ANNEXE 5.1

Technical Challenges of Subsea LNG Pipelines

Colin McKinnon J P Kenny Ltd

1. Abstract

There is a growing demand for the export and import of LNG. The traditional solution is to use a jetty to connect the loading dolphin to the shore and for the jetty to carry the LNG pipelines.

A typical LNG pipeline system consists of the following elements:

- 2 off 36-inch LNG pipelines
- 1 no. 18-inch vapour line
- 1 off power/control umbilical.

A typical above water LNG pipeline consists of 304 stainless steel pipelines with PU foam insulation and contraction spools every 250m. Such designs are not suitable for subsea service. A number of different designs are being developed and tested by companies such as ITP, Chart, Technip, GTT and Fluor.

The paper discusses the technical challenges associated with subsea LNG pipelines including:

- Review of available systems;
- Applicable codes and standards;
- Design issues;
- Welding and material issues;
- Safety philosophy;
- Construction methods;
- Operating philosophies;
- Interfaces with the jetty head and the tank farm;
- Technology gaps;
- New developments.

The paper will also present budget costs and schedules for a typical LNG project.

2. Typical LNG System

2.1. Pipe Configuration

A typical Pipe in Pipe (PIP) subsea LNG pipeline system will consist of the following components:

- 2 no. 36-inch LNG pipelines each in a 42-inch outer pipe;
- 1 no. 18-inch vapour line in a 22-inch outer pipe.

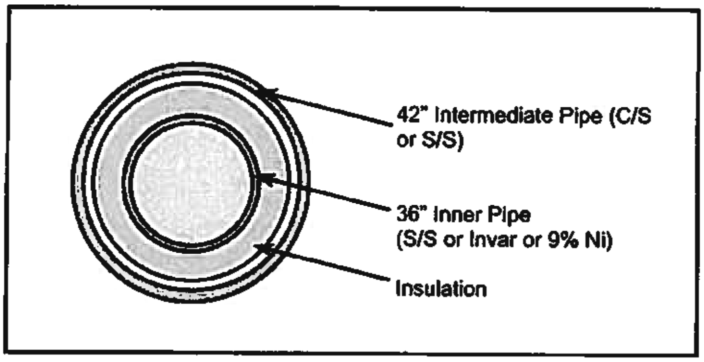

Figure 2.1: LNG Line PIP Configuration

Pipe in pipe in Pipe (PIPIP) configurations have be proposed by some of the suppliers where there is a need for secondary containment and concerns about the long term integrity of stainless steel in seawater have lead to the use of an outer pipe of carbon steel.

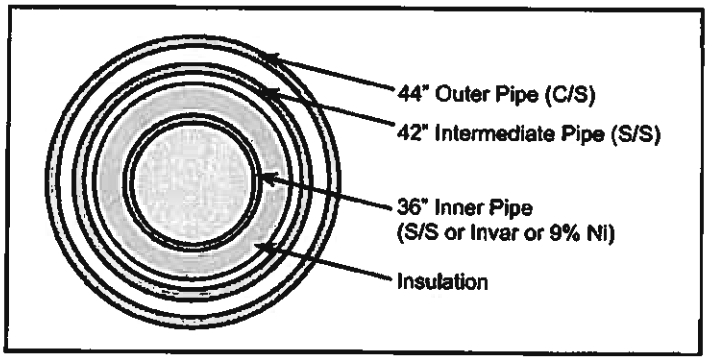

Figure 2.2: LNG Line PIPIP Configuration

2.2. Typical Operational Data

The typical operational data for the pipelines is presented below.

Table Error! No text of specified style in document.**-1: Pipeline Design Data**

Parameter		Twin 36"/42" LNG PIP Lines	18" / 22" PIP Vapour Line
Maximum Design Pressure		20 barg	
Maximum Operating Pressure		10 barg	
Design Temperature	Max	+80°C	
	Min	-196°C (To allow for liquid nitrogen cool-down)	
Design Flowrate		12000 m^3/hr	

2.3. Pipeline Material Data

Typical material data is summarised in Table 3-2.

Table 3-2 Pipeline Material Data

Parameter	9% Ni-Steel Pipe	Stainless Steel (304L) Pipe	36% Ni-Steel
Temperature (°C)	20	20	20
Steel Density (kg/m^3)	7860	8000	8120
Coefficient of Thermal Expansion (K^{-1})	9.5×10^{-6}	16.6×10^{-6}	1.5×10^{-6}
Thermal Conductivity (W/m.K)	28.5	15.0	10.5
Young's Modulus (GPa)	186	200	148
SMYS (MPa)	515	203	210
SMTS (MPa)	690	514	420

2.4. Valve Stations

Isolation valves are required in all lines at the berth and plant tie-in points (LNG storage tanks). Additional isolation valves Isolation valves may also be required at the landfall depending on the length of the onshore section of pipeline.

2.5. Vents and Drains

Cryogenic pipelines continuously absorb heat from surrounding air or soil. Each isolatable section of the liquid pipelines must therefore be provided with a high-point vent and a thermal relief valve connected to the vapour return pipeline. This will allow vapour generated by the leak of heat into trapped-in volumes of cryogenic liquid to be disposed of in the terminal's vapour handling systems.

High point nitrogen purge connections can be installed in each isolated section to enable purging of the LNG from the pipelines without waiting for the LNG to naturally boil-off. Likewise, drains can be located at low points to allow draining of the LNG from each enclosed section without the need to use the venting system. These cannot be located subsea, due to the requirement for a single pipe section and to prevent freezing, and so can only be located in the onshore areas and at the LNG berth.

2.6. Secondary Containment

Secondary containment is the practice whereby the second pipe is used to provide an additional level of containment should the inner pipe fail or leak. For this to be possible, the second pipe (either intermediate or outer pipe) cannot be carbon steel, as it would fail due to the thermal shock loads. The secondary containing pipe is therefore required to be made of more ductile stainless steel so that it can withstand an individual accidental loading down to the minimum LNG operating temperature (–165°C).

The need for secondary containment is a driven by the pipeline safety assessment and regulator requirements.

2.7. Contraction Spools

Conventional stainless steel LNG pipeline experience considerable contraction during operation and require the installation of contraction spools at regular intervals along the pipeline route.

All the systems covered by the paper are designed to avoid the need for contraction spools.

3. Design Issues

There are no pipeline codes that specifically address the needs of subsea LNG pipeline design. It is recommended that subsea LNG pipelines are designed in accordance with DNV-OS-F101 supplemented with material requirements for cryogenic pipelines from ASME B31.3 and B31.5, further supplemented with the onshore pipeline gas and hydrocarbon liquid requirements of ASME B31.8 and B31.4 respectively.

This approach will ensure a robust and safe pipeline design that addresses offshore pipeline issues such as spanning and stability, onshore pipeline issues such as pipeline burial, CP, crossings and proximity to people whist ensuring that hydrocarbon liquid and cryogenic specific issues are also addressed.

The risk of ice forming around the subsea sections of the pipelines needs to be considered. This is more of an issue at field joints, bulkheads and flanges than the main PIP sections. Calculations indicate that heat from the sea will prevent ice formation because of heat flow through the seawater surrounding the PIP by means of convection. There is a risk of an ice ball forming around buried sections of the pipeline, which needs to be considered. Calculations indicate that there is a risk of ice balls forming in certain soil conditions and temperatures.

4. Safety Issues

The main safety philosophy issues identified include the need for secondary containment, burial, venting and isolation. The mechanical safety risks for the PIP systems have been investigated through a safety review of potential risks, their causes and the system control measures that should be put in place to minimise the risks identified.

Isolation valves are required at the loading berth and the LNG plant.

Provision of a vent system for the inner pipe in the event of the isolation valves closing is required to prevent over-pressurisation with boil-off gas production.

5. ITP PIP and PIPIP Systems

5.1. System Description

The ITP LNG pipe in pipe (PIP) system comprises a 36% Ni-Fe alloy (Invar) inner pipe for LNG transport and an outer pipe of carbon steel. The annulus is filled with Izoflex insulation and has a reduced pressure (partial vacuum of around 100mbar) to reduce heat loss.

The ITP LNG pipe in pipe in pipe (PIPIP) system comprises a 36% Ni-Fe alloy (Invar) inner pipe for LNG transport, an intermediate austenitic stainless steel (304L) pipe for secondary containment and a carbon steel outer pipe for mechanical and corrosion protection. The inner annulus is filled with Izoflex insulation and has a reduced pressure to reduce heat loss, with the outer annulus filled with an inert gas (nitrogen) at a pressure slightly above local ambient to prevent flooding in the event of an outer pipe leak.

The ITP LNG 2 and 3 pipe system make-up consists of the following components:

<table>
<tr><td rowspan="3">2-pipe system (PIP)</td><td rowspan="5">3-pipe system (PIPIP)</td><td>Inner Pipe</td><td>-</td><td>Invar (36% Ni Steel).</td></tr>
<tr><td>Inner Annulus</td><td>-</td><td>Incorporating Izoflex insulation and maintained at reduced pressure for insulation property improvement purposes.</td></tr>
<tr><td>Intermediate/Outer Pipe</td><td>-</td><td>Carbon steel (PIP)
304 Stainless Steel (PIPIP)</td></tr>
<tr><td></td><td>Outer annulus</td><td>-</td><td>Maintained at a pressure slightly in excess of hydrostatic head using dry Nitrogen.</td></tr>
<tr><td></td><td>Outer Pipe.</td><td>-</td><td>Carbon Steel.</td></tr>
</table>

It is proposed that the pipe-in-pipe system is used for onshore, and subsea where secondary containment is not required. The pipe-in-pipe-in-pipe system would be used subsea where secondary containment is required. Where intermediate bulkheads are required subsea, the triple pipe system will be required (at-least locally) to prevent local heat influx from the surrounding water.

The coefficient of thermal expansion of Invar is approximately 10 times less than stainless steel and as such internal bellows and expansion loops are not required.

The insulation material, Izoflex, is a Silica Oxide, Titanium Dioxide and glass fibre mix that can withstand temperatures from –200°C to + 900°C and has a thermal conductivity of 0.005 W/m-K at LNG temperatures (0.0029 BTU/ft hr °F).

It is anticipated that for any straight sections of pipe greater than approximately 100m, an inline bulkhead would be required prior to each formed bend.

5.2. Experience to Date

ITP have wide experience of the design, fabrication and installation of subsea, high temperature PIP pipeline systems.

Izoflex has been used offshore in PIP systems for Camisea, Forvie, Rosa and Dunbar.

ITP have done a full-scale thermal performance test of an 18m section of their 24"by 30" by 32" subsea PIPIP LNG pipeline and riser system.

The ITP PIP system was used to insulate 3km of the subsea Camisea LPG pipeline system that is operational in Peru. The operating temperature was -46C. The inner pipe was carbon steel rather than Invar.

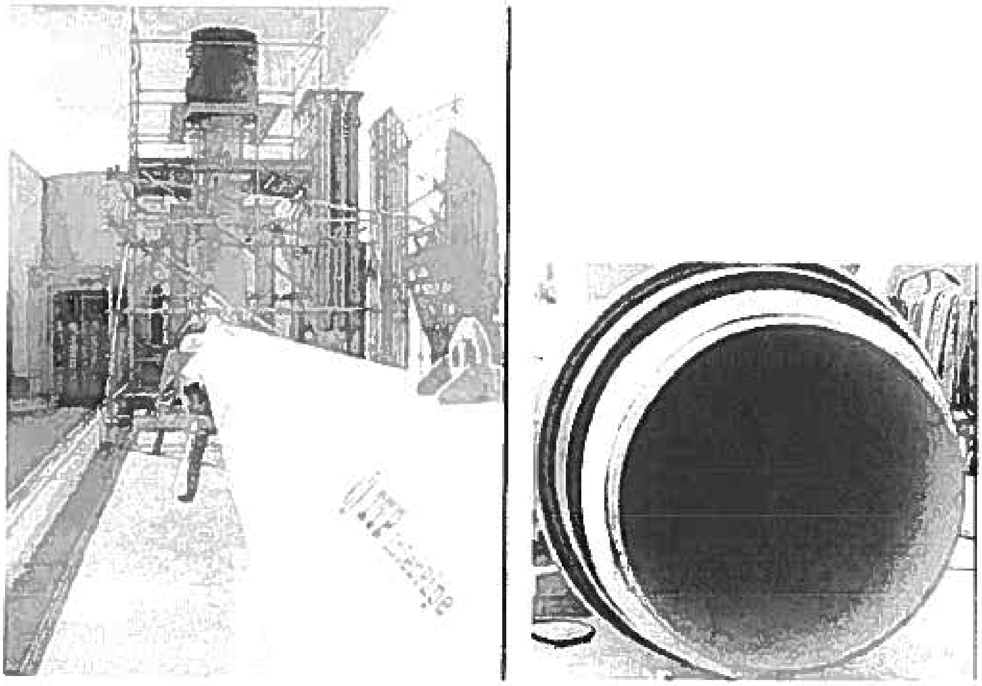

Figure 5.1 Test Rig and PIPIP Cross Section

5.3. Certification Status

ITP have the following certificates:
"Approval in Principle" from ABS.
"Statement of Feasibility" from DNV.
"Approval in Principle" from Lloyds.
As part of a current FEED project, ITP are completing the qualification of the technology with DNV. By the end of October they should have a "Statement of Fitness for Service" for DNV.

The objective of the Fitness for Service Verification is to testify that the technology qualification process has been executed in accordance with DNV OSS-401 and the principles outlined in DNV-RP-A203, and that the functional requirements and reliability targets as stated in the Qualification Basis have been adequately addressed as relevant at the given stage of the qualification process.

5.4. Pipe Sizes

The JIP test pipe was 24-inch, but ITP have had 32" and 36" INVAR pipes produced and Invar can be produced in pipe diameters up to 48". Up to about 36" diameter the pipes can be made with a single longitudinal weld depending upon the supplier. Beyond 36" diameter, two longitudinal welds are required to make up the pipe.

Carbon and stainless steel pipe, bends and bulkheads of the required size can be provided by ITP's suppliers.

5.5. Insulation system

The U-value of the standard design for the pipe-in-pipe system using reduced annulus pressure is 0.13 W/m^2-K. This can be improved by about 20% to 0.10 W/m^2-K by increasing the insulation thickness (with corresponding increases in material and fabrications costs) without changing the diameter of the second pipe.

5.6. Welding

ITP has selected the GTAW and PAW as most appropriate for their system and have developed welding procedures for the inner pipe based on these processes. The welding qualification test programme and fabrication of the full size pipe test section carried-out in JIP was satisfactory and did not indicate any problems associated with the selected welding processes.

From the work carried-out, welding of Invar is not expected to present significant difficulties for welders and welding operators. Generally, welders experienced in welding stainless steels would be expected to be able to weld Invar with a little practise. Invar welding consumables, in common with other nickel alloys tend to exhibit sluggish flow behaviour in the weld pool, compared to stainless steel, which is fluid. Consequently, welders must adopt a different welding technique when welding Invar.

Invar is susceptible to solidification cracking (hot cracking) and ductility dip cracking, which is known to be influenced by certain residual elements, particularly sulphur and phosphorus. In addition, susceptibility is increased by the presence of sulphur-containing contaminants on the surface of both parent metals and welding consumables (particularly, grease and oil).

When Invar is welded using consumables of matching composition (to give the best thermal expansion/contraction properties), the resulting deposited weld metal undermatches the yield strength of the parent metal in the order of 30-35% both at ambient and cryogenic temperatures.

Extensive materials testing have addressed these issues.

6. Chart VIP System

6.1. System Description

The Chart LNG system is a 2-pipe make-up consisting of the following components:

Inner Pipe	-	ASTM A312, 304/304L Stainless Steel.
Inner Annulus	-	Incorporating vacuum insulation and radiation shielding.
Outer Pipe.	-	Carbon Steel.

The Chart system is pre-fabricated into double joint 'spools' with the spool ready for connection to the adjoining spools in the field. Vacuum insulated field joints are therefore required every 24.4 m. Each joint consists of a butt weld inner pipe connection and welding closure over this inner pipe connection with aerogel insulation and field evacuation of this joint to improve the local insulating properties. Each shop fabricated vacuum insulated pipe spool will be supplied with an internal bellows designed for the thermal contraction of the inner line when it is cooled with LNG. This bellows is configured in the inner pipe in a manner such that the LNG process line pressure will be on the outside surface of the bellows with a vacuum on the inside surface. The bellows is located between the inner line and jacket and will contract when the inner line is cooled. A Chart patented secondary seal or controlled leak is also provided as part of this bellows assembly as an additional leak prevention measure.

In order to evacuate the annular space, a pump out valve is provided on each pipe spool assembly. This valve has an elastomer o-ring seal for sealing the vacuum in each pipe spool. There is also a secondary seal that further protects the integrity of the vacuum in the annular space of the pipe spool. This valve normally has a vacuum gauge tube provision supplied for monitoring the vacuum space during shop testing, shipping, and installation and is isolated from the vacuum space at all other times.

6.2. Experience to Date

Chart has supplied VIP for 45 years and is the industry leader in this technology.

Chart has limited experience of the design, fabrication and installation of subsea PIP pipeline systems.

400 No. 30 by 34-inch VIP spools are currently being installed at Darwin Australia.

The Freeport project consists of 5000' of 26" x 32" and 12" x 18" and is currently under construction.

A 26 by 32-inch spool is currently undergoing a testing program and has been buried and the bellows have been contracted and there is a 12 by 18" system that has been in service for 5 years.

Figure 6.1 30" VIP Spool for Darwin LNG Loading Line

6.3. Pipe Sizes

Chart is currently building a 26" by 32" test spool in New Iberia LA under a joint agreement with BP. One of the goals of this test program is to confirm that there will not be any scalability issues. No such issues have been identified to date and none are expected as the VIP technology has been used on large-scale pressure vessels for 50 years.

A 26" by 32" spool is currently undergoing a testing program with the test section buried with the bellows contracted. There is also a 12" by 18" Chart system that has been in service for 5 years.

Typically, the outer pipe will be 6" greater than the inner pipe OD and a single spool can be up to 120 ft (~36.6 m) in length, but are normally 80 ft (~24.4 m) long.

The maximum size previously produced is a 30" inner pipe with a 36" outer pipe but it is Chart's belief that these systems are available up to and including 48" inner pipe.

6.4. Insulation system

A typical 3.5W/m² for 36" case and 4.75 W/m² for 48" case (based on surface area) heat leak value would be used based on a straight length and closing section and on the assumption that the soil is at 70°F (~21°C). The leak value is an average through-spool value as in reality the cone sections at the ends of the spool will have worse insulation properties than the mid section of the spool.

The vacuum has a 30-year life cycle, which is applicable to individual spools as opposed to the entire pipeline length. Any hydrogen that emerges from the steel is dealt with by a chemical getting system that converts the hydrogen into water and absorbs it.

It should be noted that the Chart VIP system U value (0.027W/m²K) is significantly lower than the ITP system U value (0.13W/m²K).

6.5. Bellows

Chart has never had any of its bellows fail in service; however, because they recognise client's concerns, Chart have continued to work on improving the design so that a bellows failure will be minimised to the greatest extent possible. Chart's bellows' suppliers have developed proprietary failure probability data through both empirical testing of the materials and designs and by code calculation.

Chart advised that expansion joints of 48" are available.

6.6. Welding

The weldability of 304L austenitic stainless steel is very good and consumables providing matching or overmatching mechanical properties are readily available. No particular problems are anticipated provided good welding engineering practise is adopted for shop and filed welding.

Chart advised that all pressure containing joints in the VIP system are full penetration welds, which are preferred from a design point of view and can be most effectively non-destructively examined. The only exception to this is the bellows assembly, where the bellows is fillet welded to the bellows ring. However, this is conventional practise, considering the design of the bellows and is specifically permitted by ASME B31.3. In this case, the fillet weld is subject to liquid dye penetrant inspection.

Field welds must be made in a clean, dry atmosphere but standard open air welding techniques can be employed. The preferred method is to perform a GTAW welded root (good practice for stainless steels) and then a more standard method for the rest of the weld (e.g. GMAW, FCAW, SMAW). It should be remembered that any welding method must be cryogenically approved.

7. Technip PIP system

7.1. System Description

The Technip LNG system is a 2-pipe make-up consisting of the following components:

Inner Pipe	-	Invar.
Inner Annulus	-	Incorporating Aspen Aerogel thermal insulation, a multi-foil reflective layer and spacers at 40ft intervals. In addition, the annular space is filled with Nitrogen at atmospheric pressure.
Outer Pipe.	-	Carbon Steel typically, but should secondary containment be required then Stainless Steel would be employed.

In-line bulkheads are required at any change of direction in the system and not within continuous straight sections. Technip recommend that these bulkheads be installed in an open pit to maintain access to the Nitrogen piping.

Field joints employ a single butt weld in the outer pipe (by sliding the outer pipe over the spacers around the inner pipe) and only the last field joint next to a bulkhead will require a half-shell field joint.

The continuous Nitrogen circulation acts as a continuous integrity monitoring system, however fibre optics may also be incorporated within the design.

Technip suggest that stainless steel outer pipe can be used if secondary containment is needed.

7.2. Experience to Date

Technip have wide experience of the design, fabrication and installation of high temperature PIP spools.

Aerogel has been used offshore in PIP systems for K2 and Dalia.

Technip have done a full-scale thermal and mechanical performance test of a 12m section of their subsea 26" by 32" PIP LNG pipeline system. Test results were validated against predicted FEA results.

Welding procedures have been developed and are being reviewed for certification.

7.3. Certification Status

Technip have achieved the following certificates early this year:

- Approval in Principle from ABS
- Concept Approval from BV

Figure 7.1 Test Section and Test Site

8. GTT PIPIP system

8.1. System description

The GTT PIPIP system comprises a 36% Ni-Fe alloy (Invar) spiral welded inner pipe for LNG transport, an Invar spiral welded intermediate pipe and an outer pipe of carbon steel. The inner annulus is filled with aerogel and the second annulus is filled with a layer of aerogel and concrete for additional stability subsea.

The GTT LNG system is a 3-pipe make-up consisting of the following components:

Inner Pipe	-	Invar – spiral wound pipe
Inner Annulus	-	Incorporating either: Aerogel beads and foam caps, or Aerogel fabric and foam spacers.
Intermediate Pipe.	-	Invar – spiral wound pipe
Outer Annulus	-	Incorporating: Fibre optic sensor tube, Aerogel fabric and foam spacers, and Concrete weight coating.
Outer Pipe.	-	Carbon Steel.

8.2. Experience to Date

GTT have wide experience of the design, fabrication and installation of LNG tankers and storage tanks.

GTT has limited experience of the design, fabrication and installation of subsea PIP pipeline systems.

Aerogel has been used offshore in PIP systems for K2 and Dalia.

GTT are planning a full-scale thermal performance test of their PIPIP LNG pipeline system in 2006.

A full scale submerged test of a 30m section of the GTT system has been tested in a purpose built facility near Paris.

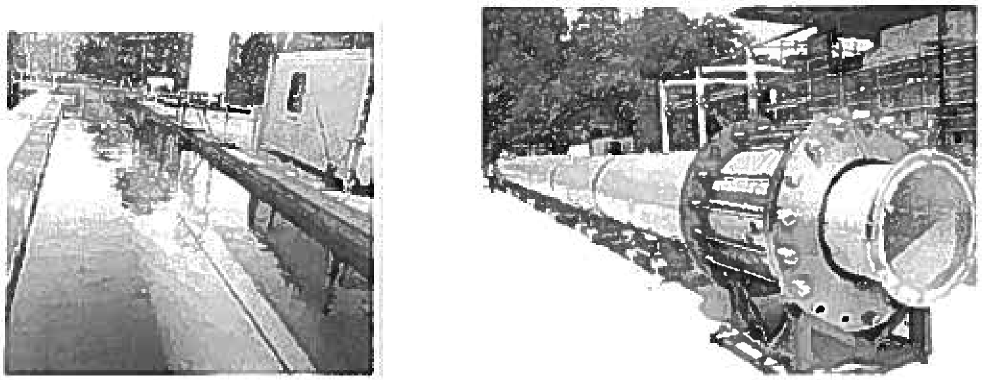

Figure 8.1 Full Scale Test Tank and Test Section

8.3. Certification Status

Working with Lloyds, BV and ABS. Qualification tests planed for 2006.

8.4. Thermal Performance

The predicted U-value for is 0.17 W/m^2/K.

9. Fluor PIP system

9.1. System Description

The Fluor PIP system comprises a 9% nickel inner pipe for LNG transport and an outer pipe of carbon steel or 9% Ni steel. The annulus is filled with Cabot Nanogel™ Aerogel.

The Fluor LNG system is a 2-pipe make-up consisting of the following components:

Inner Pipe	-	9% nickel.
Inner Annulus	-	Cabot Aerogel insulation (in Expansion Pack™ form) approximately 2" to 3" thick at ambient pressure, but previous work has included work with Aspen Aerogel.
Outer Pipe.	-	Carbon Steel, or 9% nickel for secondary containment.

In-line forged bulkheads are required at any change of direction in the system but not at regular intervals within continuous straight sections. The bulkheads will be composed of 9% Ni material, shaped to minimize heat transfer (conical, similar to the Technip PIP system).

Previous assessments have shown that the original consideration of non-metallic bulkheads is not necessary to maintain the required thermal performance of the system.

The standard mid-section field joints employ a single butt weld in the outer pipe (by sliding the outer pipe over the inner pipe and insulation packs) and only the last field joint next to a bulkhead will require a half-shell field joint (clam-shell).

To avoid localised heating of the LNG at intermediate subsea bulkhead locations, the field joint enclosure is filled with Aerogel and half-shell outer pipe enclosures welded to form a continuous outer pipe across the field joint. Additional insulation is then wrapped around the full length of the field joint (with sufficient overlap) to minimise heat transfer through the metallic bulkheads.

Fluor are now offering both ambient pressure insulated (Cabot's NanogelTM Expansion PackTM) pipe-in-pipe configurations and vacuum insulated pipe-in-pipe configurations using 9%Ni steel as the inner product pipeline. Both offer the high thermal performance expected in LNG pipelines and the lowest competitive cost of all configurations.

9.2. Experience to Date

Fluor has served the gas processing industry for over half a century, with active participation in LNG for the last forty years. Fluor LNG experience includes both liquefaction and regasification and encompasses a full range of activities from feasibility studies right through to procurement, construction and maintenance support.

Fluor's recent LNG experience includes full EPC of two LNG regasification terminals.

Fluor has completed two small-scale thermal and mechanical performance tests of a section of their subsea 6" by 12" PIP LNG pipeline system (using both 9% Ni and 316L stainless steel inner pipes). This enabled Fluor to discount the use of 316L material for the inner pipe of their PIP system due to the high loads generated in the system components.

Fluor are planning a full scale thermal performance test as part of their JIP commencing early 2007 of a 9m section of their subsea 24" by 32" PIP LNG pipeline system with a 9% Ni inner pipe. The test will be performed using liquid nitrogen, which is colder than LNG (-192°C) but safer than LNG.

Two full size metal bulkheads made of 9% Ni steel will be tested. The inner pipe is 24" OD x 0.375" WT, and the outer pipe is 32" OD X 0.750" WT. The testing will include assessments of the systems response, stress and fatigue levels and thermal performance with typical cycling of the operating temperatures. The tests will include the PIP system in air, submerged (minimal water depth) and buried with 1m cover of saturated soil.

9.3. Certification Status

Fluor have achieved the following certificates in 2006:

- Approval in Principle from ABS
- Approval in Principle from DNV

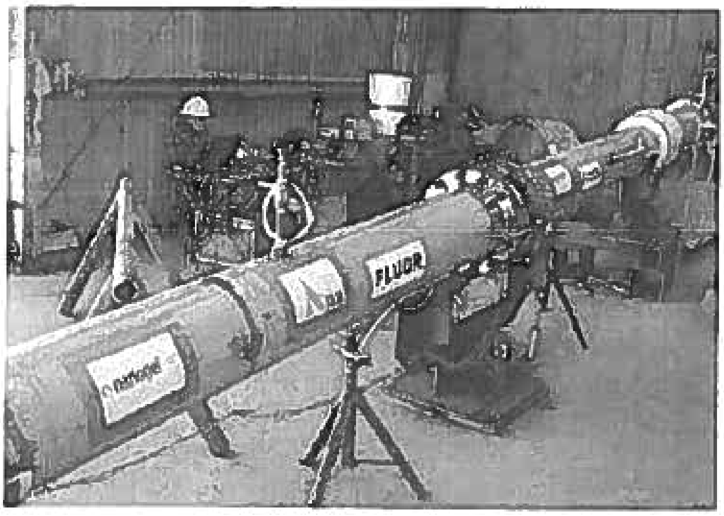

Figure 9.1 6" by 12" Test Section

9.4. Thermal Performance

The Cabot Nanogel™ insulation has a thermal conductivity of around 0.011W/m.K and fills the PIP annulus in the expansion pack form. The overall heat transfer coefficient of the Fluor LNG PIP system has not been confirmed for either the PIP sections or field-joints however, and these would need to be confirmed from the full-scale testing results. The predicted U-value for a 36" x 44" system is 0.15 W/m^2/K.

The insulation can provide some axial and radial support to the inner pipe, and transfers some load from the inner pipe to the outer pipe.

The Cabot Nanogel™ is also resistant to water and will not degrade if left in contact with water/moisture. This also aids in removal of moisture from the insulation to maintain the thermal efficiency of the system.

9.5. Weld Consumables

These materials are susceptible to hydrogen cracking, but with appropriate preheat and low hydrogen consumables, with temper bead techniques to minimise cracking, the steels are fairly weldable. Postweld heat treatment is used to improve HAZ toughness in these steels. No details of the weld qualification tests performed to date were provided, but extensive industry experience is available.

Specialty welding consumables required for the full-scale testing work are to be supplied by EBK. They have developed both longitudinal and girth welding consumables and procedures for the high strength 9% Ni pipe following Fluor's requirements, which are in the process of being patented by EBK. Technical details were therefore not disclosed by Fluor.

The longitudinal seam weld is typically made using a submerged arc welding (SAW) process, but other processes used include GMAW, GTAW, and SMAW. The longitudinal seam weld is subjected to 100% radiography and ultrasonic inspection.

Like Invar welding, the high nickel welding consumables are not deep penetrating and the weld metal does not flow, or wash the walls of the joint as readily as ferric weld metals. This does not prevent a successful weld and generally, welders experienced in welding stainless steels would be expected to be able to weld 9% Ni with a little practise. However, failure to understand this issue can result in side-wall lack of fusion (LOF) and poor penetration. Lack of fusion is therefore reported as the most prevalent weld defect. Fluor have recognised that this type if defect cannot be reliably detected using radiography, and so recommend full AUT.

The finished pipe joints are also mill hydro-tested.