Heating Systems for Gravity Based Offshore LNG Tank Concrete Structures

Donald S. Hoy, P.E.
Waldemar S. Nelson
2 Northpoint Drive
Houston, Texas
USA
don.hoy@wsnelson.com
713 270-2807

Franco Chakkalakal
Tyco Thermal Controls
7433 Harwin Drive
Houston, Texas
USA
fchakkalakal@tycothermal.com
713 865-9844

Jim Beres
Tyco Thermal Controls
2415 Bay Road
Redwood City, California
USA
jberes@tycothermal.com
650 474-7330

ABSTRACT -The Increased focus on LNG as a vital part of the energy equation around the world has resulted in the development of new concepts for the export, reception, storage, and vaporization of LNG. The offshore located Gravity Based Structures significantly differ from historical methods of cryogenic gas storages, and therefore the heating systems have to be carefully evaluated and selected as its purpose and design differs from that of traditional land-based cryogenic tank base heating systems. This paper offers a brief review of design fundamentals and will refer to the latest tools in design such as 3D finite element analysis and other such analytical tools. The paper will also offer insights into the application of skin effect heat management systems for heating the offshore Gravity Based Structures. The introduction of cutting-edge technologies in temperature control and monitoring will also be introduced as a means of delivering optimum heating to the LNG tanks located on these structures.

Index of Terms – Gravity Based Structure, LNG, Skin Effect Heating, Finite Element Analysis (FEA), optical fiber temperature sensing, coiled tubing.

I. INTRODUCTION

Natural gas has emerged as a vital player and key component of energy supplies for many nations. After the pipeline transmission of gas, LNG is the next most widely used transportation method for supplying gas, especially for transmission distances over 2000 miles. The growth of LNG is fuelled by the demand for natural gas as a fuel source for electric power generation. The natural gas driven turbines/ combined cycle power plants are reliable, safe and environmentally much more preferable to coal or oil fired power plants. In addition, the cost of LNG production has dropped significantly in the last decade, which makes it even more attractive to both producers and consumers.

However, the main stumbling block to a spontaneous growth of LNG is the negative attitude of many local communities' local governments towards new energy infrastructure. The public pressure, environmental concerns and permitting delays for onshore LNG receiving terminals have been a major source of concern for many companies. The emergence of Gravity Based Structures (GBS) which were pioneered by major players in the offshore oil and gas industry, as a viable substitute for onshore LNG receiving terminals, has accelerated the pace of offshore LNG receiving terminals. The GBS are located several kilometers away from shore, allowing tremendous flexibility to overcome public concerns.

II. OFFSHORE LNG TERMINAL CONCEPT

These structures offer an integrated offshore solution to the import, storage and re-gasification of LNG. There is a proven history of concrete-based oil and gas production structures in the harsh environment of locations such as the North Sea and the Gulf of Mexico and the success of these offshore structures has greatly contributed to the design and engineering of offshore LNG structures such as Gravity based Structures.

The offshore gravity based LNG structures feature; a jetty to off-load LNG into the storage tanks, large LNG storage tanks contained inside the sturdy concrete structure, re-gasification facilities and an efficient transfer of natural gas into the onshore distribution pipeline network. These structures employ proven technologies of the oil and gas industries into an integrated unified offshore LNG terminal. These structures incorporate cryogenic storage technologies successfully employed by LNG carriers for many decades; proven methods for onshore LNG vaporization, commonly accepted electric power generation, state of the art control and monitoring systems and state of the art communication networks.

III. GBS STRUCTURE HEATING

The GBS based LNG tank structure heating system is provided to prevent frost in the concrete base slab and walls. Heating will be provided by means of heating elements embedded in the concrete walls and concrete base slab. These heating elements will be placed inside an embedded ducting system or embedded heat tubes within the tank compartment base slab and walls. The temperature of the slab/walls will be monitored and controlled by suitable control panels by means of either an on/off system or proportional control. The heating elements shall be rugged to allow pulling long lengths (often close to 200 meters between pull points). In addition, the heating system shall be designed to have 100% redundancy, allowing the system to prevent the slab/wall from falling below a pre-set temperature limit even when there is no heat input from an adjacent conduit or heat tube.

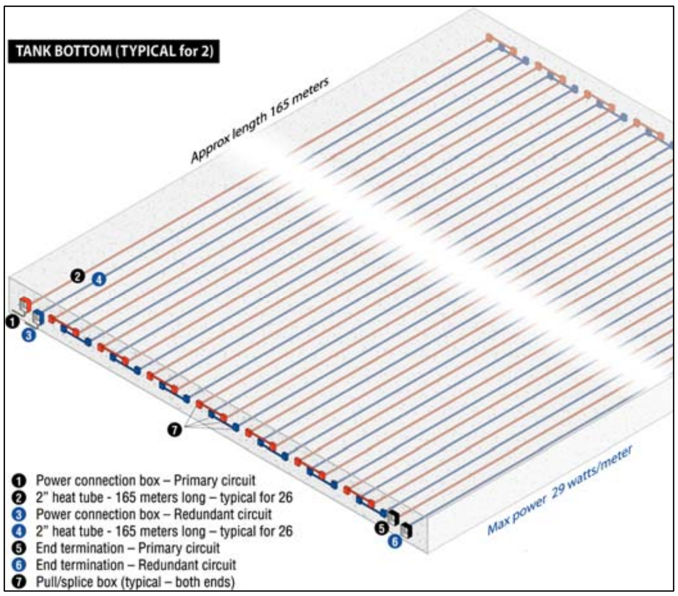

Figure 1 Cross Section of Concrete Base Slab with Embedded Heat Tubes

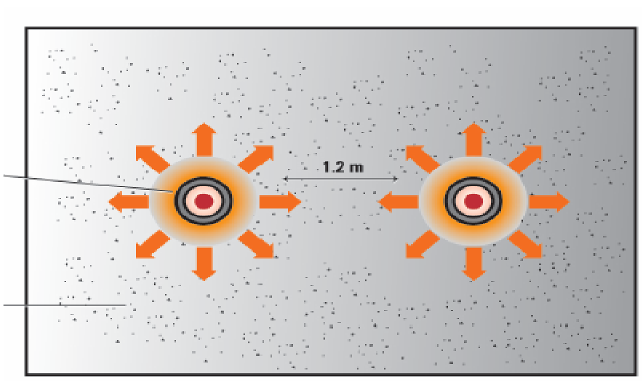

Figure 2 Cross Section of Concrete Slab with Embedded Heat Tubes

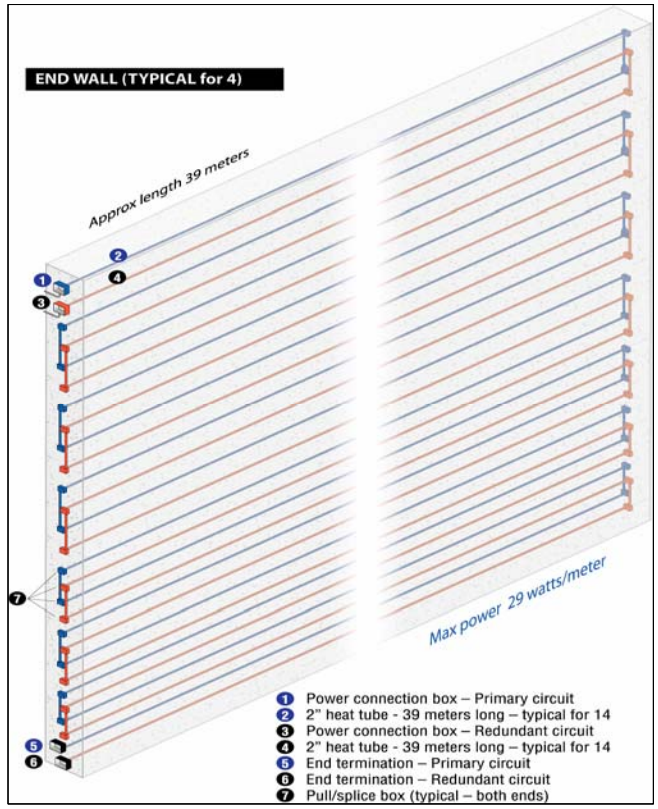

Figure 3 Cross Section of Wall with Embedded Heat Tubes

LNG is stored at -165ºC in metallic tanks with several tank fabrication methods. These tanks are enclosed within the concrete structure. Various configurations of load bearing thermal insulation are provided to prevent migration of cryogenic temperature reaching the concrete slabs and walls. However, it is not practical or cost effective to keep these concrete structures from freezing by the use of thermal insulation alone. The desired methodology is to use embedded heating elements in these concrete slabs and walls to keep these structures above freezing point. As these tank structures are relatively large, in some cases close to 200 meters long, 30 meters high to 50 meters wide, any fluid heating system is considered impractical and expensive. The heating systems are provided for the bottom and all four walls. In general, the roof structure is not provided with heating due to air gap above the tank being very large and capable of containing a perlite fill material which acts as an insulator. The purpose of heating applications could be categorized into three major categories.

a) Base Slab Heating: The LNG tank in most cases will be supported by load bearing insulation. These insulation systems will consist of material with varying densities and thermal conductivity characteristics. However, it is safe to predict that there is sizable heat loss from the storage tank to the base slab. The base slab has to be kept above freezing to prevent structural damages to the concrete structure. The heating elements are embedded in the concrete base slab to keep the slab temperature above $0^{o}C$.

b) Wall heating: Depending on the type of concrete structure and technology adopted, the concrete structural walls surrounding the tank may be exposed to the effect of cryogenic temperature stored in the tank. Outside ambient conditions could also play a role in the temperature gradient on these walls. Even though there will be thermal insulation applied between that tank and the concrete structural walls, these walls could be exposed to the low temperature and in some cases the possibility of frost heaving. Thus, in most cases, these walls need to be heated. The heating elements are embedded in these walls. In most instances, the heating duty in the walls will be somewhat lower than the heat required in the base slab. In addition, the heating requirements could be different for the portion of the wall in the submerged portion of the structure compared to the portion above the water level and exposed to ambient conditions.

IV. DESIGN CONSIDERATIONS

Preliminary power requirements for the heating system may be determined through simple one-dimensional heat loss calculations.

TWO DIMENSIONAL FINITE DIFFERENCE MODEL

Various engineering analysis programs are available to calculate the two dimensional temperature distribution in a heated slab. The model used for calculating the heat loss is based on a commonly used engineering software program[1] and consists of a nodal grid arrangement, constructed from one or more material layers. The grid represents a cross-sectional view of the material layers. The total depth (or vertical dimension for the base slab and horizontal dimension for the walls) of the model is the combined thickness of the layers, and the width is one-half the heater spacing. The heat tracing is represented by any single node on the left side of the model, with the exception of the nodes located on the top or bottom surface, and is oriented normal to the page. The uppermost surface is considered to be at zero depth, and depth is positive in the downward direction.

The grid is generated by dividing each material layer into smaller subdivisions in both the vertical (delta y) and horizontal (delta x) directions. The horizontal position is described by an x-coordinate and the vertical by a y-coordinate. Each node represents a small volume of material. The smaller the volume represented by each node (or the greater the number of nodes) the more continuous the final temperature solution will be. Algebraic equations are solved to describe the inflow, outflow, heat generation, and stored thermal energy at each node, which is known as a heat balance. The solution of these equations enables the temperatures to be determined.

Boundary conditions are used to impose thermal constraints on both the top and bottom surfaces of the model. The boundary conditions for the top and bottom of the model may be specified independently based on the application requirements.

For a detailed description of the software program and its features, please refer to the reference section of this paper.

FINITE ELEMENT ANALYSIS

A more accurate approach to profile temperatures and predict heat input requirements under a tank is Finite Element modeling of the foundation. The analysis is based on creating a system of design elements on the geometry that is being studied. Each design element has a finite set of equations that describes that portion of the geometry. Two and three dimensional studies may be created. A typical Finite Element Analysis software program[2] was used to calculate and create sample plots for this paper. Figure 4 gives a sample two dimensional contour plot for the LNG tank structure on the GBS structure (thermal profile of concrete base slab and walls where heat is introduced).

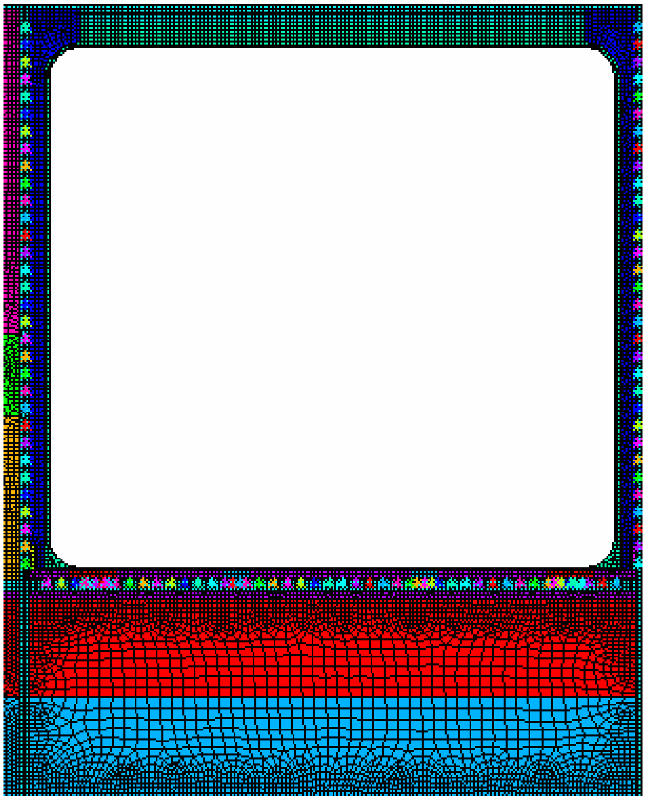

Figure 4. Two Dimensional Meshed Model

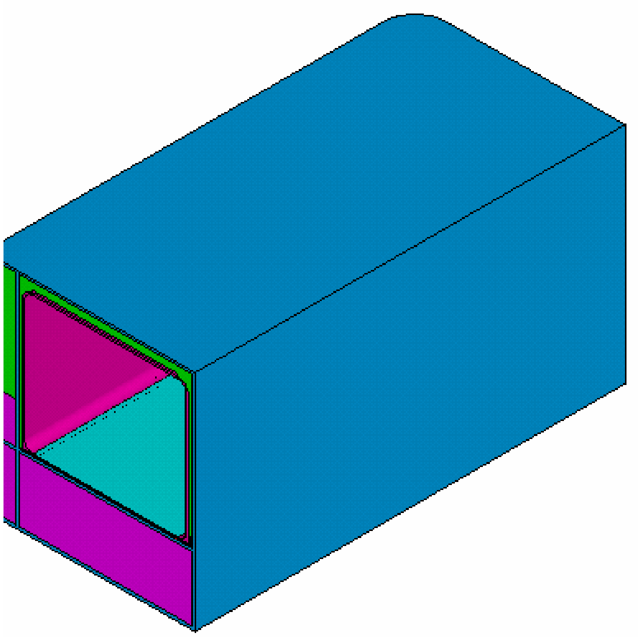

Figure 5 Three Dimensional FEA Model of Rectangular LNG Tank

A three dimensional model study of the tank is required to address the thermal performance of the entire heating system. A sample of a three dimensional model for a tank base slab and walls is found in Figure 5. An optimized heat management design shall take into consideration the variations in the thermal profile of the base slab and walls and account for additional heat requirements at the base slab.

V. HEATING SYSTEM OPTIONS

Present embedded heating systems are generally based on generating heat from heating cable placed in a conduit. The following types of heaters have been used for embedded heat applications:

1. MI Cable
2. Constant Watt Zone heaters
3. Variable wattage self regulating heaters
4. Skin Effect heat management system

MI CABLE BASED HEATING SYSTEM

Mineral Insulated type heating cables are placed inside the electrical conduits to produce heat. Generally, 1" conduits are installed in concrete and brought out to the outside concrete slabs. The conduits are terminated inside junction boxes. These junction boxes will be used for power connection and end termination of the heating cables. RTD temperature sensors are placed in separate dedicated conduits and these sensors are located inside the conduit and located at selected locations for control of the heating system. The electrical power will be connected to the MI cable circuits by running power wiring routed from the power/control panel located in a safe area.

Even though MI cable has been used for heat tracing application for a long time, its advantages tend to be more in favor of high temperature application. As the freeze protection applications require operating sheath temperature to be a minimum, MI cable is not ideally suited for this application. In addition, MI cable uses MgO_2 as its dielectric insulation and the cable will fail if there is moisture migration. Embedded heating systems use electrical conduits and these conduits are known to have moisture. The installation of MI cable with metallic sheath inside 1" conduits could be cumbersome and its lack of flexibility during the pulling process could result in sheath damage and eventual cable failure.

CONSTANT WATT ZONE CABLE BASED HEATING SYSTEM

Another option is to use a constant output zone type heating cable to produce heat. The heating element is installed in conduits installed in concrete and brought out to the outside. The conduits are terminated inside junction boxes. These junction boxes are used for power connection and end termination of the heating cables. As in the case of MI cable, RTD sensors are placed at various parts the concrete structe, inside the conduits. The electrical power will be connected to the constant watt heating cable in each power connection box located at the end of conduits.

The constant watt zone type heating cable offers some advantages as a heating element for this application. It can be cut to length as it is a parallel type heater and it is flexible and easy to install compared to the MI cable. These heaters are capable of connecting to 480V power supply thus reducing the cost of power distribution. It has a reasonably long circuit length (up to 250 meters).

The limitations of constant watt zone type heaters include the large number of circuits. These circuits require power connection and end termination connections, which in itself increases the possibility of circuit failure. In addition, the heating element, generally thin Nichrome wires are wound between power bus wires, and could break due to thermal cycling and other thermal conditions. The contact points between the Nichrome wire and the bus wire is the weak link of this type of heating cable by “contact separation”, potentially resulting in multiple zones without heat. It is also noted that these zone failures are hard to detect once installed inside the embedded applications. It has been proven that these cables will operate at a higher sheath temperature, resulting in shorter service life. The power distribution cost will be substantial due to the large number of circuits.

SELF REGULATING CABLE BASED HEATING SYSTEM

Another option is to use self regulating type heating cable to produce heat. The heating element is installed in conduits installed in concrete. The conduits are terminated inside junction boxes. These junction boxes are used for power connection and end termination of the heating cable circuits. As in previous cases, RTD temperature sensors are placed in separate dedicated conduits and these sensors are located inside the conduit and located at various parts of the tank foundation. The electrical power is connected to the self regulating heating cable circuits in each junction box.

The self regulating type heating cable offers several advantages over other heating cable based systems. The self regulating type heating cable is a parallel type cable that can be cut to length in the field. This feature allows the system design to be simpler and more “field-friendly”. The self regulating characteristics of the cable allows automatic self regulation of power output from the cable in the event there is variance in the calculated heat loss and temperature of the concrete slab. The cable also allows localized automatic power output variations to compensate for the differential heat loss. The self regulating heating cable has unconditional T-rating.

The limitations of self regulating type heaters for embedded heat applications include the large number of circuits. These circuits require power connection and end termination connections, and in the case of the zone heating option, increases the possibility of circuit failure. The maximum voltage for the self regulating cable is limited to 277V. Self regulating cable exhibits a higher in-rush current compared to the constant watt type heaters. As in the case of other heating cable based systems, the self regulating cable based system also has high electrical power distribution cost. As in the case with constant wattage systems, operation of this type system also results in excessive voltage drop.

SKIN EFFECT BASED HEAT MANAGEMENT SYSTEM

The latest innovation in embedded heating application is the use of skin effect based heat management system. The skin effect heating system includes a ferromagnetic heat tube embedded in concrete instead of the conduits embedded in the concrete structure (i.e. slab/walls). A specially manufactured skin effect wire is used to deliver electrical energy to the system. Power connection and end termination boxes are installed on the outside of the concrete structure.

VI. SKIN EFFECT SYSTEM FUNDAMENTALS

Skin effect heating is a series circuit electrical heating technology based on two well-established phenomena in electrical theory, namely, “skin effect” and “proximity effect”. The current density in a conductor carrying alternating current is not uniform over the cross section of the conductor, but rather is greater near the surface, thereby displaying a phenomenon known as “skin effect”. The effective current carrying cross section of the conductor is therefore reduced and thus its effective resistance is increased. Skin Effect in a conductor is brought about by the self-induced electromotive force set up by the variations in the internal flux in a conductor and has a greater effect at higher frequencies of the alternating current source.

The heat is generated on the inner surface of a ferromagnetic heat tube by I^2R losses of the return current flaw, and by hysteresis and eddy currents induced by the alternating magnetic field around the insulated conductor. Additionally, a small amount of heat is produced by the I^2R loss in the insulated conductor. The thermally rated, electronically insulated wire is installed inside the heat tube and connected between the heat tube and insulated wire. The induction interaction between the current in the insulated conductor and the return current in the heat tube causes the current in the heat tube to concentrate on the inner surface of the heat tube. The outside surface of the heat tube is at ground potential, while the inner surface of the tube carries full current since the voltage is applied to the inside of the heat tube. For more details refer to IEEE 844-2000, IEEE Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels[6].

Figure 6 graphically depicts an example of a skin effect system configuration for embedded heat management applications. Power is supplied from an AC power distribution system to a specialized transformer which converts the primary voltage to the required skin effect system voltage. Secondary power is fed through the skin effect panel to the embedded heat tube and conductor. Heat is dispersed into the concrete slab by means of conduction from the heat tube.

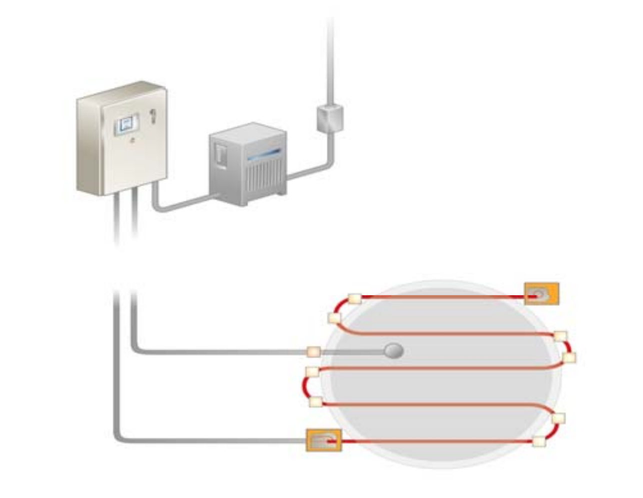
Skin Effect System Configuration

Figure 6. Concrete Slab with Skin Effect Heating

ADVANTAGES OF SKIN EFFECT HEATING FOR SLAB AND WALL HEATING

The skin effect system in its basic form will have only one circuit, with a 100% redundant design requiring two circuits. Each skin effect system is custom designed for each application, eliminating the possibility of delivering excessive heat to the concrete slab. It also allows optimal spacing of heating element under the tank. The Skin Effect system by virtue of the fact that most of the heat generated in the tube itself, is inherently a more efficient heat management system compared to the systems based on conventional heating cables. The skin effect wire operates at temperatures far below the heating cable for the same power output, hence, enhancing the life expectancy of the system. In addition, a “project specific design” for each skin effect heat management system allows the user to select the most desirable design for the application. Skin effect systems offer tank fabricators great flexibility in the selection of thermal insulation material and thickness. A skin effect based system also offers flexibility in the type of control systems to be used. A simple closed loop control scheme or a highly sophisticated distributed temperature monitoring / control system can be incorporated into the design. The skin effect based system easily accommodates higher degree of redundancy, if the customer desires a high degree of reliability for their tanks and vessels.

VII. COMPARISON OF ELECTRICAL SYSTEMS

A broad comparison of electrical power distribution systems for conventional heating cable based system and a skin effect based heating system is given in figure 7 and figure 8. For the purpose of this paper, assume a test case in which there are two LNG tanks in a GBS structure that require heating for its base and walls. Further, it is assumed that for each tank structure a minimum of 100 parallel runs of heating circuits are required. Thus the total number of heating segments for two tank structures will be 200. In the case of constant wattage and self regulating type heating system, conventional heating cable based systems will have 200 individual circuits. Figure 7 shows a simplified schematic diagram of the electrical power distribution system for conventional heating cable system. Figure 8 represents an electrical distribution system for the skin effect heat management system. When a skin effect heat management system is chosen, a comparison of these two schematics show significant reduction in power distribution equipment. Not only is there a drastic reduction in power distribution equipment cost, there is a significant cost advantage in the power cabling also. As GBS structures are designed to accommodate large LNG storage tanks, the number of circuits could be considerably higher than the figures indicated in this example.

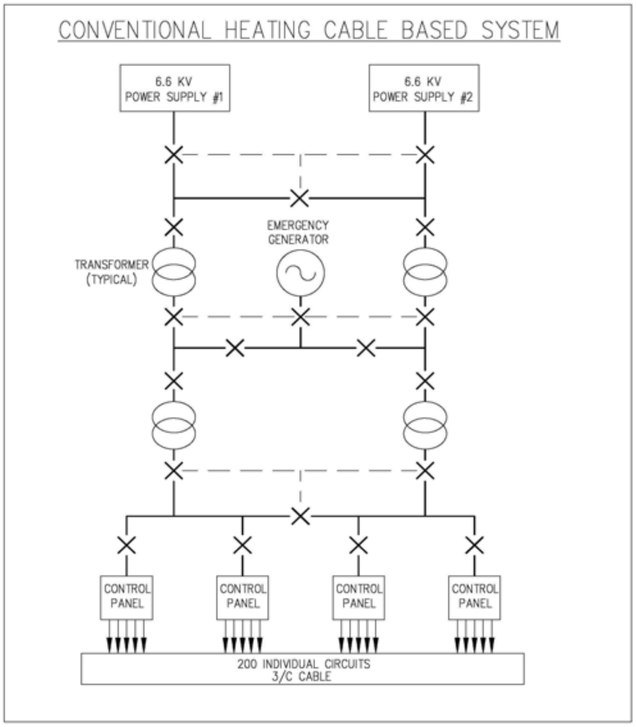

Figure 7 Electrical Schematic for Conventional Heating Cables

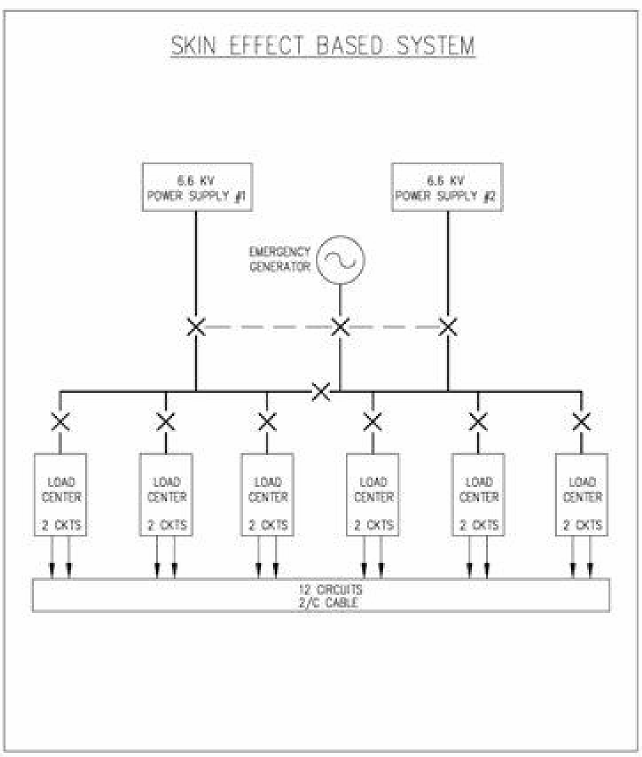

Figure 8 Electrical Schematic for Skin Effect Based System

In addition, the reduction in power distribution equipment will save valuable space on the GBS structure. In addition, a significant savings in power wiring will result in substantial reduction in the quantity and size of cable trays, allowing further space optimization and subsequent reduction in the cost of the GBS structure itself.

VIII. CONTROL AND MONITORING

The power control system of a heating system for GBS LNG tank structure requires a closed loop temperature control where the concrete temperature is continuously monitored and compared to the reference set point temperature. Each circuit will have to be monitored and controlled individually. As the concrete cools below the set point, the electrical tracing system is energized and the heat energy is replaced. Application of power to the heating circuit is done by means of a contactor or circuit breaker. A sophisticated PLC based control systems and DCS based centralized control systems can be easily incorporated, if desired.

Automatic maintain mode: in this case, the averages of temperature sensor readings are used to switch the tracing on or off in order to maintain a preset concrete temperature. Depending on the control system philosophy, multiple circuits are combined in a conventional heating cable based system. For skin effect systems, each circuit can be individually controlled from dedicated temperature sensors.

Manual On-Off mode: a remote input is used to manually switch the tracing on or off. This mode should only be used in conjunction with the high limit mode below.

High limit mode: high temperature alarm settings will be used to switch the tracing off in the event the temperature sensors detect high temperature. This mode is provided principally to protect against damage to the heater elements resulting from excessively high temperatures.

Proportional control mode: In the event the design calls for minimum heat input at all times, an optional proportional control system is incorporated in the control system design. The basic scheme is to cycle the heat input between two set output levels, thus preventing any conditions that may result in the heating elements being switched off under normal conditions.

In addition to the conventional control system used in the past, this paper advocates the implementation of technologically advanced optical fiber technology to monitor and control GBS LNG tank concrete structures.

IX. FIBER OPTIC TEMPERATURE SENSORS FOR GBS LNG TANK HEATING SYSTEMS

Distributed fiber optic sensors contribute significant intelligence to understand the thermal profile of the tank concrete structures. These sensors are placed inside the concrete slab/walls and the placement of the optical fiber is dictated by the nature of data required by the user. A typical system consists of a sensing cable with both ends connected to the interrogation system. The interrogation system can be totally self-referenced allowing periodic measurements without any preliminary calibration. Typical special resolution is 1 meter.

Alternatively, a single fiber end configuration can also be used for this application. The sensing cable is housed in a protective housing. The housing not only protects the optical fiber but also assures that the fiber stays strain free over the complete temperature range. The interrogation system can be totally self-referenced allowing periodic measurements without any preliminary calibration. Typical temperature sensitivity is 1°C and sensing distance can be up to 25 km.

X. CONCLUSIONS

The Gravity Based LNG tank structures need heat input in the tank base and concrete walls surrounding the tank to prevent frost heave and insure structural integrity. The amount of heating elements used for frost heave prevention in GBS LNG tank structures are considerably higher than typical land-based LNG tanks. The use of conventional heating cable inside conduit for GBS LNG tank structure application is not an ideal solution. The introduction of a skin effect heat management system is a significant advancement in the search for an optimum solution. The use of optical fiber based temperature sensing technology offers greater insight into the thermal profile of the concrete structures. The combination of skin effect heat management and fiber optic temperature sensing and control systems offers a significant advancement in the application of heat in GBS based LNG tank concrete structures.

XI REFERENCES

1. “Slabheat” a Software program developed by Tyco Thermal Controls.
2. “ANSYS Inc.”- Engineering simulation software supplier.
3. “Gravity Based Structure(GBS)”-Pioneered by Aker Kvaerner, Oslo, Norway
4. P.C. Wait, K De SOUZA, and T.P. Newson: A Theoretical Comparison of spontaneous Raman and Brillouin based fibre optic distributed temperature sensors. Optics Communications 144(1997) 17-33
5. Luc Thevenaz, Marc Nikles, Alexandre Fellay, Massimo Facchini, and Philippe A. Robert: Applications of distributed Brillouin fiber sensing. Proceedings of SPIE -- Volume 3407, International Conference on Applied Optical Metrology, Pramod K. Rastogi, Ferenc Gyimesi, Editors, September 1998, pp. 374-381.
6. IEEE 844-2000, IEEE Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels.

XII. VITA

Donald S. Hoy, P.E. received a BSEE in 1973 from Lehigh University and is a licensed professional electrical engineer in the state of Texas. He is employed by Waldemar S. Nelson and Company, Inc. in the Houston office. He has taken the lead electrical role in numerous engineering projects for many of the world’s leading petroleum companies and independent power producers in the United States, Dominican Republic, Saudi Arabia, Venezuela, Alaska, Norway, Virgin Islands and Malaysia.

Franco Chakkalakal received a BS degree in EE from Kerala University, India, a MS degree in EE from St. Louis University, St. Louis, MO and a MBA from DePaul University, Chicago, IL.

Franco joined Chicago Bridge and Iron Company in 1972. Prior to joining Tyco Thermal Controls in 2001 as Global Product Manager for Skin effect heating technologies, he held several management positions in heat tracing industry, including the position of Chairman and Managing Director of a large heat-tracing operation in India, and Vice President of Engineering for another heat-tracing manufacturer based in the United States, responsible for Project, Product and System Engineering involving multinational projects.

Franco was a member of IEEE 844 working group that developed the industry standards for skin effect systems. He is a member of IEEE and ISA.

Jim Beres (M’73) received a BS in Electrical Engineering in 1974 from Carnegie Mellon University, Pittsburgh, Pennsylvania. He received a MS in Electrical Engineering and an MBA from Carnegie Mellon in 1978.

In 1974 he began his work in industrial automation and artificial intelligence at Westinghouse Research in

Pittsburgh, Pennsylvania. After various positions at Rockwell International and Chevron, he joined the Chemelex Division of Raychem Corporation in 1980. He has held various Technical and Marketing positions in both Raychem and Raynet, its former fiber optic telecommunication subsidiary. For the past 10 years, he was actively involved in the development of various heating technologies, sensing and instrumentation systems. Mr. Beres is presently the Vice President of Business Development at Tyco Thermal Controls in Redwood City, California. He is a member of IEEE and ISA.