UTILIZING THE "COOL" IN LIQUEFIED NATURAL GAS

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Abstract

Liquefied natural gas (LNG) from a tanker or storage tank is commonly vaporized into a pipeline using sea water, ambient air, or the hot products from the combustion of a small portion of LNG as a source of heat, thereby neglecting the exergy associated with its cryogenic temperature. The investigation reported on herein indicates that utilization of this exergy for refrigeration and the generation of electricity is feasible technically and economically.

Introduction

The depletion of liquid and solid fossil fuels has led to an increasing role for natural gas as a source of energy. Natural gas is combustible and burns cleanly with reduced CO_2 emissions and without producing SO_2 and NO_2. Natural gas is found all over the world in underground pockets. Formed from the decomposition of organic materials that have been subjected to high pressures, natural gas is composed of 90% methane with the remainder consisting of a mixture of heavier hydrocarbons and traces of CO_2, N_2, O_2 and H_2S. The nitrogen and carbon dioxide are typically removed from the natural gas before its liquefaction. In general, the sulfur content of natural gas is significantly lower than that of crude oil and need not be removed.

Natural gas is transported domestically as a pressurized vapor using networks of pipelines. Due to the excessive distances across which pipelines would need to be constructed and maintained, and to the inherent risk involved when crossing politically unstable nations, importing natural gas by pipelines from sources other than Canada is impractical. In order to transport natural gas by ocean tankers, it must be condensed to LNG, which decreases its volume by a factor 600. The tankers themselves are highly insulated double-layered vessels capable of storing LNG at its boiling point of -162°C at atmospheric pressure. Upon reaching its destination, LNG is pumped from the tankers into storage tanks at a terminal, regasified, and introduced to one or more pipelines. The process described here is concerned with increasing the thermodynamic and economic efficiency of regasifying LNG by harnessing the exergy of the cold LNG to produce electricity and refrigeration and by selling each of these products for supplemental revenue.

The Early History of LNG

It is important to know the early history of LNG because it influences attitudes and the choice of processes and venues. LNG was apparently first produced and stored in quantity by the US Bureau of Mines at Amarillo, Texas in 1917 in connection with the extraction of helium from natural gas. That plant may still be operating today.

In 1941 the East Ohio Gas Company constructed a plant to liquefy and store natural gas for "peak shaving", that is to allow a pipeline from Texas to continue to deliver gas at an unreduced rate during the period of reduced demand during the late spring, summer, and early autumn. The capacity of the pipeline was 4MM standard cubic feet per day and the storage capacity for the liquid was equivalent to 240MM standard cubic feet of gas. The plant operated continuously and satisfactorily for 3 years but on October 20, 1944 one of the four storage tanks failed. In the absence of any dikes, LNG ran down the streets and into the storm-sewer system. Eventually the vapors were ignited and fire spread through a large area destroying 79 homes, 217 autos, and 2 factories, and killing 135, including one worker in the LNG plant. Two of other 3 tanks, which were spherical rather than cylindrical, as was the one that failed, survived the fire because of their heavy coating of thermal insulation. An appreciation of the damage can be seen in a photo taken after the fire and reproduced here as Fig.1. The report by Elliott, et al.[1] that describes the investigation of the fire by the U. S. Bureau of Mines included two conclusions that have critically influenced the LNG industry to this day. The first was that, although the exact cause of the accident was indeterminate, the process of liquefying, storing, and regasifying LNG was not invalidated insofar as proper precautions were taken. This recommendation made possible the subsequent development

Figure 1. Scene near the Site of theCleveland, Ohio LNG Plant after the Fire

of the LNG industry. The second recommendation was that the boundaries of future installations should be more than half a mile from the nearest inhabited building. This recommendation has discouraged the location of LNG installations in residential and even industrial areas. Several serious although lesser accidents involving LNG have since been reported, but they need not be described here because the disaster in Cleveland is a sufficient warning that special attention must be given to safety in the development, construction, and operation of plants involving large concentrations of energy and new technology.

The Early History of Using the “Cool”

The early history of using the “cool” is also of interest in the present context. In 1952, The Union Stock Yards and Transit Company of Chicago, Illinois conceived of the idea of designing a portable unit to liquefy the residual natural gas from “spent” oil and gas wells in the navigable portions of the bayous of Louisiana, to barge tank-loads of the LNG up the Mississippi and Illinois rivers, to use the “cool” for the freezing of meat, and to burn the revaporized gas as a source of energy. In support of this plan, construction of the required facilities and extensive tests of the concept were begun at Bayou Long, Louisiana.

In 1955 the Continental Oil Company joined in the venture and the Constock Liquid Methane Corporation was formed. At the same time the scope of the venture was shifted away from the Mississippi river to oceanic transport, with world-wide sources and destinations. Oceanic transport called for further testing, and in 1958 the test facilities were relocated to a site south of Lake Charles, Louisiana, in part to accommodate deep-draft ships. The new tests focused on safety in handling and storage, including ignition, combustion, and extinguishment, but also included thermal factors such as heat losses and the associated rate of boil-off. . The senior author was a participant in these tests.

In 1959 seven shipments of LNG totaling over 10MM gallons were shipped from Lake Charles to a storage tank on Canvey Island near London, England in the *Methane Pioneer*, a 35,000-bbl ship of necessarily unique design. The anticipation of the first voyage prompted the following comment by Sir Albert Braithwaite in the British House of Commons: "It must not be forgotten that we have another American menace coming." Ironically, this opposition to ships transporting LNG has surfaced in some areas of the USA that are now possible recipients rather than suppliers.

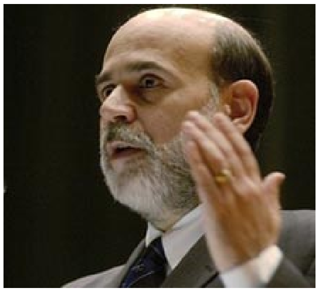
The “proof of concept” provided by the voyages of the *Methane Pioneer* led Royal Dutch Shell of London to become a partner in the venture in 1960 and the company was renamed once more, this time as Conch Methane Services. The shipments to London were soon followed by shipments from Algeria to France in the *Jules Verne*, a ship named after the science-fiction writer who advocated the use of LNG as a rocket fuel in one of his novels. LNG is now being shipped all over the world.

The “cool” has, however, generally been unused. Indeed, in many instances some of the LNG is burned as a source of the heat needed for revaporization.

Who Cares about LNG?

The rising demand for natural gas in the USA has begun to outweigh the domestic supply. The demand for natural gas is currently driven by its use to generate electricity, as well as by increases in the price of oil. Even before the latest oil crisis, the advent of tougher environmental laws favored natural gas because it burns more cleanly than oil and coal. Almost all US power plants built in the last twenty years have been designed for natural gas. While natural gas plant capacity has increased steadily in recent years, the domestic supply of natural gas has not. As a result, the USA has overbuilt plants that use natural gas, creating inefficiency in the energy market. One result has been a demand for substitutes for fossil fuels. The recent surge in oil prices and the decreasing domestic supply of natural gas have made the extra costs associated with transporting and regasifying LNG more attractive. .

The political response to this situation is illustrated by the following graphic.



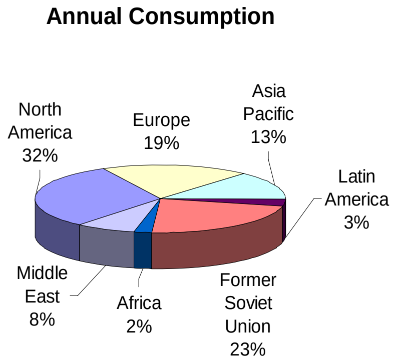
Ben Bernanke: “Building ***LNG*** terminals is one thing that we can do and we should continue to do to create a more global market for natural gas.” – *February, 2006*

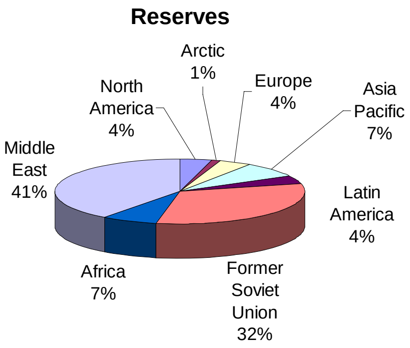
Alan Greenspan: North America needs “to be able to adjust effectively to unexpected shortfalls in domestic supply [and that] access to world natural gas supplies will require a major expansion of ***LNG*** terminal import capacity.” – *April, 2004*

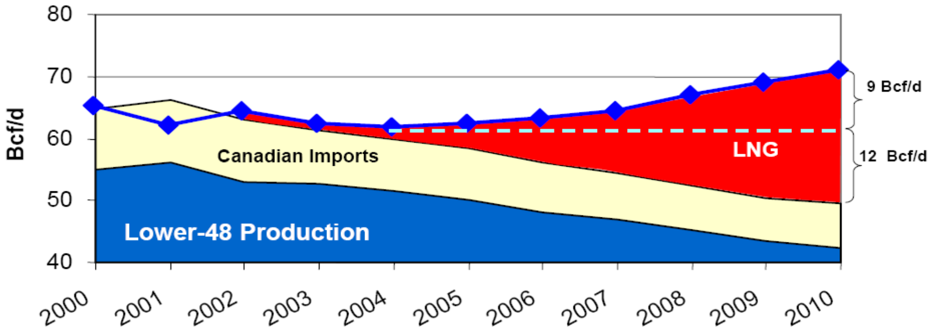
President Bush: “We’ve got to make sure that we’ve got enough natural gas to meet our home heating and industrial needs. And one of the best ways to secure supply is to expand our ability to receive ***liquefied natural gas***.” – *February, 2006*

The Supply and Demand for Natural Gas

As shown in the following pie charts and graph, North America and Europe account for 51% of natural gas consumption but only 8% of worldwide natural gas reserves. LNG is expected to constitute 30% of the domestic natural gas supply by 2010.







As shown below in Fig. 2, LNG prices are predicted to be significantly below the cost of importing gas by pipeline from Canada (the largest foreign source of natural gas for the USA) over the next 5 to 10 years, but after 2012 the prices are expected to converge once LNG processing capacity has reached an equilibrium. Ultimately, a delicate balance will exist between domestic natural gas and LNG prices. However, this initial development must occur before that flexibility can be realized.

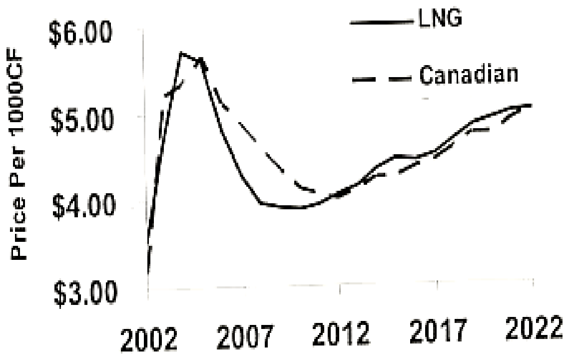


Figure 2. Projected Prices of Natural Gas by Pipeline and LNG (US Department of Energy)

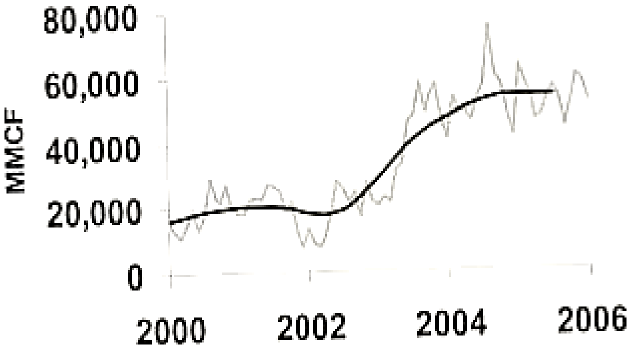
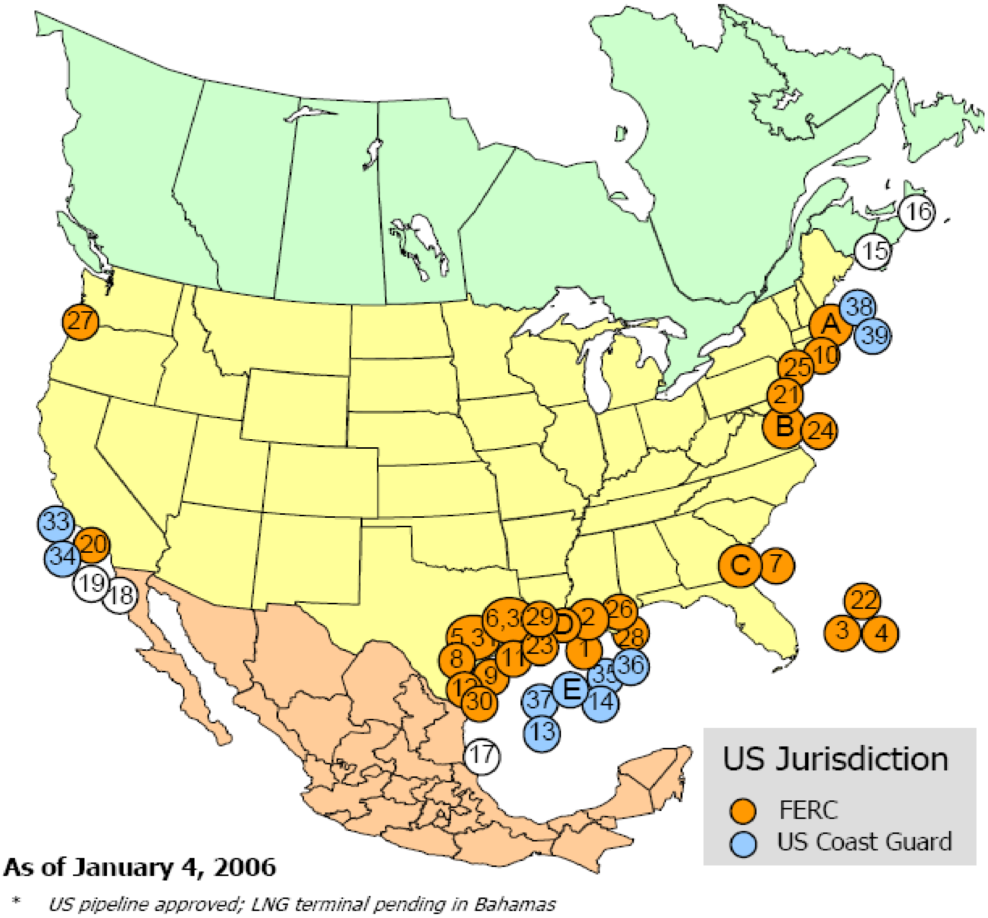


Figure 3. **Monthly Imports of LNG to USA (US Department of Energy)**

The spike in the usage of LNG in USA in the last few years, as shown below in Fig. 3, suggests that a large amount of capital is going to be invested in expanding the infrastructure for LNG over the next five to ten years. For decades, major energy companies have been liquefying natural gas for transportation from large reserves in Africa, Asia and the Middle East. There are currently about forty regasification terminals worldwide of which five are located in the in the USA. Forty more terminals are at various stages of construction, design and approval in the USA, Canada, Mexico, and the Caribbean. The locations of the existing and planned locations are shown in the following graphic. Although it is estimated that only twelve of these forty plants in progress will actually be built, even that number will constitute an increase in capacity of over 300%. Although only 2-3% of natural gas consumed in the USA currently comes from LNG, consumption is expected to more than triple over the next few years, producing a ramp-up in need for facilities for regasification..



As of January 4, 2006

* *US pipeline approved; LNG terminal pending in Bahamas*

Projected Terminals in USA, Canada, and the Caribbean

The Traditional Process of Regasification

The primary function of the process of regasification is to convert LNG at ambient pressure and -163°C to a vapor stream at either 500 psia, corresponding to local pipelines, or to 1,200 psia, corresponding to a long-distance pipelines, in both cases at ambient temperature. LNG is ordinarily pumped from ships into specially designed storage tanks and then either gasified at atmospheric pressure by means of heat exchange and subsequently compressed to the pipeline pressure, or else the liquid is pumped to the pipeline pressure and then regasified by means of heat exchange. The high-pressure vaporization benefits from the supercritical state of the LNG and thereby the avoidance of film boiling., Ambient air, seawater, or the hot burned gas obtained by burning some of the natural gas are ordinarily used as sources of heat for revaporization. The consumption of LNG for this purpose represents a direct monetary loss as compared to its sale. The variable costs with sea water are less but the capital costs are substantially higher due to the necessarily lower ΔT and the associated high rate of flow. The advantages and disadvantages with ambient air are similar to those for seawater but the heat transfer coefficient is far less.

All of these direct methods of revaporization fail to take advantage of the "cool", which can be used in an expansion and compression cycle to generate electricity, and/or to cool a recirculating stream of a refrigerant such as aqueous ethylene glycol. This untapped and often unrecognized potential may produce an incremental economic gain. It is this possibility that is the focus of the balance of the presentation.

Description of the New Proposed Process of Regasification

The new process employed to regasify liquefied natural gas is characterized by three conceptually distinct yet highly integrated processes. The first process is the actual regasification of LNG. The second process is the generation of electrical energy from the expansion of a working fluid and compressed natural gas. The third process is the cooling of a stream of aqueous ethylene glycol that can be delivered to an off-site location and then recycled back to the LNG plant. The production of electricity and refrigeration takes advantage of the cooling potential of LNG that is wasted in conventional processes for regasification. Although these three processes are integrated, it is important to analyze each one separately in order to formulate comparisons with the base case. In performing an economic analysis, the estimated cost of generating electricity and refrigeration excludes that associated with the base case of direct regasification, which is common to all processes. In this manner, the marginal economic viability of generating electricity and refrigeration can be assessed with respect to their associated fixed and variable costs.

Base Case

This process utilized as the "base case" is shown in Fig. 4. Pump (P-200), compresses the LNG to 1207 psia and -159°C. By pumping the LNG to the pipeline pressure before regasification, the installation of a costly post-vaporization compressor is avoided. Because LNG is supercritical at 1,207 psia, a phase change within the heat-exchanger (HX-200) is eliminated and film boiling, which would occur during the heating of low pressure LNG, is avoided. The seawater is cooled from −21.9°C to −0°C and the methane goes from a liquid at −159°C and 1207 psia to a gas at −0°C and 1205 psia..

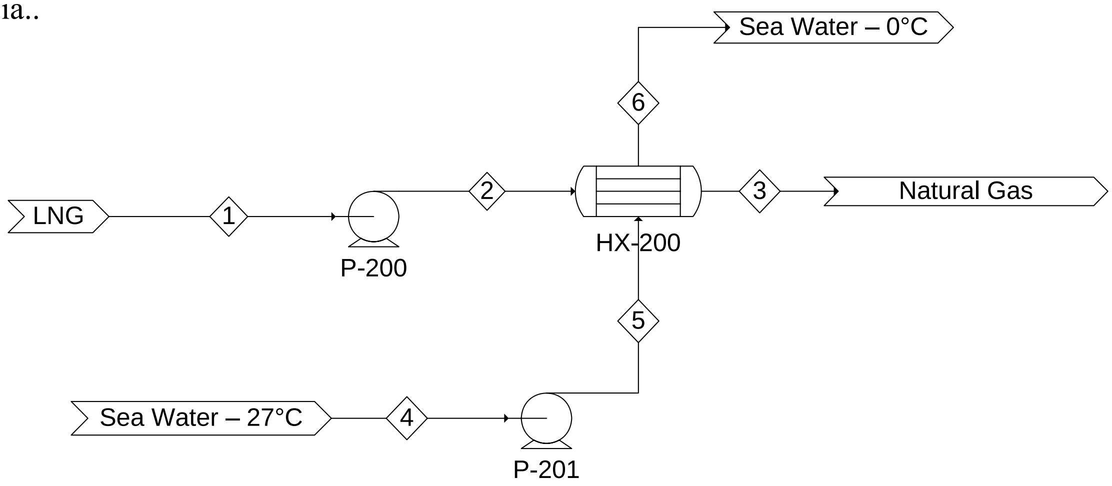


Figure 4. Base Case for Revaporization

Overall Process

Fig. 5 is an overall flow-diagram for the proposed new process including delivery to pipelines at both 500 psia and 1200 psia. After being compressed by a series of pumps, the LNG passes through an exchanger (HX-100) in which it is heated to -65.0°C. It is then heated to 21.9°C in another exchanger (HX-101). Natural gas at 21.9°C and 1,204 psia then passes through a splitter where it can be directed to a pipeline at 1,204 psia, or to a turbine (T-102) which drops the pressure of natural gas to 500 psia, depending on the consumer's requirements. Rather than expanding natural gas using a valve, the turbine generates electricity. Because the temperature of natural gas is decreased from 21.9°C to -34.0°C by the expansion, an additional heat exchanger (HX-102) is needed to reheat the natural gas to the ambient temperature.

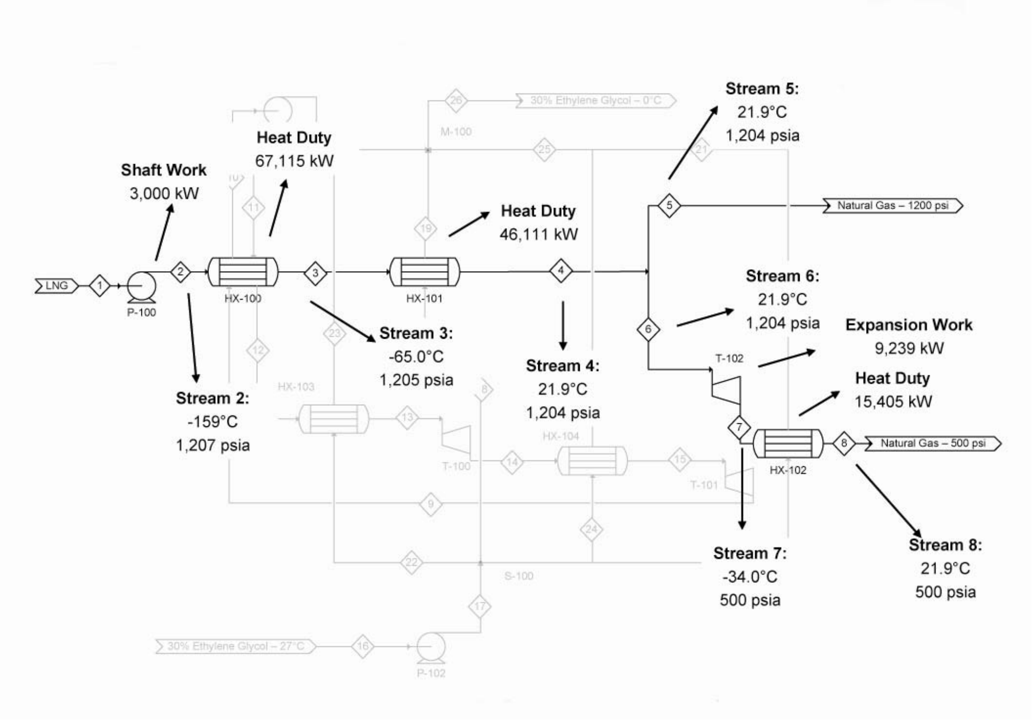


Figure 5. Flow Diagram for Revaporization

The Generation of Electricity

The second process utilizes a working fluid to heat supercritical natural gas and generate additional electricity through a series of expansion turbines as shown in Fig. 6.

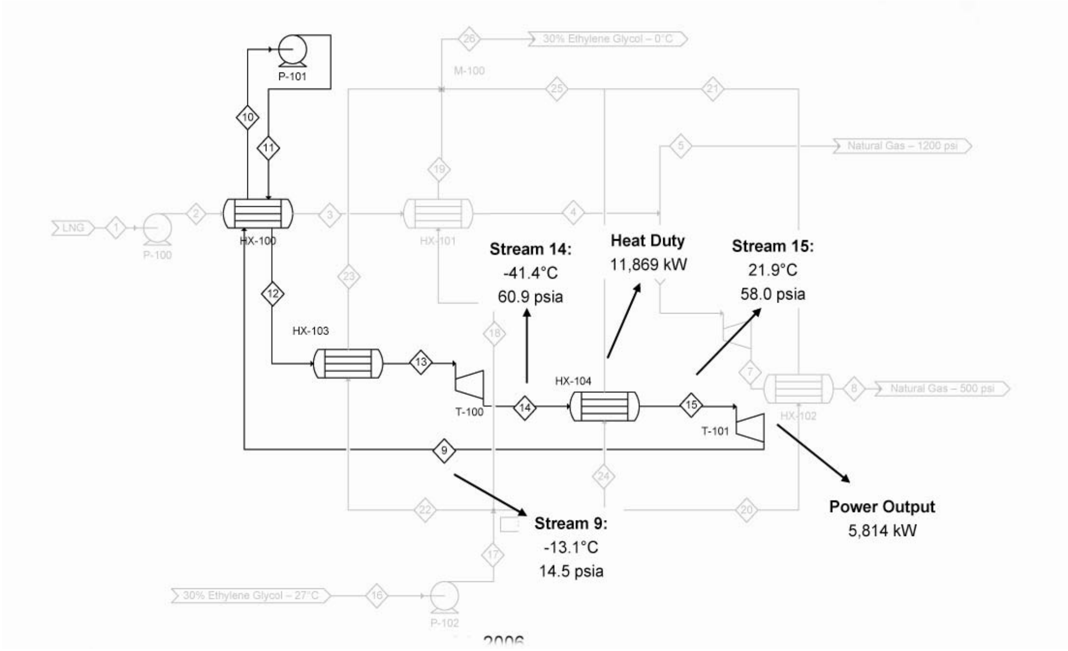


Figure 6. Flow Diagram for Generation of Electricity

The working fluid, a commercial fou-component mixture of fluorocarbons, enters the LNG-working fluid exchanger (HX-100) as a vapor at -13.1°C and 14.5 psia. The working fluid is liquefied to -154°C at 10.2 psia in exchanger HX-100. The stream is compressed to 364.0 psia using the refrigerant pump (P-101), and then heated to -62.0 °C by sending it back through HX-100. The working fluid enters the first of two ethylene-glycol exchangers (HX-101) where it is vaporized to 21.9°C at 362.6 psia. The first turbine is employed to generate electricity from the expansion of the working fluid to 60.9 psia and -41.4°C. In a second ethylene-glycol/water exchanger (HX-102), the temperature of the working fluid is increased to 21.9°C such that stream 9 exits the second turbine (T-101) as a vapor and does not need to be reheated. Finally, T-101 expands the working fluid back to its original conditions at -13.1°C and 14.5 psia. While the first turbine utilizes a maximum pressure ratio of 6:1, the second turbine has a pressure ratio of just 3.9:1 due to the temperature and pressure requirements for the refrigerant stream needed to heat the LNG. The refrigerant loop serves the dual purpose of heating the LNG stream to -65.0°C and generating 11,437 kW of electricity from the turbines, allowing for a net electric output of 10,966 kW taking into account the refrigerant pump.

Production of a Recirculating Refrigerant Stream

The final function of the regasification process, as shown in Fig. 7, is the generation of refrigeration at 0°C by integrating the streams of aqueous ethylene glycol crossing both the LNG and refrigerant streams. A 30%, aqueous solution of ethylene glycol enters the system at a rate of 1119 kg/s at 14.6 psia and 26.8°C and is pumped up to 59.5 psia (stream 16). The splitter divides stream 16 into four streams with flow rates of 380 kg/s, 150 kg/s, 470 kg/s, and 119 kg/s for HX-101, HX-102, HX-103, and HX-104, respectively. Each of these heat exchangers is designed to heat the tube-side fluid to ambient or nearly ambient temperatures while cooling the aqueous ethylene glycol streams to 0°C. In this manner, an incoming stream of 30% ethylene glycol at ambient temperature and pressure will be cooled to 0°C across the system. The refrigeration stream will be transported to an off-site location and will be returned to the LNG terminal at ambient temperature (27°C).

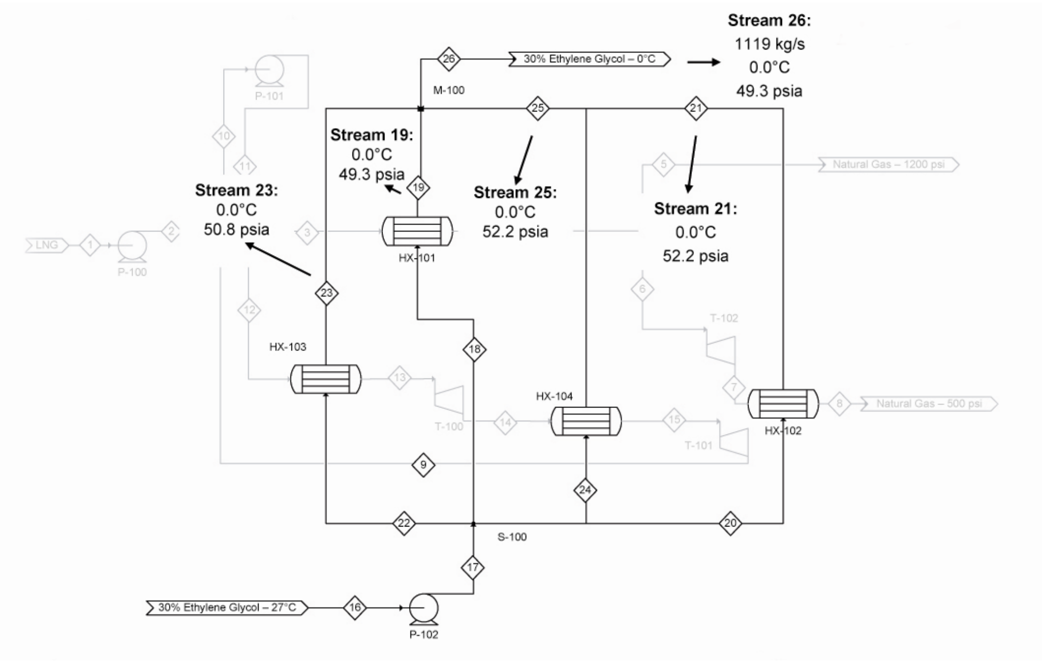


Figure 7. Refrigeration Cycle

Economic Analysis

The analysis was based on the postulate of one tanker (as illustrated) every 5 or 6 days carrying 4.7 MMCF of LNG to a port on the Gulf Coast near Lake Charles, Louisiana. This quantity of LNG is equivalent to 2.8MMMCF of gas at 22^{o}C and 1 atm. Economic considerations favor as large ships as can be accommodated by the ports of embarkation and debarkation, but the associated quantity of energy poses questions of safety. Although unloading and revaporizing directly from the tanker to the pipeline is possible, unloading into storage tanks provides flexibility. The proposed facilities are designed to vaporize 500MMCF/day, thereby requiring 5or 6 days per tanker

Representative Tanker for LNG

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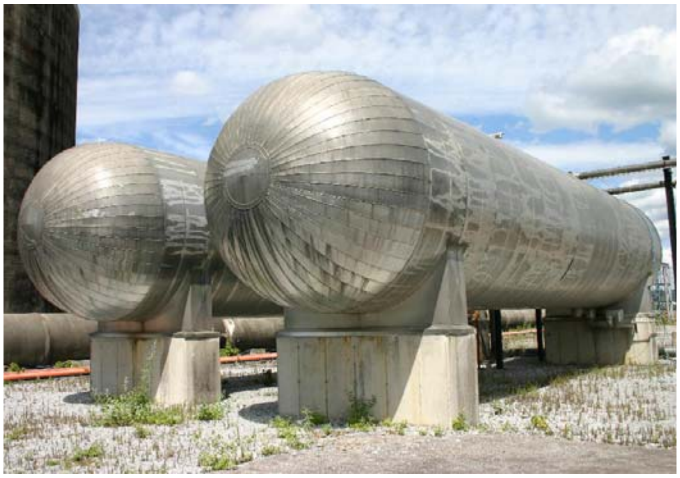
The costs associated with the LNG storage vessel are not included in the economic considerations because they are essentially the same as for the base case. However, a 52 m^3 vessel for the storage of 83,000 kg of working fluid in the liquid phase at 435 psia, and a 796 m^3 vessel for 671,000 kg of refrigerant at 27°C and 15 psia, as illustrated below, were included.



Representative **storage tanks for the working fluid and refrigerant**

It is presumed that the refrigeration provided by the chilled aqueous ethylene glycol can be sold in the form of a recycling stream to one or more of the nearby industrial plants.

The added economic return from the sale of electricity and refrigeration significantly exceeds the capital and working costs for this process. This economic benefit is readily explained on thermodynamic grounds as a consequence of utilizing some of the exergy associated with the difference between the ambient temperature and that of LNG at its condition of delivery and storage, as summarized below

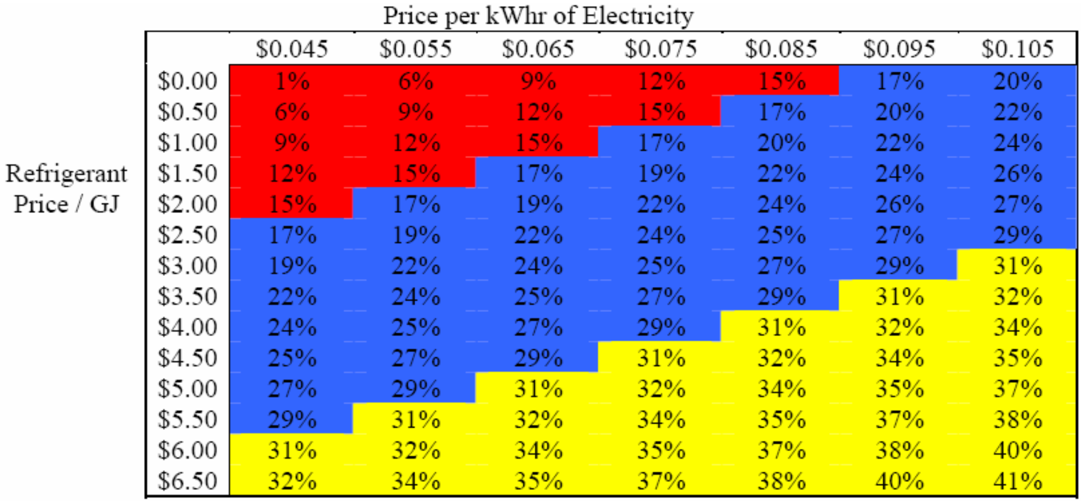
Method of Production	Second-Law Efficiency
Base Case	0.00%
Natural Gas at 500 psia	29.43%
Natural Gas at 1200 psia	17.05%

Thermodynamic Summary

Unit Category	Bare Module Cost
Heat Exchangers	$12.6 MM
Pumps	$5.2 MM
Turbines	$5.2 MM
Generators and Transformer	$1.5 MM
Storage	$1.2 MM
Base Case Units	($15.8 MM)

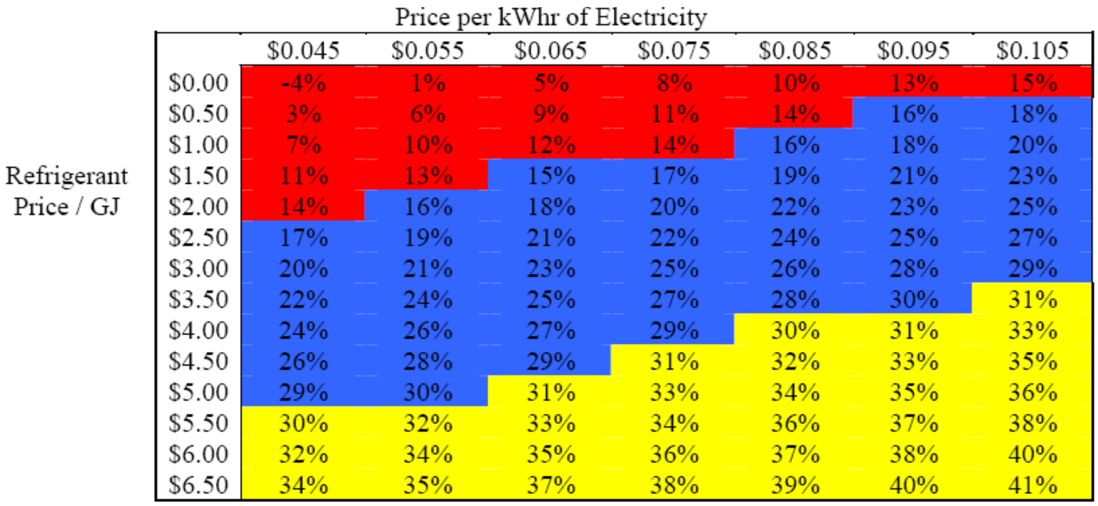
Equipment Costs

<u>IRR Sensitivity for 500 psia Gas</u>



Refrigerant Price / GJ	Price per kWhr of Electricity						
	$0.045	$0.055	$0.065	$0.075	$0.085	$0.095	$0.105
$0.00	1%	6%	9%	12%	15%	17%	20%
$0.50	6%	9%	12%	15%	17%	20%	22%
$1.00	9%	12%	15%	17%	20%	22%	24%
$1.50	12%	15%	17%	19%	22%	24%	26%
$2.00	15%	17%	19%	22%	24%	26%	27%
$2.50	17%	19%	22%	24%	25%	27%	29%
$3.00	19%	22%	24%	25%	27%	29%	31%
$3.50	22%	24%	25%	27%	29%	31%	32%
$4.00	24%	25%	27%	29%	31%	32%	34%
$4.50	25%	27%	29%	31%	32%	34%	35%
$5.00	27%	29%	31%	32%	34%	35%	37%
$5.50	29%	31%	32%	34%	35%	37%	38%
$6.00	31%	32%	34%	35%	37%	38%	40%
$6.50	32%	34%	35%	37%	38%	40%	41%

IRR Sensitivity for 1200 psia Gas



	Price per kWhr of Electricity						
Refrigerant Price / GJ	$0.045	$0.055	$0.065	$0.075	$0.085	$0.095	$0.105
$0.00	-4%	1%	5%	8%	10%	13%	15%
$0.50	3%	6%	9%	11%	14%	16%	18%
$1.00	7%	10%	12%	14%	16%	18%	20%
$1.50	11%	13%	15%	17%	19%	21%	23%
$2.00	14%	16%	18%	20%	22%	23%	25%
$2.50	17%	19%	21%	22%	24%	25%	27%
$3.00	20%	21%	23%	25%	26%	28%	29%
$3.50	22%	24%	25%	27%	28%	30%	31%
$4.00	24%	26%	27%	29%	30%	31%	33%
$4.50	26%	28%	29%	31%	32%	33%	35%
$5.00	29%	30%	31%	33%	34%	35%	36%
$5.50	30%	32%	33%	34%	36%	37%	38%
$6.00	32%	34%	35%	36%	37%	38%	40%
$6.50	34%	35%	37%	38%	39%	40%	41%

The purpose of the following photo of a typical terminal is to indicate the relatively small scale of the equipment for vaporization. The majority of new terminals will be 2 to 4 times larger. The new process would benefit from such a larger scale.

Conclusions

1. Increased capacity for LNG vaporization is expected to be needed over the next 10 years

2. The process described here for regasifying LNG is more efficient thermodynamically and economically because
    - it generates electricity using a reverse refrigeration cycle, and
    - it utilizes excess “cool” to produce a salable stream of refrigerant

3. The improvement in the second-law thermodynamic efficiency is
    - 29.43% in the 500 psia case, and
    - 17.05% in the 1200 psia case

4. In both of the above cases, the incremental investment delivers a 32% annualized return to capital

5. The analysis performed for a relatively small LNG terminal
    - The majority of new terminals will be 2 to 4 times larger
    - Even greater economic value can be realized due to economies of scale

Reference

1. M.A. Elliott, C.W. Seibel, F.W. Brown, R.T. Artz, and L.B. Berger, *Report on the Investigation of the Fire at the Liquefaction, Storage, and Regasification Plant of the East Ohio Gas Company, Cleveland, Ohio, October 20, 1944,* US Department of the Interior, Bureau of Mines, R. I. 3867, February 1946.