A NOVEL PROCESS TO USE SALT CAVERNS TO RECEIVE SHIP BORNE LNG

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FINAL REPORT

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I. EXAMINE AND EVALUATE A PROCESS TO USE SALT CAVERNS IN THE RECEIPT OF SHIP BORNE LNG

II. FIELD TEST AND FULL SCALE DESIGN OF CRITICAL COMPONENTS OF A SALT CAVERN BASED LNG RECEIVING TERMINAL

BY
MICHAEL M. MCCALL
WILLIAM M. BISHOP
Marcus KREKEL
JAMES F. DAVIS
D. BRAXTON SCHERZ

CONVERSION GAS IMPORTS, L.P.

2929 BRIARPARK SUITE 220
HOUSTON, TEXAS 77042
WWW.CONVERSIONGAS.COM

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1. ABSTRACT

This cooperative research project validates use of man made salt caverns to receive and store the cargoes of LNG ships in lieu of large liquid LNG tanks. Salt caverns will not tolerate direct injection of LNG because it is a cryogenic liquid, too cold for contact with salt. This research confirmed the technical processes and the economic benefits of pressuring the LNG up to dense phase, warming it to salt compatible temperatures and then directly injecting the dense phase gas into salt caverns for storage.

The use of salt caverns to store natural gas sourced from LNG imports, particularly when located offshore, provides a highly secure, large scale and lower cost import facility as an alternative to tank based LNG import terminals. This design can unload a ship in the same time as unloading at a tank based terminal. The Strategic Petroleum Reserve uses man made salt caverns to securely store large quantities of crude oil. Similarly, this project describes a novel application of salt cavern gas storage technologies used for the first time in conjunction with LNG receiving. The energy industry uses man made salt caverns to store an array of gases and liquids but has never used man made salt caverns directly in the importation of LNG.

This project has adapted and expanded the field of salt cavern storage technology and combined it with novel equipment and processes to accommodate LNG importation. The salt cavern based LNG receiving terminal described in the project can be located onshore or offshore, but the focus of the design and cost estimates has been on an offshore location, away from congested channels and ports. The salt cavern based terminal can provide large volumes of gas storage, high deliverability from storage, and is simplified in operation compared to tank based LNG terminals.

Phase I of this project included mathematical modeling that proved a salt cavern based receiving terminal could be built at lower capital cost, and would have significantly higher delivery capacity, shorter construction time, and be much more secure than a conventional liquid tank based terminal. Operating costs of a salt cavern terminal are lower than tank based terminals because “boil off” is eliminated and maintenance costs of caverns are lower than LNG tanks.

Phase II included the development of offshore mooring designs, wave tank tests, high pressure LNG pump field tests, heat exchanger field tests, and development of a model offshore LNG facility and cavern design. Engineers designed a model facility, prepared equipment lists, and confirmed capital and operating costs. In addition, vendors quoted fabrication and installation costs, confirming that an offshore salt cavern based LNG terminal would have lower capital and operating costs than a similarly sized offshore tank based terminal. Salt cavern storage is infinitely more secure than surface storage tanks, far less susceptible to accidents or purposeful damage, and much more acceptable to the community.

More than thirty industry participants provided cost sharing, technical expertise, and guidance in the conduct and evaluation of the field tests, facility design and operating and cost estimates. Their close participation has accelerated the industry’s acceptance of the conclusions of this research. The industry participants also developed and submitted several alternative designs for offshore mooring and for high pressure LNG heat exchangers in addition to those that were field tested in this project. HNG Storage, a developer, owner, and operator of natural gas storage facilities, and a participant in the DOE research has announced they will lead the development of the first offshore salt cavern based LNG import facility. Which will be called the Freedom LNG Terminal. It will be located offshore Louisiana, and is expected to be jointly developed with other members of the research group yet to be named. An offshore port license application is scheduled to be filed by fourth quarter 2005 and the terminal could be operational by 2009. This terminal allows the large volume importation of LNG without disrupting coastal port operations by being offshore, out of sight of land.

2. EXECUTIVE SUMMARY & CONCLUSIONS

The goal of this U.S. Department of Energy cooperative research project is to define, describe, validate, and move to commercial application, a novel process to use salt caverns to receive and store the cargoes of LNG ships. Called the Bishop Process™ this includes receiving LNG from a ship or tank, pumping the LNG up to cavern injection pressures, warming it to cavern compatible temperatures, and injecting the warmed vapor directly into salt caverns for storage, and distribution to the pipeline network. The industry participants in the research (Para 3), include firms involved in natural gas and LNG production, transportation, distribution, storage, marketing, engineering, environmental sciences, marine facilities, risk and hazard assessment, and earth sciences. These participants provided about one third of the funding for this project and significant expertise in the development and execution of the field tests and design of the prototype facilities. Most importantly, the industry participants raised the questions and presented the issues representative of the energy industry which were addressed and answered in the field tests and analyses.

Phase I (Tab 16) of this project entailed document research and mathematical analyses of salt cavern design, heat exchangers, LNG pumps, marine facilities, potential site evaluations, and preliminary facility cost estimates. It concluded that the critical components of cavern design, LNG pumps and heat exchangers, marine mooring and LNG transfer systems and potential high volume locations, were feasible but needed further development to answer the skeptics in industry before commercial acceptance would be achieved.

Phase II included field tests, at full scale where possible, of the critical components and the number of industry participants grew from three companies in Phase I to over thirty in Phase ll. Field tests of the mooring system, the high pressure LNG pumps, and a high capacity, high efficiency, water warmed heat exchanger have been successfully completed providing technical validations of the science behind the concepts. The components were then incorporated into an integrated LNG terminal design and costs and operating characteristics of the model offshore facility were developed.

This project was a successful collaborative effort between government and industry. It focused on proving that an alternative to tank based LNG terminals could be moved from research concept to commercial application in a short time frame. It involved several very different technical fields ranging from naval architecture to rock mechanics, from centrifugal pump design to heat exchange, from offshore platform design to gas storage cavern operations. This research project proved that salt cavern based LNG receiving facilities can provide a very secure, very flexible, economically advantaged alternative to tank based terminals. It also indicated that locating such facilities in the Gulf of Mexico could reduce port congestion and reduce the security concerns of coastal communities related to increasing volumes of LNG importation.

There are an array of laws and regulations that govern the use of federal lands, the development of offshore port facilities, and the acquisition of licenses, leases, permits, easements, and other necessary authorities for a commercial development as described in this project. It was beyond the scope of the project to define a clear path forward through the implementing agencies. It is apparent, however, that without a clear path forward, the significant funds necessary to accomplish a commercial development will not be committed. The offshore project contemplates the creation of salt caverns for storage not the production of the mineral salt, it contemplates the storage of imported gas in these caverns not domestic production, it contemplates the operation of platforms and pipelines for import terminal operations, not domestic production. In short, this is a concept that has achieved technical validation and can provide a significant increase in the nation's energy infrastructure but may be delayed in implementation because it doesn't fit the more familiar pattern of oil and gas leases on the Outer Continental Shelf.

2.1. Research Conclusions

This project concludes that a salt cavern based receiving terminal could be built in a shorter construction time, at larger scale, with lower unit capital cost, lower unit operating costs, and be much more secure than a conventional liquid tank based terminal. There is a significant body of knowledge and practice concerning natural gas storage in salt caverns, and there is a considerable body of knowledge and practice in handling LNG, but this is the first attempt to directly combine the two technologies. Salt cavern storage is infinitely more secure than surface storage tanks, far less susceptible to accidents or purposeful damage, and more acceptable to the community. Salt cavern gas storage currently provides an important element in the country's natural gas logistical network; this report concludes it will also play an important role in a direct application to LNG importation.

Rigorous analyses of the field test results, vetting of the conclusions by the industry participants, and incorporation of the lessons learned in improved or "optimized" designs have accelerated commercial development directly arising from this body of work. The replacement of large volume liquid storage LNG storage tanks with gas storage in man made salt caverns makes the terminal process design and operation simpler than those normally seen in the LNG industry. A salt cavern based terminal, with permits in hand, could be constructed in about 2.5 years, a considerably shorter construction time than that required for tank based designs located either onshore or offshore.

More than two dozen potential sites were identified that combine salt formations suitable for storage, located near multiple pipelines for large take away capacity and navigable water. The sites are about evenly split between onshore salt formation locations and offshore salt formation locations. This research reveals that because of the convergence of pipeline capacities and salt formations that a few very large capacity salt cavern based receiving terminals could provide a significant portion of the U.S.'s future LNG import needs (Tab 16).

3. INDUSTRY COST SHARING PARTICIPANTS

ABS	FMC
AGL Resources.	Heogh LNG
AMEC Paragon	HNG Storage
Arthur D. Little	International LNG Association
Bluewater Offshore	Marathon
BP	Marsh USA
Carter Cryogenics	Mustang Engineering
Charles River Associates	Nikkiso Cryo
D Braxton & Associates	Northstar Industries
DNV	PB Energy Storage Services
Dominion Resources	Remora Technology
Ebara	RRS Engineering
Ecology & Environment, Inc.	SBM
Encana	Texas Brine
ExxonMobil	Tennessee Gas Pipeline/ El Paso
FLUOR	Tulane/Entergy Energy Institute

4. EXPERIMENTAL

The test protocols for the conduct of the field tests, data gathering, and computational requirements for the analysis of each field test followed industry practices for that particular field. These are discussed separately in each of the tabs for each test. All aspects of the conduct of each field test were reviewed and approved by both the industry participants and the NETL.

The field test of a high pressure LNG pump was conducted on the factory test stand, using LNG at Ebara's manufacturing facilities in Nevada. The pump tested was being prepared for delivery to a customer outside the US. Ebara designed a test protocol that would demonstrate discharge pressures in excess of 2,000psi, a benchmark for cavern injection pressures. The tests were conducted successfully without incident, observed by several of the project's industry participants and confirming performance data was recorded.

The high pressure LNG heat exchanger was constructed at an AGL Resources LNG peak shaving plant in Cherokee County, Georgia. The site had large quantities of water and LNG, room for equipment and a highly experienced and capable staff. After consultation with the DOE it was determined that the test LNG heat exchanger would be built at full scale, tested at maximum rates, and performance recorded across a broad combination of flow rates and temperatures. This was a broader testing program than originally envisioned but conclusively proved the concept of heat exchange in the dense phase. At the same time an unusual cold spell during the testing allowed for full throttle performance and provided large quantities of gas for consumers in the Southeast US. The testing program was observed by a number of the industry participants and more than 50 persons attended a performance review and test conclusion meeting at the site following the testing program.

Bluewater's LNG offshore mooring system, called the "Big Sweep", was wave tank model tested at the Canadian Marine Research Center in St. Johns, Newfoundland, Canada. The testing program is common for marine designs for ships hulls, semi submersible oil rigs, offshore platforms, gravity based structures and other marine equipment. In this case it mimicked the sea states for the shallow areas of the Gulf of Mexico both for standard weather conditions of winds and waves and for hurricane survival conditions. The model constructed was the standard 1/40 scale so the LNG ship model pictured in the tests was about 8 meters long representing a scale model of an LNG ship which would be over 300 meters long. During parts of the testing program the winds, waves, and currents were moving in the same direction but at varying velocities, then their directions and velocities were varied relative to one another to represent the full gamut of sea conditions. Data recording is done by an array of electronic sensors and then subjected to appropriate analyses. Emergency break off conditions were simulated and evaluated in addition to more normal mooring conditions. The tests were observed by several industry participants and the results presented to the entire group at meetings in Houston upon completion. This testing program clearly proved that a successful method exists to moor an LNG ship at sea in the Gulf of Mexico.

5. RESULTS AND DISCUSSION

Technological change in the energy sector is a long and difficult process. Change requires large investments, and failure has serious consequences. Generally change only occurs in response to a crisis, i.e. "something needs to be fixed", or to implement improvements that are immediate and obvious, i.e., "a better mousetrap". LNG importation into the US has elements of both motivations. The US needs to significantly expand its ability to import natural gas, and to develop more economical, more secure, and larger scale alternatives to the traditional tank based terminal. (Tab 15)

This report describes an economically advantaged import terminal design using salt caverns rather than LNG tanks. The economic advantages come primarily from the significantly lower costs of salt cavern gas storage compared to LNG tank storage, and the larger scale of storage and deliverability that can be achieved using caverns. Generally, anything done offshore costs more to build and operate than its onshore alternative. This project concludes that an offshore salt cavern based LNG terminal can be built at a unit cost competitive with onshore tank based terminals and at less expense than offshore tank based alternatives. (Tab 2)

The environmental advantages of natural gas over other fossil fuels or as a feedstock to hydrogen are well known and are responsible for the projected growth in natural gas demand. (Tab 15). The terminal described in this project immediately converts the incoming LNG into natural gas upon unloading and stores it as gas. The elimination of LNG storage also eliminates "boil off" from LNG storage tanks which requires energy intensive compression or reliquefaction. Using seawater as a warmant this terminal has significantly lower operating costs than a tank based terminal using submerged combustion vaporizers. Compared to tank based terminals using submerged combustion vaporizers this is more than $ 1 million per day worth of gas that will go to customers rather than be consumed at the terminals if imports reach 15Bcf/Day. This project describes a seawater warming system using a closed loop for biocidal treatments that is believed to maintain the economy of seawater warming while mitigating and reducing ichthyoplankton mortality (Tab 5). In addition, an ambient air LNG warming system is described (Tab 10) that materially reduces the amount of gas consumed in vaporization and uses no water.

Energy security is a broad topic that includes availability of supply, protection of facilities, avoidance of disruption, logistical alternatives and much more. Cavern storage is fundamentally more secure than any surface alternative. North American Aerospace Defense Headquarters in Cheyenne Mountain and the Strategic Petroleum Reserve share the security of thousands of feet of rock overburden. A salt cavern LNG terminal would have those same characteristics. The offshore facilities described in Tab 2 uses multiple caverns, each cavern independent from another. A platform design could segregate pump and vaporization trains to achieve the same redundancy with the process equipment. Large gas volumes stored under pressure in caverns, ready to be dispatched to the pipeline provides operating flexibility. In a tank based terminal, the storage is generally so small that the delay of even a few days of a ship could disrupt gas dispatch. Early arrival of a ship without sufficient tank capacity to receive it is another potential scheduling problem. Cavern gas storage equivalent to 5, 10, or even 20 times the cargo capacity of an LNG ship decouples the storage from the ships' arrivals and can compensate for all types of marine delays.

5.1. Integrated Offshore LNG Facility & Cavern Design (Tab 2)

The final product of the research project is the integration of the test results into the design, engineering, and cost analyses on the construction and operation of a salt cavern based offshore LNG receiving terminal. We concluded that this is a technically valid concept, and that it requires lower unit capital and operating costs, and is a secure method of receiving imported LNG, storing it as gas and distributing it to the nation by the existing natural gas pipeline grid. Further, the results confirm that salt cavern based LNG receiving facilities could be built at sea in the Gulf of Mexico and the ships would thus never enter into congested US navigable channels or ports, significantly reducing the NIMBY effect encountered by land based LNG tank terminals. The placement of process equipment, power generation, control rooms, and crew quarters on platforms characterizes this facility as being much closer in design and operation to the 3,000+ oil and gas production facilities in the Gulf of Mexico than to the five LNG terminals in America.

5.2. Salt Caverns Provide Secure, Inexpensive Storage (Included in Tab 2)

Man-made salt caverns are an integral part of the energy infrastructure of the United States. The entire Strategic Petroleum Reserve, totaling 700 million barrels of crude oil is stored in salt caverns on the Gulf Coast. Private industry stores hydrogen, natural gas, natural gas liquids, olefins, refined products, and crude oil in salt caverns in the US and Canada. Solution miners create caverns to precise size, shape and operational requirements by injecting fresh or seawater into the salt formation thus dissolving the salt and creating a man made cavern.

Salt caverns provide about five (5%) percent of the natural gas storage capacity in the United States, but none of these caverns are associated with the LNG receiving terminals currently in operation. Salt caverns can deliver gas at high rates to pipelines which is important in natural gas distribution and confirmed by this project as important in LNG receiving.

Salt formations will not tolerate direct injection of LNG because of the low temperatures but this research confirmed methods that would allow their use in LNG receiving by pumping the LNG up to cavern injection pressures with pumps and warming the LNG to salt compatible temperatures. Unlike the design of this study, the opposite is true in natural gas storage in salt caverns which requires compressors to create injection pressures thereby heating the gas which must then be cooled by heat exchangers before it can be injected into salt caverns.

5.3. Offshore Mooring Design and Wave Tank Tests (Tab 3)

Offshore mooring and transfer of crude oil is a well established practice for over 40 years with an excellent safety and environmental record. Building on this body of experience, Bluewater Offshore designed and model tested a mooring system for offshore transfer of LNG during April 19 – April 30, 2004. The wave tank testing concluded that the designs were adequate for sea states encountered in the Gulf of Mexico and would survive hurricane conditions. This confirmation that an LNG ship could be moored at sea and the product unloaded is important to reducing the risks and disruption to port and channel operations as the numbers of LNG ships calling on America increases. LNG import requirements of 15 Bcf/Day are the equivalent of 2000 or more LNG ship port calls per year. Each LNG ship arrival and port departure involves heightened security, and exclusion zones disruptive to commercial and recreational marine transportation. Moving most of those port calls to offshore ports will materially ease coastal community security concerns and mainland port and harbor congestion. Bluewater's system transfers the LNG to a nearby platform containing the process equipment, power, pumps, heat exchanger, measurement, salt cavern wellheads, etc. Other systems by SBM, FMC, OPE, and Remora (Tabs 6-9) have been submitted as part of the research.

5.4. High Pressure LNG Pump Field Tests (Tab 4)

LNG pumps in common use are of multistage centrifugal design. Those used in terminals receive LNG from the storage tanks at atmospheric pressures and discharge at pipeline pressures. To achieve direct cavern injection pumps must be capable of achieving discharge pressures in excess of 2000psi. New designs with greater capability were developed by Ebara, Nikkiso Cryogenics, and Carter, three of the largest LNG pump manufacturers. Field tests have confirmed the designs and operating characteristics of these machines. It is important to use pumps for the liquid instead of compressing gas because of the energy efficiencies that result. Using pumps to achieve cavern injection pressures saves about 80% of the energy required for this work.

5.5. Heat Exchanger Field Tests (Tab 5)

At the commencement of this project there was no high capacity, LNG heat exchangers in operation or in design at pressures suitable for cavern injection. Therefore, we developed a new pipe-in-pipe design incorporating a cryogenic LNG pipe inside a water warmant pipe. In Phase I this design was extensively mathematically modeled. In Phase II there was more modeling and in addition a prototype was designed and constructed by Northstar Industries for field testing. This serial number 1 Bishop Process™ Heat Exchanger was field tested April 12-16, 2004, at full scale, at the AGL Resources LNG Plant near Canton, Georgia. Tests were performed at varying LNG rates, varying warmant water ratios, and varying water temperatures. Flow rates as high as 160 MMcf/Day were tested in this prototype. Multiple units will allow the warming of the LNG simultaneous with cargo unloading at standard rates.

The field test results indicated some significant improvements compared to the mathematical predictions and important design changes which will improve operations in commercial applications.

5.6. Commercial Project Announcement (Tab 1)

HNG Storage, a developer, owner, and operator of natural gas storage facilities, and a participant in the DOE research has announced they will lead the development of the first offshore salt cavern based LNG import facility. Called the Freedom LNG Terminal, it will be located offshore Louisiana, and is expected to be jointly developed with other members of the research group yet to be named. An offshore port license application is scheduled to be filed by fourth quarter 2005 and the terminal could be operational in 2009. Offshore, out of sight of land, with large volume gas storage below the sea bed, this may be the ultimate cure for the NIMBY effect and allow the large volume importation of LNG without disrupting the coastal port operations.

5.7 Related Studies

There was significant industry interest in this project which resulted in additions to the work not originally in the work plan. For example, while wave tank testing was conducted on the Bluewater “Big Sweep” offshore LNG mooring systems, other competent systems were presented to the industry group by, SBM, Remora, FMC, and OPE (Tabs 6-9 respectively) and are included in this final report. An ambient air high pressure heat exchanger design and a comparative analysis of various heat exchangers were submitted by AMEC Paragon in Tabs 10 & 12. Subsea cryogenic LNG pipeline designs were submitted by OPE and ITP in Tab

12. An Ichthyoplankton study for the model facility in Vermilion block 179 was conducted by Environment and Ecology and included as Tab 13. A very informative and well done study on the broad implications of increased LNG importation was provided by the Entergy-Tulane Energy Institute – "LNG Imports and Their Impact on the State Regional, and National Economies and included as Tab 15.

These related studies, additive to the original scope of this project, are indicative of the interest of industry in this topic and the cooperative nature of the work conducted.

6. DOCUMENT CONTENTS – LIST OF TABS