Design and Thermal Modelling of LNG Tank Base Heating

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This article describes the different technologies in use for LNG tank base heating, their optimization with the help of accurate thermal modelling using finite element analysis, and the best practice in design and operation to ensure efficient, reliable, and trouble-free heating systems.

Above-ground cylindrical LNG storage tanks have a concrete base or foundation which is either pile-supported or supported directly on the underlying ground. An electrical heating system is provided within the foundation to prevent soil freezing (and the adverse effects of "frost-heave" that could damage the foundation and the tank itself) resulting from the flow of heat from the ground through the base insulation into the LNG tank. The electrical heating elements are usually arranged in an array of parallel conduits in a horizontal plane, as shown in Figure 1.

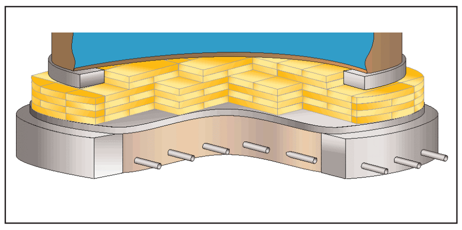


Fig. 1 Section through base of above ground LNG tank showing heating system

The Heat Transfer Model

Early efforts to model the heat flow from the foundation-heated plane upward into the cold or cryogenic fluid were primarily based on one-dimensional heat flow models. The heat distribution between heating conduits was also rather simplistically modeled with the use of a one-dimensional radial heat distribution model.

Clearly, when considering the entire foundation structure, there cannot be a perfect symmetry in the heat flow patterns as would be implied by such models. Due to structural load bearing requirements, the foundation usually has a different insulation arrangement in the outer perimeter (ring wall). There are edge heat losses (or gains, depending on ambient temperatures) to be considered. The internal part of the foundation actually has heat loss (or gain) to the deep soil below as its dominant heat transfer mechanism.

Today with the availability of numerical FEA (Finite Element Analysis) modeling software which can operate on a PC or engineering workstation, the complex heat flow patterns which actually occur in a heated foundation can be simulated by either an approximate two-dimensional FEA model or (preferably) more accurately simulated by a three-dimensional FEA model. The general FEA method involves dividing the foundation structure into a mesh of geometric elements all interconnected. Each of these elements is then computationally defined as to location, dimensional size, and material properties. Once convection boundary conditions at the edges of the exposed concrete ring wall and the heat generation resulting from the regularly spaced heaters are defined, the FEA software/method develops a set of equations for all of the elements which can be solved computationally by elimination techniques.

The use of the FEA modeling technique is of greatest advantage in the design of foundation heating systems due to the presence of non-uniformity (primarily in the ring wall area) in the load bearing insulation that is typically installed in a cryogenic vessel foundation. In addition, the convective heat losses to ambient at the foundation edge and the conduction heat losses to the soil perimeter also contribute to the non-uniformity in heat flow. To illustrate the temperature profile that can occur, a three-dimensional foundation model has been created by Thermon for a typical LNG storage vessel which is being electrically heated. When the heating is placed uniformly across the foundation in

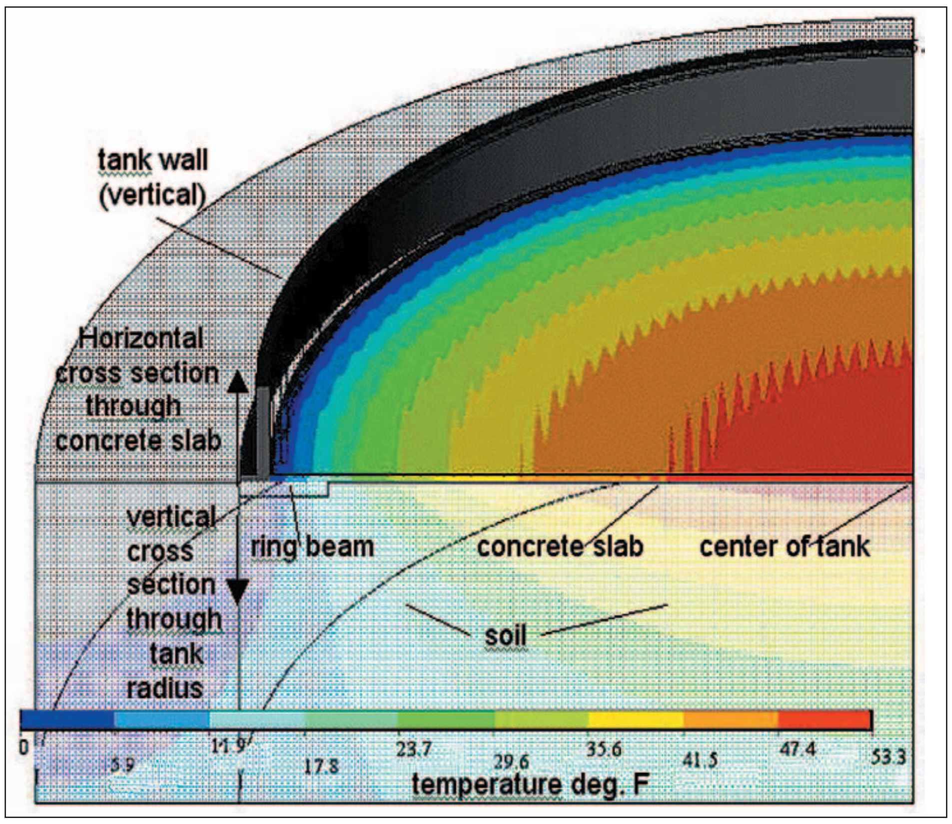


Fig. 2 Thermon three dimensional FEA model - without ring wall heater

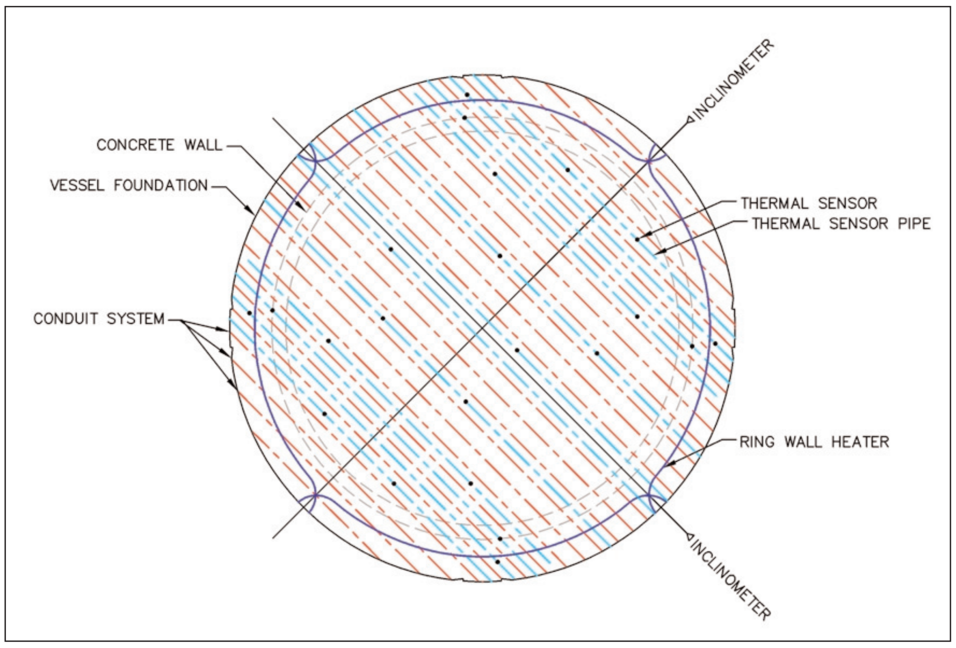


Fig. 3 Typical ring wall heater layout

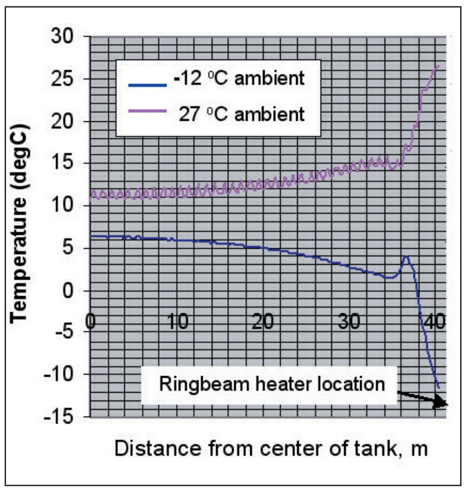


Fig. 4 Thermal profile comparison of operation in two different ambient conditions

conduits on 1 m centers, the results of the FEA modelling show that the temperature distribution is not uniform and varies from center to edge of the tank, as shown in Figure 2, by some 35 °C.

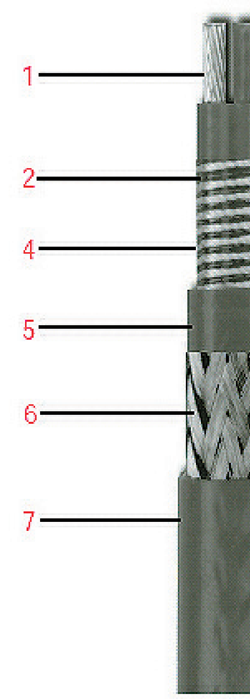
Thus in order to maintain the entire heated plane at above freezing, it is necessary to put additional heater power into the design. In order to correct this, an additional ring wall heater installed as typically shown in Figure 3 should be considered. Repeating the FEA model with the ring wall heater operating yields new, more uniform temperature profiles as shown in Figure 4 for two cases : operation in an outdoor ambient of -12 °C, and with the same loading but at a summertime average ambient of 27 °C.

Different Cable Technologies

In general, two basic categories of heaters have found general acceptance for service in the design of electrically heated planes for foundations. These heaters are generally of the parallel construction. That is, the heater is comprised of a series of heater zones or a continuous matrix connected along a common set of power bus wires. The advantage of this construction is that the power output per unit length of the heater is relatively constant with length within the manufacturer's recommended maximum circuit length guidelines. Thus the design of each individual conduit heater based on its specific length or groupings of a number of heaters as one single series heater is not required. The parallel constructed heaters generally use non-hygroscopic dielectric insulation materials that are ideal where the potential for moisture build-up is evident. In addition, because each conduit heater is independent, providing service to a single conduit without removing adjacent heaters is possible. These parallel-constructed heaters can be further divided into two categories that are generally distinguished by the nature of their power delivery characteristics. The first category is constant wattage type heaters, which deliver a power level that is independent of temperature.

The constant wattage type permits installation without design consideration of power changes with heater operating temperature. That is, there are no cold start-up currents to design around. These heaters can be simply unreeled, cut to length, and terminated at the proper location within the conduits. Because of the zone construction, a non-heated cold lead connection is built-in. When designing a system with this type of heater, the calculation of the maximum operating sheath temperature in the actual operating environment of the application is required to assure expected longevity as well as to assure hazardous area compliances. Because of the nature of frost heave protection operation, only parallel constant wattage heaters that have a thermal cyclic rating should be used. A typical heater of this construction is shown in Figure 5.

The second category of heater is the self-regulating type heater, which is comprised of a continuous, positive temperature-coefficient, resistive polymer matrix connected along a common set of power bus wires. The advantage of this construction is that as the heater temperature increases, the power output reduces to give the self-regulating effect. This feature is especially of interest in situations where the tank may be partially buried and where the heat loss strongly varies with tank depth. Depending on the nature of the resistive polymer matrix material used, various slopes of power turn down are possible. The self-regulating aspect of this heater permits installation without the design consideration of calculating operating and maximum sheath temperatures. It



Construction . . .

1 Copper Bus Wires (3,3 mm²)
2 Nichrome Heating Element
3 Heater Bus Connection (not shown)
4 Fiberglass Overlay
5 Fluoropolymer Dielectric Insulation
6 Tinned Copper Braid
7 Fluoropolymer overjacket provides additional protection to cable and braid

Fig. 5 Typical parallel zone type constant wattage heater

Fig. 6 Typical parallel self regulating heater

has its maximum operating sheath temperature rating for hazardous area installations fixed based on operation under near adiabatic laboratory test conditions. A typical heater of this construction is shown in Figure 6.

Power System Optimization

Factors affecting the power system design in a foundation heating system are as follows:

1. Cold storage or cryogenic temperature
2. Load bearing insulation type(s) and thickness
3. Size or diameter of foundation
4. Type of heating system chosen and the safety or over-design factors implemented
5. Power distribution (zones of heating)
6. Presence of water in the heating conduits
7. Power supply voltage
8. Minimal ambient temperature
9. Inner tank anchoring due to the seismic conditions

LNG is typically stored at temperatures of -164 °C. The heated plane for such a foundation is ideally controlled at temperatures of 5 °C (plus or minus 2 °C.)

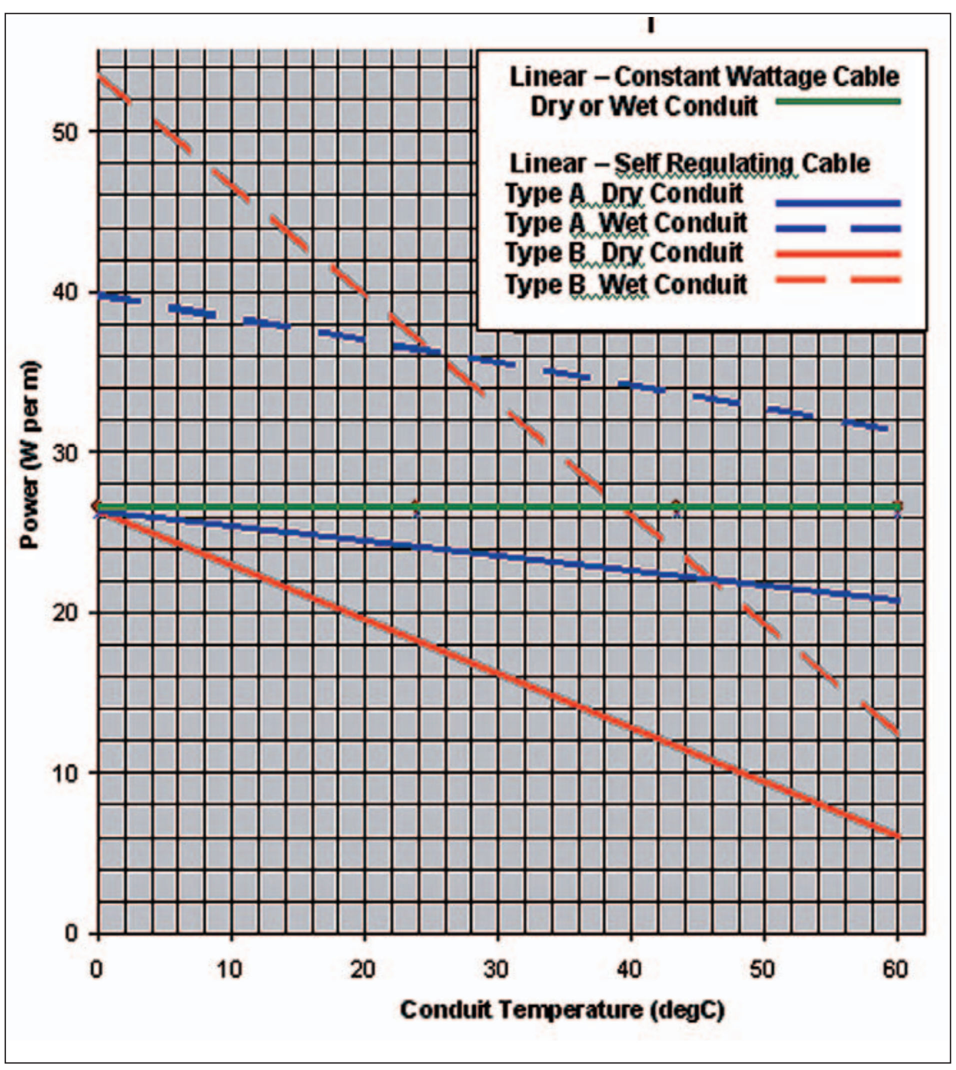
The load bearing insulation layer beneath the tank can be minimized as a design strategy thereby reducing initial installed cost. Design strategies where energy costs over the life of the tank are considered will typically implement more substantial insulation thickness and reduce the heat leakage and thus lower overall power requirement. In either case, the insulation layer must be designed to withstand the structural loading anticipated. In the specific case of an LNG tank, there is usually a higher compressive strength layer of cellular glass in the outer ring wall area and a lower compressive strength layer in the internal region of the foundation. It is important to note that the higher compressive strength insulants are in general more thermally conductive. Insulation thicknesses of 380 mm and higher are typical for an LNG foundation. As an order of magnitude, total power requirements can range up to 100 kW for a tank foundation 80 m in diameter or more. Because of this high power level, the supply voltages normally selected are 230 Vac or higher. Often three phase power with operating voltages such as 380, 400, 415 and 480 Vac are used because of the desire to deliver balanced power from the supply transformers, reduce the current draw and hence the size and cost of the power distribution system.

The very selection of the system operating voltage has an impact on the type of heating system selected. That is, if self-regulating parallel type heaters are to be used, their voltages are generally limited to operation at 277 Vac or lower due to the limitations on the voltage stress field allowed to be generated within the heating element polymer matrix. Constant wattage parallel type heaters, on the other hand, can be used at voltages up to and exceeding 600 Vac since the heating elements are generally metallic and remain largely unaffected by high voltage stress fields. Where three-phase power is used, the power of each conduit should operate on a different phase to minimize the impact of a temporary phase power loss on the overall system operation. Typically, all instrumentation and monitoring equipment is supplied by a separate independent power source. This provides better assurance that independent monitoring information is still available should an upset in the primary heater power occur.

Because of the criticality of operation in foundation heating systems, power levels of at least 40% safety margin and more are usually built in to the electrical design. In addition, more safety margin (above the 40%) is added in to allow for situations where one or more electric heated conduits may need to be temporarily removed from service.

To achieve the desired power control and temperature uniformity, the power control system for the interior region operates based on temperature inputs from resistance temperature detectors (RTD) located at representative points in the heated plane. These sensor points are typically located midway between two conduits in the heated plane. The power in the interior region may be divided into multiple zones each with its own RTD sensor to allow for minor deviations in the foundation structure as well as to allow balancing of the power load on a phase basis, or as a single zone. For large diameter LNG tanks, as many as 18 control zones have been employed. It is important to note that due to the large mass of the foundation, the response time to changes in RTD control settings can be quite long (of the order of days, even weeks). It is therefore sometimes an exercise in patience to fine tune the temperature control settings during start-up.

Fig. 7 Effect of moisture build-up on heater power



The power in the ring wall heater system is monitored by its own RTD which is located to the side of the heater at a distance midway to the distance of the ring wall heater conduit from the outside foundation and just above the primary heated plane (between the crossing conduits). In cases where multiple ring wall heaters may be required, the sensor should be located midway between the two ring wall heating conduits.

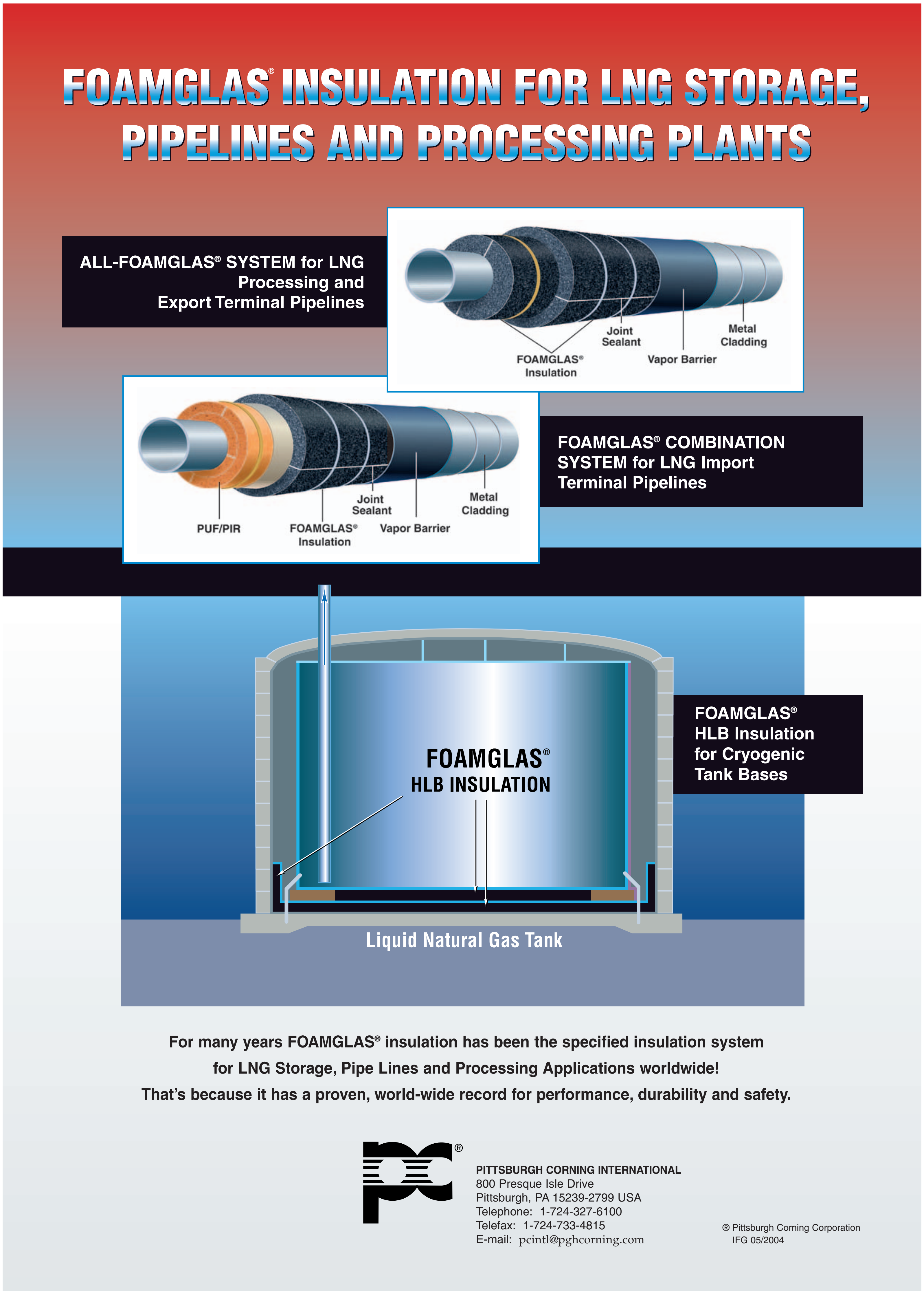
Due to the below ambient temperatures which are usually being maintained in the electric heating plane, condensation build-up within the conduits can occur. In order to minimize the amount of condensation build-up, one control method commonly used utilizes a proportional cycle omission control algorithm, in which the percentage power output typically increases from 60% at 7 °C to 100% at 0 °C.

By the use of the proportional control method in conjunction with zero crossing solid state switching relays, it is possible to maintain a level of heating at all times in the heating conduits (by 50-60 Hz cycle omission). By maintaining heat on at all times, the breathing effect resulting from on-off control and temperature swings - that results in moisture build-up within the conduit system - is minimized.

Where moisture build-up within the conduits does occur, it is important to consider the effect on the heater type being considered for installation. In Figure 7 the effect of water filled conduits on the various types of heaters typically used is shown in comparison to its standard power output in a dry conduit. As can be seen, constant wattage type heater power is relatively unaffected by the moisture build-up. This is to be expected since when a heater operates in a water-filled conduit, its operating temperature drops dramatically. The heating elements used in a constant wattage heater experience minimal resistance change with decreasing temperature. On the other hand, depending on the resistance versus temperature curve for the particular self-regulating heater being considered, the increase in power in a water-filled conduit can be rather substantial. For the steeper self-regulating curve of the Type B cable, the increase in power is a factor of two. From a power system design standpoint, this increase in power must be anticipated in the switchgear sizing procedures.

As the electrical power system in a foundation heating system such as an LNG tank can be located in an electrically classified area, special design provisions must be taken to satisfy the safety requirements as specified by the electrical codes having jurisdiction. For LNG tanks located in areas having a hazardous area classification (typically Class I, Div.2 or Zone 2), the use of explosion proof (Exd) enclosures and/or purged (Type P) enclosures for equipment is generally required. The heating system and all components should conform to the appropriate standards such as IEEE, IEC or CENELEC and should be certified by a nationally recognized testing laboratory for use in the electrically classified area.

It is equally important in any electric power system optimization to build in sufficient operational monitoring capability to allow system operators to fully understand the system during both normal and abnormal operating conditions.



Foundation heating system control and monitoring equipment for LNG tanks can range from multizone dedicated temperature, current, and ground leakage control and monitoring units located near the vessel with RS 485 data highway interlinking to a PC in the control room, or can be controlled directly by connection/operation through the facility DCS system. In whichever system is utilized, provisions are generally made to allow the operator to recognize at minimum the following alarm events:

1. Low temperature alarms
2. Low current alarm within a control zone
3. High current alarms within a control zone
4. High ground leakage current within a control zone
5. Loss of purge pressure within purged panels
6. Loss of communications to the PCS or DCS monitoring equipment
7. Loss of RTD sensor
8. Loss of power/phases
9. Loss of instrument power

The Enviromental Factor

Under the best scenario operating conditions, the performance and reliability of an electrically heated foundation heating system today is such that a service life of twenty years or more can be expected. The actual service life experienced, however, is dependent on how well the system is designed to endure "the environmental factor". This, of course, is first of all how well the system is designed (and the system installation is executed) to combat the presence of moisture resulting from condensation from cold surfaces.

Fig. 8 Tank base under construction

As a separate environmental factor, depending on the specific water table characteristic in the vicinity of the vessel foundation, the foundation can be subjected to fluctuating water table levels over time. The heating plane conduits can thus be subjected to periodic flooding. In extreme cases, the addition of a moisture barrier below the foundation may need to be considered.

As protection against water intrusion and corrosion, in some cases, the additional cost of stainless steel conduits has been justified. Corrosion protection by applying cathodic protection (tying the negative pole to the conduit system) is generally required when using stainless steel conduits. In addition the stainless steel conduits must be isolated with nonmetallic sleeving wherever the conduits necessarily touch the steel reinforcing rod system within the concrete.

To better seal conduit systems from the possibility of water leaking in at conduit joints, the application of joint sealant and a secondary seal of heat shrink sleeving is a common practice. All electrical connections that are within the conduit system are required to have a redundant sealing design to further ensure that moisture does not enter into the heater itself. The grounding braid on the heater (required on all systems to ensure proper operation of the equipment protection devices) shall be corrosion resistant and shall be further covered with an overjacket. The overjacket not only protects the heater as it is pulled into the conduit but also forms a secondary moisture protection layer for the heater. Likewise, all temperature sensors must be suitable for use in, under the extreme case, continuous water immersion conditions.

Today's Best Practice

Based on the teachings of past experience in design of LNG foundation heating systems, the following are key ingredients in a successful LNG foundation heating system installation.

- The design of a foundation heating system for an LNG tank (though simple in concept) requires a great deal of attention to detail in the design phase. Optimizing the functionality of the system should be the primary objective if system longevity is to be achieved.
- When the foundation heating system is properly designed using three-dimensional FEA analysis, the addition of a ring wall heater zone in addition to the standard uniformly spaced conduit system will result in the most uniform temperature profile within the heated plane. Energy savings of up to 20% or even more can be achieved due to reduced refrigeration capacity requirements by adding the ring-wall heating zone.
- The designer and owner should in the very early design stages establish clear

specifications for interrogation and monitoring of the heating system's performance to ensure that operators have a clear picture of the performance especially during possible abnormal operating condition scenarios.

- The high thermal inertia in the foundation mass makes fine tuning of the temperature control in a foundation heating system a process spanning weeks of observation. Patience is required.
- The power system should be designed with sufficient design margin to compensate for the removal of a specified number of conduits from service without allowing localized freezing to occur.
- The effects of water entry into the conduit system must be anticipated and proper design allowances taken to ensure continued operation in such cases.

Conclusion

The value in the use of state-of the art three-dimensional FEA analysis to optimize the thermal design of foundation heating systems has been demonstrated. Likewise, the power system can be optimized through the use of best practice as has been described. Implementation of the optimization techniques presented here can result in improved operational performance, reduced energy cost, and enhanced system reliability for owners and operators of LNG and other cryogenic vessel storage facilities. ■

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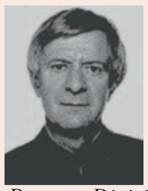

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