Transportation of Natural Gas Using Liquid Carriers at Ambient Temperature

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Abstract

The purpose of this report is to determine whether an existing method of natural gas storage could be used as a transportation method across oceans. This analysis is compared to the Liquefied Natural Gas (LNG) transportation method in order to evaluate whether it could compete as a valid method. The search for a competing method of natural gas transportation was the driving force behind this research. Additional initial research into the lack of ASME codes for carbon fiber reinforced piping, use of additives to increase methane dissolution in propane, the use of other solvents as liquid carriers, and the costs associated with loading and unloading of the mixture was performed.

The analysis used information from the patent "High-Energy Density Storage of Natural Gas at Moderate Temperatures" developed by Dr. Roger G. Mallinson, Dr. Kenneth E. Starling, and Dr. Jeffrey H. Harwell at the University of Oklahoma. This patent details the storage of natural gas in pressurized liquid hydrocarbons at ambient temperature. The idea behind this analysis assumed temperatures of 80 ºF as a threshold to what may be expected during ocean transport and a pressure of 1500 psi to rival compressed natural gas (CNG) transportation. It also investigated several storage architectures for the storage of this mixture on board ocean tankers. The project was done with research into the maximum storage capability of this mixture on large ocean tankers. After determining this it was possible to find the profitability of this method based on shipping costs, operation costs, and depreciation.

The results of the project showed that this method of transport could not compete with LNG as a valid transportation method. Along with the costs required for constructing loading and unloading stations in locations competing with LNG, the operating costs were high and the lack of available transport vessels keep this method from being viable. The operating costs were calculated to be upwards of $65 million for capacities starting at 1 million tons per annum. The fixed capital investment at these capacities calculated to be upwards of $246 million compared to an FCI of $349 million for LNG transport. This was the only respect that cost less than LNG due to the higher density of LNG. The net income based on a gross profit of gas shipped at various distances starting at 1000 miles showed that even at a gas price of $100/ton method was not profitable. Increasing the price of gas would only improve LNG profits so again this method cannot overtake LNG.

This method of transport is concluded to be uneconomical. The cost required for shipment of the same amount of natural gas per year as LNG is almost 4 times as large. The only way to compete with LNG would be to improve the shipping methods to reduce the cost, but these improvements would likely extend to LNG tankers as well. Also, the exploration into natural gas additives that could increase dissolution of methane gas into liquid propane may improve this method if the increase is substantial. The search for a new solvent for storing the methane gas proved that only at pressures above 3000 psi could a 50/50 mol % methane mixture be achieved at ambient temperature so there is no need to investigate this further. The error in profitability proved to be only 2.0% when varying the thermodynamic equations of state for analysis. Operating costs for the loading and unloading stations were lower than that of LNG, but the required extra investment for new locations limits this method.

Introduction

Natural gas exists in reservoirs spanning the globe. The search for transportation of this fossil fuel is and will be ongoing for a very long time. The estimated world natural gas reserves as of January 1, 2007 were 6,182.692 trillion cubic feet according to the *Oil & Gas Journal*[1]. The current methods of natural gas transportation, such as liquefied natural gas (LNG), pipeline transportation, and compressed natural gas (CNG) are well established and are efficient for many locations of natural gas fields. Technology is constantly being researched and improved upon in order to reduce the costs of transportation and production.

Objective

The purpose of this project is to determine if an established method of natural gas storage can be utilized for ocean transport. The storage method of interest is identified in the patent "High-Energy Density Storage of Natural Gas at Moderate Temperatures." Dr. Roger G. Mallinson, Dr. Kenneth E. Starling, and Dr. Jeffrey H. Harwell developed this patent at the University of Oklahoma. The storage method is evaluated for different storage architectures, primarily Coselle units and tube bundles. The tube bundles investigated were stainless steel and also a type of carbon fiber reinforced piping discussed in the following section. Spherical tanks were neglected in this analysis because of the high cost due to extra steel required for high-pressure spheres. An economic analysis of this method is then compared to LNG and CNG methods of transportation. Additional issues addressed were the lack of ASME codes for carbon fiber reinforced piping, use of additives to increase methane dissolution in propane, the use of other solvents as liquid carriers, and the costs associated with loading and unloading of the mixture.

Technology

Supergas™

The patented storage technology is concerned with the storage of the gas at moderate temperatures and pressures in order to have a high energy density. The mixture at these conditions has an energy density which is 40-67 percent that of gasoline[2]. The optimum hydrocarbon to use for the natural gas storage was determined to be propane and at 1800 psi the optimum composition is 70 mol % methane at temperatures 30 ºF and lower[3]. The technology can also be referred to as Supergas™.

Carbon Fiber Reinforced Pipe

Carbon fiber reinforced pipe is used as potential storage architecture in this analysis. It is stainless steel pipe wrapped in carbon fiber filaments that has the strength of stainless steel pipe 5 times the thickness while having costs 6 times higher[4].

Coselle Units

These storage units were developed by Sea NG and are named for coiled pipe in a carousel[5]. This unit contains 17 kilometers worth of 6 in. diameter pipe and weighs 45 metric tons without gas[5]. The capacity of these units for CNG is 3.3 MMscf at ambient temperature and 220-bar pressure[5]. Figure 1 below gives dimensions and the appearance of a Coselle unit.

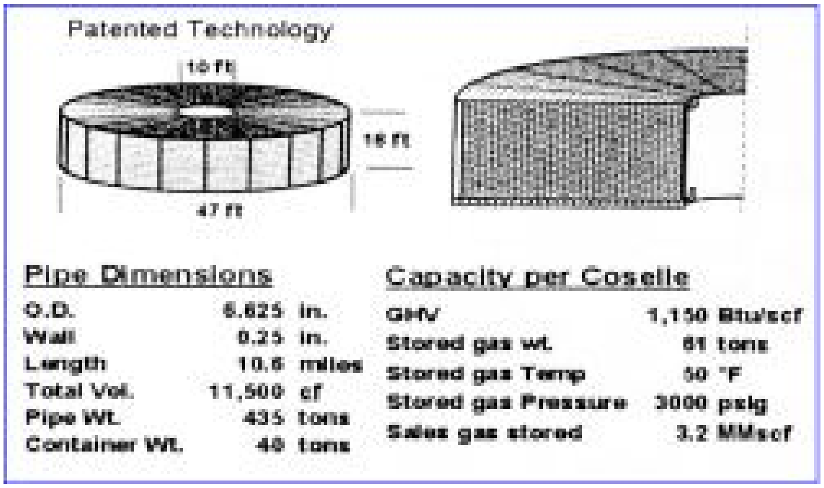

Figure 1 - Coselle Dimensions

Brief Overview of Other Methods

Liquefied Natural Gas

This process takes natural gas from the well and treats it to remove hazardous components like hydrogen sulfide, H_2S, or equipment damaging components like water. It is then cooled to –260 ºF reducing the gas to a liquid with 600 times less volume than that at standard temperature and pressure[6]. This liquid is transported at ambient pressure in insulated spherical tanks on tankers. The gas is cooled using gas compression refrigeration cycles with the refrigerant gases being propane, ethylene, and methane. The compression work required this refrigeration is the cause for high operating costs.

Compressed Natural Gas

This method takes natural gas and treats it initially like LNG. Then it is compressed to pressures around 3000 psi though higher pressures will allow for more natural gas to be transported. Coselle units and tube bundles are the most used method of transportation for compressed natural gas. This process requires only the compression of the gas as an operating cost and is a less expensive method of transport, although it requires more shipments to meet the capacity of LNG.

Preliminary Comparison

The natural gas stored in liquid carriers used in this analysis was a 50/50 mol% mixture of methane and propane at 80 ºF and 1500 psi for storage conditions. This decision was made based on PROII results that showed the mixture was a vapor at any pressure lower than this and the temperature was chosen to be a threshold, above which the mixture would probably not reach. The higher temperature was used to establish the limit for this method as the conditions would not likely reach higher than this. At this temperature the liquid densities vary with increasing pressure as shown in Figure 2.

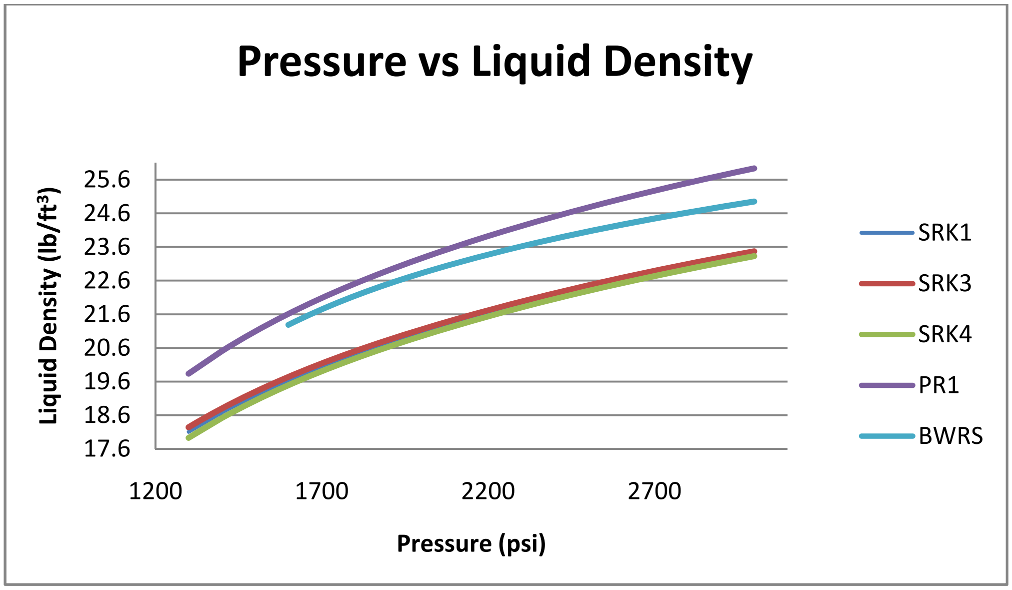

Figure 2 - Liquid Densities of 50 mol % Methane Mixture at Various Pressures

The various lines in Figure 2 are for each thermodynamic equation of state used to find the liquid density. The equations of state used were Soave-Redlich-Kwong, Peng-Robinson, and Benedict-Webb-Rubin-Starling. The purpose of using each of these equations of state was to find if there would be any error in the profitability in the transportation method.

In the following table, Table 1, there is a comparison of the densities and methane content of each of the established methods.

Table 1 - Density and Methane Content Comparison

	50/50 mol % mixture at 80 ºF, 1500 psi	LNG	CNG at 60 ºF, 3000 psi
Density (kg/m^3)	329	410	128
Methane content (mol CH_4/m^3	4,800	25,000	6,400

From the previous table it can be noted that the LNG would have the greatest restrictions in transport due to tanker weight limits, but the 50/50 mol % mixture would have the least energy capacity due to the low methane content.

Description of the Shipment Method

It is assumed that the natural gas has already been treated and is available at ambient temperature and pressure. This gas must be compressed and cooled to storage conditions before being loaded onto the tanker. The process is shown below in Figure 3.

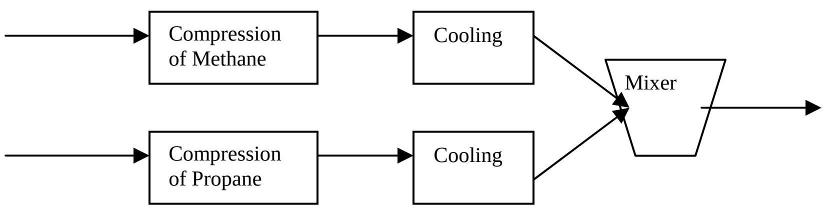

Figure 3 – Loading Flow Diagram

The process assumes a 62,000 lb-mol/hr flow rate, which was based on a one day loading time for the capacity of the tanker, 1.5 million lb-mols. The unloading process requires a heat exchanger, a flash drum, an expander, and a distillation column. The process is shown below in Figure 4.

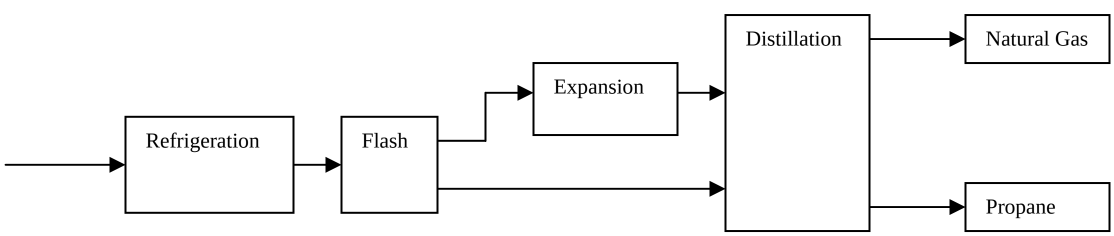

Figure 4 – Unloading Flow Diagram

This process assumes a two-day unloading process for a flow rate of 31,000 lb-mols/hr during this time. Operating and equipment costs are outlined below in the **Economic Analysis** section.

Tanker Capacity Analysis

The possible storage architectures used in this analysis were Coselle^{TM} units and tube bundles. The tube bundles considered were either stainless steel tubes or carbon fiber reinforced tubes. The tanker loading capacity was assumed to be 145,000 metric tons with a volume capacity of 6.57 MMcf. First, some calculations were done to determine how much equipment and gas could be stored onboard based on the mass. The following table, Table 1, shows how much gas could be stored onboard with the equipment.

Table 2 - Maximum Storage of Gas in Hydrocarbon Carrier

	Coselle^{TM} Units	Carbon Fiber Reinforced Pipe	Stainless Steel Pipe
Total Storage Volume (m^3)	95,822	110,024	27,051
Equipment weight (metric tons)	13,905	111,188	136,689
Gas weight (metric tons)	29,715	33,812	8,311
Total weight (metric tons)	57,258	145,000	145,000

From the previous table it is shown that there is over 87,000 metric tons available for use on the tanker with the Coselle^{TM} units. This is due to volume constraints by the units. The volume required per Coselle^{TM} unit is 600 m^3 and a maximum of 309 units can be fit within the hold of the tanker. For the remaining analyses, the carbon fiber reinforced piping is used to evaluate economic issues.

Economic Analysis

After finding the maximum amount of this liquid hydrocarbon mixture able to fit onto one ship, 14,275 tons of methane, it was needed to find a platform to compare this method to LNG. The LNG process has higher natural gas transport capability due to the higher density, so this method could not compare, but it was desired to find how much difference existed in the costs.   The following table, Table 2, shows the required number of tanker trips per year based on the capacity required per year.

Table 3 - Tanker Loads Per Year

	Tanker Loads per Year		
Capacity (tpa)	Stainless Steel Tube Bundles	Coselle Units	Carbon Fiber Reinforced Piping
1000000	324	92	79
2.00E+06	648	183	159
3.50E+06	1135	320	278

Using this information, the amount of tankers that would be required to fill this need for various distances can be calculated. This is shown in the following figure, Figure 5.

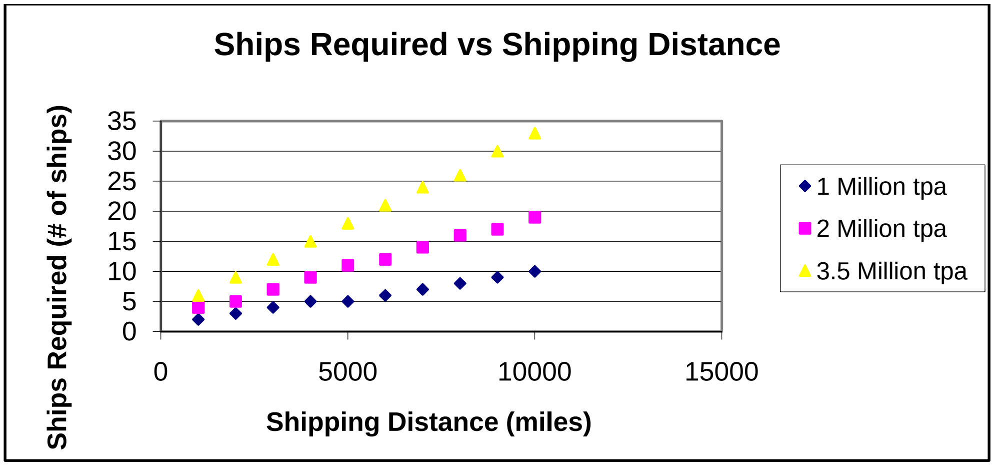

Figure 5 - Shipping Requirements

The shipping costs evaluated for this method were assumed to be $65,000 dollars per day. This is the worst-case scenario, but was used for the LNG estimates as well to level the estimation. The following figure, Figure 6, shows a comparison of LNG and the 50 mol% mixture using the yearly required shipping costs based on the days needed to reach the capacity specified.

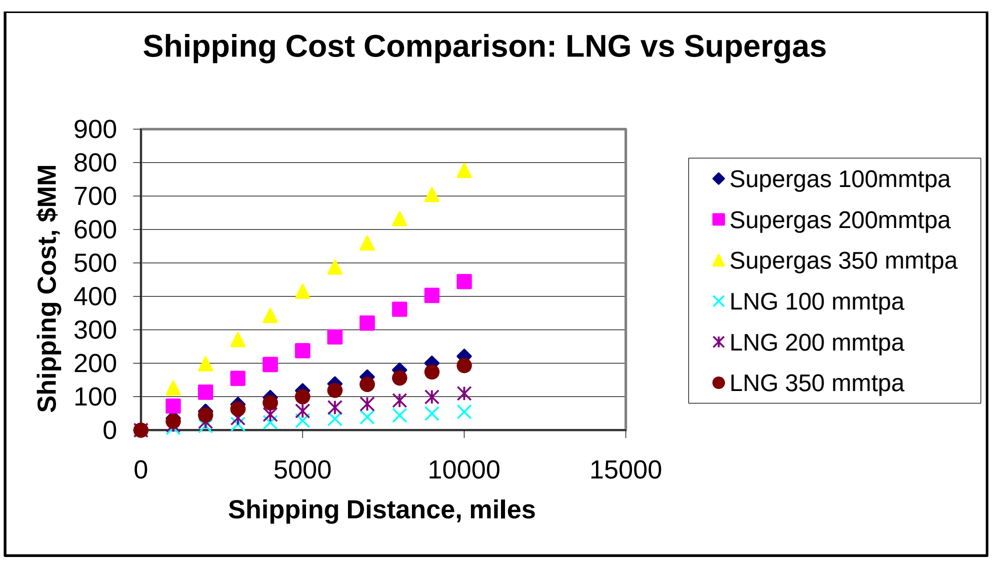

Figure 6 - Shipping Costs Comparison

The figure above shows that even at the lowest capacity comparison, 1 million tons per annum, and the cost for Supergas^{TM} is still above that for LNG. In fact the costs may be even higher because of the required construction of special ships for transporting the mixture before they are available for use.

Equipment Costs

This section details the expense of the construction of the specialty loading and unloading required for this method. A total of $49 million was required for the purchased equipment cost giving a total capital investment of $290 million. The compressor requirement of more than $24 million dominated the equipment expenses.

Operating Costs

The operating costs were mostly due to the compression of the two gases at the start of the loading process and the energy requirements of the distillation column in the unloading process. In the following figure, Figure 7, the operating costs and fixed capital investment per ton of natural gas are presented. These costs are summarized in Table 4 below.

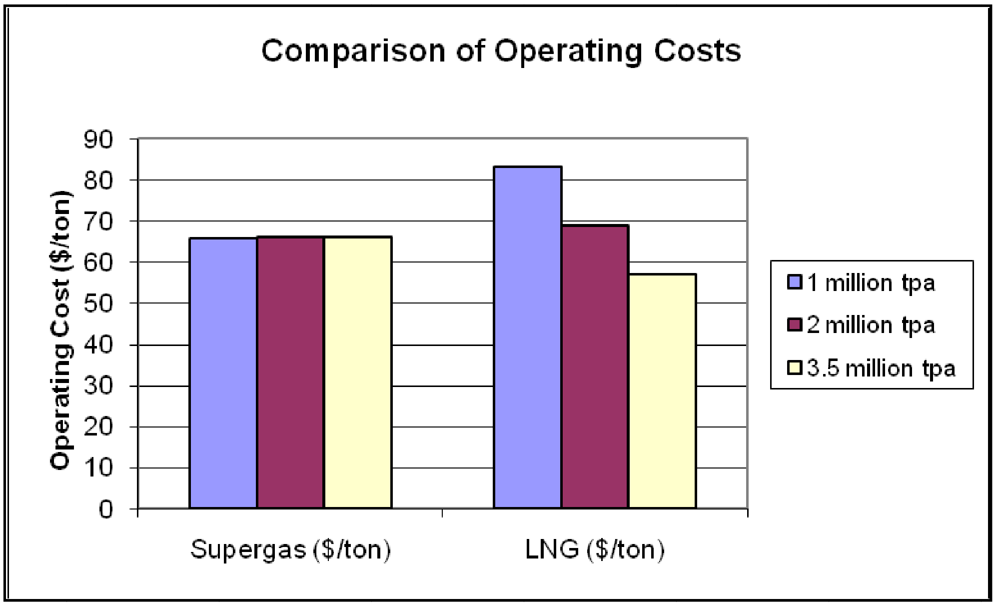

Figure 7 - Operating Cost Comparison

This graph shows that with an increase in production the operating costs stay the same for the natural gas in propane mixture, but decrease for the LNG process. This is due to the assumption that there is no storage for the 50 mol% mixture and that the plant operates only on days when shipments are leaving or arriving. The LNG costs assume constant production spread out over the entire year with storage capabilities. This slight advantage for the method in question is without the shipping costs included and so does not show that this method is actually better at lower capacities.

Table 4 below shows the comparison of several economic measures between the Supergas™ and LNG methods.

Table 4 - LNG and Supergas™ Economic Comparison

Capacity (million tons per year)	Total Operating Costs ($MM)	FCI per ton ($/ton)	TAC ($/ton)
Supergas™			
1	65.6	246.9	290.43
2	132	123.4	145.22
3.5	230	70.5	82.98
LNG			
1	83.125	349.5	411.19
2	137.75	262.1	308.4
3.5	200	145.6	171.33

Error Due to Thermodynamic Equation of State Prediction

The final result for the variation of the thermodynamic equation of state was a maximum of 2.0% in the gross profit. The error is not that consequential in the prediction of whether this method is profitable, but it is worth mentioning here. The following figure, Figure 8, shows each storage method (Coselle units, etc.) and their respective projected income for a rate of one shipload per day. The gross profits are much higher than what is actually predicted because of this assumption. Previous profits mentioned were analyzed on a million ton per year basis.

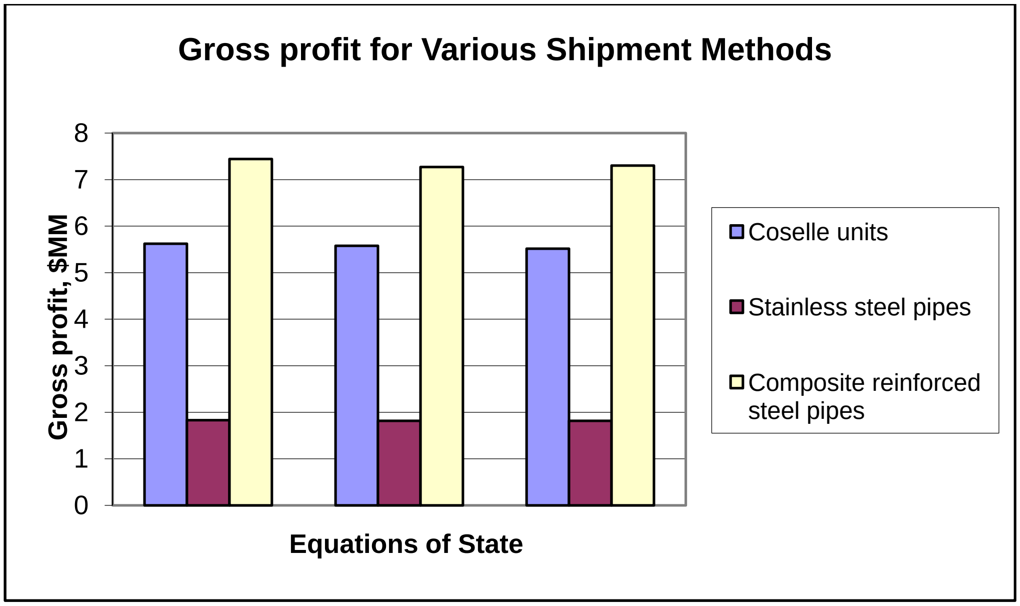

Figure 8 - Gross Profit Error

An investigation into the net profit of this method shows that even at prices as high as $100/ton of natural gas it is not profitable. The method is almost profitable at low distances (1000 miles), but does not compare with LNG.

Additional Issues

Lack of ASME Codes for Carbon Fiber Reinforced Piping

Currently there are no codes established for carbon fiber reinforced piping by the American Society of Mechanical Engineers. This issue needs to be resolved before this method could be considered as a potential storage possibility because of the limited natural gas density of the 50/50 mol % mixture compared to LNG.

Possible Additives to Increase Methane Dissolution into Liquid Propane

Additives could potentially be added to the pressurized liquid propane in order to increase the attractive forces to methane. Both of these substances are nonpolar so only weak intermolecular forces exist between them. A possible solution to this problem could be a polar molecule that would create polar and nonpolar regions. This could cause attractions to occur and increase the dissolution capacity, but it would require some of the storage space to achieve this. If it required small amounts to increase the attraction considerably then this would be something to investigate. The behavior of polar and nonpolar components keeps two liquid phases present in the container, but some sort of agitation could create an almost continuous phase.

Use of Other Solvents as Liquid Carriers

An initial investigation into this possibility yielded less than positive results. Only a few carriers were studied using PROII© at the required conditions (80 ºF and 1500 psi), but none of them maintained liquid composition at 50 mol% methane at pressures lower than 3000 psi. At these pressures there is no increase in efficiency because of the higher pressures required.

Conclusions and Recommendations

The results of the project showed that this method of transport could not compete with LNG as a valid transportation method. Along with the costs required for constructing loading and unloading stations in locations competing with LNG, the operating costs were high and the lack of available transport vessels keep this method from being viable. The operating costs were calculated to be upwards of $65 million for capacities starting at 1 million tons per annum. The fixed capital investment at these capacities calculated to be upwards of $246 million compared to an FCI of $349 million for LNG transport. This was the only respect that cost less than LNG due to the higher density of LNG. The net income based on a gross profit of gas shipped at various distances starting at 1000 miles showed that even at a gas price of $100/ton method was not profitable. Increasing the price of gas would only improve LNG profits so again this method cannot overtake LNG. The operating costs per year, FCI, and TAC are better for the Supergas™ method. This is great, but when it comes down to the cost of shipping the favor is lost.

This method of transport is concluded to be uneconomical. The cost required for shipment of the same amount of natural gas per year as LNG is almost 4 times as large. The only way to compete with LNG would be to improve the shipping methods to reduce the cost, but these improvements would likely extend to LNG tankers as well. The only aspect of this shipping method keeping it from competing with LNG and CNG transportation methods is the shipping costs. Investigating the detailed cost of a tanker specifically meant to ship Supergas™ would likely lower the shipping costs. If this cost could be reduced to about 4 times less than that required for LNG, this method will be perfectly competitive with LNG.

The exploration into natural gas additives that could increase dissolution of methane gas into liquid propane may improve this method if the increase is substantial. The search for a new solvent for storing the methane gas proved that only at pressures above 3000 psi could a 50/50 mol % methane mixture be achieved at ambient temperature so there is no need to investigate this further. The error in profitability proved to be only 2.0% when varying the thermodynamic equations of state for analysis. Operating costs for the loading and unloading stations were lower than that of LNG, but the required extra investment for new locations limits this method.

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