Liquefied Natural Gas—A New Source of Energy

Part I, Ship Transportation

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By C. M. SLIEPCEVICH

THE POPULATION explosion accompanied by an ever rising standard of living is dramatically reflected in the world's gigantic demand for more energy. As aptly stated by Schurr [1]:

> "Modern man has made himself largely by burning fuel. The supply of fuel appears to be almost inexhaustible, and a high level of fuel consumption is not a prerequisite of development but a result of it."

Sporn [2] emphasizes that the availability of energy does not guarantee industrial development; rather the capacity to consume energy, not to produce it, is the factor. Sporn's point is directed toward misconception by world leaders following the 1955 Geneva Conference on the Peaceful Use of the Atom. They believed that the advent of the atom as an energy source would not only provide a cheap, inexhaustible source of energy, but it would also convert overnight even the most underdeveloped countries into an economy and civilization comparable to the United States and Western Europe. What they failed to recognize was that the mere presence of available energy could accomplish little without the capital equipment to utilize it.

Man's social, economic, and technical progress can be measured by his progress in utilizing energy effectively [3]. The United States serves as a vivid example, with only 6% of the world's population it consumes about 35% of the world's commercial (excluding wood, animal power, etc.) energy; whereas India with about 15% of the world's population used only 1.5%. A study of our annual energy consumption reveals the economic and technical history of the United States as it emerged from an agricultural economy during the colonial period to the present age of spectacular industrial growth [4].

As late as 1880, wood was our major source of energy, but, by 1890, coal was supplying as much energy as wood. With the growth of electricity, coal quickly replaced wood and, by 1910, was accounting for 75% of the energy. Coal consumption peaked in 1918 but, with the advent of the automobile, liquid petroleum products began to rise rapidly in prominence. Following World War II, as a result of the development of welded, seamless pipe which made long distance gas transmission lines feasible, combined with an enormous upsurge in new residential housing,

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* A Sigma Xi-RESA National Lecture, April 1962.

natural gas further depressed the position of coal in the world's energy picture. The growth in energy consumption and the shift in distribution of energy sources over the past three decades are summarized in Table 1.

TABLE 1

CHANGES IN ENERGY CONSUMPTION BETWEEN 1929–1960[1]

	World		United States	
	1929	*1960*	*1929*	*1960*
Total consumption in million metric tons of hard coal equivalents[2]	1711	4235	777	1448
Distribution in per cent				
Solid fuel	79.8	52.3	67.9	24.6
Liquid fuel	14.9	31.1	22.3	40.8
Natural gas	4.5	14.6	9.3	33.3
Hydroelectric	0.8	2.0	0.5	1.3

[1] *Sci. Am.*, September 1963, 114.

[2] The thermal value of all energy sources is converted to equivalents of hard coal.

It will be noted from Table 1 that natural gas experienced the greatest rate of growth, 350%; most of it has occurred in the United States. While the growth of liquid fuels in the last few years has stagnated, natural gas has maintained about a 7% annual growth rate such that, by the end of 1965, it could surpass liquid fuels as the major source of energy.

The world production and proved reserves of natural gas for 1961 are presented in Table 2.

TABLE 2

WORLD PRODUCTION AND RESERVES OF NATURAL GAS[1]

(Trillions of Cubic Feet)

	Cum. Prod. Through 1961	*Prod. 1961*	*Proved Reserves End 1961*
North America	242.8	14.6	321.0
Middle East	10.0	1.14	178.3
Iron Curtain	19.4	2.65	83.4
Africa	0.3	0.08	54.5
South America	19.5	1.7	44.8
Far East	2.8	0.17	19.6
Europe	3.0	0.55	19.1
Total Free World	278.4	18.24	637.3
Total Iron Curtain	19.4	2.65	83.4
Total World	297.8	20.9	720.7

[1] Summarized from *Oil and Gas J.*, March 12, 1962, 75.

The amount produced as shown in this table does not include the vast quantities of gas that are wasted by flaring into the atmosphere, particularly in the Middle East and South America. The proved reserves, particularly in Europe, are subject to substantial revision as of 1965 due to the large amount of gas discovered in Holland in 1959 but only recently disclosed as the third largest gas field in the world. About 70% of the gas produced in 1961 was in the United States. The distribution among users and the corresponding revenues are summarized in Table 3.

TABLE 3

U.S. SALES OF NATURAL GAS DURING 1961[1]

Category	*Average Number of Customers*	*Thousands of Therms*(1)	*Revenues*
Residential	29,105,000	31,790,900	$3,183,981,000
Commercial	2,392,000	9,599,200	760,033,000
Industrial	136,000	46,844,400	1,622,595,000
Other	38,000	4,845,100	165,236,000
Total	31,671,000	93,079,600	$5,731,845,000(2)

Note: (1) One therm = 100,000 Btu = 100 cu ft of 1000 Btu gas
(2) Represents a gain of 8.0% in revenues over 1960 as opposed to a 2.8% gain in therms

[1] Summarized from *Oil and Gas J.*, January 1, 1962, 56.

It is interesting to observe in Table 3 that the residential customer provides more than 55% of the annual revenue which approaches 6-billion dollars. The revenue produced by the residential customer amounts to 10 cents per unit of thermal energy (equivalent to 100 cu ft of gas), whereas the industrial customer provides only 3.5 cents per therm. As will be explained later, it is this superficial bargain price that industry receives—based on interruptible supply—which actually catalyzed the development of the liquefaction and transportation of natural gas on an international scale.

TABLE 4

COMPARISON OF VARIOUS SYSTEMS FOR STORING AND TRANSPORTING NATURAL GAS[1]

System	*Cu Ft of Volume Req'd. to Contain 1000 Cu Ft of Gas*	*Conditions*	
		Temperature, °F	*Pressure, psi*
Liquefaction	1.6	−250	14.7
Adsorption (Fuller's Earth)	5.0	−250	14.7
Hydrate	5.9	35	450
Absorption (in propane)	6.5	− 52	600
Compression	25.0	100	600

[1] *Chem. Eng. Progr.*, November 1962, 47.

Judging from its effective utilization in the United States, particularly in the last 20 years, natural gas plays a prominent role in an expanding, industrial economy. The situation in the United States has been unique in that it not only has about half of the world's proved reserves of natural gas, but also the gas can be distributed competitively from the major producing areas in the southwest* to all the consuming centers by means of pipelines. On the other hand, a number of the highly industrialized nations like England and Japan are (as yet) neither blessed with indigeneous gas reserves nor can they be reached by pipeline from major producing areas. Since it is impractical to transport natural gas as a gas in bulk form, one obvious solution would be to liquefy the natural gas and transport it as such in ocean-going tankers. The advantage in liquefaction is that roughly 600 cu ft of natural gas at atmospheric pressure shrinks to 1 cu ft of liquid. Other techniques which have been considered are transporting in the gas phase at high pressure, by absorption in liquids, by adsorption on solids, and by reversible chemical combination [5]. A comparison of these various systems is given in Table 4.

TABLE 5

PROPERTIES OF METHANE

Formula	CH_4
Molecular weight	16.042
Gas density at 60°F and 1 atm. in lb/cu ft	0.0424 (0.679 gm/liter)
Specific gravity at 60°F and 1 atm (air = 1)	0.555
Critical temp., °F	−116.5°F (−82.5°C)
Critical press., psi abs.	673.1 (45.8 atm.)
Boiling point at 1 atm. press.	−258.68°F (−161.5°C)
Freezing point at 1 atm. press.	−296.46°F (−184°C)
Density of liquid at −263°F in lb/cu ft	25.9 (415 gm/liter)
Heat of vaporization at boiling point in Btu/lb	219.7 (122.1 cal/gm)
Net heat of combustion at atm. press. in Btu/cu ft	911 (21,240 Btu/lb or 11,800 cal/gm)
Flammability limits volume per cent in air	
Lower	5.0
Higher	15.0

Since it is impractical to store or transport large volumes of gas at any pressure above atmospheric, the most competitive alternative to liquefaction is absorption on fuller's earth. Other solids such as carbon can be

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* Natural gas has been found under less than 1% of the land area of the United States. This gas is transmitted in pipelines (10 to 36 inches in diameter) to consuming markets as far as 2000 miles away at pressures between 200 and 1000 psi.

used, but its adsorptive capacity is less than 10% of fuller's earth. Considerable development work was done, including the operation of a pilot plant in Warren, Pennsylvania, by the Floridin Company and J. F. Pritchard Company in 1949–50, on fuller's earth adsorption [6]. However, because of its 3:1 disadvantage on containment volume as compared to liquefaction, and the fact that the same temperatures and pressures are required, this process has never been commercialized.

At this point, it may be well to review some of the more pertinent properties of natural gas. It is found in porous, subsurface, imperviously-capped formations in various parts of the world (see Table 2). Some wells are more than three miles deep. Natural gas is frequently found with petroleum; about one-third of the U.S. production comes from oil wells.

TABLE 6

BOILING POINTS OF SOME COMMON GASES

Substance	*Normal Boiling Point in °F*
Ammonia	− 28.1
Freon 22	− 41.4
Propane	− 43.7
Carbon dioxide	−109.3 (sublimes)
Ethane	−127.6
Ethylene	−154.8[1]
Freon 14	−198.4
Methane	−258.7
Oxygen	−297.3
Nitrogen	−320.5
Hydrogen	−423.0
Helium	−452.1

[1] Temperatures below −150°F are usually considered cryogenic in the trade.

Natural gas in the United States generally contains between 80 and 95% methane;* the balance includes ethane, propane, butane, pentane, etc. Small amounts of carbon dioxide, nitrogen, helium, water vapor, and hydrogen sulfide are present in most natural gases. Natural gas, along with petroleum, oil shale, natural gas liquids, coal, and lignite, is classed as a fossil fuel.

Where the natural gas is composed primarily of methane, much of the characteristic behavior of natural gas can be predicted from the properties of methane, which are summarized in Table 5.

Since the critical temperature of methane is −116.5°F, it cannot be liquefied at any pressure, however great, above this temperature. The liquefaction temperature or boiling point at one atmosphere pressure is −258.68°F. This boiling point is compared with other gases, which are commonly liquefied, in Table 6.

Liquid methane is a colorless, clear liquid that resembles liquid air;

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* In the Middle East, much of the gas contains less than 50% methane.

its density is about one-half that of liquid air. Because it possesses superior wetting characteristics, liquid methane produces a more severe irritation in contact with the human skin than liquid air does. It is this characteristic wetting property that may serve a useful purpose in cryogenic surgery as a replacement for liquid nitrogen.

Historical

The commercial liquefaction of natural gas dates to a small plant which was built in West Virginia in 1910 to compress natural gas, refrigerate and separate what was called liquid natural gas—mostly ethane and propane—which was bottled and sold locally. A patent application had been made by Cabot as early as 1914 for the liquefaction, storage, and barge transportation of liquid natural gas [7] and, in 1917, a patent was issued (U.S. Pat. 1,225,574) to him covering the apparatus for condensing natural gas under high pressure and cooling.

In 1917, during World War I, the United States Government comissioned the Linde Company, working in cooperation with the Bureau of Mines, to construct a plant in Forth Worth, Texas, for extracting helium from natural gas. The helium was to be used in dirigibles for the Allies. By the time enough helium (90% purity) had been produced to fill one dirigible and was readied for shipment overseas from New York, the Armistice was signed [8, 9]. The process of recovering helium was based on liquefaction of natural gas. Some 10 years earlier, Professors H. P. Cady and D. McFarland at the University of Kansas discovered that many natural gases contained around 1% helium.

After the war, the government, under the jurisdiction of the Navy, constructed a larger extraction plant at Forth Worth in 1921. In 1925, Congress placed all helium activity under the U. S. Bureau of Mines at Fort Worth. When the gas field near Forth Worth played out, the plant was closed and dismantled. A new one was erected near Amarillo, which went into operation in 1929 and has continued to produce helium ever since.

In the early 1920's, patents were issued on insulated containers for river barges suitable for transporting liquefied gas [10]. In 1937, two patents were issued (U.S. Pat. 2,082,189 and 2,090,163) to L. Twomey on methods of liquefaction, storage, and delivery of liquefied natural gas through distributing lines [11].

In 1937, H. C. Cooper*, then president of the Hope Natural Gas Co., became interested in liquefaction of natural gas with the result that a pilot plant was erected at Cornwell compressor station of the Hope Natural Gas Co. of West Virginia in 1940. The liquefaction capacity was 300,000 cu ft of natural gas per day into a cork—insulated storage con-

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* About this same time, Egerton in England was trying to promote the separation and storage of liquid methane by the British Gas Industry to meet seasonal variations in demand on manufactured gas [12].

tainer for 1 million cubic feet of gas (equivalent to 14,500 gal of liquid). Because of the successful operation of this plant, it was used as the basis for the design of a larger installation at Cleveland [10].

The Cleveland Natural Gas Liquefaction Plant of the East Ohio Gas Company went into operation on January 29, 1941. Total construction costs were $1.25 million. This plant was known as a *peak-shaving plant* since its purpose was to liquefy surplus natural gas from the pipeline during the periods of low customer demand in the summer and to regasify the liquid from storage to supplement the pipeline gas during peak demands in the winter. This plant was the first and only one of its kind in the United States: however, at least two liquefied natural gas, peak-shaving plants are scheduled to go on stream in 1965.

The Cleveland plant had a capacity to liquefy 4 million cubic feet of gas a day, to store a total of 150 million cubic feet of gas as a liquid (equivalent to 1.8 million gallons of liquid) in three cork-insulated, (3 ft thick) spherical tanks (57 ft in diameter), and to regasify the liquid at a daily rate of 72 million cubic feet. After three years of successful operation, a fourth tank was installed in 1944. This tank was a vertical cylinder, 70 ft in diameter and 43 ft high surrounded by 3 ft of rock-wool insulation. Its capacity was 90 million cubic feet of gas (equivalent to 1.1 million gallons of liquid). Eight months after installation, the new cylindrical tank failed on October 20, 1944. Because of inadequate dikes, liquefied natural gas (hereafter referred to as LNG) flowed over the ground surface and into the sewers of the city. The resulting explosion and fire caused widespread destruction ($6.8 million) and loss of lives (128). A team of investigators from the Bureau of Mines observed that, among several possibilities, the most likely cause of failure was due to the improper selection of metal. The 3½% nickel steel, which was used, is not considered adequate for this service even by present day standards of greatly improved fabrication techniques. The resulting damage, following tank rupture, was attributed to the lack of confinement of the storage tanks by earthen dikes. Despite the magnitude of the disaster, a significant conclusion by the investigation team is quoted from the Bureau of Mines report [13]:

> "Regardless of the cause of the disaster at the liquefaction, storage, and regasification plant of the East Ohio Gas Company, the application of the system for liquefying and storing large quantities of natural gas is not invalidated, provided proper precautions are taken."

Nevertheless, the Cleveland plant was not operated again.

In 1947, Dresser Industries Limited of Dallas, Texas, designed and constructed a plant near Moscow, Russia at a cost of $6,000,000. This plant had a liquefaction rate of 4.5 million cubic feet of gas per day (comparable to the Cleveland plant) with an equivalent gaseous storage volume of 162 million cubic feet. Little information is available on the operating record of this plant other than it has been giving continuous, satisfactory service. Although the original purpose of the plant was to supply standby gas for Moscow, it is being used to supply vehicle fuel and to supply large customers at points not on gas lines. A description of this plant has been published [14, 15].

In 1949, detailed designs were completed and approved by regulatory authorities for the liquefaction and storage of 400 million cubic feet (equivalent gaseous volume) of LNG by the People's Gas Company of Chicago. This plant would have been built had it not been for the concurrent development of the alternative and cheaper means of storing gas in depleted, undergound, oil and gas reservoirs.

Throughout the 1940's, there was substantial activity in the nature of engineering studies and designs for the liquefaction, storage, and transportation of LNG. Huntington observed in 1950 [16]:

> "Though it may sound fantastic and impractical to many, the proposed transportation of liquid methane by tanker from South Texas to the Atlantic seaboard has been given serious consideration."

However, despite the wishful dreams of the petroleum, gas, and utility companies to capitalize on LNG in its various ramifications and the fact that the technology of liquefaction and storage (particularly in the rapid growth of air liquefaction plants in the 1940's) was well established, none seemed willing to make the capital investment. Two explanations are suggested:

(1) The so-called Cleveland disaster was still fresh in their minds.
(2) The transportation of LNG by tanker or barge involved the solution of a number of technological problems which were not straightforward. For this reason, economic analyses of this phase of the venture always tended to be so ultra-conservative that the overall economics became unattractive.

It was left to a relatively small power company, which was generating power for the Chicago Stock Yards, and its dynamic chief executive, William Wood Prince, to break the ice and take the bold plunge. Armed only with his self-imposed motto of awareness: "Remember Cleveland," he rolled-up his sleeves and went to work on LNG in 1951.

The Constock Breakthrough

Most of the gas supplied to industry falls into the so-called interruptible category. Contracts with gas companies recognize that domestic consumers have first priority on the supply. In periods of severe weather, the supply to industry frequently has to be restricted. For this reason, industry must maintain standby facilities such as coal, liquid fuels, or manufactured gas to carry them through the period of interrupted service. However, industry is willing to accept this inconvenience so long as the gas companies will grant them a bargain price for the gas when there is a surplus during the summer months. As was noted in the comments related to Table 3, the average price paid by the industrial customer is about one-third as much as the domestic customer per unit of thermal energy.

According to one source [17] "a Chicago gas company injudiciously tried to raise the price of the natural gas (interruptible) it was selling to a power company controlled by William Wood Prince," then president of Union Stock Yard and Transit Co. and a managing trustee of the 30-company Prince trust.* It was then—in 1951—that W. W. Prince and one of his consultants, Willard Morrison, conceived the idea of liquefying natural gas on the Gulf Coast and barging it up the Mississippi River to Chicago. The original plan, which was handed to his Chicago Stock Yards Research Division to develop, was to construct a barge-mounted liquefaction unit which could move around to nearly-depleted or remote gas wells (where the cost of gas is very low) and to liquefy the gas directly into another barge for transporting the cargo to Chicago. Another feature of the plan was to utilize the refrigeration contained in the LNG, during regasification at Chicago, to freeze and preserve the various products from the stockyards operation.

After considerable preliminary investigation, research, and development, construction of the barge-mounted liquefaction plant and the transport barge were undertaken in 1954 at the Ingall's Ship Yards in Pascagoula, Mississippi. About this time, Prince decided it would be desirable to have a close working association with a company experienced in gas processing. After talking to several prospects, he found an understanding ear in E. F. Battson, senior vice-president of Continental Oil Company. Continental Oil took a one year's option on a possible joint venture with the Stock Yards Group. A task force composed of Continental Oil Company personnel and several consultants was organized under the direction of J. A. Murphy, who at that time was serving as Battson's technical advisor. This group not only made a detailed evaluation of the work done by the Chicago Stock Yards Research Division, but they also carried out an independent, economic and engineering feasibility study. These studies concluded that the Mississippi barge venture was not economical, but that ocean transportation of LNG from gas-surplus countries to gas-deficient countries offered a very attractive potential. With this understanding, Continental Oil exercised its option to a joint venture, and, in 1955, Constock International Methane Ltd. was organized with equal ownership by Continental Oil Co. and Union Stock Yards and Transit Co. The name Con-stock was obviously derived from the parent companies.

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* Currently, also, Chairman of the Board and Chief Executive Officer of Armour & Co.

Even though the original barging scheme was abandoned, it was decided to utilize both barges as pilot plants for demonstrating the technical feasibility and obtaining valuable design data for a commercial venture. The barges were completed in late 1955 and were then transfered to Bayou Long, Louisiana, for extensive testing throughout 1956.

While these tests were underway in Bayou Long, Constock concentrated on a crash program of research, development, and engineering analyses on all phases of the project, directed toward the commercial venture. Included were innovations in gas processing and liquefaction techniques, material evaluation and development, ship designs, cargo handling, storage tanks, etc. The most amazing aspect of the program was the way it was accomplished by its subsidiary, Constock Liquid Methane Corporation. They operated with a skeleton staff directed by J. A. Murphy and housed in less than 500 square feet of space in a New York office building. Specific research and development assignments were doled out to the laboratories of the parent companies in Chicago and Ponca City, Oklahoma. In addition, several consultants from universities were employed on a part-time basis, primarily to translate the research results into design criteria for practical applications. The bulk of the engineering design and construction was handled by the following:

J. F. Pritchard Co., Kansas City, Mo. (gas processing, liquefaction, and plant construction)
Gamble Brothers, Inc., Louisville, Ky. (wood and insulation specialists)
J. J. Henry Co., N.Y. (naval architects and marine engineers)
A. D. Little, Inc., Cambridge, Mass. (storage and cargo handling methods)

By the spring of 1957, complete designs, specifications, and drawings for the liquefaction plant, tanker, and terminal facilities had been completed. Comprehensive analyses of potential gas sources and markets were also made. It was therefore possible to establish the economics for LNG shipments between a variety of ports all over the world. At this stage, a number of foreign countries, among which were England, Germany, France, Italy, Sweden, and Japan, expressed interest in importing LNG. By the fall of 1957, the British Gas Council made a declaration of intent to import LNG at a rate equivalent to 100 million cubic feet of gas per day, which amounted to about 10% of their total gas consumption. However, the signing of a firm contract was deferred until after several trial shipments of LNG were made between the Gulf Coast and London. Even though the Constock ship designs appeared to be sound, there was as yet no proof that LNG could be transported overseas by tanker, particularly in rough weather.

Constock agreed to erect liquefaction and land storage facilities on the

Calcasieu River near Lake Charles, Louisiana, while the British Gas Council supplied the unloading and terminal storage facilities at Canvey Island near London. Constock and the Gas Council agreed to share in the costs of converting a dry cargo tanker; for this purpose, a new company, British Methane, Ltd. was formed to own and operate the ship.

Lake Charles Facilities: The liquefaction plant, land storage, and loading terminal were erected on a 20-acre site and placed in operation during the latter part of 1958. The barge-mounted liquefaction unit, which was used in the Bayou Long tests, was moved to Lake Charles. A simplified flow sheet of the modified Claude (expander) cycle used on the barge is shown in Figure 1. Although this cycle is relatively inefficient, it has the advantage of being lighter and more compact, and therefore more adaptable to installation on a barge where space is limited. It is interesting to note that this pilot liquefaction unit with a rated liquefaction capacity of 7 million cubic feet of gas per day was 1.7 times larger in capacity than the Cleveland or Moscow plants of the 1940's.

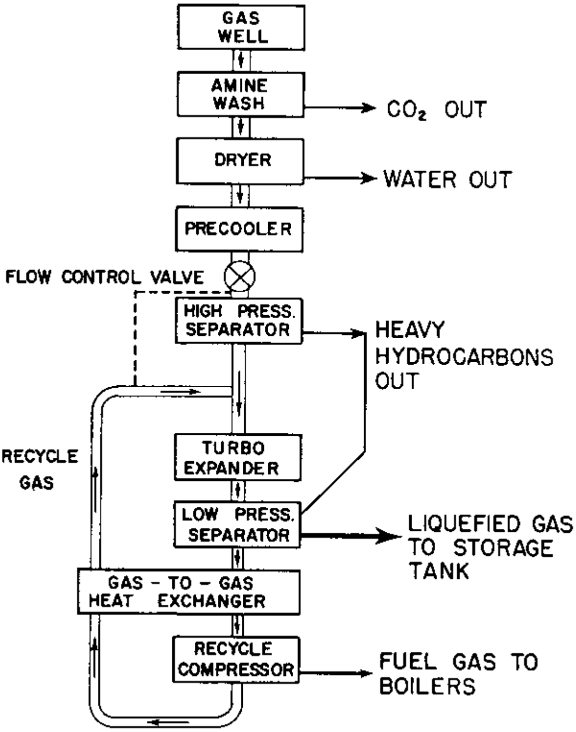

FIG. 1. Flow sheet of methane liquefaction barge

The liquid from the plant was stored in a tank having a capacity of 1.47 million gallons (equivalent to 120 million cubic feet of gas). Up until 1964, this tank was the largest ever built for storing cryogenic liquids (below −150°F). This container is double-walled, with an aluminum inner tank separated from an outer steel tank by 3 ft of perlite insulation. Its outer dimensions are 73 ft in diameter by 61.5 ft high. A photograph of the site at Lake Charles, Figure 2, shows the storage tank and barge-mounted liquefaction unit [18, 19].

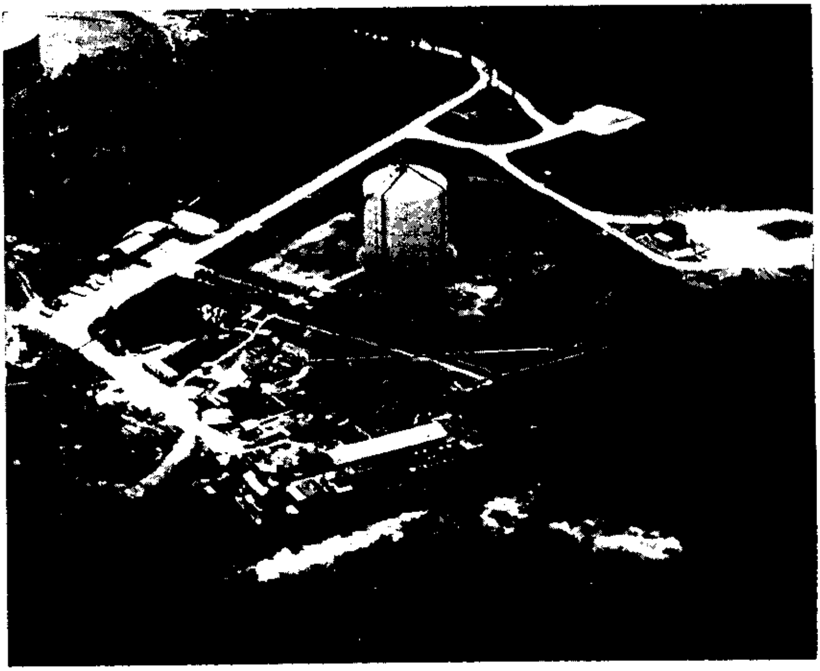

FIG. 2. Constock's LNG liquefaction terminal at Lake Charles, La.

Methane Pioneer: For transporting the LNG, a Cl-M-AVl dry cargo ship (5000-ton class) was converted to the MV Methane Pioneer at the Alabama Drydock & Shipbuilding Co. in Mobile, Alabama, during 1958, according to plans and designs developed by Constock and J. J. Henry Company. A dry cargo ship was selected because it has large double bottoms and wing tanks which can be used for ballasting, a particular problem raised by the low density of liquid methane (about 40% of the density of water). In addition, a number of other innovations in outfitting the ship for cryogenic service were required [19, 20, 21]. However, only the insulation and cargo tanks will be mentioned here since they represent the major accomplishments upon which the success and economics of the project hinged [22].

The horizontal cross section of a tanker's hold space is essentially rectangular. Therefore, in order to obtain the maximum utilization of this space for liquid cargo, the horizontal cross section of the cargo tanks must likewise be rectangular. Cylinder tanks would be easier and much cheaper to fabricate, but unfortunately they would utilize only $\pi/4$ or about 80% of the cargo space. Because of the high cost of the ship—almost twice the conventional tanker—for LNG service, the economics dictate that the space utilization should be greater than 90%; thus prismatical tanks (rectangular parallelopipeds) are used. Unfortunately, prismatical tanks introduce two severe design problems:

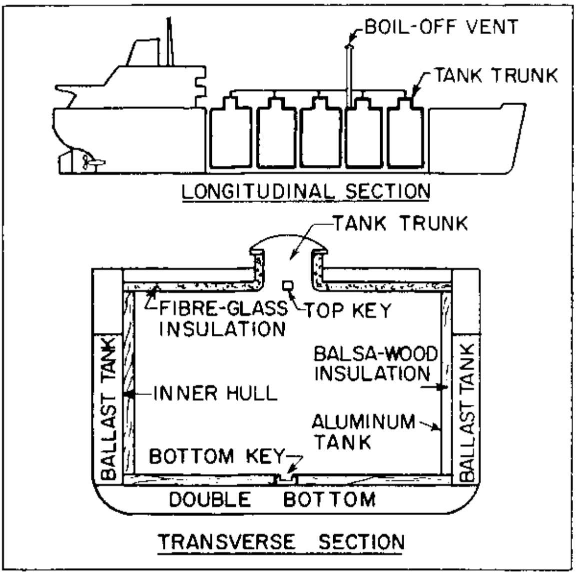

FIG. 3. Cross sections of vessel showing prismatical tanks

(1) High stresses in the flat walls caused by cyclical, dynamic loads from rolling, pitching and heaving of the ship.
(2) Thermal stresses in the walls caused by sharp, vertical temperature gradients when the tank is only partially filled.

Obviously, one large tank filling the entire cargo space would be cheaper than several small ones. However, regulatory bodies for ships have limits on the size of individual compartments with respect to dynamic loadings, free-surface liquid effects, and safety under collision conditions.

Working within these shape and size limitations, the next step is to select the material of construction. Although all materials, metals, plastics, concrete, wood, etc., show an increase in strength with decreasing temperature, most of them become brittle at low temperatures. For this application, the choice narrows to aluminum (5000 series alloy), stainless steel, or 9% nickel steel [23]. Aluminum is selected on the basis of economics.

As was mentioned before, the prismatical tanks are expensive so it was necessary to optimize the design. In order to do so, a method for making stress analyses had to be developed [22]. The general configuration of the tanks and relative location in the ship are shown in Figures 3 and 4.

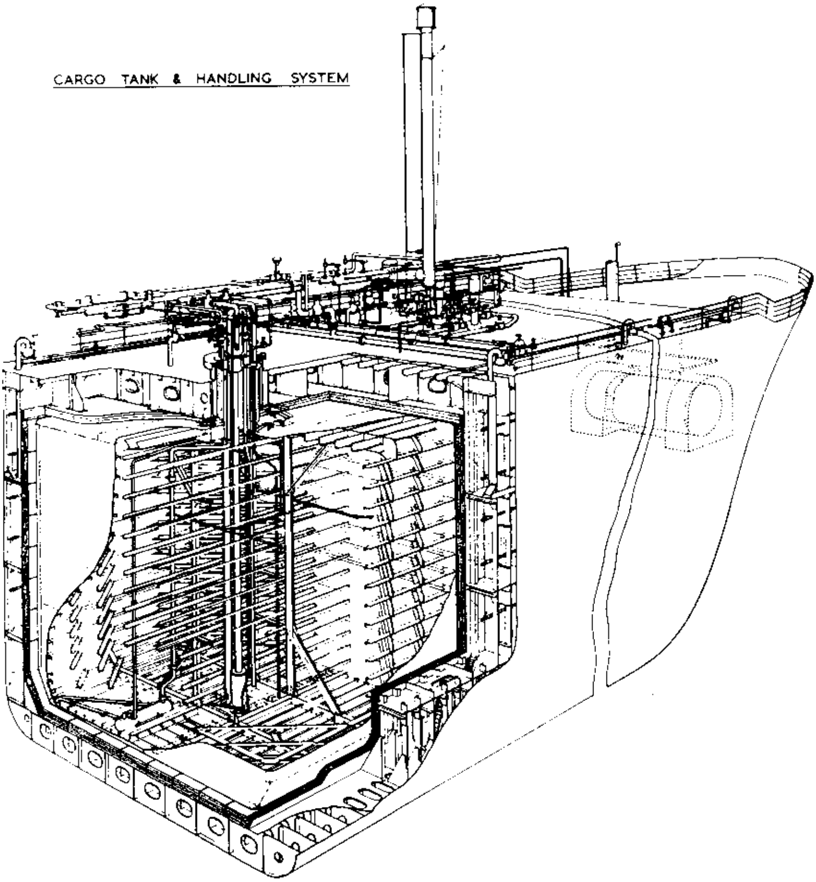

FIG. 4. Cutaway of cargo tank showing internal bracing

In Figure 3, it can be noted that the aluminum tanks are surrounded with insulation, which had to meet the following requirements:

(1) The insulation must maintain the ship's structure near ambient temperatures. Since the steel used in the hull cannot withstand LNG

temperatures without becoming brittle, the insulation must also perform as a secondary, liquid-tight barrier in the event one of the aluminum tanks springs a leak.

(2) The bottom insulation must be capable of withstanding the enormous stresses (due to the ship's motion) generated at the bottom key of the tank.

(3) The insulation must provide a prescribed rate of boil-off of LNG if the vapors are to be used to generate power for propelling the ship.

(4) Since the insulation has to be attached to the ship's inner hull, it must be able to withstand the severe thermal stresses (−250°F on one face and ambient on the other) without yielding.

(5) In the event of fire on board ship, the insulation must be able to maintain structural integrity for at least four hours when its outer face is exposed to a temperature of 1200°F.

TABLE 7

RATIO OF YIELD STRESS TO THERMAL STRESS FOR COMMON MATERIALS

Material	$(S_{\mathrm{YP}}/\alpha E(\Delta T)_{\max}$[1]
Wood	2.2–9.2
Cast iron	2.3
9% nickel steel	1.2
Foamglas	0.45
Concrete	0.3
Stainless steel (304 annealed)	0.28
Aluminum alloy (5000 series, annealed)	0.22

[1] S_{YP} = Yield point in compression.
α = Coefficient of thermal expansion.
E = Modulus of elasticity.
ΔT = Temperature differential, 70°F to −320°F = 390°F.

To satisfy these particular requirements, balsa wood was the only insulating material that was adequate in all respects. In general, any material, whose ratio of yield stress to thermal stress is greater than one, can be subjected to cryogenic temperatures in a fully restrained condition so that it is not free to contract. Table 7 compares this ratio for several common materials of construction. Although cast iron has a ratio of 2.3 it is not suitable for cryogenic service because it becomes brittle even at 0°F. Nine per cent nickel steel is not recommended for use below liquid nitrogen temperatures. With its high ratio, 2.2–9.2, wood is one of the best materials for cryogenic service.* Its chief disadvantage lies in the difficulty to predict stresses. Being an anisotropic material, one must consider three ultimate strengths and 9 Poisson ratios in analyses.

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* Wood is even finding use at high temperatures, such as in spacecraft nose cones [24].

The final design problem involves the insulation and cargo tanks together. Economics might indicate a thickness of insulation which results in prohibitive thermal stresses being generated in the tank walls, since the thermal stresses increase with decreasing insulation thickness as shown in Figure 5.

The installation of the aluminum tanks is shown in Figure 6. Figure 6A shows the hold space lined with balsa panels which are so laminated as to give identical physical properties in two dimensions. The panels are faced with ⅛ inch plywood. They are 4 × 8 × 1 ft thick and are joined together with plywood scabs and fiber glass rosettes. Figure 6B shows one of the aluminum tanks, measuring 29 × 40 and 32 ft high, having a capacity of about 280,000 gal being lowered into the hold. Figure 6C shows the first tank in place, the clearance between the sidewalls of the tank and insulation averages about 1 inch in order to maximize on cubic carrying capacity. Four more similar tanks, when installed, bring the total capacity to over 1.40 million gallons (equivalent to 115 million cubic feet of gas).

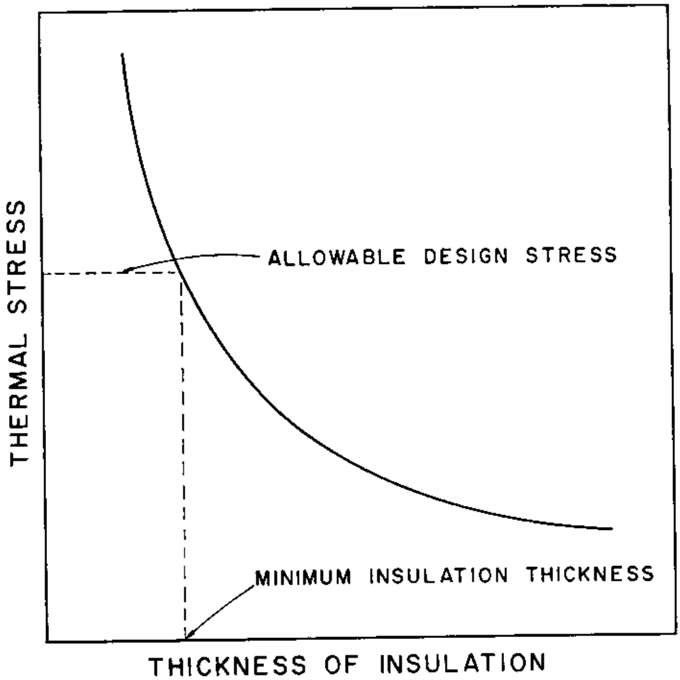
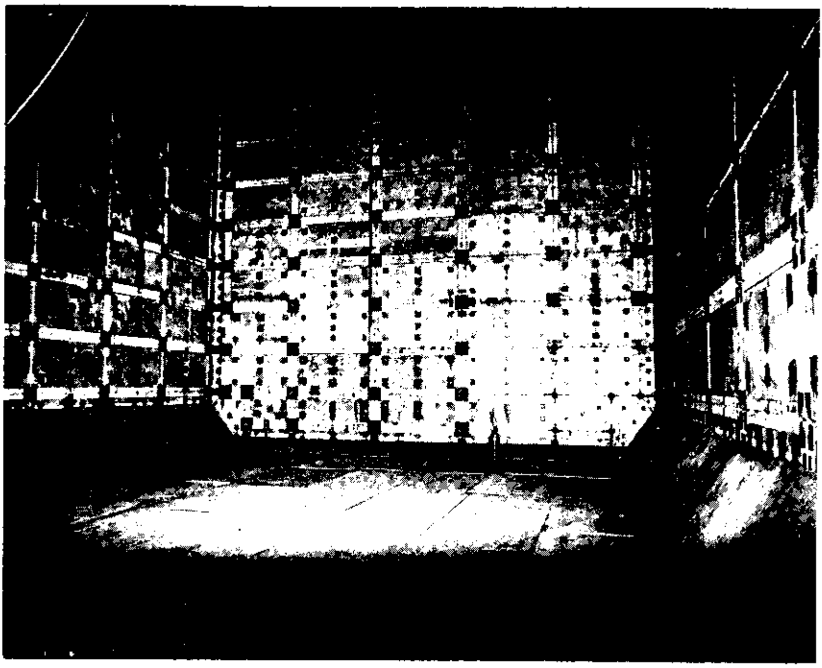
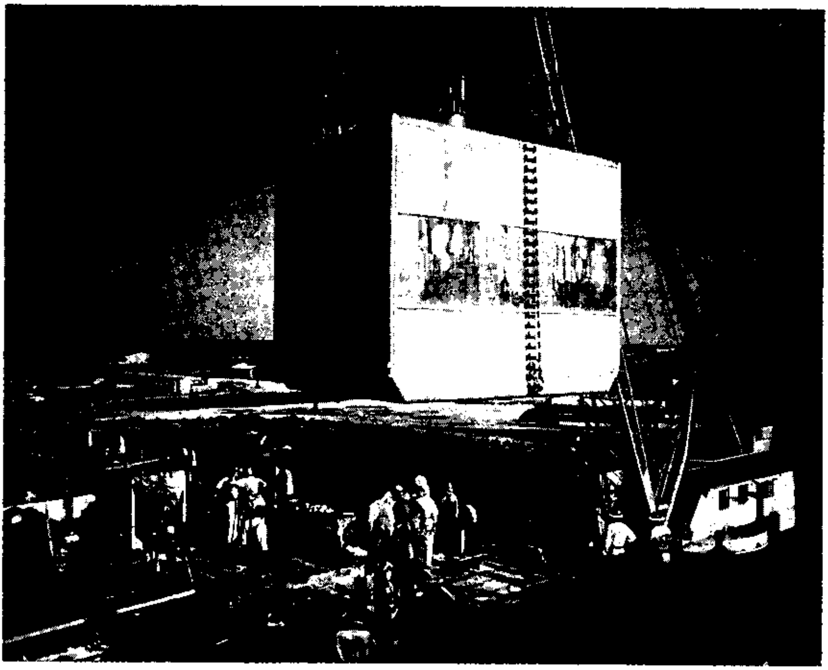


FIG. 5. Variation of thermal stresses in tanks with thickness of insulation

Figure 7A shows the appearance of a Cl-M-AVl dry cargo ship before conversion, and Figure 7B, the Methane Pioneer after conversion. The





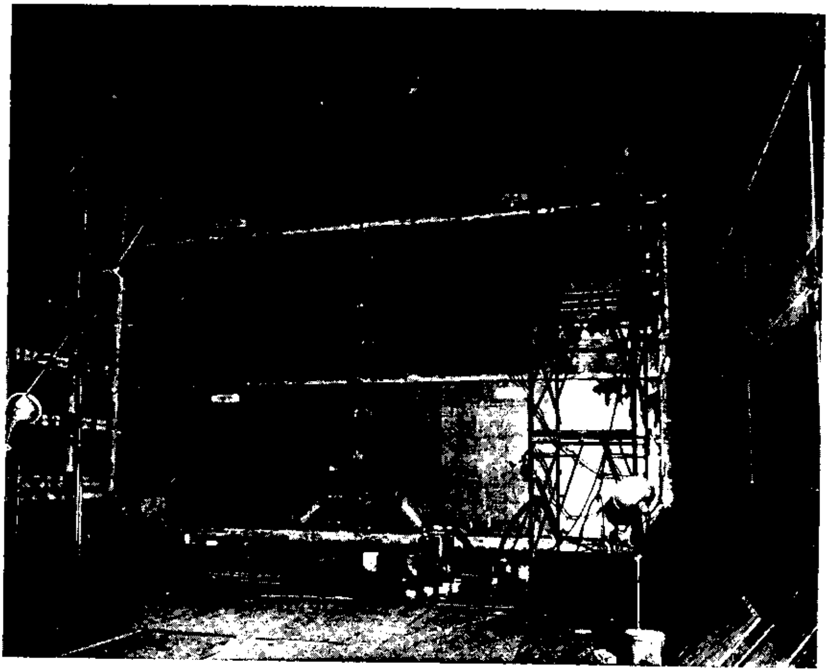


FIG. 6. Installation of aluminum tank in methane pioneer
A. Insulated hold space
B. Lifting the tank
C. Installed tank

ship is over 350 ft long, 50 ft wide, and 40 ft deep, a healthy-sized pilot ship but tiny compared to present day tankers.

The Methane Pioneer took on its first load of LNG, equivalent to 115 million cubic feet of gas, and departed from Lake Charles on its historic voyage, January 28, 1959. It arrived at Canvey Island on February 20, 1959, and discharged its cargo into 2 insulated, land storage tanks, each having a capacity of 670,000 gal (equivalent to 55 million cubic feet of gas).

Over the next year, ending in March 1960, the Methane Pioneer made six more trial shipments. The ship performed admirably, even in very heavy seas where rolls exceeding 45° were recorded [19, 20, 25]. Having proved that LNG could be transported overseas by tanker, LNG shipments from Lake Charles were terminated because the Methane Pioneer was only a pilot ship and had less than one-fifth of the minimum carrying capacity for economical operation. Since then, the Methane Pioneer has continued in service as a refrigerated butadiene carrier between the Gulf Coast and Holland.

An idea which was conceived nine years earlier by W. W. Prince to solve a local power company's problem in Chicago had become an international enterprise. The world awaited with great interest, particularly the skeptics—and there were many—for the maiden voyage of the Methane Princess. Hardly had she docked at Canvey Island before many others were dashing madly to get into the LNG business and reap the benefits at the expense of Constock's pioneering leadership. Constock, after nine years and some $15 million of investment had proved not only to herself but—with full knowledge aforethought—for all her potential competitors that the job could be done. Although Constock had developed a protective wall of several hundred international patents, these alone were not enough to discourage competition.

Commercial Ventures

Early in 1960, Royal Dutch/Shell joined forces with Constock, and a new company, Conch International Methane Ltd., was formed. Royal Dutch/Shell and Continental Oil Company each acquired a 40% interest and Union Stock Yards and Transit Company retained the balance of 20%. (The name Conch is derived from CON = Continental, CH = Chicago Stock Yards, and CONCH = (sea) Shell.) The headquarters were moved to London to initiate the first commercial venture for hauling LNG from North Africa to England. The only activities that remained in the States were the pilot plant projects on gas purification, submerged pumping, in-ground storage, and fire tests, at Lake Charles; insulation development at Gamble Brothers in Louisville, and basic research at Continental Oil Company in Ponca City, Oklahoma.

The London headquarters were rapidly expanded to provide for research, development, engineering, marketing, and patent services. Their first step was to initiate construction of a liquefaction plant and larger tankers modeled after the plans developed by Constock. Shortly thereafter, in the spring of 1960, Conch entered into an agreement with the French government to purchase gas* from the big Sahara Hassi R'Mel gas field and to build a liquefaction plant near Arzew, Algeria, on the North African Mediterranean Coast. The liquefaction plant was to be financed and built by a new company, CAMEL (Cie Algierienne du Methane Liquid) owned jointly by Conch and French interests.

Although Britain presumably was to provide the initial market for this plant, and construction of the plant was undertaken, more than 18 months elapsed before the U. K. government announced its approval in January 1962 [26]. The delay was due to political angles involved: coal-industry opposition and the Algerian turmoil following its liberation, which raised questions regarding the stability of the Saharan gas as a source for imports. However, in the final analysis, the

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* Contrary to popular belief, the contract price for the gas was around 25 cents per 1000 cu ft which is no better than current gas prices on our Gulf Coast.

British Gas Council decided that the Sahara gas was as reliable as the British sources for oil which—in the minds of many Europeans since the Suez crisis—are not too reliable [27].

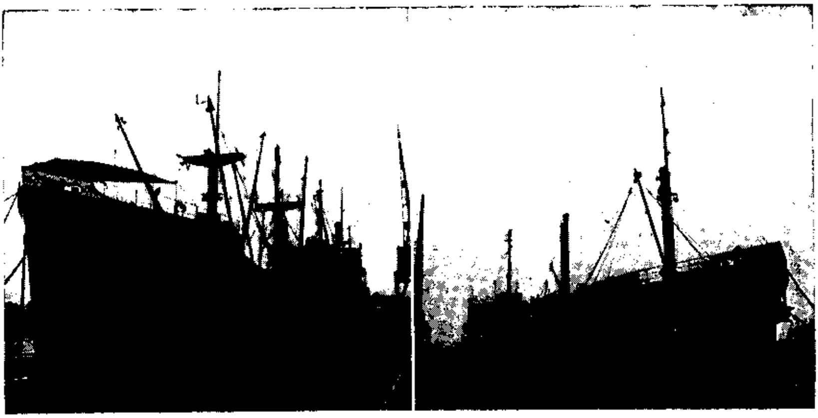

FIG. 7. A. Cl-M-AV1 before conversion
B. Methane pioneer after conversion

After Algeria gained its independence, it demanded and obtained additional participation in the LNG venture. The final lineup of operating companies is as follows [28]:

1. Liquefaction Plant by CAMEL (40% Conch, 40% French interests, and 20% Algerian Government).
2. Gas Production at Hassi R'Mel Gas Field by Ste. d'Exploitation des Hydrocarbures d'Hassi R'Mel.
3. Pipeline* from gas field to Arzew by SOTHRA (combination of French and Algerian interests).
4. Transportation by British Methane Ltd. (50% Conch and 50% British Gas Council) which buys LNG, ships to England, and sells to British Gas Council.
5. Transportation by Gaz de France, the French counterpart of the British Gas Council, which buys LNG and ships to France [29].

With the decision by the French to participate in the initial venture by contracting for 50 million cubic feet of gas daily, the capacity of the liquefaction plant was raised from 100 million to 150 million cubic feet per day, with Britain under a 15-year contract to take 100 million cubic feet per day. The liquefaction cycle selected was based on a cascade cycle developed by Constock. The terminology "cascade" derives its usage from the fact that the gas is progressively cooled in a series of

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* Three hundred miles of 24-inch pipeline.

steps as shown schematically in Figure 8. The second law of thermodynamics provides that, as the difference in temperature between the refrigerating medium and the medium being cooled is diminished, the more efficient the process becomes. In the limit, the most efficient process would be one in which the temperature difference was zero. However, practical, cost limitations force a compromise to a finite temperature difference, which as noted in Figure 8 amounts to 5°F in each step except one of the ethylene stages (8°F).

TABLE 8

COMPARISON OF LNG LIQUEFACTION CYCLES

Cycle	*Inlet Gas Pressure, psi*	*Horsepower Per Million Cu Ft Gas/Day*	*Per Cent of Total Feed Used as Fuel*
Ideal	500	185[1]	
Practical limit	500	400[2]	
Cleveland cascade	615	662[1]	15
Russian cascade	725	660[3]	
Constock barge expander	1000	1000[1]	30
Arzew cascade	465	469[1]	8
Conch expander	465	540[1]	10
Transco cascade peak shaving	315–490	716[4]	

[1] C. L. Ritter, *Chem. Engr. Progr.*, *58*, 61–69 1962.

[2] Estimated.

[3] P. S. Parker and R. H. Armston, *Gas Age*, March 11, 1954.

[4] R. Martin, *Petrol. Management*, Dec. 1964, 84–89 (Actual Horsepower Required is 624).

A comparison of the power and fuel consumptions for the various LNG liquefaction plants that have been built to date is presented in Table 8. Although the theoretical, ideal power requirement is only 185 horsepower per million cubic feet of gas per day, the practical fact that no machinery, such as compressors and expansion engines, have been built, as yet, which are 100% efficient, and all economical heat exchangers must operate with finite temperature differences, raises the theoretical limit from 185 horsepower to a so-called practical limit (by today's standards) of 400 horsepower. The Arzew plant is not far away from this limit with 469 horsepower.

The storage facilities for liquefied natural gas at Arzew amount to 17 million gallons of liquid or equivalent to 1-billion cubic feet of gas [28]. There are 3 double-walled, above-ground storage tanks, each having a capacity of over 2.5 million gallons. These tanks are modeled after the Lake Charles tank with a scaleup factor of about two. Two of these tanks have an inner shell of aluminum and the third a 9% nickel steel inner tank. All three have 3 ft of perlite insulation between these inner shells and an outer shell of conventional steel.

The rest of the storage, which amounts to 55% of the total, or 9 million gallons, will be in a frozen cavity 122 ft in diameter and 114 ft into the ground. This in-ground storage principle was developed by Conch [30] and is based on the principle that the moisture in the ground freezes to form a frozen cavity, which serves as an ice barrier that prevents leakage and at the same time supplies adequate insulation. The use of this in-ground storage results in a saving over conventional aboveground storage in the neighborhood of about 5 cents per gallon or, in this case, about $450,000.

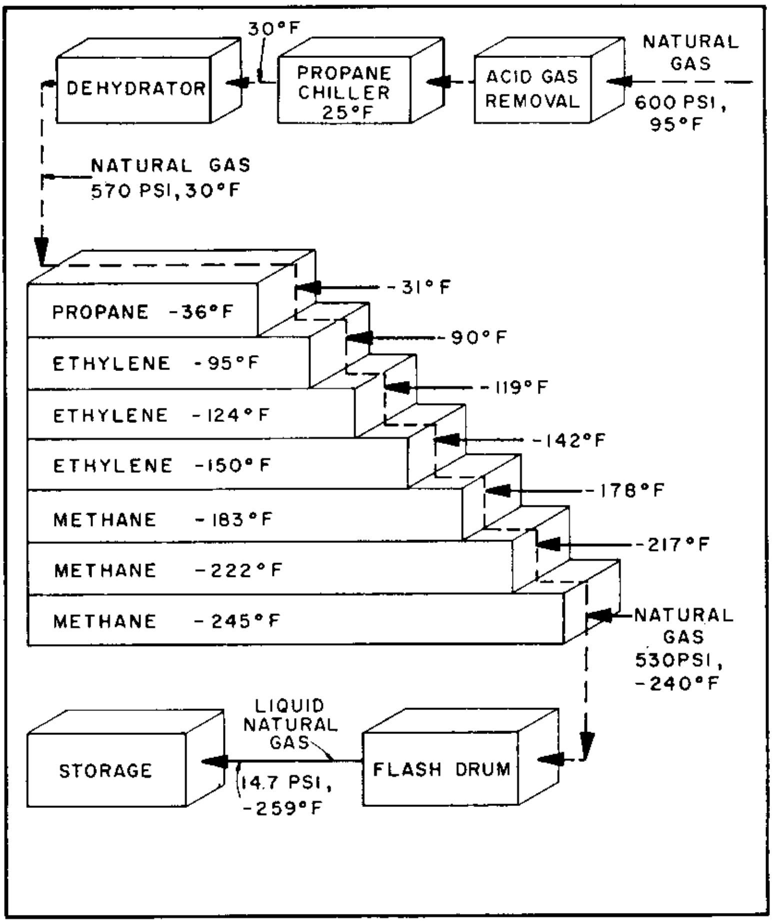

FIG. 8. Schematic of liquefaction of natural gas by means of cascade cycle in Algeria (data from *Chemical Engineering*, October 12, 1964, 182–184).

The storage facilities will supply three tankers, each of them making about 30 round-trips per year, and delivering about 7 million gallons of liquid (equivalent to over 500 million cubic feet of gas) per trip. Two of the tankers, the Methane Princess and the Methane Progress were built in British and Irish shipyards respectively. These tankers are essentially replicas of the Methane Pioneer in having prismatical aluminum tanks and balsa wood insulation. However, the French-built tanker, appropriately christened the Jules Verne,* has seven cylindrical tanks of 9% nickel steel insulated with 17 inches of Klegecell[1] on the bottom (conical shaped, rather than keyed). The vertical walls and roof consist of 2½ inches of Klegecell covered with a liquid-tight sealant to act as a secondary barrier. The walls and roof are further insulated with perlite [31]. Apparently, the French were able to realize sufficient economies in going to the cylindrical, rather than prismatical tanks, despite the 20% loss in cubic capacity. It has been reported [31] that the French ship cost $10 million to build against the $13 million for its British counterpart; the $3 million savings could have tipped the balance for cylindrical tanks, not to mention a possibility that the Conch-patented ship designs might have been evaded.

TABLE 9

APPROXIMATE COSTS FOR LIQUEFACTION AND OVERSEAS TRANSPORTATION

1. Capital investment			
a. Liquefaction plant 100 million cu ft/day		$\$40 \times 10^{6}$	
b. 2 Tankers @ $\$13 \times 10^{6}$			
Basic ship	50%		
Cargo handling	20		
Insulation	12		
Alum. tanks	18	26×10^{6}	
			$\$66 \times 10^{6}$
2. Annual operating costs (source to market about 1500 miles)			$\$13 \times 10^{6}$
3. Direct cost liquid natural gas delivered: *Before* taxes, administrative, research, and sales expense and *excluding cost of* gas at source			$0.36/1000 cu ft

The terminal facilities on Canvey Island consist of seven conventional above ground storage tanks, including the two that were used on the trial shipments with the Methane Pioneer, for a total capacity of 140 million gallons or a gas equivalent of over 1.1 billion cubic feet. The liquid is vaporized from storage in a novel scheme of heat exchange with propane and sea water which results in a net production of about 1.7 megawatts of power as a bonus. The vaporized gas then goes into an

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* French science fiction writer who half a century ago referred to natural gas as a major energy source.

[1] Polyvinylchloride.

18 inch pipeline extending some 300 miles northwest for delivery to 8 local Gas Boards; who will either blend the natural gas with manufactured gas or reform it to the lower calorific value needed in domestic burners [32].

The investment costs for an operation liquefying and transporting LNG are enormous; an order of magnitude estimate is given in Table 9. To these figures must be added the cost of the unloading terminal facilities, which are comparable in cost to the liquefaction plant if gas reforming and pipeline distribution facilities are included.

The costs given in Table 9 are to be viewed with reservation since they can vary widely depending on the locality. For example, one reference [33] quotes that the Arzew liquefaction plant cost $60 million. Even correcting the figure of $40 million given in Table 9 for a 100- to 150-million cubic feet per day plant, the corresponding figure would be around $50 million. A later reference [32] pegs the total costs in Algeria at $70 million; another reports $86.8 million [28]. From these figures, it is possible to arrive at an estimated total investment in this first LNG project as summarized in Table 10 in round figures.

Whatever the final investment figures become, Conch is under a 15-year contract to supply Britain with 100 million cubic feet of gas per day at a price of 88 cents per thousand cubic feet, which indicates a slow payout. The corresponding costs of manufactured gas in England from both oil and coal range from $1.07 to $1.75 per thousand cubic feet depending on the process used [27].

Future of LNG *Transportation*

The first commercial shipment of LNG from Algeria arrived in London on the *Methane Princess*, October 12, 1964. Since then, the Methane Progress and the Jules Verne have been brought into service. Much of the excitement regarding the potential markets for LNG in Western Europe was chilled to sub-zero proportions when gas was discovered on July 29, 1959 [34] by NAM (Nederlandse Aardolie Maatschapij—jointly owned by Royal Dutch/Shell and Standard Oil of New Jersey). The extent of the reserves was not publicized until around the middle of 1962, when it became rather evident that the field was the largest in Europe [35]. Up to this time, the Po Valley in northern Italy and Lacq in southeastern France provided the bulk of the natural-gas supply in Europe. By 1964, it became clear that the Dutch field was the third largest in the world, ranking behind only the Texas Panhandle and the Sahara field. Although the extent of the Dutch discovery was not known prior to 1963, Royal Dutch/Shell as a partner to this discovery surely must have been aware of the ultimate impact of Dutch gas on LNG when they joined forces with Constock in 1960.

It is certain that the Dutch gas will cut deeply into the formerly,

TABLE 10

REVISED ESTIMATE OF TOTAL INVESTMENT IN FIRST LNG VENTURE

		Millions of Dollars Invested
Gas pipeline (300 miles of 24 inch line from Sahara gas fields to Arzew)		$ 35.0
Liquefaction plant, Arzew		85.0
Two tankers		25.0
Unloading and distribution in London		
Canvey Island facilities	= $ 8.0	
Reforming plant	= 21.0	
Distribution line	= 21.0	50.0
Total		$195.0[1]

[1] This total does not include the French tanker and the unloading and distribution facilities in France. However, the gas pipeline in Africa was constructed apart from this particular project. Its cost probably balances the French investment in a tanker and unloading terminal. Therefore, the total investment resulting directly from the gas liquefaction is in the neighborhood of $200 million.

potential LNG markets in Holland, Belgium, Sweden, northern France, and Germany. The Dutch discovery has kicked-off an exploration panic across the North Sea and extending inland into northern England. Engineering feasibility studies on laying a gas pipeline across the English Channel are already in the advanced planning stages.

France is attacking the natural gas supply problem on all fronts. The Jules Verne had not even made its first shipment when France announced plans to build another tanker 4 times as large [31]. For several years, they had studied and experimented on a pipeline under the Mediterranean to bring Algerian gas to Spain and on into France [36, 37] but recently admitted that the project was shelved due to Franco-Algerian political problems [31]. However, at the same time, Ben Bella revealed his plans for a Mediterranean gas pipeline to Europe with a second gas liquefaction plant in Eastern Algeria [38].

Even with the Dutch finally announcing that they were pricing their gas competitively with other fuels, as low as 35 cents per 1000 cubic feet while continuing with expansion of distribution lines, Jersey Standard, the other half of NAM (discoverers of, and partners in producing Holland gas) gave their answer to the North Sea successes by releasing plans for shipping Libyan gas to Italy and Spain. The liquefaction plant, which will be located on the Mediterranean Coast, 100 miles from the Essos Zelten area fields, will have a capacity of 300 million cubic feet of gas per day—twice the size of the Arzew plant. Tankers will start shuttling to Italy and Barcelona, with the former taking 80% of the cargo, by late 1967. Total investment will be around $200 million [39].

While others are looking at Middle East and West Pakistan gas for transporting to Japan, Australia and South Africa, Polar LMG Corp., a subsidiary of Union Oil and Marathon Oil Co., is negotiating a contract with Tokyo Gas. Co. to deliver 35 million cubic feet of gas per day from either Alaska or British Columbia [40, 41]. Originally, the timetable looked for 1965 as a shipping date, but it was delayed to 1967 after natural gas was discovered in Niigata, Japan [42].

Scandinavian oil industry leaders are talking about a joint venture to import Sahara gas, despite the proximity of the Holland and North Sea fields [42].

It is no secret that Conch, Union Oil, Ohio Oil, and others are looking at both the U.S. East and the West Coasts with an expectative eye. California's demand for gas is expected to reach 8 billion cubic feet of gas per day by 1982, at which time it is estimated that they will be producing less than 1 billion cubic feet [43, 44].

Australia, which is still considered a good market, is continuing to show substantial increases in their own gas fields [45].

Venezuela flares more gas by a factor of almost two than is currently consumed in all of Western Europe. They missed their chance of becoming the first source for LNG when they could not come to an agreement with Constock on gas price back in 1958 [44], but they very likely will enter the picture soon.

Looking to the year 2000, when the world's energy consumption will climb to five times the current rate [1] it is reasonable to conclude that transportation of LNG will continue to prosper. Even though natural gas continues to be discovered all over the world, there is an interesting, opposing force which will act to increase the cost burdens on distribution by pipeline. As population density increases, right-of-way cost for pipelines rises drastically. Holland, with a population density of 910 per square mile, coupled with the need for myriads of underground road and water crossings is already faced with pipeline construction costs that are two to three times higher than the average elsewhere [34]. Already, they are resigned to the fact that at least half of their production will have to be exported.

Competition from other fuels will always be a problem, but the petroleum and gas industries thus far have demonstrated a unique—so far as energy sources are concerned—adaptive, pricing-control characteristic which keeps its products moving on the open market. Continued research and development will lower the cost of producing LNG. Modest improvements can be expected in the liquefaction and storage aspects; however, the next big jump will occur when ship builders abandon the notion that an LNG carrier must look and act exactly like a conventional oil tanker and start building a carrier to conform to the needs of the cargo. Some trends have already been noted, ranging from modest [46, 47, 48, 49, 50] to others more daring [51, 52, 53].

Concluding Note

In retrospect, if the writer has failed to convey the significance of Constock's successful pioneering effort, then let it be remembered as an outstanding, technological achievement. In this era of daily breakthroughs, however, it is appropriate to quote Dr. Harvey Brooks, Dean of Engineering and Applied Physics at Harvard University:

> "Breakthroughs are mainly figments of publicity agents' imagination. They come slowly, a series of steps, advancing the art. There's more prior art than we're led to believe. It's a matter of sudden realization."

Acknowledgment

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