory Commission (8). The Staten Island controversy with the gas companies provides a backdrop for this discussion of liquefied natural gas.

Liquefied Natural Gas

Natural gas, the fuel we use in our gas ranges and gas furnaces, may be transformed from a vapor to an odorless liquid by cooling in a liquefaction plant. In this liquid form the natural gas will occupy only 1/600th of the space it occupied in vapor form. This volume reduction makes it possible to transport and store vast amounts of energy in comparatively small spaces. For example, a transport tanker carrying 150 000 cubic meters of LNG is carrying the equivalent of 90 000 000 cubic meters of natural gas. The liquefied gas is transported in cryogenic (low-temperature) tankers and then stored in special tanks. Then, by a process of warming, the liquid is revaporized and is ready for transmission to the utilities by pipeline. LNG is both difficult and dangerous to handle because it is intensely cold. Its energy is highly concentrated: 600 times greater than for the same volume of gas. Its -162°C temperature requires complex handling, shipping, and storage techniques.



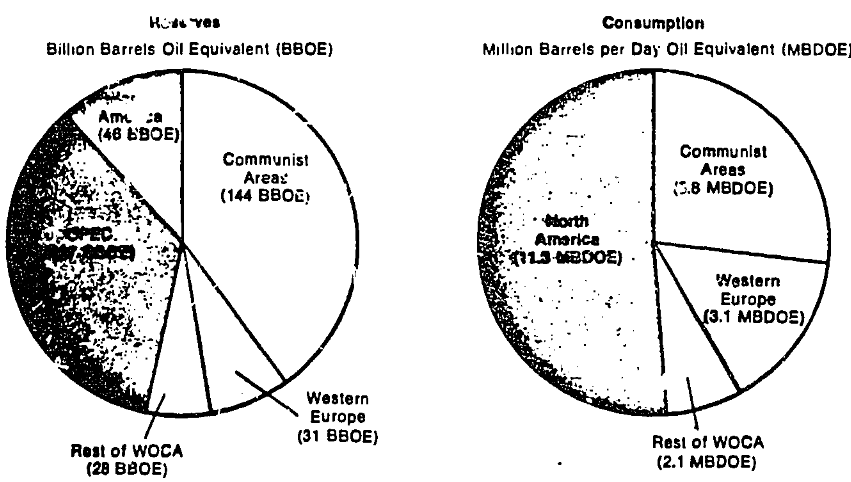
The smaller white LNG storage tank in foreground holds 25 times the equivalent gaseous capacity of the larger natural gas tank of the Philadelphia Gas Works.

Imports of LNG

Advances in the technology of liquefying gas, increasing world demand for natural gas and higher prices for this fuel have encouraged a growing world trade in natural gas. This development enables nations with great reserves and potential for production of natural gas, nations which now waste it by flaring or venting it into the air, to ship the gas to nations with large consumption needs and limited reserves. North American countries possess only 12 percent of the world reserves of natural gas but presently consume 51 percent of world natural gas production (see figure 1). The OPEC nations possess 35 percent of the world's reserves of natural gas but consume less than 1 percent of world production. Anticipating a great deal of commerce because of these disparities the gas industry in the 1970's viewed trade in LNG as an extremely important factor in the energy business over the following years.

FIGURE 1[a]

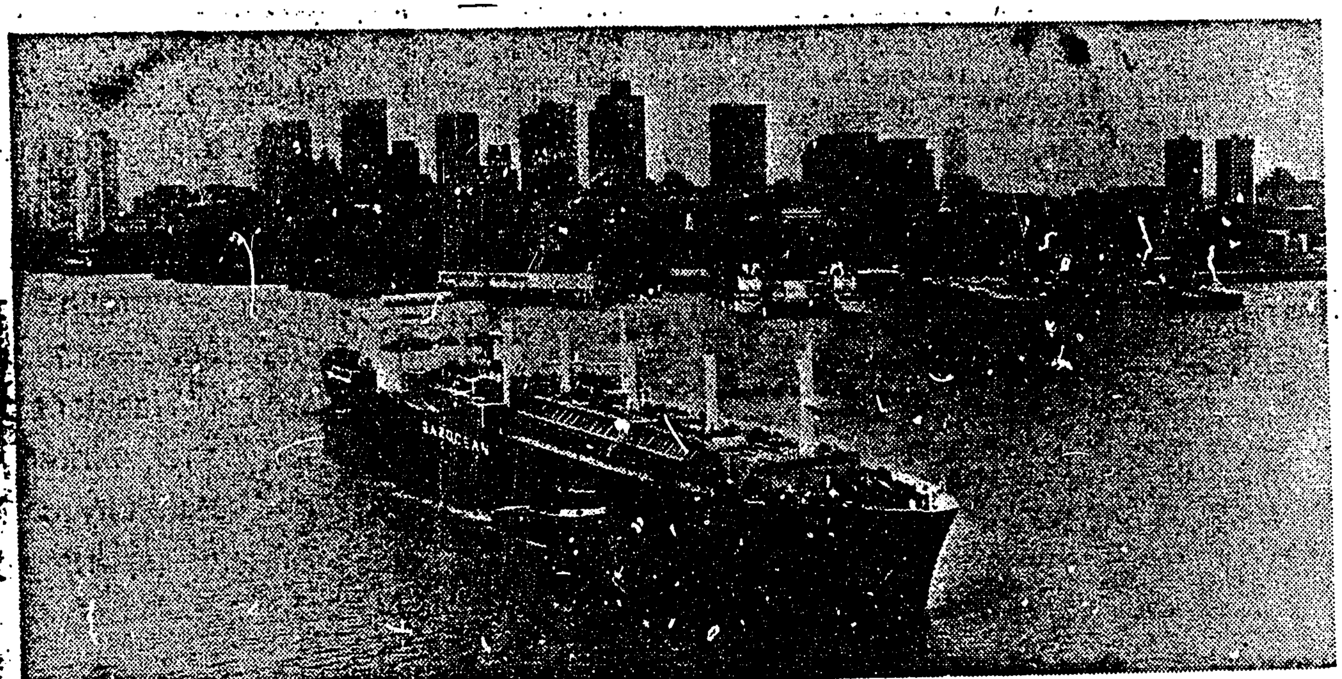
Proven Reserves and Consumption of Natural Gas in 1975



(a) Energy: Global Prospects 1985-2000. Report of the Workshop on Alternative Energy Strategies. New York: McGraw-Hill Book Co., 1977, p. 33.

(b) WOCA--World Outside Communist Areas

Imports to the U.S. began on a modest scale in 1971 when the terminal in Everett, Mass. received its first shipment under a 20 year contract with Sonatarch, the national oil firm of Algeria. By 1977, two additional terminals were completed in Cove Point, Maryland and Elba Island, Georgia. The new tanks in Rossville, Staten Island were to be part of a new import receiving terminal --- one of seven new plants planned for the U.S.



The New York Times/Arthur Grace

Boston Harbor is empty of traffic except for tank ship Descartes bringing in shipment of liquefied natural gas

The New York Times, Oct. 7, 1976
p. 1

Intensive trade in LNG could begin and was expected to do so as soon as these facilities were completed. The New York Times reported on October 7, 1976 that "these terminals would be as vital to the regular supply as the fields of Texas, Louisiana or the Gulf of Mexico... Day in and day out, through summer heat as well as winter cold, the terminals will pump 28 million cubic meters of vaporized LNG into the nation's interstate pipeline network." It was predicted that by 1985 there would be many more terminals receiving gas from as many as 41 LNG tankers, delivering as much as 15 percent of the nation's gas.

Apparently then, importation of gas was considered a valid solution to any potential shortages of supplies in the United States. Algeria is particularly well endowed with natural gas, and there are other rich sources---Indonesia, Nigeria, Australia, Malaysia, South America. Even though there was some concern that becoming dependent on supplies from other nations would leave us vulnerable, the real problems resided elsewhere: namely in the sharply increasing prices of LNG and the danger in the shipping and storage of LNG.

The Price of Liquefied Natural Gas

The following comments explain the trends described by the graphs in figure 2. The first deliveries of LNG from Algeria in 1971 cost the consumer a little more than domestic gas--both were cheap in those days. However, as energy costs generally increased, the difference between LNG and domestic gas prices widened greatly.* The volume of imports of LNG dropped after 1979 as sharply as it rose just a few years earlier.

In 1977, Panhandle Eastern Pipe Line Company was permitted by the Federal regulating agency to contract for the imports of large quantities of LNG from Algeria at a price of $11.90 per 100 cubic meters, more than twice the $5.12 price the agency allowed U.S. producers to charge pipelines for domestic natural gas. The pipeline company planned to buy 4.75 billion cubic meters of LNG annually from Algeria for 20 years beginning in 1980. Algeria's demand for $21.81 per 100 cubic meters jeopardized and eventually invalidated that contract, resulting in a sharp drop in imports.

* LNG prices were less than double domestic prices in 1972 ($1.09 and 67 cents per 100 cubic meters respectively). A somewhat higher average rate of annual growth in the price of LNG than in domestic natural gas increased the multiple of difference to 2.31. (See Appendix 2, p. I.)

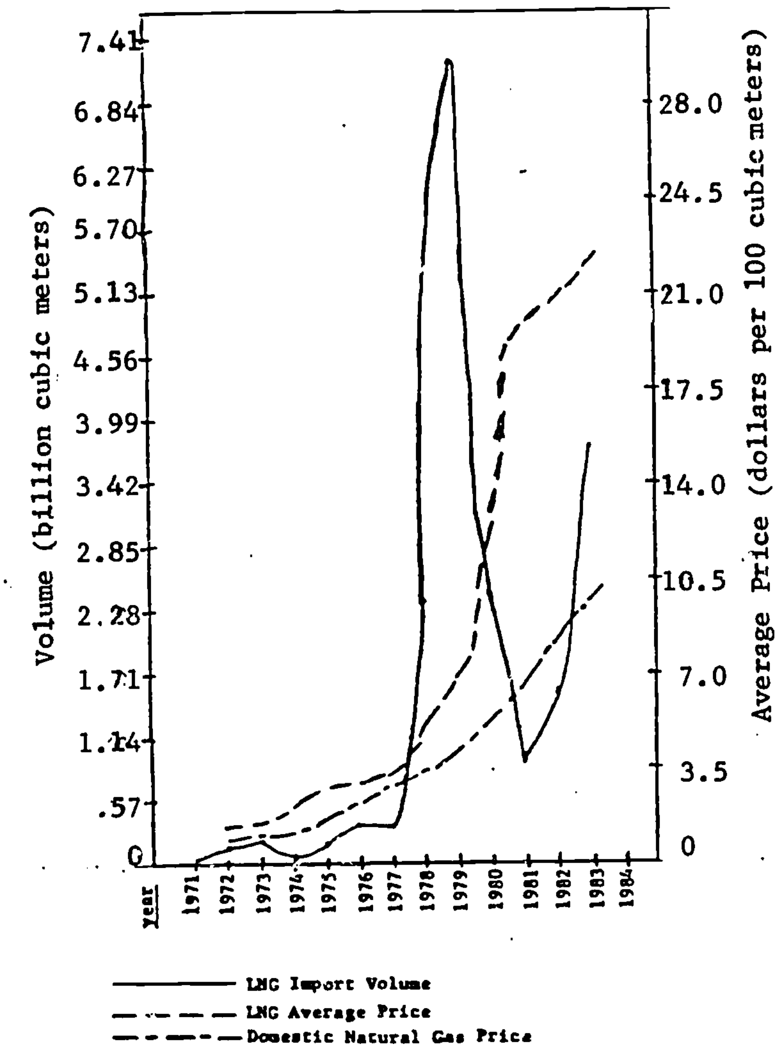
Figure 2

Volume and Average Price of LNG Imports

and

Average Price of Domestic Natural Gas

1971 - 1983



The price of LNG, nevertheless, kept up with the higher price of oil --- a price determined to a large extent by the OPEC cartel. Indeed, the price of gas imported by ship was substantially higher than the gas imported by pipeline from Mexico and Canada. For example, in 1983 the price of domestic gas was $9.81 per 100 cubic meters; the price of imported gas from Mexico was $16.59; the price of regasified LNG was $22.63 per 100 cubic meters. If we consider the shipping costs for LNG, the total cost of imported LNG was more than $28.24, (See Appendix 2, p. II.)

Why were we willing to pay such a high price when it seemed unnecessary to do so? My explanation which follows is necessarily incomplete but these brief comments should give the reader a basic understanding of the situation.

The importer of LNG is usually the company that owns the pipeline in the United States. This company is effectively a monopoly buyer in the gas field and a monopoly seller to consumers; there is no competitive market. Obviously, if the pipeline company invests in a liquefaction plant which costs close to a billion dollars it will want to make that plant productive and profitable; for this the company must obtain ample supplies of LNG. Thus, excess supply elsewhere (e.g.,from conservation policies, increased domestic production, or increased imports from Mexico and Canada) would not reduce the necessity to keep the LNG terminal functioning and profitable. Furthermore, there were other powerful investors, particularly the owners of the very expensive fleet of LNG ships, who used their influence to have the government approve continued LNG imports.

Other factors related to the Federal regulatory system reduced greatly the concern of companies with higher prices. First, the companies generally were allowed to pass these costs on to the utilities. Second, the utilities could pass on high LNG prices to the consumer but in a way that prevented the consumer from being aware of the high LNG costs. The utilities average the expensive LNG price with the price of the larger amount of lower priced domestic gas. As a result the consumer is not aware that the company is paying at least twice as much for the LNG as for domestic gas. For example, in 1981, when LNG cost the Brooklyn Union Gas Co. $21.67 per 100 cubic meters and domestic gas cost $12.50, the average price (rolled-in price) to the customer was $13.59 before utility expenses. The ultimate consumer price of $22.87 included the price of delivery and a profitable return on investments.*

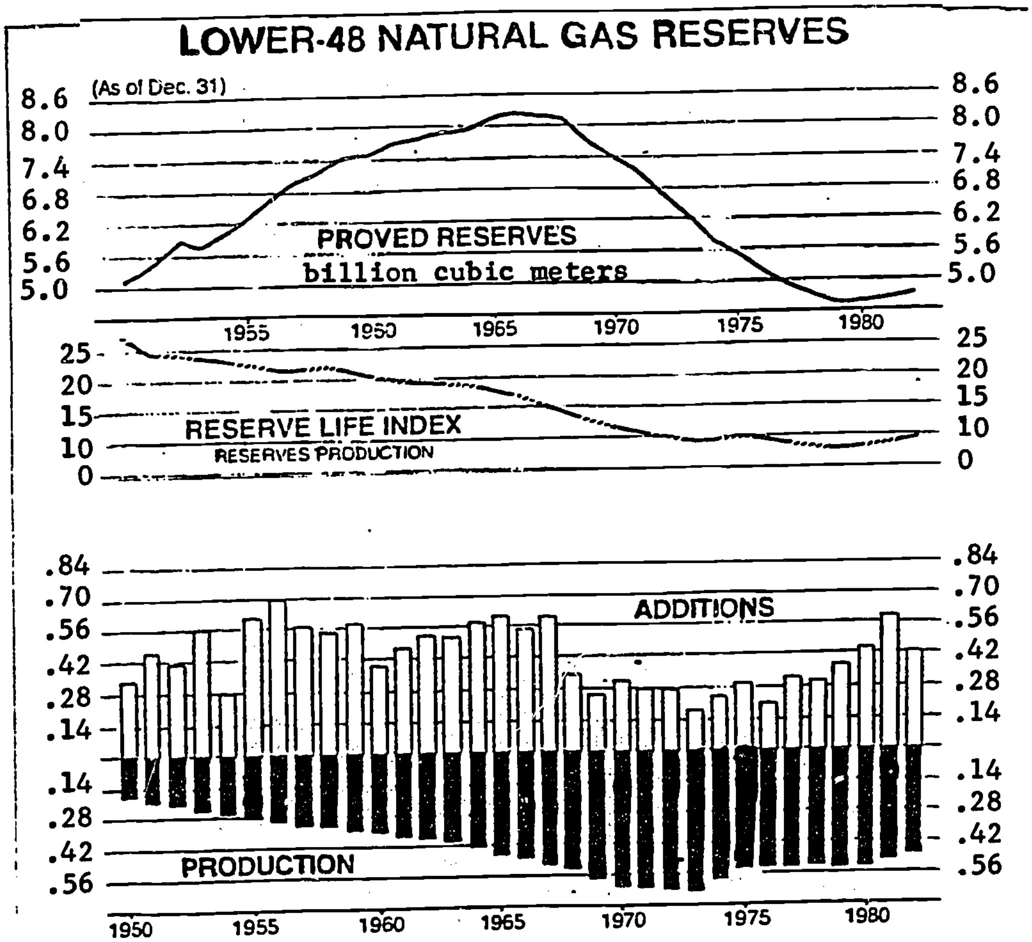
*Average price in 1981 = [The percentage of LNG (.12) x The cost of LNG (21.67)] + [The percentage of domestic gas (88) x The price of domestic gas (12.50)] = $13.59. Averaging increased the cost per hundred cubic meters only a small amount but when one considers the total quantity of gas sold by the utility, 3.26 billion cubic meters, then the total cost to the customers was substantial. (See table 1 in Appendix 2.)

There was a degree of manipulation in the willingness of the company to pay high LNG prices. The energy industry had always bristled at the Federal regulation of natural gas prices as mandated by the Natural Gas Act of 1934. This legislation authorized controlling prices at the well. Further legislation in the 1950's regulated prices at the pipeline. The companies were determined to get rid of price controls from their inception. At a time in the 1970's when oil prices were escalating rapidly and super profits were within reach in a freer market, the companies were even more determined. Higher LNG prices would tend to acclimate the consumer to a high average price (assuming large amounts of LNG were imported) and would tend to undermine the regulated price for domestic gas.

One does not necessarily have to portray the companies importing LNG as anti-consumer. They could also have been operating in "good faith." We must recall that in the 1970's, when increasing numbers of import terminals were given their licenses to operate by the energy department, there was a nation-wide concern that we were running out of natural gas. Look at the graphs in figure 3. Proved reserves had shrunk to such an extent that if no more gas became available from our own resources we would run out of gas within 10 years. As the bar graphs show, production (really the same as consumption) of natural gas was greater than new additions to natural gas supplies since the mid 1960's. Only after 1978, with the deregulation of natural gas prices, was there an increase in, or at least a stabilization of, additions to the domestic gas supply. Notice how the ratio of reserves to production (Reserve Life Index) declined until it stabilized at a low rate after 1975. By 1980 it seemed that the remaining reserves would last only 9 years.* It was this sense of shortage that was a major reason or at least a justification for the pressure to fill these tanks and to generally accept increases of higher prices for shipments from Algeria.

*Compare the ratio of reserves to production (R/P) in the U.S. with the approximate R/P of some OPEC nations: Algeria-136; Qatar-254; Saudi Arabia-69; Iran-594; Venezuela-83. (See American Gas Associations, The Gas Energy Supply Outlook: 1983-2000.) Reserves of natural gas in 1980 totaled approximately 4.7 billion cubic meters. Production (consumption) in that year was .52 billion cubic meters. The ratio of reserves to production (R/P) was $\frac{4.7}{.52}$ or 9.

Figure 3



SOURCES: A.G.A. Committee on Natural Gas Reserves through 1979, EIA Form-23 Reserves Report,

Whether the shortages were real or contrived by the energy industry to obtain higher prices is debatable. However, by the time the LNG industry got into full swing the utility companies found less and less reasons for paying such high prices for foreign gas. The National Gas Policy Act, passed at the end of 1978, allowed all new production of domestic natural gas to be gradually deregulated. The result was -- almost immediately -- a glut of gas supplies (an economic recession at the time also contributed to the surplus of natural gas) which has continued to the present. Consumers and the State Public Service Commissions (regulators of utilities) were resisting high prices.

The Federal government, after having given the okay to build import terminals, would not allow the purchase of LNG at the requested price of the national oil company of Algeria. The result was that from a high volume of 7.2 billion cubic meters in 1979, imports of LNG dropped to 1.04 in 1981 (see table 2 and figure 2). Two terminals stopped importing and others which had been planned, such as the one in Rossville, Staten Island, were not completed or did not get off the ground.

TABLE 2 [(a)]

LNG IMPORTS

1977-1983

Volume (million cubic meters)

Receiving Point[(b)]	1977	1978	1979	1980	1981	1982	1983
Cove Pt., Md.	0	1345	3863	1048	0	0	0
Everett, Mass.	320	413	810	688	1042	906	969
Elba Island, Ga.	0	634	2486	697	0	0	0
Lake Charles, La.	0	0	0	0	0	654	2744
Total LNG Imports	320	2392	7159	2433	1042	1560	3713

(a) "U.S. Imports and Exports of Natural Gas 1977"; "U.S. Imports and Exports of Natural Gas 1978"; Office of Oil and Gas Statistics, Dept. of Energy, June 1979 and June 1980; Natural Gas Monthly, July 1983 and July 1984, Energy Information Administration.

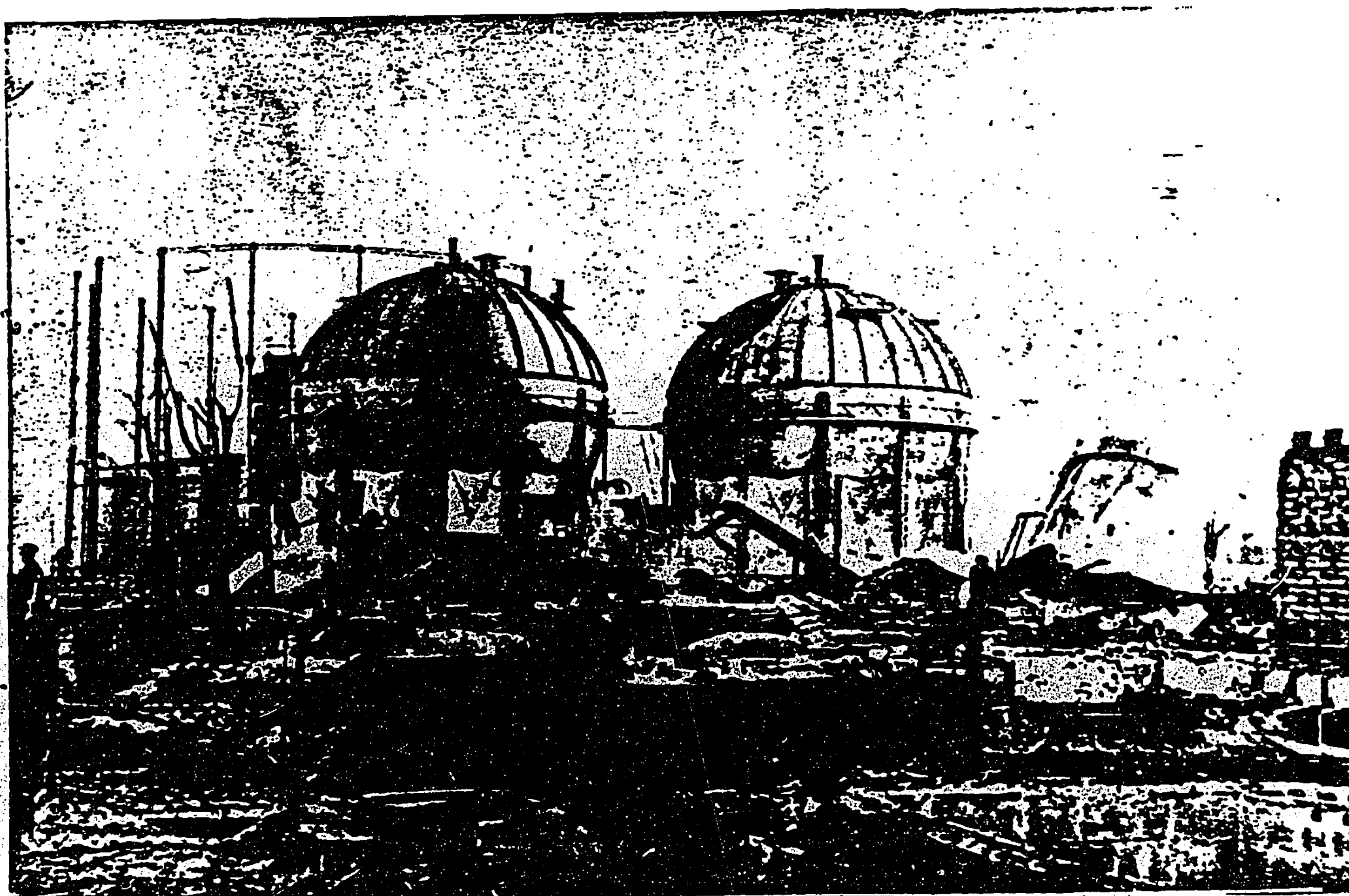
(b) The following companies imported the LNG: Columbia LNG Corp. and Consolidated System LNG Co. -- Cove Pt.; Distrigas Corp. -- Everett; Southern Energy Co. -- Elba Island; Columbia LNG Corp.--shipping LNG to Elba Island in 1980; Trunkline LNG Co. -- Lake Charles.

One terminal which had just been completed, in Lake Charles, Louisiana, with a capacity of receiving 4.67 billion cubic meters of LNG annually, received its first shipment in 1982 after getting a cut-rate price from Algeria of $14.05. However, by the time the company transported and reconverted the gas and sent it into the pipeline system, the price was $25.35. The utilities contended that at $25.35 per 100 cubic meters the LNG was more than double current domestic gas prices and forced the importing company to end its contract with Algeria. A $640 million investment, like others, was to stand unused.

What finally contributed greatly to the demise of the LNG importation industry was the increasing sense of its potential danger to the communities where the facilities were located.

Controversy Over the Danger of Liquefied Natural Gas

Long before the 1973 accident on Staten Island, an LNG accident had occurred in Cleveland on October 20, 1944. A 4 200 cubic meter LNG peak-shaving storage tank suddenly gave way. Vapor from the spilled liquid ignited as it spread into streets, storm sewers and basements. Later, another tank containing 2100 cubic meters failed, flames shooting high into the air. The fires and explosions of this disaster killed 133 people and injured hundreds of others. The repercussions were so great that it was not until the mid 1960's that utilities again began using LNG.



THE CLEVELAND, OHIO, LNG DISASTER, 1944

United States General Accounting Office, Liquefied Energy Gases Safety Report, 1978, Volume 1, p.10 - 2.

The argument of those opposing the LNG tanks on Staten Island is that accidents like this will inevitably occur from time to time and therefore it is necessary to keep such facilities far away from heavily populated areas. The argument of industry was and remains that previous techniques and quality of materials were responsible for the accidents and have since been greatly improved so that it is now virtually impossible for such accidents to recur. According to industry the risk factor is so small that the community should not worry.

The concern of the community was given support by a 1978 study of LNG by the General Accounting Office, an official advisory group to the U.S. Congress(6). This 3-volume analysis concluded that LNG used as an energy source is potentially so dangerous that its storage and transportation should be restricted, if possible, to remote, unpopulated areas. Asserting that a liquefied gas spill in a densely populated area would be catastrophic, the GAO urged new federal policies that would ban the expansion of current liquefied gas facilities in urban areas.

The GAO report was attacked by gas utility engineers who claimed that the Cleveland accident could not recur with current technology. They asserted that LNG has an excellent worldwide safety record, with over one hundred LNG installations operating safely throughout the world, including more than eighty-five in the United States. Safety is maintained by taking every precaution against any possible danger to the public. The GAO report was also attacked by the Department of Commerce and the Department of Energy as being misleading and a highly imaginative and alarmist compendium of potential disasters, rather than a dispassionate review of their actual probability of occurrence (6).

The hearings on Staten Island dragged on for several years (11) until two terrible accidents occurred within a month of each other. On November 20, 1984, in a crowded suburb, only 8 miles out of Mexico City, four spherical tanks, each holding at least 1,588 cubic meters of liquefied petroleum gas (not the same as LNG), exploded shooting balls of fire into the air, raining down fire and debris on homes and businesses; 452 people were killed, 4 248 were injured. Then on December 3, 1984, a gas leak at a Union Carbide Corp. chemical plant in Bhopal, India, killed over 2 000 people and injured as many as 200 000. A New York Times investigation concluded that this disaster resulted from operating errors, design flaws, maintenance failures, training deficiencies and economy measures that endangered safety. In May 1985 a freelance journalist in India was given a national journalism award for "perseverance" and for protecting the public interest. The journalist had warned more than two years before of safety hazards at the Bhopal plant. These warnings had been debated in the Indian State Legislative Assembly in 1982, when it was suggested that the plant be moved to a "safer place",

The current gas glut, the postponement of a decision by the Federal Energy Regulatory Commission (FERC), the persistent opposition of the community and local politicians, and finally, the accidents in Mexico and India all contributed to the Public Services Electric and Gas Co. announcing in December 1984 that it was giving up its quest for a federal license to operate its liquefied natural gas storage complex in Rossville, Staten Island, and would abandon the giant facility. FERC estimated the value of the in-completed complex at $170 million. Public Service said the cost would be "written off" over the next seven years.

PROBLEMS *

1. 600 cubic meters of natural gas at 15.5°C is reduced in volume to 1 cubic meter of supercold liquid at -162°C when undergoing special cryogenic technology. When its use is required, the LNG must be vaporized by heating in order to return it to its gaseous state. For example, 5 cubic meters of LNG at -162°C yield 3000 cubic meters of natural gas at 15.5°C. LNG tanks now hold up to 227 thousand cubic meters of liquefied natural gas. To how many cubic meters of natural gas is this equivalent?

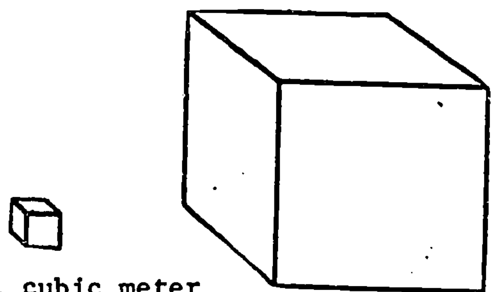


FIGURE 4
LIQUEFIED NATURAL GAS VS. NATURAL GAS

(a) Complete table 3

TABLE 3

Relationship Between Volumes of Natural Gas and Liquefied Natural Gas (LNG)

Natural Gas at 15.5°C	LNG at -162°C
3000 cubic meters	5 cubic meters
30000 cubic meters	-------------
100 000 cubic meters	-------------
300 000 cubic meters	-------------
900 000 cubic meters	-------------
1 000 000 cubic meters	-------------
30 000 000 cubic meters	-------------
60 000 000 cubic meters	-------------
100 000 000 cubic meters	-------------

(b) Let x = volume of natural gas and y = volume of LNG, draw a graph showing their relationship. Write an equation.

* The author wishes to express his gratitude for the significant contribution to this section of Michael Kress, Professor of Computer Science, College of Staten Island, City University of New York.

2. The Brooklyn Union Gas Co. has two cylindrical peak-shaving tanks for storage of LNG.* The LNG stored in these two tanks is equivalent to 45 million cubic meters of natural gas. Tank #1's capacity is equivalent to 17 million cubic meters and tank #2's capacity is equivalent to 28 million cubic meters of natural gas. Let us explore possible dimensions for tank #1. Recall that 600 cubic meters of natural gas are equivalent to 1 cubic meter of LNG. Complete the following list of possible dimensions for a tank containing 28000 cubic meters of LNG.

Diameter (meters)	Height (meters)
11	-------
21	79
-----	39
30	-------
41	-------
-----	16
-----	-------

Which tank will have approximately the same height as the diameter? How are the dimensions of a tank determined?

* Used to store gas during periods of low demand. The LNG is vaporized to supplement the normal supply of pipeline gas during periods of extremely high demand.

3. The dimensions of the tank in the previous problem would be the dimensions of the interior of a double walled shell. Every LNG tank is simply a giant thermos-container--double walled, with thick layers of insulation. There are many designs, but the LNG storage tank, like all structures related to LNG, must be built according to extremely high safety criteria. The inner wall which contains the LNG at minus 162°C is constructed of proven low-temperature materials. This inner shell tank may have an approximately cubic or cylindrical shape. The outer wall, cylindrical in shape and constructed of high grade carbon steel, surrounds the inner wall. The annular space between the two walls contains insulating material usually consisting of perlite in a nitrogen atmosphere or panels of polyurethane.

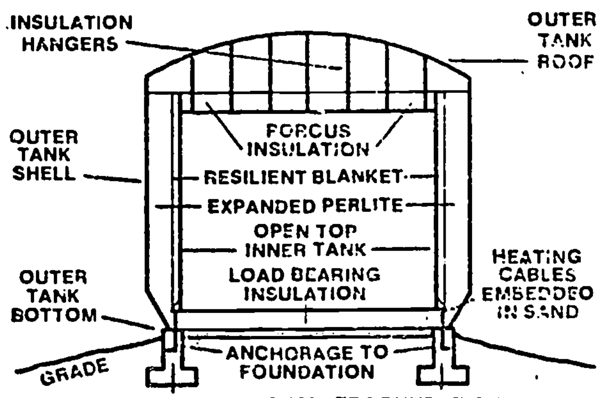
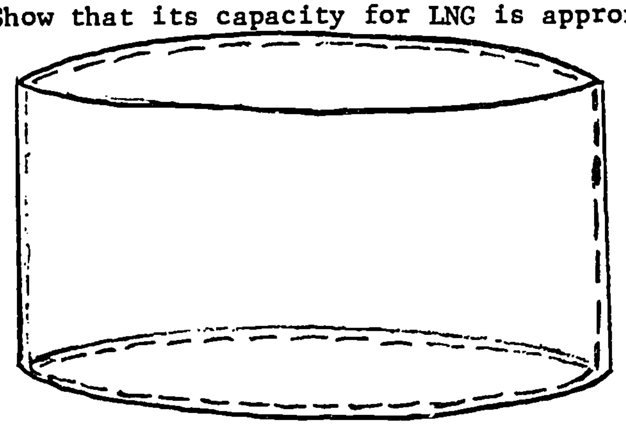


FIGURE 5
ONE OF SEVERAL DESIGNS

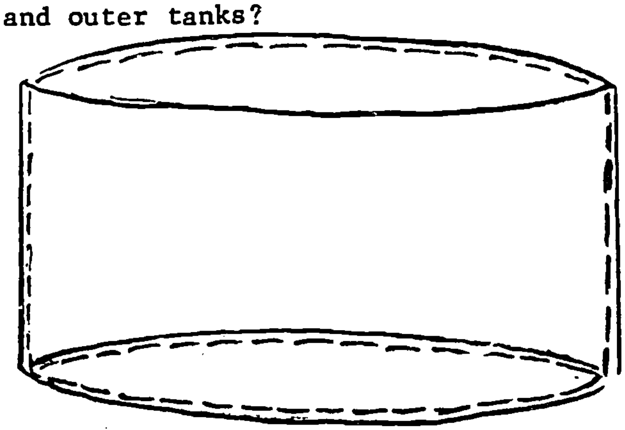
Problem 3 continued

a. One of the tanks in the Cleveland LNG plant built in the early 1940's had a cylindrical inner shell 21 meters in diameter by 13 meters high, containing 4 500 cubic meters of LNG. The Bloomfield, Staten Island tank, completed in 1970 has a capacity of 95 000 cubic meters. This tank has a diameter of approximately 80 meters, a 20 cm. thick insulation and a liquid depth of 19 meters. What are the dimensions of the inner tank? Show that its capacity for LNG is approximately 95 000 cubic meters.*



Diameter of outer tank = 80 meters
Insulation = 20 centimeters
Inner Depth = 19 meters

b. The LNG capacity of each of the Rossville, Staten Island, tanks is approximately 143,000 cubic meters. These tanks, completed in 1974, are 73 meters in diameter and 36 meters high. What are the possible dimensions of the inner tank which contains the LNG? What is the capacity for insulation between the inner and outer tanks?



Diameter of outer tank = 73 meters
Height of outer tank = 36 meters
Volume of LNG = 143 000 cubic meter

*The tank remained in service until the spring of 1972 when it was emptied, purged with nitrogen, repurged with air and entered to investigate its internal condition, to conduct maintenance and make modifications. On February 10, 1973, when repairs were near completion, a fire occurred inside the tank creating a pressure build-up which caused the prestressed reinforced concrete roof to collapse.

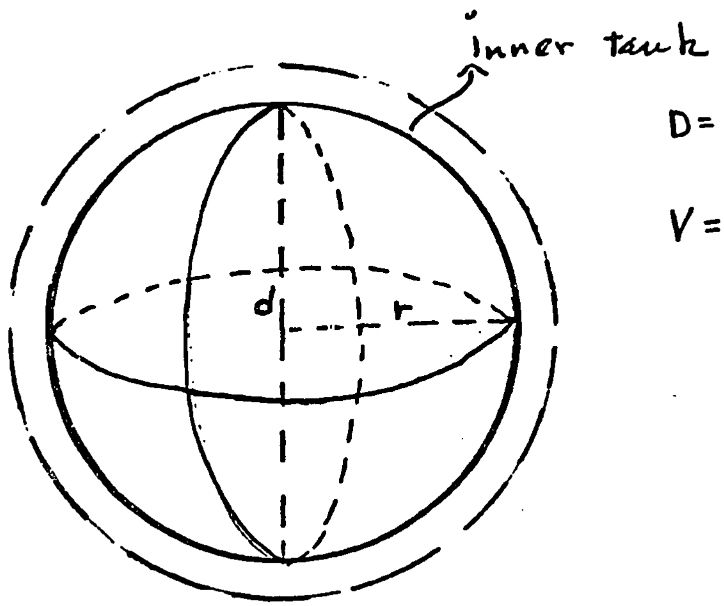
c. The burning of 1 000 cubic meters of natural gas produces energy that is equivalent to 9×10^9 Cal. How much potential energy could be contained in each Rossville tank? If one ton of TNT (dynamite) contains the potential energy equivalent of 2.7×10^9 calories, how many tons of TNT would be equivalent to the energy contained in each Rossville tank?

d. BLAST (Bring Legal Action to Stop Tanks), the group of Staten Island activists who opposed the storage of LNG in highly populated urban areas, had claimed that each of the LNG tanks in the Rossville section of Staten Island could hold the energy equivalent of 37 Hiroshima-type atomic bombs. Investigate and discuss this assertion.

4. If the volume of an LNG tank is 96 300 cubic meters and the tank is in the shape of a cylinder, what are the dimensions of the cylinder that give the smallest surface area of the tank? This is an important problem since it is in the interest of the builders to use the smallest amount of materials possible and, of course, the smaller the surface area, the smaller the use of materials. Another possible advantage in a smaller surface area is that it minimizes the possible surface evaporation.

5. LNG ships are built up to 305 meters long, with cargo tanks over 31 meters deep. LNG ship owners and operators are fully aware how vulnerable to accident these ships are. Much research has been done to minimize dangers of accidents. These ships are fine-tuned, down to the smallest detail, like a space ship. Cargo tank sections are precision-made, deviating from one another only by extremely small margins; all parts and instruments are delicately designed and constructed so that they can expand and contract without jamming, splitting, or cracking as the ship is loaded and unloaded. Nevertheless, danger still remains. A large spill could result if an LNG ship were to be struck by a sufficiently large vessel or sabotaged. An accident from human error or otherwise in the loading or unloading of the liquefied gas could have devastating results. While completing the following problems, consider the potential danger which exists in the cargo of these ships.

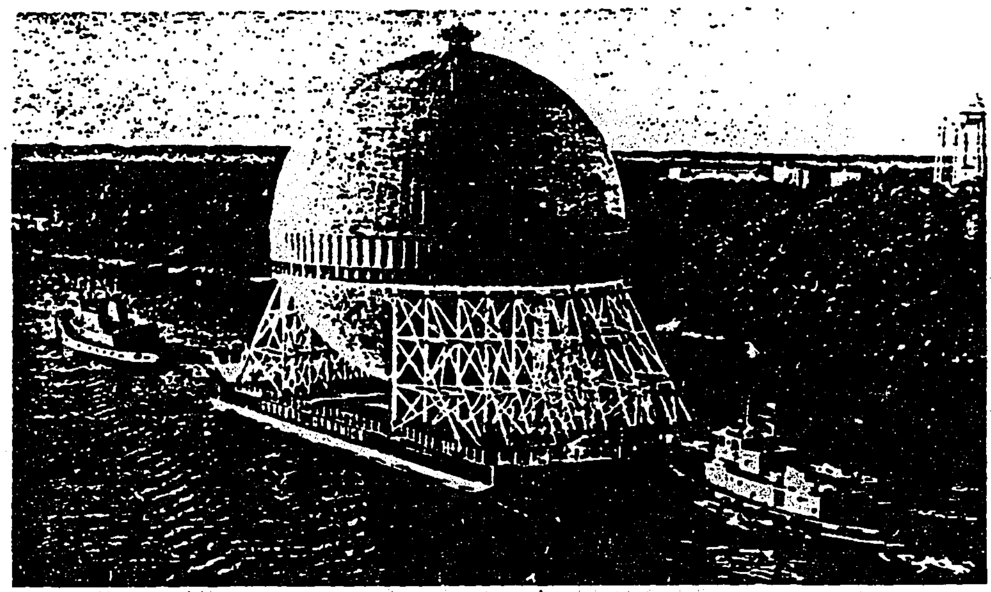
a. The diameter of one of the aluminum spherical containers in an LNG tanker is 37 meters. (See figure 6.) How many cubic meters can be contained in each container? If a tanker carries 5 such containers, what is the total capacity of this tanker? (Remember, this tanker carrying LNG is energy-equivalent to 600 similar sized ships carrying natural gas.)



D = 37 meters

$V = \frac{4\pi r^3}{3}$

FIGURE 6



A 120' diameter aluminum sphere to be placed in an LNG tanker.

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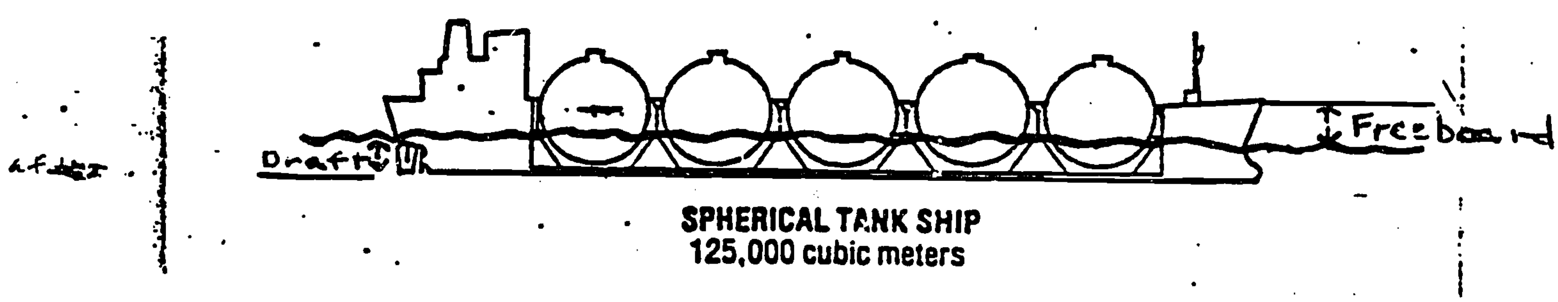
Problem 5 continued

b. A typical ship with a capacity of 125 000 cubic meters of LNG is approximately 283 meters long (approximately the length of three football fields) with a beam (width) of 43 meters, a draft (under water) of 11 meters, and a freeboard (above water) of 15 meters. Assuming that the volume of the ship can be approximated by a rectangular parallelepiped 265 meters long (18 meters less than the total length of the ship to allow for the bow and stern), as wide as the ship and as deep as the combined draft and freeboard. Find whether the volume of the ship would be more or less than the volume of the 5 LNG tanks and by how much.*

FIGURE 7

FIGURE 8



*There is at least one supertanker that has a capacity of 165 000 cubic meters---enough liquid to cover a football field to a depth of over 37 meters (some 12 stories high).

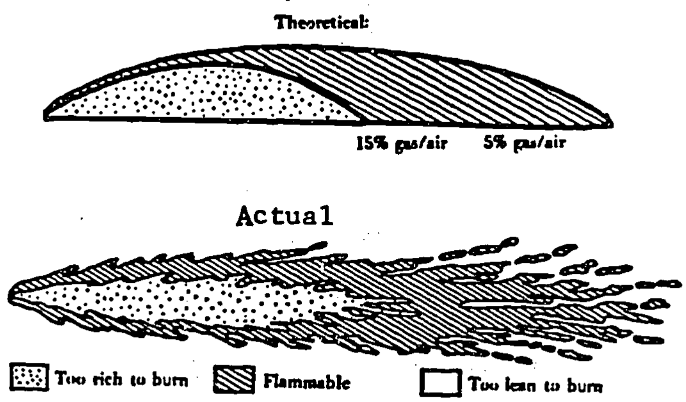
6. Once escaped from its frigid storage, LNG would quickly revert to a highly volatile gaseous form. LNG is so much colder than the surrounding air or earth or water that it immediately begins to vaporize at an extraordinarily rapid rate. The liquid disappears; the resulting LNG cloud will hug the ground and roll out horizontally in all directions, far too cold and too dense to rise away into the atmosphere, as would gas at normal temperatures. The gas cloud continues to expand in size as it gradually warms up, mixes with air, and blows downwind, lengthening out into a plume (see figure 9). Initially, the freezing cold gas cloud is not flammable - it is too "rich" to burn. Only when the vapor has mixed with the air around it at proportions of 5 to 15 percent gas to air will it flame if ignited. Any materials in its path are vulnerable. Due to its slow evaporation rate, LNG does not suddenly ignite or explode. If the plume should catch fire, it becomes a "lazy flame," slowly working its way back to the ignition source--a burning ship, for example.

Industry spokesmen and some authorities, including experts at the Environmental Protection Agency, contend that such an occurrence is extremely remote. Other scientists, however, warn that LNG has the potential for causing massive holocausts, threatening in particular the densely populated areas surrounding ports.

Problem 6 continued

FIGURE 9

LNG VAPOR PLUMES



Frozen Fire, P.29

a. What is the potential volume of a combustible mixture of gas and air in one cubic meter of LNG?
Write an equation and solve.

b. Forty cubic meters of LNG vaporized and mixed with air in flammable proportions could fill 189 kilometers of a 1.8 meter diameter cylindrical sewer line or 24 kilometers of a 4.9 meter diameter cylindrical subway system. Check these calculations and discuss the statement.

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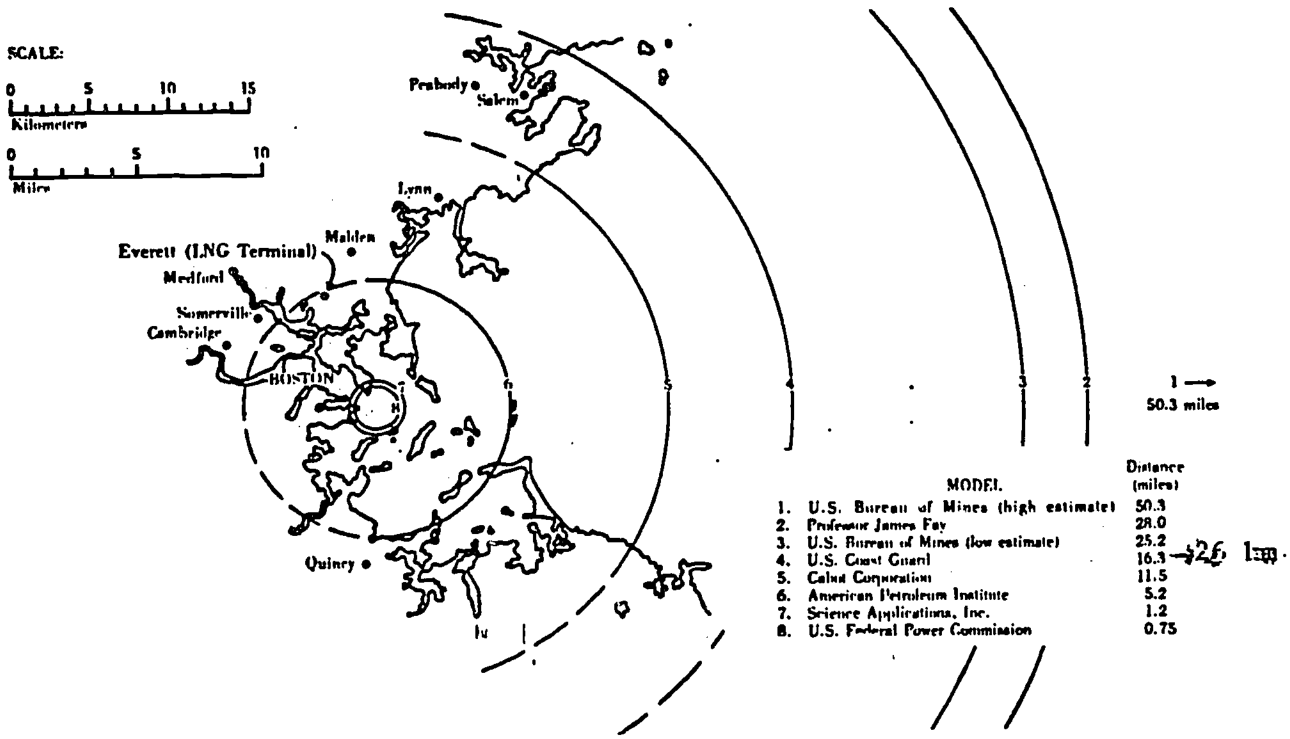
6c. How far downwind would an LNG plume be flammable? Scientists differ on this question -- they must make certain assumptions about weather conditions, temperature, and wind speed, as well as the amount of the spill. They must decide which combination of these factors represents the "worst possible case." These disagreements are crucial to anyone living near an LNG terminal. Whether the plume travels 5 miles or 20 miles downwind before it has thinned out so that it is no longer flammable is crucial to anyone living near an LNG terminal.

The map in figure 10 illustrates how far the flammable plume from a 25 000 cubic meter LNG spill (one fifth the cargo of a typical super-tanker) would travel from the center of Boston Harbor. The circles represent different estimates made by seven experts. For each circle, the radius equals the distance the plume is expected to travel downwind before the average proportion of gas to air at its leading edge reaches 5 percent, the point at which it is no longer flammable.

Assume the plume widens as it moves downwind, forming a wedge of 20°, traveling 26 kilometers, the radius estimated by the U.S. Coast Guard. How many square miles would be threatened by the plume? What is the worst scenario that the wind could create?

FIGURE 10

Distance the flammable plume will travel downwind following an instantaneous spill of 25,000 cubic meters of LNG on water: Boston harbor



"Distance (miles)" refers to the distance at which the "time average" vapor concentration is 5% gas to air. Dotted lines indicate that the plume would probably not reach this far in reality, but be ignited earlier.

Source: U.S. Coast Guard (Department of Transportation): Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment (Washington, D.C., April 1977) P. 24

7. Risk analysis can be a risky subject since the same statistics and probability can be used by different parties in a case to draw opposite conclusions.

One of the issues on Staten Island that was brought before the hearing by the Federal Power Commission Bureau of Natural Gas was the potential danger of barge transportation for shipping gas stored in the Rossville tanks to other places around the New York - New Jersey harbor. The risk analysis done by the gas company and reported in the Final Environmental Impact Statement, (8) deemed the risk of a possible LNG barge accident acceptable. The basis of the acceptable conclusion was a comparison of the probability of a person living in the Risk Corridor actually dying from an LNG barge accident to the probability of an individual living in the United States dying from an automobile accident or from any common mortal disease.

The citizens group BLAST together with a group of scientists from Richmond College opposed the interpretation of the Federal Power Commission (FPC) statistics and argued that an LNG barge accident would be an accident of catastrophic proportions and should be compared to other catastrophic accidents and not to the probability of death due to an automobile accident or other common mortal diseases. The LNG opponents' conclusion was: When an LNG barge accident is compared to catastrophic events reported by the United States Atomic Energy Commission (AEC) it is clear that the risk of LNG barge transportation is unacceptable.

Consider the statistical facts and probabilities, then you decide which is the appropriate conclusion.

The following probabilities and statistics were reported by the FPC (8):

* The probability of an LNG barge accident is 1/(4000) per year.

* The total number of people exposed to the hazard of an LNG barge accident (the Risk Corridor) is 807 000 people.

* The total number of expected fatalities from an LNG barge accident occurring in typical atmospheric conditions is 40 000 people.

The conclusion of the proponents of LNG was deduced as follows:

First, the probability that a person living in the Risk Corridor is killed is (40 000) / (807 000) = 1/19.

Next, the probability that an LNG barge accident will occur in a one year period is 1/4,000.

Therefore, the probability that a person living in the Risk Corridor is killed by an LNG barge accident (the Probability of Death to an Individual) is 1/(76,000).

$$\text{Probability of Death to an Individual} = (1/19) \cdot (1/4\,000) = 1/76{,}000.$$

The proponents' conclusion:

The Probability of Death to an Individual living in the Risk Corridor due to an LNG barge accident is small compared to the probability that a person who lives in the U.S. will die due to an automobile accident or other common mortal disease which is 1/100 per year. In terms of this risk analysis the exposure of an individual to the hazard of LNG barge transportation is acceptable.

The LNG opponents' conclusion was based on exactly the same probabilities and statistics. However, these facts were interpreted in a different manner and lead to an opposite conclusion.

The LNG opponents argued as follows:

First, an LNG barge accident with an expected 40 000 fatalities is a catastrophe. The probability of an LNG barge accident (1/4,000 per year) should be compared to the probability of other catastrophic accidents with an expected number of fatalities of 40 000 people.

Next, a comparison of catastrophic accidents was done by the U.S. Atomic Energy Commission (AEC) (9). The Commission compares a number of multiple fatality events.* It reports a graph of the frequency of occurrence of multiple fatality events per year (this is equivalent to the probability of occurrence of the event per year) versus the expected number of fatalities per event for airplane crashes, dam failures, explosions, chlorine gas releases, and 100 nuclear power plants. The risk analysis of an LNG barge accident, insisted the opponents of the gas tanks, should be compared to these accidents by using the graphs in figure 11.

Therefore, plotting the point corresponding to a probability of occurrence of 1/4,000 of an LNG barge accident with an expected number of fatalities of 40 000 on Figure 11 shows such an LNG accident is of comparable significance to the total of all other man caused accidents considered by the AEC. That is, it is more probable that an LNG barge accident with 40 000 fatalities occurs than the total man caused accidents considered by the AEC resulting in 40 000 fatalities occur.

LNG opponents' conclusion:

The probability that a catastrophic LNG barge accident occurs claiming the lives of an expected 40 000 people is greater than the probability of occurrence of <u>all</u> other man caused catastrophes considered by the AEC with an expected number of fatalities of 40 000 people.** Clearly, asserted the

*In this case, multiple fatality events are equivalent to catastrophic accidents caused by man.

**The curve of the "total man caused" events is the sum of all the other curves.

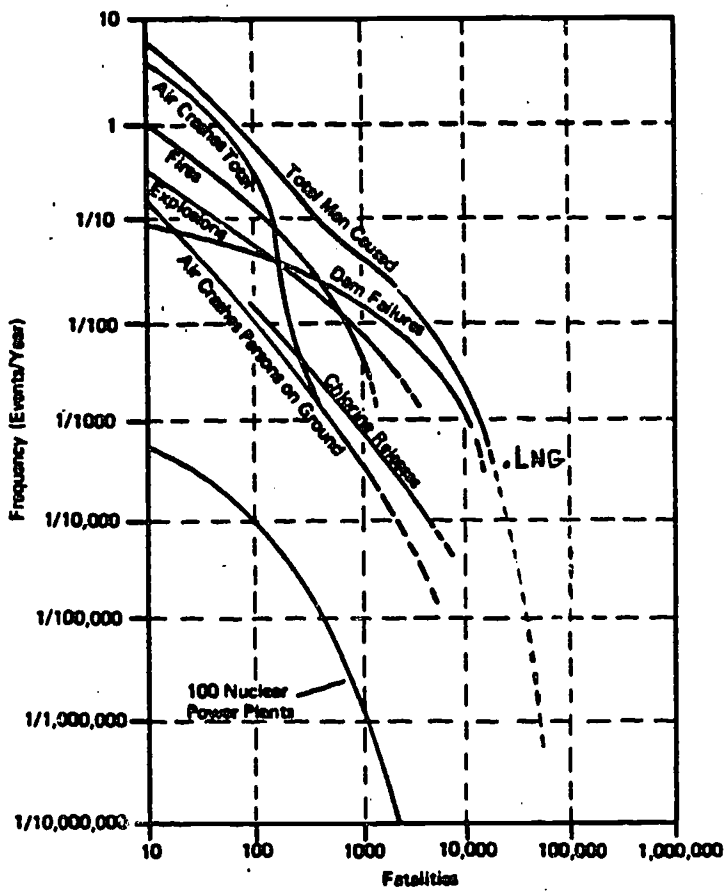


Figure 11. Frequency of Fatalities Due to Man-Caused Events*

** An example of the numerical meaning of Figure 11 can be seen by selecting a vertical consequence line and reading the likelihood that various types of accidents would cause that consequence. For instance, in Figure 1, 100 plants would cause this consequence with a likelihood of one in 10,000 per year. Chlorine releases are about 100 times more likely, or about one in 100; fires are about 1,000 times more likely, or about one in 10 per year; air crashes are about 5,000 times more likely, or about one per 2 years.*

1 U.S. Atomic Energy Commission
"An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants," August 1974, page 1.

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Staten Island community opponents, LNG barge transportation poses an unacceptable hazard to the people who live in the Risk Corridor.

The above comparison shows opposite conclusions from the same probabilities. The difference is in the interpretation of the statistics with regard to the basis of comparison. What conclusion would you use?

Note:

Notice that in the proponents' analysis the probability that a person living in the Risk Corridor is killed and hence the Probability of Death to an Individual can be made arbitrarily small by increasing the number of people exposed to the hazard. That is, if the LNG barge were towed around Manhattan Island as well as the shoreline of Brooklyn and Staten Island exposing an additional 3.5 million people to the risk of an LNG barge accident then

the Probability of Death to an Individual = (40.000/4 307 000) · (1/4 000) = 1/430 000.

By exposing a larger section of the population to the catastrophic hazard the probability considered in determining acceptability is actually decreased by nearly a factor of 6 in this example; therefore the hazard is more acceptable. A most interesting paradox.

References

1. American Gas Association (1515 Wilson Blvd., Arlington, Va. 22209). Many excellent publications on LNG and natural gas. See: LNG Information Book 1981; The Gas Energy Supply Outlook: 1983-2000.

2. United States Department of Energy, Energy Information Administration, Washington, D.C. 20585. Indispensable for information about energy sources. See: Annual Energy Review; Natural Gas Annual; Natural Gas Monthly.

3. Annual Reports of the Utility Companies. Very useful information.

4. Davis, L.N., Frozen Fire, San Francisco: Friends of the Earth, 1979. A well written controversial study of LNG.

5. Lom, W.L., Liquefied Natural Gas, New York: John Wiley & Sons, 1974. A good basic study.

6. United States General Accounting Office, Liquefied Energy Gases Safety (3 volumes), Report to the Congress by the Comptroller General, 1978. An exceptionally powerful study.

7. The New York Times and The Wall Street Journal have been very important as sources of data and general knowledge about LNG. (The Staten Island Advance and publications of BLAST were also helpful.)

The following items are related to the risk analysis:

8. "Final Environmental Impact Statement for the Construction and Operation of an LNG Import Terminal at Staten Island, New York," Federal Power Commission, Bureau of Natural Gas, July 1974.

9. "An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants," Wash-1400, U.S. Atomic Energy Commission, August 1974.

10. "LNG Transport and Storage: Relative Risks, Hazards and Alternatives," Michael E. Kress, George J. Vachtsevanos and Brian P. Leonard, Proceedings Staten Island Institute of Arts and Science, Volume 28, Number 2, December 1974.

11. Staten Island LNG Project: Environmental Impact Statement, Final Supplement Appendices, Federal Energy Regulatory Commission, February 1982.

APPENDIX 1

Volume, Length, Price and Energy Equivalences

Volume

1 cubic foot = .02832 cubic meters

1 cubic meter = 35.314 cubic feet

1 barrel = .15901 cubic meters

Length

1 meter = 3.281 feet

1 foot = .3048 meters

Price

if x = price per 1000 cubic feet

y = price per 100 cubic meters

$\frac{35.314x}{1000}$ = price per cubic meter

.035314x = price per cubic meter

3.53x = y

Energy

1 Btu* = 252 Calories*

1000 cubic feet of natural gas has the energy equivalence of 1 million Btu.

1000 cubic meters of natural gas has the energy equivalence of 9 billion calories.

1 barrel of crude oil has the energy equivalence of 5.6 million Btu.

*The British thermal unit (Btu) is the amount of heat needed to raise the temperature of 1 pound of water $1^{\circ}F$.
The calorie is that quantity of heat which will raise the temperature of one gram of water $1^{\circ}C$.

APPENDIX 2

In most U.S. journals, where price is given per 1000 cubic feet of natural gas, the price is often compared to the price of a barrel of oil. In the U.S. the energy produced by burning natural gas is measured in British Thermal Units. The burning of one thousand cubic feet of natural gas produces energy that is equivalent to 1 million Btu. The energy potential for a barrel of crude oil is 5.6 times the energy content of 1000 cubic feet of natural gas. A Btu equivalent price for oil and natural gas can therefore be computed by multiplying the price of gas by 5.6. Thus, if the total cost of imported LNG was more than $8 per 1000 cubic feet, this price is comparable in energy equivalence to about $45 a barrel of oil - which could have been bought for approximately $30 in 1983.

To express this in metric units we use the following conversions:

1 barrel of oil has 5.6 times the energy content of 1000 cubic feet of natural gas.

We want to compare the energy content and price of a barrel of oil with the energy content and price of 100 cubic meters of natural gas.

Since 100 cubic meters = 3,531 cubic feet,

then 1 barrel of oil has the energy content of 1.586 the energy content of 100 cubic meters of natural gas. $\left(\frac{5.6}{3.531}\right)$

If x = price of 100 cubic meters of natural gas, and

y = price of barrel of oil

then y = 1.586x

If 100 cubic meters of regasified LNG cost $28, the equivalent price for a barrel of oil is 1.586 x $28 or $44.41.

Appendix 2

Find the average annual rate of growth in the price of LNG and domestic natural gas.

Domestic Gas

Price in 1972: \$ .67 per 100 cubic meters

Price in 1983: \$9.81

Use the formula

$P_n = P_o (1 + r)^n$ where

P_o = Price at beginning of period

P_n = Price after n years

r = average annual rate of growth for n years

Log 9.81 = Log .67 + 11 (Log 1 + r)

Solving for r, we get $r \cong 27.6\%$

LNG

Price in 1972: \$ 1.09/100 m^3

Price in 1983: \$22.63

Log 22.63 = Log 1.09 + 11(Log 1 + r)

$r \cong 31.75\%$

The average annual rate of growth for both domestic natural gas and LNG was very high. During this period of energy crisis, prices of natural gas were doubling every 2 to 3 years.

LNG (average price of LNG and domestic natural gas) to be expressed in metric measure, only the price has to be converted (using the equation 3.53x = y). We are interested only in the percentages of domestic and imported (LNG) gas purchased.

TABLE 1

VOLUME AND PRICE OF DOMESTIC GAS AND VOLUME AND PRICE OF IMPORTED LNG PURCHASED BY THE

BROOKLYN UNION GAS COMPANY [1]
(1973-1981)
(1 billion cubic feet)
(dollars per 1000 cubic feet)

Year	Total Quantity of Gas Purchased	Volume of Domestic Gas	Average Price of Natural Gas to B.U.G. (dollars per mcf)[4]	Volume of Regasified LNG	Average Price of Processed LNG to B.U.G.[2] (dollars)	Average Price of Natural Gas to the Customers[3] (dollars)
1973	100.1	100.1	.62	---	---	1.91
1974	94.0	93.4	.69	.6	1.58	2.26
1975	85.6	85.6	.92	---	---	3.03
1976	88.0	84.3	1.16	3.7	2.32	3.66
1977	94.0	90.3	1.39	3.7	2.32	4.01
1978	95.5	91.9	1.59	3.6	3.82	4.29
1979	102.6	93.4	2.07	9.2	3.93	4.85
1980	106.7	98.8	2.55	7.9	4.79	6.45
1981	115.1	101.5	3.54	13.6	6.14	6.48

1. Brooklyn Union Gas Review of Operations, 1979-1981.

2. The cost of LNG to the Brooklyn Union includes the cost of shipping, unloading and regasifying.

3. The cost to the consumer includes the price of gas and delivery, plus other expenses and a profitable return on investments.

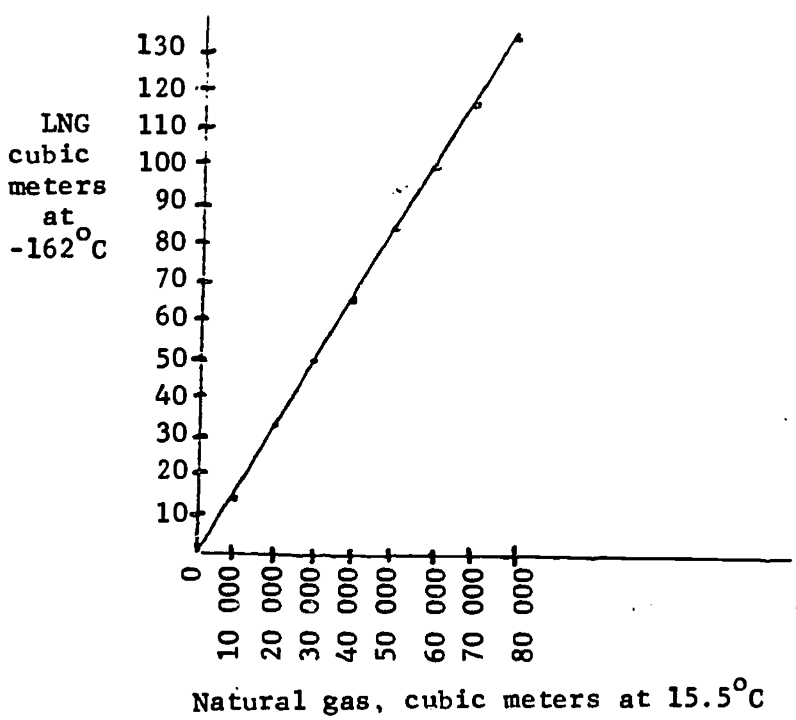
4. 1 mcf = 1000 cubic feet

Problem 1

Natural Gas	LNG
(Volumes in cubic meters)	
3 000	5
30 000	50
100 000	167
300 000	500
900 000	1 500
1 000 000	1 667
30 000 000	50 000
60 000 000	100 000
100 000 000	166 667

if x = volume of natural gas and y = volume of LNG

$$y = \frac{1}{160} x$$



227 000 cubic meters of LNG at -162° would be equivalent to 136 200 000 cubic meters of natural gas at 15.5° C

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Problem 2 Volume of inner LNG tank = 28 000 m^3

P.19 Possible Dimensions

Diameter	Radius	Height	
11	5.5	295	$\longrightarrow$ $r = \pi r^2 h$; $28\ 000 = \pi\,(30.25)\,h$; $h = 295$
21	10.5	79	
30	15.0	39	
30	15.0	39	
41	20.5	21.2	
47	23.6	16	$\longrightarrow$ $28\ 000 = \pi r^2(16)$; $r^2 = 557$; $r = 23.6$
33	16.5	33	

Which tank will have the same height and diameter?

$$\begin{aligned}\pi r^2(2r) &= 28\ 000\\ 2\pi r^3 &= 28\ 000\\ r^3 &= 4\ 456.34\\ r &= 16.456\\ 2r = h = D &= 32.9121\end{aligned}$$

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Problem 3a

Dimensions of inner tank with volume of 95 000 m^3

h = 19 m

Inner Diameter = Outer diameter - 2 x width of insulation space

Inner diameter = 80 m - 2 x 20(cm)

= 80 - (2 x .20)m

= 79.60 m

Radius = 39.80 m

$V = \pi r^2 h$

$= \pi (39.8)^2 (19) \approx 94\ 552\ m^3$

Problem 3b

Inner tank has capacity of 143 000 m^3.

Capacity of outer tank (D = 73 m, h = 36 m)

outer $V = \pi r^2 h$

$= \pi (36.5)^2\ 36$

$= 150\ 674\ m^3$

$-\ \underline{143\ 000\ m^3}$ (given capacity of inner tank)

$7\ 674\ m^3$

Capacity for insulation is 7 674 cubic meters.
Is there space for more than 20cm. thick insulation?

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Problem 3c

1000 cubic meters of natural gas contains potential energy of 9×10^9 calories

Each Rossville, S.I., tank has the capacity for 143 000 m^3 of LNG or 85 800 000 cubic meters of natural gas with the energy potential of

$$(85.8 \times 10^3) \times (9 \times 10^9) = 772 \times 10^{12} \text{ calories.}$$

or 772 trillion calories.

1 ton of TNT contains potential energy of approximately 2.7×10^9 calories.

Therefore, the volume of LNG which could have been contained in the Rossville tank (if it had been filled) is equivalent to

$$\frac{772 \times 10^{12}}{2.7 \times 10^9} = 285.93 \times 10^3$$

Or 286 thousand tons of TNT.

LNG does not suddenly ignite and explode like TNT; it becomes a lazy destructive, asphyxiating flame.

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Problem 4

solution: 1) $V = \pi r^2 h$

2) $S = 2\pi r^2 + 2\pi rh$

Where r and h are the radius and height of the cylinder respectively.

Since V is a constant we can solve

1) for h in terms of r.

$h = \frac{v}{\pi r^2}$, substituting this in 2,

$$S = 2\pi r \left(\frac{v}{\pi r^2}\right) + 2\pi r^2 = \frac{2v}{r} + 2\pi r^2$$

Differentiating S with respect to r we get $\frac{dS}{dr} = \frac{-2v}{r^2} + 4\pi r$.

Setting this derivative equal to zero to find critical values of r yields

r = 24.83 m

d = 49.68 m

h = 49.68 m

Note that the height and diameter of the cylinder with minimum area are equal.

Is this generally true?

Observe that the Bloomfield tank which held 95 000 cubic meters of LNG has dimensions which are very different from the above measures. However, if the bottom of the tank is not to be included in the surface area ($S = 2\pi rh + \pi r^2$) we find r = h = 31.296 and d = 62.592. The dimensions in this case are much closer to Bloomfield's actual dimensions.

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Problem 5a

$V = \frac{4\pi r^3}{3}$, Diameter of inner tank = 37 m
radius = 18.5 m

V = 26 522 cubic meters for each spherical tank

The total LNG capacity of the tanker is (5 x 26 522) = 132 609 cubic meters.

Problem 5b

The volume of the parallelepiped is

$265\text{m} \times 43\text{ m} \times (11 + 15) = 296\ 270\text{ m}^3$.

The ship, approximated by a rectangular parallelepiped, has more than twice the volume of the five spherical tanks. This is true even though approximately one-third of each of the spherical tanks is above the freeboard line and therefore not included in the calculations for the volume of the parallelepiped. In addition to other factors, the space between the inner and outer tanks for insulation and the space for insulation between the tanks must make up for the difference in volumes.

The ship could hold 296 270 - 132 609 or 163 661 m^3 in excess of the five tanks.

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Problem 6

a. 1 cubic meter of LNG = 600 cubic meters of natural gas. When the vapor of the plume mixes with air at ratios between 5 and 15% gas to air it is ready to burn if ignited.

Then, .05x = 600, where x is the volume of combustible mixture of gas and air (5% gas, and 5% air).

$x = 12000$ cubic meters, resulting from 1 cubic meter of LNG.

Thus, spherical tanks with 25 000 cubic meters of LNG have the potential for forming 300 000 000 cubic meters of flammable gas and air mixture.

b. 40 cubic meters of LNG can form 480,000 cubic meters of a combustible mixture of gas and air.

This quantity has the potential of filling a sewer line, 189 Km. in length and 1.8 meters in diameter.

$D = 1.8$ m, $r = 0.9$ m, $h = 189\,000$m

capacity of sewer line $V = \pi r^2 h$

$$480\,000 = \pi \times (.9)^2 \times h$$

$$h = \frac{480\,000}{\pi \times (.9)^2} = 188\,628 \approx 189 \text{ Km}$$

c. Area of the circle = πr^2

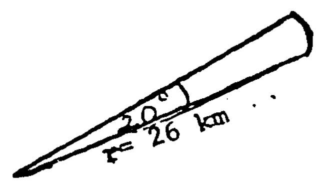
$r = 26$ Km

$r^2 = 676$

$\pi \times 676 = 2124$ square Kilometers

20° wedge covers 1/18 the area of a circle

In this case, 118 square Kilometers



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