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HFI WELDED STEEL PIPES FOR LOW TEMPERATURE PIPELINES

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ABSTRACT

Due to an ever increasing endeavor for the reduction of greenhouse gas emissions over the next few decades, with a gradually increasing demand for energy world-wide and despite a society which is becoming more and more civilized and industrialized, the actual challenge in handling this problem is intensified by decreasing sources of energy, a global economic recession as well as energy market instabilities.

Replacing fossil energy sources such as oil with alternative energy concepts is at best difficult because of the high initial investment costs needed installing alternative energy concepts.

As an answer to the problems faced, the industry offers several solutions ranging from advanced technologies with a high efficiency ratio such as fuel cell and hydrogen energy, up to and including alternative new or renewable energy sources such as solar, hydro and wind power.

One of the major solutions for the transitional period to economical and reliable renewable energies is considered to be the use of Liquefied Natural Gas (LNG).

To accommodate for these requirements, Salzgitter Mannesmann Line Pipe has continuously developed highly sophisticated materials in the form of bainitic pipes for the transportation of gaseous or liquefied medium at ultra-low temperatures.

In the first part of this presentation paper the process route as well as the material and pipe properties will be shown and explained. In cooperation with our construction partner Fernwaerme-Technik (FW), the bainitic pipes were used to construct a special multi-pipe system for the conveyance of liquefied natural gas (LNG) at a temperature of -162 °C. The pipe system as well as results from the field testing is presented below and tests have been conducted on this system for three years using liquid nitrogen. It can be shown, that not only the low temperature pipe material requirements for transportation of LNG are fulfilled, moreover it offers further potential as an alternative for the replacement of expensive austenitic steels applied at temperatures down to -196°C.

INTRODUCTION

Over the last decade thoughts, plans and activities have increased world-wide, to minimize energy consumption, to reduce greenhouse gas emissions, and to start an “energy revolution”, even on short-, mid- and long-term time-scale. One example for nearest future referring from Germany, where the government has decided to prohibit the use of nuclear energy generation from 2020 altogether and simultaneously aims at reducing the CO_2-pollution by a massive 40 % until 2020, and 80 % until 2050 (compared to 1990), additionally aiming to reach a portion of 60 % of regenerative energies [**1**].

One of the most discussed scenario deals with the mobility of tomorrow. The development of nonpolluting fuel concepts has been started with as example pure electricity or hydrogen fuel cells, with energy originating from alternative energy sources such as Wind, Solar or Hydro technologies. Alas there is still a long way to go in establishing a widespread technology and realistic time-frames of up to 20 or more years are frequently discussed. In order to start earlier with the reduction of greenhouse-gases, short-term improvements based on optimizing existing technologies have to be applied.

One of the promising technologies for all mobility sectors is represented by the use of natural gas. It can be collected from natural (fossil) sources, or generated from renewable energies by power-to-gas and re-methanation. One of the advantages of this energy source for example is the reduction of 25 % of CO_2-emissions compared to the combustion of diesel fuel sources. More or less no smut, fine dust and sulfur oxides are being produced and even the local emission of nitrogen oxide is reduced by 80-90 %, without noteworthy limitations on the cruising range [**2**]. Additionally the energy efficiency along the value-added chain is more positive compared to oil based energy, and with the use of renewable methane the carbon footprint can be improved even further [**3**].

Today more than 90 % of all natural gas used is transported conventionally via pipelines to power plants, for industry usage and to consumer homes. As a more efficient transportation method, natural gas can be liquefied by reducing its core temperature down to roughly -162 °C, which in turn reduces its volume by a factor of 600 (LNG). The LNG technology is well-known and widely accepted as an environment friendly next generation source of energy. On the one hand one major advantage is that it can be easily collected from "isolated" and/or remote exploration sites, as well as transported to "isolated" consumption areas, today mainly by ships. On the other hand, a wide investment chain including gas pre-treatment, liquefaction, LNG tankers, a reception terminal with LNG storage and regasification facilities as well as a connection to pipeline infrastructure is needed. Therefore LNG projects are far more capital intensive and complex to develop, compared to pipeline projects. The transportation via long distance pipelines could be favourable, if LNG is imported and collected in huge terminal stations and then be transported onshore to main consumer centres like industry, cities etc., as pipeline based transport involve mainly pipeline and compressor stations [e.g. **4**-**7**]. However, the disadvantages in use of pipelines is the limited capacity to serve new fields, high investment costs for possible extensions, politically motivated delivery problems if subject to geopolitical interests, and little flexibility in terms of exploiting new market opportunities.

Over the last decade LNG has become one of the world's fastest-growing energy sector, with demand increasing rapidly. The market for LNG has grown substantially in the last years with the number of pipeline gas almost being doubled [3]. World-wide an increase in capacities for liquefaction is ongoing from today's 390 Billion m³ natural gas, with forecasts which allows for a future trend almost doubling this capacity in the next ten years [e.g. **8**]. From today's point of view, most of the LNG is favored for export, and with the discovery of new reservoirs e.g. in Africa (Tanzania and Mozambique) a potential of an estimated 4,000 Billion m³ can be shown with the main key markets being (as also today) Asia [**9**].

The use of LNG is generally widely accepted as being a secure energy source, as it is in itself inflammable and as a gas can only be ignited with certain limitations. Additionally the industry, together with governments and authorities, has been successful from the very beginning in establishing the very highest of safety standards.

Following the examples of the USA, China and the Netherlands the feasibility of LNG as a motor fuel has been proved and by way of example, since the launch of LNG-operated trucks in China in 2009, more than 200,000 vehicles with LNG-engines are being operated today. In the USA, LNG prices benefit compared to diesel prices and further support the market growth of LNG. Not only in the Netherlands where together industry and politics are pushing for the introduction of LNG as a general fuel source. Also in Spain, Great Britain and Norway "small-scale" LNG is ready-for-market [3].

HFI-WELDED PIPES

Conventional low-alloyed ferritic-pearlitic line pipe steels are not suitable for the transport of LNG, as the level of adequate fracture toughness is not given at very low medium temperatures. At the same time the use of low temperature high toughness austenitic stainless steel grades is excluded for long distance pipelines because of the extremely high material costs and the restricted amount available.

Salzgitter Mannesmann Line Pipe GmbH (MLP) addressed the situation by searching for an alternative material concept therefore enabling the production of longitudinal welded pipes via the high frequency induction (HFI) welding process. The HFI welding method which disregards the necessity for additional filler material is an established and recognized welding method, even with project requirements on mechanical-technological properties of the pipes becoming more and more demanding. Due to the high welding speed and efficiency of this welding process, and combined with a high geometrical accuracy of diameter and straightness, more than one third of the global annual pipe production of low alloyed steels is longitudinal high frequency electric resistance welded (HF-ERW).

Figure 1 shows a schematic overview of the pipe production process. After chip-removing of the strip edges, continuously forming of the prepared endless strip is performed in two steps, first a cage-roll forming-line, followed by a finpass line. High welding speeds of up to 30 m/min have to be achieved, depending on wall thickness and intended application, as well as welding of higher wall thicknesses of up to 1” (25.4 mm) has to be enabled. In order to cope with the challenge of transmission of high amounts of electrical energy into the strip edges MLP uses the contactless induction welding method with a frequency of above 100 kHz (Figure 2), instead of the conduction technology. A high-frequency electromagnetic field is generated around the induction coil, and induces in the "open pipe" an electric field. This causes a current flow from the inductor along the surface of one strip edge to the welding point and back to the inductor, with the circuit closed on the back of the pipe. The heated edges are forced together by the top rolls, producing a fusion line of around 50-150 µm. Afterwards the internal and external flash is scraped off from the finished weld. Because of the high welding speeds and high cooling rates present in the weld metal and the heat affected zone, martensitic and bainitic microstructures are formed with corresponding mechanical properties. Therefore reheating of the weld and the heat affected zone is necessary in order to improve the mechanical properties. This is carried out by a local inductive heat treatment following the flash removal. The final step is a calibration on a straightening machine, by means of compression rollers, with a reduction of 0.5 to 1.0 % in pipe diameter occurring at this stage. A more detailed description of the process-computer-controlled production route of HFI-welded pipes is given in e.g. [**10**].

At MLP the available HFI-steel grades range up to API 5L – X80M [**11**] and casing up to API 5CT – N80/L80/P110 [**12**], with outside diameters up to 24 “ (610.0 mm) and pipe wall thicknesses up to 1 ” (25.4 mm).

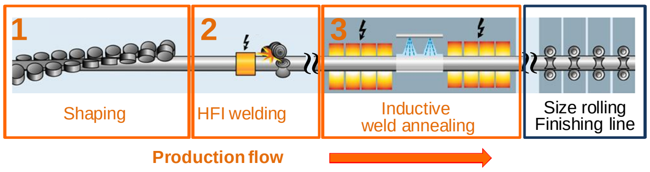

Figure 1: Pipe production via HFI-process (schematic)

PRODUCTION OF LOW-TEMPERATURE PIPES

MLP has developed an optimized grade of hot-rolled strip for the transport of LNG, in close collaboration with its pre-material supplier Salzgitter Mannesmann Flachstahl GmbH. The material fits to the standards ASTM A333 [**13**] and DIN EN 10028-4 [**14**], with a chemistry composition according to X8Ni9 (1.5662) (**Table 1**). This type of 9% Ni steel is already known for the production of heavy-plates for LNG-tanks [see examples **15, 16**] and SAW-pipes for the use as low-temperature transportation pipe [**17**]. The hot wide strip had been produced in dimension 5.0 x 1,410 mm and was afterwards processed into HFI-welded pipes with an outer diameter of 219.1 mm and a wall thickness of 5.0 mm (**Figure 2**). In order to achieve the aimed mechanical-technological properties a quenching and tempering (Q&T) treatment has been carried out (**Figure 3**), consisting of the austenitisation, hardening and tempering steps. After the ferritic-pearlitic structure is transformed into austenite during austenitisation at 930 °C, a hardening is carried out. This is done by cooling down the material quick enough, enabling a time-independent transformation of austenitic grain into martensite. The used grade is a so-called air-hardening material, which means that no accelerated cooling e.g. with water is necessary. This is also beneficial, as it helps to avoid the generation of residual stress during cooling, which may result in a negative influence on geometrical properties. As the hardening process results in a dramatic increase of brittleness, it is followed by a tempering activity of the martensite microstructure at a temperature of 620 °C, followed by air cooling again. This provokes a decrease of strength and an increase of toughness. An example of the tempered martensite/bainite structure is shown in **Figure 4** for the base material and in **Figure 5** for the HFI-weld area.

Table 1: Chemical composition of X8Ni9 acc. to DIN EN 10028-4 (in wt.-%)

C_{max}	Si_{max}	P_{max}	S_{max}
0.10	0.35	0.020	0.005
Mn	Mo_{max}	**Ni**	V_{max}
0.30 – 0.80	0.10	8.5 – 10.0	0.05

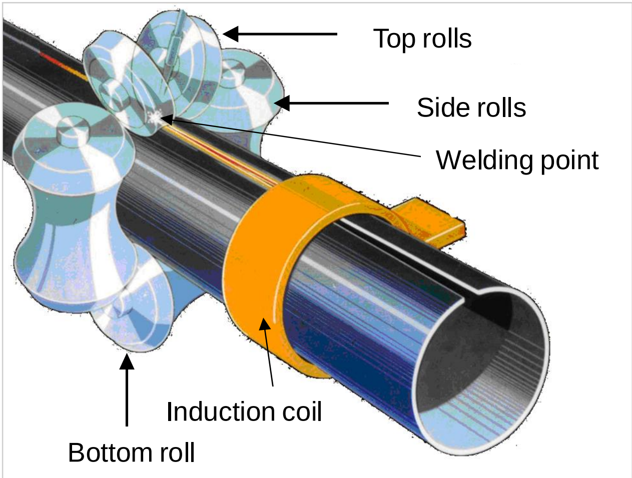

Figure 2: Schematic and real pipe welding via HFI-process

Figure 3: Pipe during full-body annealing

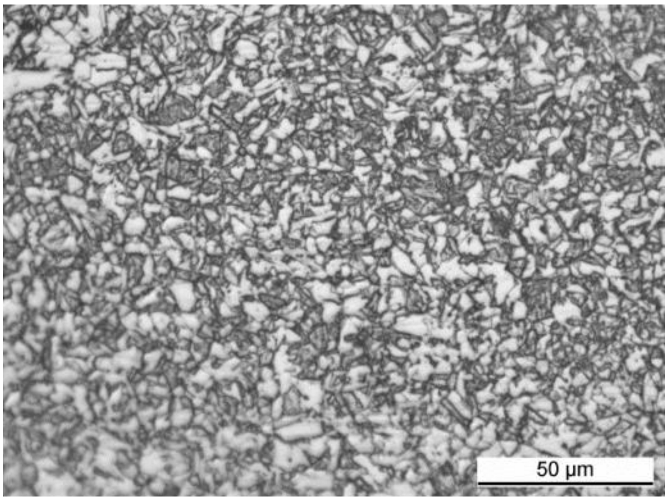

Figure 4: Microstructure of base material after Q&T-process

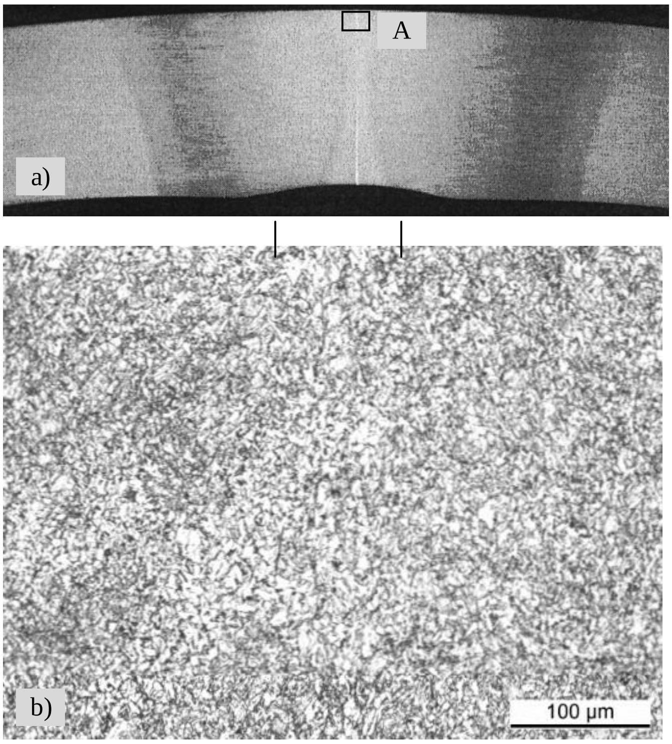

Figure 5: Microstructure of HFI-weld area after Q&T-process with b) as enlargement of position A in a) and marking of fusion line width in b)

After the heat treatment was finished the pipes showed tensile properties which comply well with the specified values (**Table 2**). The Charpy impact energies at -80 °C, -100 °C and -196 °C are shown in **Figure 6**. There is no significant difference between the longitudinal and transverse orientated specimen in the base material. Even at -196 °C the values are well above the specified lower limit of 40 J in the base material. Lower values have been found for the HFI-weld, but in all cases the minimum value has been exceeded.

As all values were found to be in the specified range, the pipes were ready to be used in a prototype project.

Table 2: Tensile properties after Q&T-process (example)

Specimen position	YS in MPa	TS in MPa	A5 in %
specified values	*≥ 490*	*640 – 840*	*≥ 18*
Base material, transverse	574	751	21,8
Base material, longitudinal	603	740	24,2
HFI-weld, transverse		776	

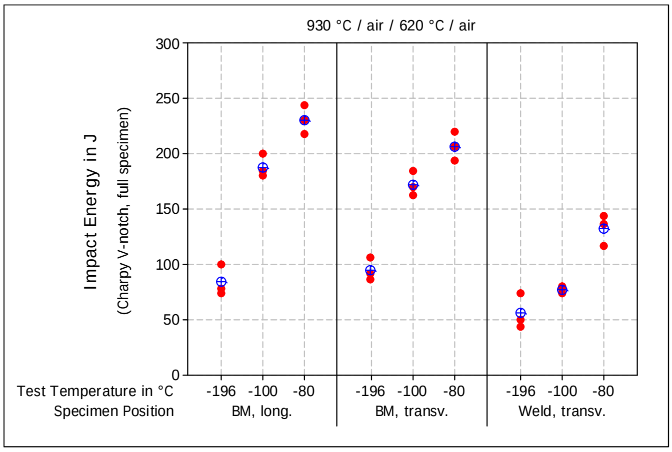

Figure 6: Impact energy after Q&T-processing as a function of test temperature and specimen positioning

SPECIAL MULTI-PIPE SYSTEM FOR THE CONVEYANCE OF LNG

The FW-KAMMER-PIPE is a multi-pipe system developed by the company FW-FERNWÄRME-TECHNIK GmbH for the safe underground conveyance of LNG, raw oil and environmentally hazardous fluids.

A triple pipe system with chamber for the transport of fluids in the cryogenic temperature range shall fulfill the following requirements:

- Avoidance of thermal bridges and little warmth transfer to the fluid
- Passive protection against corrosion at the exterior pipe laying in the soil
- Permanent vacuum (over 30 years) in the chamber
- Cost-saving by use of compounded or uncompounded fine-grain structural steel as exterior pipe

Moreover triple pipe systems offer several advantages in comparison to the standard pipe-in-pipe systems:

- In case of a leak of the inner pipe or a leak of the outer pipe: continuation of operation of the pipeline until repair
- In case of an encasing pipe leakage neither the medium pipe nor their bearing supports get into contact with penetrating water.

- With LNG pipelines a freezing of the ring space due to penetrating humidity can be excluded because of the avoided thermal bridges to the medium pipe.
- Natural compensation of the cold-induced contraction

Research tests about installation, fabrication and functioning of a triple pipe system were carried out in an EFRE-project within the innovation promotion [**18**].

TECHNICAL BASICS OF THE TRIPLE PIPE SYSTEM

The FW-KAMMER-PIPE consists of an inner pipe with continuous insulation, a chamber pipe and an encasing pipe (**Figure 7**). The chamber is operated with permanent vacuum, the inner pipe is insulated with high-quality cold-proof insulation.

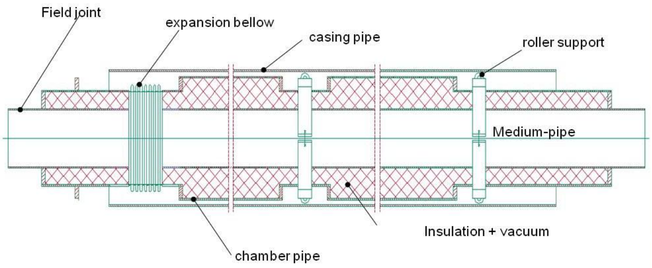

Figure 7: Sketch FW-KAMMER-PIPE

For the inner pipes the material X8Ni9 was used, for the chamber pipe 1.4301/1.4307 and for the encasing pipe P355NL, with an exterior anti-corrosion protection of polyethylene.

Due to the temperature profile occurring during operation and the different materials of inner pipe (temperatures of -196 °C), the chamber pipe (temperatures of -17 °C up to 5 °C) and the encasing pipe (temperatures of -3 °C up to 8 °C) show different linear expansion coefficients (**Figure 8** and **Figure 9**).

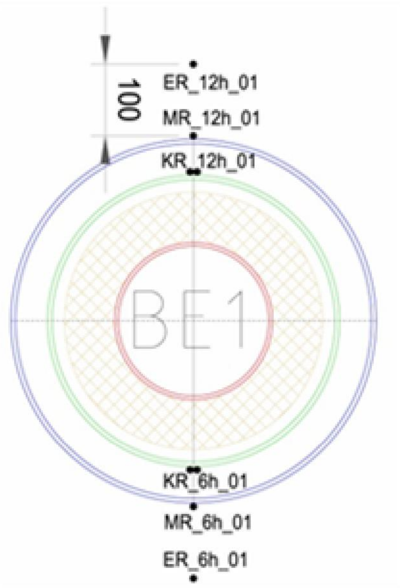

Figure 8: Example position measuring sensor

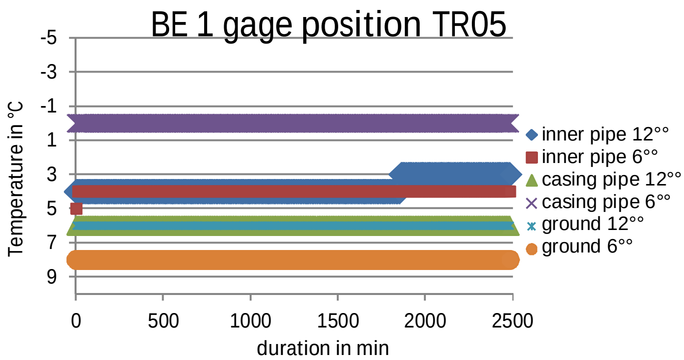

Figure 9: Example temperature progression

If the whole FW-KAMMER-PIPE was fabricated out of one single material, the difference of the contraction during operation between chamber pipe and inner pipe would be very high. This contraction could lead to internal stresses in the pipe material, exceeding the maximum design stress. The advantage of material X8Ni9 is that this material is suitable for the cryogenic temperatures of -196° C, has a higher strength compared to stainless steel and because of its linear expansion coefficient shows a smaller contraction compared to the materials 1.4301 / 1.4307. It is further less cost intensive and can be easier processed in comparison to stainless steel.

RESEARCH PIPELINE TRACK TRIPLE PIPE SYSTEM FOR THE CONVEYANCE OF LNG

The research pipeline track triple pipe system for the conveyance of LNG has a total length of 48.5 m. **Table 3** lists the pipe diameters which were used.

Table 3: Pipe dimensions, pipe data of research pipeline track

	Nominal width	Diameter	Wall thick-ness	Material	Coating
Inner pipe IR	DN 200	219.1 mm	5 mm	X8Ni9	-
Distance pipe DR	DN 300	323.9 mm	5 mm	1.4301	-
Chamber pipe KR	DN 400	406.4 mm	6.3 mm	1.4307	-
Encasing pipe MR	DN 500	508 mm	6.3 mm	P355NL2	PE-N-n
	DN 600	610 mm	8 mm	P355NL2	PE-N-n

The research pipeline track consists of an underground and an above ground area (the latter indoors) of the FW-KAMMER-PIPE pipeline. All the important components used by FW-FERNWAERME-TECHNIK for SIS-pipelines are implemented in the research pipeline as FW-KAMMER-PIPE construction elements. The exact course of the line is shown in the drawing (**Figure 10**). The filling of the pipeline is done via a storage tank which itself is filled via a LN2-tanker semi-truck.

PROJECT IMPLEMENTATION

For the development of the FW-KAMMER-PIPE until readiness for serial production a verification of every fabrication step and operating process is needed. For this reason the research pipeline track was laid on the company premises of FW-FERNWÄRME-TECHNIK GmbH. The research pipeline track consists of prefabricated construction units (**Figure 11**).

After fabrication, drying and shutting off of the construction units, the pipe-laying in the pipe trench was carried out. Via a refilling container the LN2 level in the inner pipe of the research pipeline was kept constant. About 100 Temperature sensors were applied over the whole length of the research pipeline; at the chamber, at the encasing pipe, the soil in the area of the bends, fix points, bearings and the straight part of the pipeline.

The measured temperature values are visualized and saved for evaluation and control of the temperature profile by means of a data measuring reader. In addition to the thermocouples a monitoring cable was installed on the outer casing pipe for recording temperature along the line. Cryogenic temperature tests (with liquid nitrogen T = -196 °C) were carried out at this research pipeline. These tests lasted several weeks.

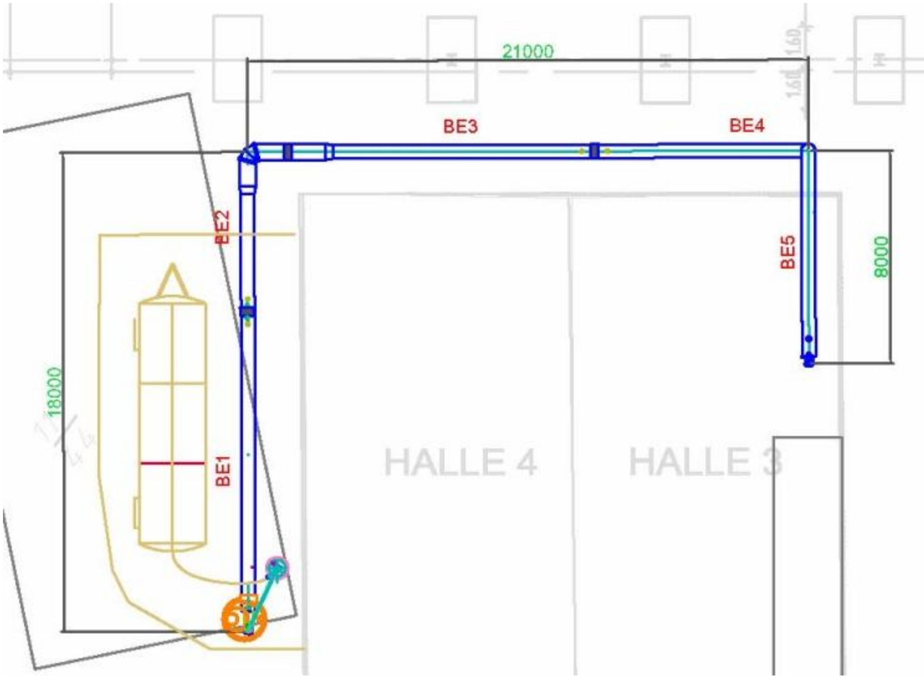

Figure 10: Research pipeline

Figure 11: Fabrication of the construction units

PROJECT RESULT

FW-KAMMER-PIPE as triple pipe system for the conveyance of LNG, oil and environmentally hazardous fluids is ready for production. All the results of the research pipeline show that there is no area where the encasing pipe is exposed to a temperature which would cause pipe deterioration. The leak detection via sensor cable was successful. Even in the case of a leakage, the FW-KAMMER-PIPE could carry on operating. All the construction elements which are used in SIS-pipelines – consisting of guiding bearings, bearing plates, fix points, encasing pipe enlargements, axial compensators and pipe bends – could also be used in the triple pipe system with corresponding modification. Bearings made of industrial plastics for cryogenic engineering will lead to a further improvement of the insulating capacities and therefore to the reduction of heat inputs in the pipeline. The evacuation of the ring spaces of the pipeline reduces the heat inputs additionally. The preferred insulating material would be an Aerogel. The inner pipe material which was employed has lead to an optimization of the expansion receptors and to smaller encasing pipe diameters.

SUMMARY

Salzgitter Mannesmann Line Pipe and its pre-material supplier Salzgitter Mannesmann Flachstahl have developed an optimized grade of hot-rolled strip for the transport of LNG on basis of the material X8Ni9. It was processed into HFI-welded pipes with an outer diameter of 219.1 mm and a wall thickness of 5.0 mm, but all other pipe diameters in the range of MLP (4½″ to 24″) are available. The HFI-process was followed by an adjusted quenching and tempering treatment. The material is characterized by high toughness even at lowest temperatures. At -196 °C values above 80 J in Charpy impact tests were found. At the same time the yield strength lies above 550 MPa in transverse and around 600 MPa in longitudinal direction.

The acceptability of the material MLPX8Ni9 for HFI-welded pipes for low temperature applications was verified by a steel jacket pipe test pipeline. FW-Fernwaerme-Technik in Celle used these X8Ni9 pipes, delivered by MLP, for construction and operation of a triple pipe system, the so-called „FW-KAMMER PIPE“, for the conveyance of LNG. During the tests the pipeline with a length of 48.5 m was cooled down with liquid nitrogen to -196 °C. It was demonstrated, that a substitution of stainless steel pipes by HFI-welded pipes of X8Ni9 is not only possible, but also reasonable with respect to aspects like favourable technical characterristics, availability and costs.

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