

OFFSHORE LNG LOADING PROBLEM SOLVED

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Introduction

The LNG industry has developed into a mature industry over its thirty-year history. The LNG industry, however, is transforming to meet the needs and realities of the future. New markets are opening in developing countries, such as India and China. The spot market, selling from excess LNG plant capacity, is continuing to grow. The large and highly competitive US gas market is beginning to absorb more LNG. Gas reserves are increasingly being discovered in offshore reservoirs, often in deep water. In the future, the industry will likely continue to evolve from the paradigm of shipping LNG from large onshore LNG plants to onshore import terminals backed by long-term sales contracts. Offshore LNG plants^{1,2,3} and import terminals^{4,5} offer a cost-effective solution to supplying gas to customers. One of the greatest challenges for these plants and terminals is the offshore transfer of LNG. ExxonMobil saw the need to improve the technology for this transfer and, in cooperation with Senior Flexonics and IMPaC, has developed a scheme that is economic, safe and reliable.

Background

LNG is currently transferred between ships and onshore storage almost exclusively via fixed articulated loading arms. These arms incorporate swivel joints to accommodate the relative motion between the stationary dock and the buoyant LNG ship. A typical scheme is illustrated in Figure 1 showing the LNG loading facilities at the Ras Laffan harbor in Qatar.



Figure 1

Three or four arms are used to transfer the LNG cargo and one arm is used to return the LNG vapors evolved or displaced to the shore based facilities. These systems have an excellent experience record in the LNG industry. Reliable operation of these arms is critical to the success of the LNG chain, since all LNG must pass through them. However, since they are only utilized for about 12 hours every three to ten days and there are installed spares, 100 percent reliability is not required.

Extension to Offshore Loading

Offshore loading becomes much more complicated when both the LNG terminal or liquefaction plant and the LNG ship are moving independently. Despite this complication it is important to have a system that maintains the high safety and reliability history of the LNG industry⁶. The loading arms described above could be used for offshore loading with some modifications, but only in the mildest offshore environments.

For harsher environments, alternative loading schemes must be considered. The all-metal arm concept can be used with these same swivel joints in a pantograph piping arrangement. The system must accommodate the necessary six degrees of freedom that can occur due to the motions of the terminal and the ship. This system, currently under development⁷, will be more expensive than the onshore system.

Based on the large gas reserves offshore, northwest Australia, ExxonMobil saw a need to develop a system based on flexible cryogenic hoses that was able to load during a one-year storm in this harsh environment. Cryogenic hoses are currently manufactured by a number of vendors in smaller sizes than those needed for customary LNG transfer operations. Since flexible hoses are used routinely for offshore transfer of crude and LPG, there is experience with the concept of using hoses offshore. In addition, development of flexible cryogenic hoses in the size range needed for LNG transfer was viewed as potentially leading to cost reduction through the introduction of additional competition in the marketplace.

Flexible Hose Loading Concept

To be acceptable, a loading system using flexible hose must meet the following criteria:

- The loading system must be easily adaptable to existing LNG ship designs.
- The system must be robust and highly reliable.
- The system must be as safe as current loading systems and be able to accommodate all conventional safety systems.
- The cryogenic hose should not be a limiting factor due to weather or environmental conditions.
- The service life of the hose must be sufficiently long to avoid continual replacement of worn hose.
- The hose must meet all applicable standards and must be certified.
- The system should be cost competitive with alternatives.
- Loading rates should be comparable to those now achieved in shore-based terminals.

The loading system concept envisioned is shown in Figure 2.

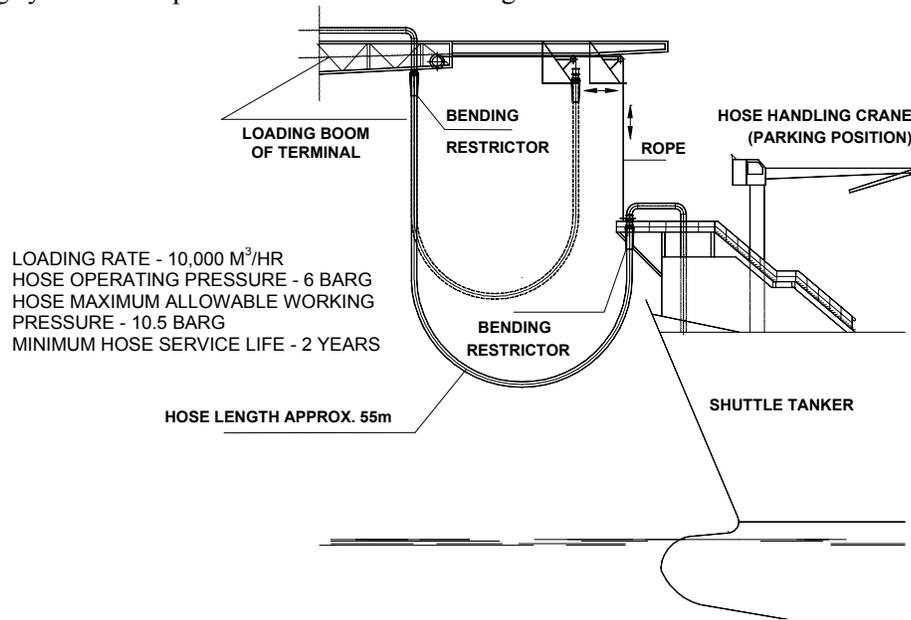


Figure 2

The system uses two 20-inch diameter hoses, one for LNG and one for the vapor return, in a hanging catenary between a loading crane boom and the LNG tanker. The loading sequence is envisioned to occur as follows. The LNG shuttle tanker is brought into position assisted by tugs or dynamic positioning. A hawser is connected between the terminal or plant and the tanker and is maintained taut by tug assist, dynamic positioning or other means. The loading boom is positioned pointing toward the tanker. A winch line attached to the end fitting of the hoses is used to lower them into position to permit connection to the loading piping aboard the tanker. When both the loading and vapor-return hoses have been connected and properly tested and pre-cooled, transfer can begin. The disconnect sequence would occur in reverse order. When the loading system is not in use, the hose boom is rotated so that the tanker end of the hose string can be lowered into a protective cradle. This minimizes the fatigue loads on the hose and facilitates inspection, testing and maintenance of the hose.

Hose Selection

There are basically two types of flexible hoses that could be used for LNG transfer:

- a composite hose consisting of layers of polymer fabric and film wound with stainless wire for integrity
- corrugated stainless steel hose

Elastomeric hoses are sometimes used for LPG transfer, but are not candidates for use at LNG cryogenic temperatures.

Corrugated hoses have been developed for LNG transfer in small sizes⁸ (up to eight inches) and are currently being extended to a 16-inch size⁹. Due to this ongoing work and because corrugated hoses cannot withstand torsion loads as well as composite hoses, the composite hose design was chosen for further development and testing.

Composite hoses have been used for offshore loading of cryogenic liquid in sizes up to ten inches. However, since there were no commercially available 20-inch hoses for routine offshore LNG offloading, it was necessary to conduct a development program with a hose manufacturer to design and construct a prototype hose for testing and certification.

Because of previous successful experience in cryogenic hose development and manufacture, ExxonMobil chose Senior Flexonics as the hose manufacturer for this larger scale development. Senior Flexonics (as Compoflex Hose Company) began cryogenic hose development in 1971. They manufacture a range of Cryoflex® composite hoses up to ten inches. Today, these hoses are supplied throughout the world in a number of applications: ship to shore, terminal to rail and road tanker and road tanker to plant. These hoses transfer a range of cryogenic gases including, butane, propane, vinyl chloride, nitrogen and LNG.

Three of the more significant applications of Senior Flexonics cryogenic hose include the following:

- 20-inch bore cryogenic hose as a backup system for shore to ship LNG loading at the Brunei plant. The development commenced in 1971 and concluded with the delivery of 28 hose sections in 1976. This hose design was never added to Senior Flexonics product line because it was not certified and at the time there was no other commercial interest in hose this large.
- Ten-inch bore cryogenic hose for a ship to ship transfer for use in emergency lightering of a LNG tanker. Intensive trials were carried out including one fully simulated sea trial off Das Island in 1984. After successful completion of these trials, hoses were delivered to Dubai and Singapore where they are in permanent storage to this day¹⁰.
- Eight-inch bore cryogenic hose for a ship to barge transfer of liquid ethylene at -104°C in 1992¹¹. In the development for this application off the coast of India, the hoses were prototype tested and certified by Germanischer Lloyds to comply with the IMO International Code for Construction of Equipment and Ships Carrying Liquefied Gases in Bulk, 1993 Edition, hereafter referred to as the IMO Gas Tanker Code.

Prototype Hose Design

The basic design of the current Senior Flexonics composite cryogenic hose is a result of a theoretical design established by T.I. Research Laboratories in 1976. The design work may be summarized as a mathematical analysis of the convoluted wall geometry and a computer program dealing with the anisotropy of the product. Verification of the theoretical design was initially carried out by Senior Flexonics on a small-scale (two-inch diameter) model followed by full scale testing on larger hoses. Evidence obtained from destructive examination of the tested hose provided details on areas where stress concentrations occurred. Modifications and improvements were then made to the hose design. These modifications included a specially formed fabric, which acts to gradually relieve the stress induced immediately behind the end fittings.

In 1998 a new effort was begun by Senior Flexonics to develop a 20-inch LNG loading hose to meet ExxonMobil's system requirements for offshore LNG transfer. The design criteria and the method used to test the previous Cryoflex LNG hoses were studied in detail and then compared with the loading system requirements provided by ExxonMobil. Previously, the hoses had been installed in a vertical test rig, pressurized with liquid nitrogen and subjected to 10,000 load reversals of $\pm 10^{\circ}$ angular displacement. ExxonMobil fatigue requirements were much more severe, requiring one million load reversals during the two-year service life of the hose. ExxonMobil requirements for a burst test (minimum five times MAWP) and a bending test were similar to those carried out previously and are a standard requirement for composite hose design.

ExxonMobil requirements for service life and related fatigue cycles were reviewed and compared with the experience database at Senior Flexonics. From a mix of theoretical, empirical testing, production requirements and practical experience, the prototype design was developed. A design change was made in the hose body to replace the original film material with a specialized film material with greater fatigue performance. The material properties for such film had markedly improved, since its use in the early 1980's. Design changes were also made to:

- The end fitting sealing area and method of attachment.
- The use of more modern resins recommended for cryogenic temperature.

Once a hose design was established, Senior Flexonics Quality Department assisted with the development of the procurement standards, manufacturing procedures and internal inspection and test criteria.

Prototype Hose Construction Details

A cross-section of the cryogenic hose is shown in Figure 3.



Figure 3

The hose construction consists of multiple layers of polyester fabric and polymeric film sandwiched between an inner and outer stainless steel wire. Each element is described in more detail below. The hose is built up on a mandrel with integral flanged end fittings not shown in the figure.

The outer wire gives the hose its hoop strength, providing sufficient strength to meet the burst requirement of five times MAWP. The inner wire prevents hose collapse. Both wires also establish the flexible geometry of the hose body and provide radial sealing pressure to the film layers. The inner and outer wire sizes, pitch, tension, etc. of the composite cryogenic hoses have been selected to offer the optimum combination of hoop strength and flexibility. Hose wire design is derived from the mathematical modeling carried out by T.I. Research. The reinforcing wire is certified to meet the relevant specifications (31619 BS 1554 1990, Din 50049 3.1b).

The fabric layers provide the majority of the hose axial strength. The selection of fabric material for cryogenic hoses is based on cryogenic tests carried out on two-inch and eight-inch hoses and continued for the ten-inch assembly. Testing of the polyester fabric material shows that it has excellent resistance to cryogenic temperatures and the marine atmosphere. Additionally, the fabric does not support mold or fungal growth in a marine atmosphere. The fabric has a yield strain 10 times greater than required for the maximum anticipated hose flexure. The polyester fabric meets Senior Flexonics' material standards for construction with each batch tested and certified with respect to minimum strength, density and thickness. The polyester fabric used falls within the scope of BS 3121 for low flammability. BS 3121 requires that when brought into a flame, the fabric will not flare up, nor will fire continue in the fabric if the flame is removed. Optimum fabric widths and lay angles used in the fabrication have been determined by

mathematical analysis and practical tests. Vendor aging data has confirmed that the fabric is suitable for more than the two-year service life.

The purpose of the polymeric films in a composite hose is to provide a leak-free seal within the hose body. The labyrinth construction of the film pack provides a barrier against percolation with the film material selected to provide low permeation. Although the primary purpose of the film packs is sealing, these packs also offer a significant contribution to the axial strength of the hose. The selection of film material properties, width, thickness, lay angles, number of layers, and number of film packs is based on prototype testing carried out by T.I. Research and experience from similar products and exposures. For more than twenty years, the polymers selected have been routinely used in hoses in liquid nitrogen service which is colder than LNG.

The end fittings of the cryogenic hose are an extension of the in-built fittings used in rubber-hose assembly manufacture. The thickness of the metal fittings is such that they can easily withstand the highest expected internal pressure. The method of securing the fittings to the hose is by wire binding of the hose material onto the fittings using high tensile stainless steel wire. The wire strength, number of layers and applied tension are sufficient to seal the hose body to the fittings and prevent relative movement between the fittings and the hose. The wedge-type design results in a tightening effect on the fittings with increasing axial load.

The completed hose is lagged with polypropylene rope to provide additional scuff protection for the outer wires and hose carcass. Although the cryogenic hose itself has excellent thermal, i.e. insulating properties, the addition of the rope further adds to this dimension.

Hose Test Protocol Development

ExxonMobil selected IMPaC Offshore Engineering GmbH of Hamburg, Germany to assist in the testing and certification of the Senior Flexonics 20-inch prototype hose. Germanischer Lloyd (GL) was selected as the certification agency for the hose. IMPaC and GL jointly developed the test program in co-operation with ExxonMobil and Senior Flexonics.

The basis for the prototype test program included the following:

- The hose should fulfill the requirements of the IMO Gas Tanker Code.
- Test conditions should be consistent with the expected hose service conditions at the target application off NW Australia including configuration of the hoses during LNG offloading, lifetime reliability considerations, and operational loads such as temperature, pressure, weights and motions.
- The test program should lead to certification of the 20-inch diameter hose for transfer of LNG and LPG offshore and at loading terminals. Certification of the 20-inch hose should automatically certify hoses of smaller diameter manufactured of the same materials and using the same fabrication process.

The test philosophy was to perform:

- Dynamic fatigue tests to verify dynamic bending and tension capabilities under operational conditions for a service life of two years. Testing for the equivalent of two years at the one-year return period wave conditions, which is the maximum allowable loading condition, is considered to demonstrate that the fatigue capability of the design is adequate.
- Static tests to verify that the hose is suitable for the required pressure, temperature and static-bending radius. This would include burst testing in accordance with the IMO Gas Tanker Code.

It was not practical to test the complete hose string of approximately 55 meters in the fatigue test rig. Since previous experience has shown the most likely location for hose failure is at the end connection, the test hose was divided into two parts to include four end fittings in the fatigue test. To model the most severe fatigue locations, the fatigue test was planned to include:

- A bending test to simulate the flexural and axial loading at the bottom of the U-shaped hose configuration (see Figure 4).
- A tension test to simulate the loading at the top vertical position of the hose string.

Five-meter long test hoses were used for all static and dynamic testing and in the case of fatigue testing, two hose sections were flanged together.

After the test philosophy was agreed, it was necessary to determine the test criteria. SINTEF was commissioned to calculate the test conditions for the fatigue bending test. Inputs for SINTEF analysis were:

- Physical hose data (supplied by Senior Flexonics)
- Relative motion data (supplied by ExxonMobil) for the one year return period conditions off NW Australia (2.5 meter significant wave height with ten second period)
- Hose configuration (supplied by IMPaC)

The results of SINTEF calculations served as a guideline for:

- Sizing of the test rig
- Positioning of the hoses in the test rig
- Actuator stroke for inducing the maximum cyclic deflections expected at the NW Australia site in a storm with a one year return period
- Actuator sizing and power requirements

Consequently, the following test program was established:

- Fatigue bending test with a set of two newly manufactured five-meter hoses
- Fatigue tension test with the same set of hoses used in the fatigue bending test
- Static bending test 1 using one of the hoses from the fatigue tests
- Static bending test 2 using the same hose used in bending test 1
- Burst test using one newly manufactured hose

Test conditions are shown in Tables 1 and 2.

Table 1
Dynamic Fatigue Tests

Test	Pressure	No. of Cycles.	Cycle Period
Fatigue Bending Test	6 barg	1×10^6	approx. 2 sec
Fatigue Tension Test	6 barg	1×10^5	approx. 4 sec

Test conditions for the fatigue bending test simulated the predicted hose curvature variation at the bottom of the loading hose catenary. 1×10^6 bending cycles represents a two-year service life consisting of 134 loading operations with 6500 flexural cycles per 18 hour loading operation.

For the fatigue tension test, a maximum force of ten metric tons was applied. This exceeds the maximum tension force on the hose end connection attached to the loading crane. The force is the result of the weight of the hose, the hose contents, a 15-mm layer of ice and dynamic amplification. Exposing the prototype hoses to 1×10^6 tension cycles after they completed the fatigue bending test was thought to be overly conservative since they were exposed to cyclic tension loads of four metric tons during this test. Therefore the number of tension cycles was limited to 1×10^5 cycles. No hose in the loading string would be exposed to both the maximum cyclic tension and bending.

Table 2
Static Tests

Test	Hose Configuration	Pressure	Duration
Bending Test 1	min. bend radius	1.1 x MAWP	24 hr
Bending Test 2	min. bend radius	1.5 x MAWP	8 hr
Burst Test	straight hose	5 x MAWP	5 min

Maximum allowable working pressure (MAWP) = 10.5 barg

All tests were to be carried out with liquefied nitrogen at a temperature of -170°C . Acceptance criteria were established prior to the tests as indicated in Table 3.

Table 3

Test	Duration	Pressure	Acceptance Criteria
Fatigue Bending Test	1×10^6 cycles @ 50mm stroke	6 barg	No leaks
Fatigue Tension Test	1×10^5 cycles @ 225mm stroke and 10 tons max. tension	6 barg	No leaks
Bending Test 1	24 hr. @ bend radius < 6.5m	11.6 barg	No leaks
Bending Test 2	8 hr. @ bend radius < 6.5m	15.8 barg	No leaks
Burst Test	5min	52.5 barg	No major leaks

Test Facility Design and Fabrication

Once the test program was established, existing test facilities were evaluated to determine whether they were suitable for carrying out the tests. It was soon evident that existing facilities were either not available or the costs for modification were excessively high as compared to the design and construction of new facilities. It was therefore decided to build new test rigs to meet the test program requirements and to stay within the test budget.

Design criteria for the test facilities were the test program requirements, hose dimensions (weight, bending radius, etc.) and data acquisition requirements. Another important design criterion was that the test facilities should be highly reliable during operation. Apart from the loss of time, a

breakdown could damage the test hoses and make the entire test worthless. Therefore, the design was robust and, where required, standby elements were introduced, e.g. a complete hydraulic pump unit was on standby during fatigue testing. Due to the different requirements for the fatigue tests and the static tests, two test rigs were designed and fabricated, one large unit for the fatigue tests and one smaller rig to carry out the static bending tests.

Fatigue Test Rig

Two test hoses, each five meters long, were flanged together to form a ten-meter long hose string. This string was mounted in the test rig (see Figure 4 below) where both ends were bolted to counter flanges. The counter flanges were arranged so that the hose ends were free of bending moments. One counter flange was fixed in the longitudinal direction, whereas the other was attached to a hydraulic actuator that induced the pre-determined horizontal cyclic motions. A load cell was fitted between the actuator and the hose end to measure the axial tension. Curvature variations during testing were measured by linear variable differential transducers mounted externally on the hoses. Liquid nitrogen was fed into the hose from a storage tank via a vacuum supply hose connected to the longitudinally fixed end of the hose. A pressure control valve regulated the hose internal pressure during the test.

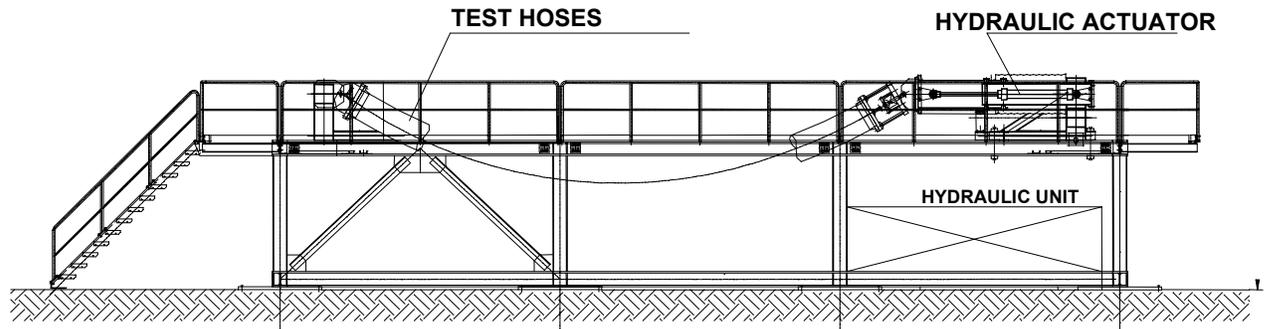


Figure 4: Fatigue Test Rig

Static Bending Test Rig

One five-meter test hose was mounted in the bending test rig (see Figure 5) and strapped down into cradles so that the minimum bend radius was achieved. Liquid nitrogen supply and pressure control was provided by the same systems used during fatigue testing.

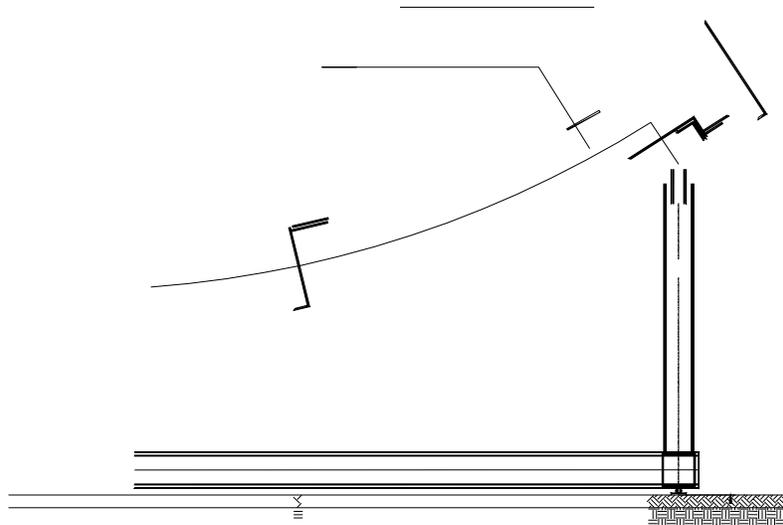


Figure 5: Bending Test Rig

The test rigs utilized the following auxiliary systems:

- Liquid nitrogen system, consisting of a storage tank, piping, instrumentation and exhaust for evaporation. The storage tank was filled by road tanker.
- Electrical power supply and distribution
- Hydraulic system, consisting of electrically driven hydraulic pumps, coolers, hydraulic oil storage tank, hydraulic cylinder and control unit (only fatigue test rig)
- Data acquisition and control system

A safety study was conducted on the test rig design and test procedures. As a result it was decided to carry out the burst test on a military test range, where safety for test personnel, material and the environment could be ensured. Protective sheathing against liquid nitrogen spills was installed on the fatigue test rig.

Results of Prototype Hose Testing

The tests were carried out in accordance with an approved test procedure. During the test the following parameters were continuously measured and recorded as functions of time:

- Pressure
- Temperature
- Axial tension at hose end
- Hose curvature (extension and contraction)
- Number of cycles

These data were displayed in real time and recorded by the data acquisition system.

The fatigue bending tests were begun with a set of newly manufactured hoses as planned. After 260,000 bending cycles, the test was stopped because small gaseous leaks were discovered where the hose end fittings connect to the hose. Senior Flexonics performed an in-house analysis of the failure and fabricated a new set of test samples with an improved interface between the end fitting and the hose body that provides a better balance of pressures and loads and is self-energizing. The second set of prototype hoses successfully completed the 1×10^6 cycle fatigue bending test with no leaks. These hoses also successfully completed the fatigue tension test with no leaks.

One of the prototype hoses from the fatigue tests then successfully passed both static bending tests with no leaks. Because of a delay in the manufacture of the new hose for the burst test, it was decided to burst test both hoses that successfully passed the fatigue tests. Although both hoses were at the end of their assumed fatigue life, the hoses withstood pressures of 41.6 barg and 45.2 barg respectively with minor leaks. Test pressure was achieved by filling the hoses with liquid nitrogen and allowing the pressure to rise as heat leaked into the hose. Because the hose natural insulation limited heat leak into the hose, it was not possible to increase hose pressure to the desired 52.5 barg once the hoses began to leak. Neither hose showed any signs of structural failure during the test. A third burst test was carried out when the new prototype hose was completed. This hose was filled with liquid nitrogen and then bottled nitrogen was used to achieve the test pressure of 52.5 barg. The 52.5 barg pressure was held for eight minutes with only small vapor leaks at the interface between the end fittings and the hose body.

Hose Certification

For the new and larger composite hose design, verification of the hose reliability is important. Although operational experience for smaller size composite hoses is available (sizes up to eight inches) the reliability data cannot be scaled up to the 20-inch hose for two reasons. First, the 20-inch hose utilizes a different method for connecting and sealing the flanged end fitting to the hose. Second, the stress and strain model for the 20-inch hose is different because more layers of fabric and film are used.

The first fatigue bending test and previous test experience showed that the most likely failure mode in operation is a small leakage in the area where the rigid flanged end fitting is sealed to the more flexible hose. The revised sealing design passed the burst test, the complete fatigue test and the static bend tests. Some leaks did occur at more than three times rated pressure when a burst test was attempted on fatigued samples with the equivalent of 2 years in operation. A final laboratory analysis revealed that the load bearing fabric showed no wear. Thus the design is safe from leaks in service and from structural failure even after fatigue testing. The related mean time to failure qualifies the hose for about 2 years in service because the intended operation is intermittent. If leakage occurs, the hose should be taken out of service, although depending on the severity of the leak, the transfer operation underway at the time of the leak may be completed.

As a result of the successful prototype testing, Germanischer Lloyd issued the following certification:

- One of the test hoses was manufactured under the surveillance of the Certifying Agency and a test certificate similar to 3.1-C was issued. This particular hose was then burst-tested as a prototype in order to fulfill the requirements of the IMO Gas Tanker Code.
- A Certificate of Compliance was issued stating that this hose type is fit for the purpose of transfer of LNG and LPG offshore and in terminals.
- Any further hose production will be covered by individual test certificates (similar to 3.1-C). As soon as permanent production is established, the manufacturer may ask alternatively for a general Type Approval Certificate to qualify the hose product.

Conclusions

A team comprised of ExxonMobil, Senior Flexonics and IMPaC Engineering has developed an alternative approach for offshore LNG transfer at floating LNG plants and terminals. Based on incorporating a composite-fabric hose for conveying the LNG, the transfer system will be safe, reliable and cost competitive compared to conventional transfer systems. Senior Flexonics

supplies this hose in sizes up to 20 inches. The testing program has shown the hose to meet all requirements of the IMO Gas Tanker Code and Germanischer Lloyd has certified it for the transfer of LNG and LPG offshore and at loading terminals. Fatigue testing was conducted to confirm that the hose has a two-year service life for an offshore loading application in NW Australia. Application of the 20-inch hose in more severe seastates, different configurations or with different vessel motion characteristics may require additional analysis and testing. Design of the remaining loading system components, including the hose handling system and control system as well as the development of system operating procedures is planned.

Acknowledgement

The authors wish to acknowledge the contributions and dedication of Marie Naklie in making this cryogenic hose development a success.

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