Skin Effect Heat Management Systems and Optical Fiber Technology – A Quantum Leap in Reliability and Efficiency of Frost Heave Prevention Systems

Franco Chakkalakal, *Member, IEEE,* Johan Vlekken, and Benjamin Primm

***Abstract*--The subject of frost heave formation under cryogenic tanks and vessels is well documented and investigated in a number of technical papers and literature. It has been established that the introduction of some form of heat to the tank foundation substrate is a basic requirement to prevent frost heave formation. With this knowledge, this paper will focus on various methodologies to deliver optimum heat, to evaluate the use of the latest technologies and to describe design methodologies toward the goal of enhancing the reliability and efficiency of a Frost Heave Prevention (FHP) system for cryogenic tanks and vessels. This paper offers a brief review of design fundamentals and existing practices commonly used for the selection of products and will discuss the latest tools in design such as 3D Finite Element Analysis (FEA). The paper also offers insight into the application of Skin Effect heating, and optical fiber based temperature monitoring technology for frost heave prevention. Various design philosophies in developing an optimum frost heave prevention system are also addressed.**

***Index Terms*-- Coiled tubing, Finite Element Analysis (FEA), Frost heave prevention, optical fiber temperature sensing, Skin Effect heating.**

I. INTRODUCTION

Safety, reliability and accuracy of design methodologies for frost heave prevention systems are major concerns for the owners and operators of cryogenic storage tanks and vessels. The thermal characteristics of the soil and sand fill, and other thermodynamic conditions of the tank bottom could pose overheating and/or under heating leading to tank failures and safety concerns.

The use of a conventional trace heater (heating cable) has often resulted in unpredictable thermal performance in FHP systems. In frost heave prevention applications the heating cables are typically installed inside conduits or pipes located beneath the tanks. When a heating element is located inside a small diameter (generally 1”) conduit, the efficiency of heat transfer from the heating element to the soil is reduced and the heating element may operate in a high thermal domain, thereby affecting the life expectancy and reliability of the heating system. This paper presents a heat management system that offers a clear improvement over such systems and presents various design features and technologies to make the heat management system safe, reliable, and accurate.

II. FROST HEAVE PREVENTION DESIGN BASIS

Ice particles are formed as the water in soil freezes below a cryogenic storage structure. The pressure difference in the soil caused by the phase change from liquid to solid forces the water surrounding the ice to migrate towards the location of the phase change. An ice lens is eventually formed causing expansion of the soil, resulting in the ice lens enlarging from water in the soil traveling above the frost line. This phenomenon is called frost heaving. The lack of a suitable prevention method will compromise the integrity of structures that store cryogenic fluids. The method used most often consists of a combination of heat input and thermal insulation to maintain surrounding soil above the freezing point (0˚C, 32˚ F).

Fig. 1 represents an example of cryogenic tank foundation construction, showing various material layers including typical ringwall configuration. Load bearing insulation, having a low conduction coefficient, is the primary thermal barrier that prevents frost heave to the tank foundation. Multiple layers of load bearing insulation are included in this example. Other materials commonly found in the foundation are dry stabilized sand and perlite concrete

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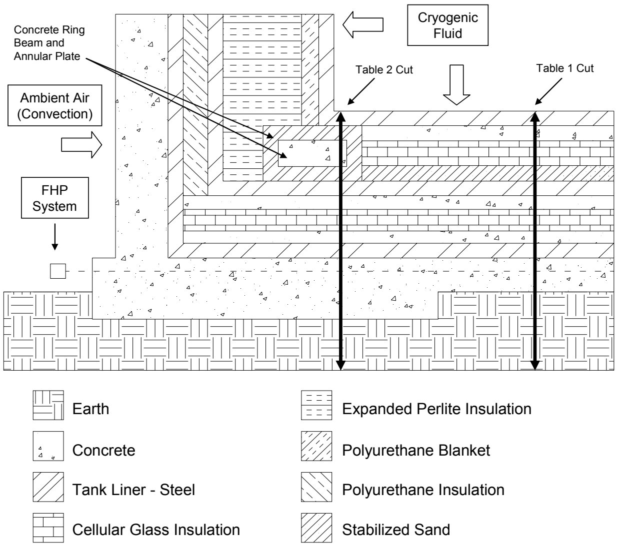

Fig. 1. Example of a Cryogenic Tank Foundation Geometry

In addition to the application of suitable thermal insulation, heat is applied using pipes or conduit embedded in the concrete layer under the thermal insulation. Various methods are used to establish economic thickness of insulation and optimum electrical heat to be applied.

Geometry and material changes in the foundation are encountered at the tank wall – foundation interface. A concrete ring beam is included for structural support at the tank wall-foundation interface location. The incorporation of the ring beam to the tank geometry dramatically changes the thermal profile of the system. Considerations of the change to the thermal profile of the foundation due to the ring beam must be considered when designing an FHP system.

TABLE I lists the assumptions made for the material layers at the center of the cryogenic tank. The "ring wall area" material layers used in the example model are found in TABLE II.

TABLE I
MATERIAL LAYERS FOR SAMPLE TANK (CENTER OF TANK)

Area - Center of Tank		**$1359m^2$**
Material	**Thickness**	**Conduction Coefficient**
Perlite Concrete	75mm	1.730 W/m-˚C
Fiberglass INSL	250mm	0.045 W/m-˚C
Dry Sand	75mm	1.255 W/m-˚C
Perlite Concrete	75mm	1.730 W/m-˚C
Fiberglass INSL	300mm	0.045 W/m-˚C
Perlite Concrete	75mm	1.730 W/m-˚C
Perlite Concrete	700mm	1.730 W/m-˚C
Soil	2000mm	0.836 W/m-˚C

TABLE II
MATERIAL LAYERS FOR SAMPLE TANK (RING WALL OF TANK)

Area - Ring Wall		**$189m^2$**
Material	**Thickness**	**Conduction Coefficient**
Perlite Concrete	400mm	1.730 W/m-˚C
Perlite Concrete	75mm	1.730 W/m-˚C
Fiberglass INSL	300mm	0.045 W/m-˚C
Perlite Concrete	75mm	1.730 W/m-˚C
Perlite Concrete	700mm	1.730 W/m-˚C
Soil	2000mm	0.836 W/m-˚C

Thermal material properties shown in TABLES I and II are taken as a single value at a specified temperature for the example models included in this paper. Single value properties are assumed in order to ease understanding. It is critical that the final design of an FHP system consider thermal material properties vs. temperature.

A. Design Specifics

Preliminary power requirements for the FHP system may be determined through simple one-dimensional heat loss calculations. Assuming one dimensional steady state conduction having no heat generation and uniform material properties, the heat equation takes the form of equation 4.1.

$$\frac{d}{dy}\left(k\frac{dT}{dy}\right)=0$$

(Equation 1)

$\frac{dT}{dy}$	Temperature gradient in y direction
K	Thermal conduction coefficient

The thermal resistance for conduction of the insulation may be modeled as in equation 4.2 by applying boundary conditions and Fourier's Law.

$$R_{cond}=\frac{T_{s,1}-T_{s,2}}{q_y}=\frac{L}{kA}$$

(Equation 2)

R_{cond}	Thermal resistance for conduction
k	Thermal conduction coefficient
$T_{s,1}$	Temperature on upper surface
$T_{s,2}$	Temperature on lower surface
q_y	Heat transfer rate in the y direction
L	Length of model
A	Area of model normal to the direction of heat transfer

The total resistance is related to the total power of the system in equation 4.3. One-dimensional heat conduction in the y direction is displayed graphically in Fig. 2.

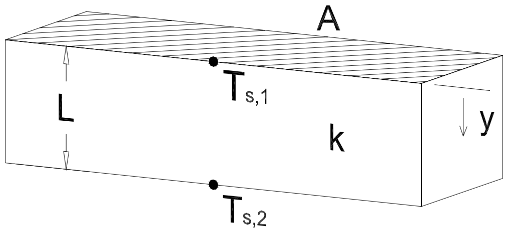

Fig. 2. One Dimensional Heat Conduction

$q_y = \frac{T_{s,1} - T_{s,2}}{\Sigma R}$	(Equation 3)

ΣR	Sum of all thermal resistances

Equations 2 and 3 give an estimate for the total heat loss from the foundation of the tank. The power requirement determined by this method should not be the sole basis in establishing a final design of a FHP system. The simple hand calculation method should only be used to give the FHP system design engineer a valid approximation. Further analysis is required to determine the actual system requirements, which must take into consideration changes in material properties due to temperature, changes in foundation geometry, ambient conditions etc.

Based on the details given for the tank in TABLES I and II the above calculation method yields a value of 23.3 kilowatts to maintain the foundation at 5˚C. Isothermal temperatures of -168˚C and 5˚C are assumed at the upper boundary and lower boundary respectively.

A heating system based on 1 meter spacing between conduits shows that 13.7 watts per meter are required for the conduits installed in the center portion of the tank and 17 watts per meter are required for the ring wall conduits.

B. 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 this report is based on a commonly used engineering software program1 and consists of a nodal grid arrangement, constructed from one or more material layers. Each layer is represented by input variables consisting of material type, thickness, thermal conductivity, specific heat and density. This model offers a reasonably accurate representation of heated slabs for frost heave prevention analysis and related calculations. Some of the limiting conditions of this program are:

[1]. The heated slab is two dimensional
[2]. Edge effects are considered to be negligible
[3]. The heater is a point source
[4]. The heater is in intimate contact with the concrete around it
[5]. Material layers have uniform thickness

Based on the details presented for the tank shown in Fig. 1, TABLE I AND TABLE II, the heat input required to maintain the concrete slab at 5˚C, as calculated by the software program is 14.5 watts per meter for the center (1 meter spacing between conduits) and 14.2 watts per meter for the ring wall (580mm spacing between conduits).

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

C. 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 program2 was used to calculate and create sample plots for this paper. Fig. 3 gives the resulting two dimensional contour plot for the tank details shown in Fig. 1 (thermal profile of concrete slab where heat is introduced shown in Fig. 3).

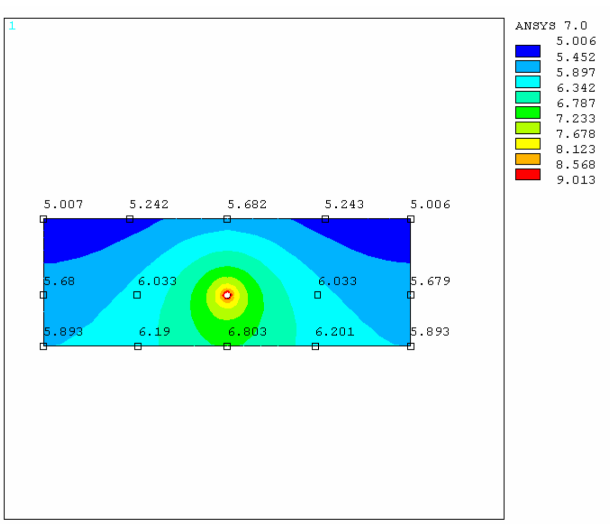

Fig. 3. Two Dimensional Contour Plot

A three dimensional model study of the tank is required to address the thermal performance of the entire FHP system. An example of a three dimensional model for a tank foundation is found in Fig. 4. The model represents a quarter section of the overall tank foundation. A sample plot for the resulting three dimensional finite element analysis solution is seen in Fig. 5, and indicates a temperature gradient from the center of the tank to the outer ring of the foundation. The effect of the concrete ringwall due to the reduced thermal insulation and the edge effects from the ambient surroundings are clearly seen. An optimized frost heave prevention design shall take into consideration these variations in the thermal profile and account for additional heat requirements at the outer ringwall.

The power requirement for the center portion of the tank closely correlates with the calculated values given earlier. As the analysis of the foundation reaches closer to the ringwall portion, it is seen that the soil temperature falls below 5˚C.

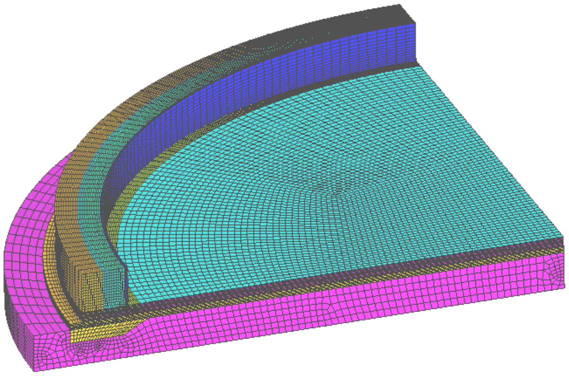

Fig. 4. Meshed Three Dimensional Model

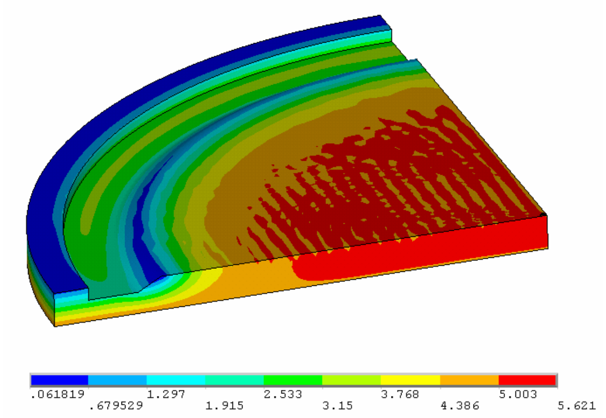

Fig. 5. Thermal Profile Plot from 3D Model

III. HEAT GEOMETRY AND APPLICATION OF HEAT

The base of the tank, as shown in Fig. 1, often sits on a foam glass load bearing insulation with relatively low thermal conductivity. Metallic conduits are installed under the tank foundations to facilitate the placement of electrical heating elements. The most common layout of heating conduit is parallel arrangement with equal spacing resulting in a pattern of chords on a circle. The network is installed in a leveling layer, just under the insulation layer. This layer is generally between 250 mm and 500 mm thick and made of either dry sand or concrete. Concrete layers are considered a better choice, as it is a better thermally conductive material that allows better distribution of heat. Depending on the design offered by various tank fabricators, other configuration of material layers could be used under the tank. The conduit system for heating elements must be water tight and in many instances cathodically protected. The components of the heat system shall meet classified area requirements. The annulus ring wall shaped construction is designed to carry the load of the storage tank. These are generally constructed with a mixture of high load supporting cement mixed with insulation material such as perlite concrete. An extra heater circuit placed in circular conduit form is usually added just below the ring beam to locally compensate for the higher heat loss.

The heating cable, placed in the conduit is often designed for an output range of 25 to 33 watts per meter. Conduit spacing is normally specified as maximum 1 meter (often 800 mm to 900 mm). A duty cycle for the system is established by the design safety factor, the rating of heater cable, the spacing of the conduit and the chosen control mechanism . In the past, the frost heave prevention design was based on a very conservative approach as it takes into account the worst case of heat flow, resulting in extra heat being generated which is not required to prevent frost heave and which raises the interface temperature to a level considerably higher than the preferred 5˚C.

Recent heating system designs have incorporated various control features to address the extra power requirements of past installations as well as to optimize energy use and the extra cost associated with the increased boil off and its re-condensation. Several types of proportional controls, multi-level controls, zone based controls and combinations of all of the above have contributed to a more efficient use of energy.

IV. HEATING CABLES FOR FROST HEAVE PREVENTION

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

[1]. MI Cable
[2]. Constant Watt Zone heaters
[3]. Flexible Series resistance heaters
[4]. Variable wattage self regulating heaters

All systems incorporate the same design philosophy: The heating element, when connected to an AC power source, generates heat. The heat generated by these elements is transferred to the conduit primarily through radiation, elevating the temperature of the conduit. By being in contact with the concrete (or sand), the conduit dissipates heat into the concrete slab (or sand) resulting in the concrete layer maintaining a desired temperature. The conduits allow replacement of damaged or failed heating elements. Conventional heating cables with a power output range of 25 to 33 watts/meter are often considered as a proven heating element for frost heave prevention applications based on their use in other type of heat tracing applications. A ready availability of these heating elements and an absence of a better alternative technology have resulted in the widespread use of various types of heating cables.

A. Limitation Of Conventional Heating Cables In Frost Heave Prevention Applications

Even though the past studies on frost heave prevention applications were based on standard heating cable (either series or parallel resistance), the primary focus was to establish the advantages of one type of heating cable over the other. However, an examination of the performance characteristics of heating cable in conduit as the “heat generation source” shows some fundamental weaknesses. Heating cables are developed and installed to deliver heat primarily through conduction. Several installation methods are developed by heating cable manufacturers to enhance conductivity between the heating cable and the surface it is attached to. In frost heave prevention applications, the heating cable is “pulled into” and left inside a conduit. The heating cable inside the conduit may or may not be in contact with the inner walls of the conduit and the resulting heat transfer is thereby less efficient than direct conduction. Furthermore, as the heating element is “trapped” inside the confines of this thermal envelope, it will be operating at elevated temperatures, which may in turn compromise the life expectancy of the heating cable, and the heating system. A typical heating cable based system is designed to have individual circuits in each parallel run of conduit, resulting in a large number of circuits. Each one of these segments requires an individual power connection and end termination. The large number of power and end connections increases the possibility of circuit failures. The increase in the number of circuits results in an increased number of circuit breakers and panel boards, further reducing the reliability of the installed system. Typical heating cables designed to deliver specific heat outputs often result in a heating system that delivers significantly more power and over heating. This aspect of the heating cable based system could result in an undesirable duty cycle, frequency cycle and increased operating cost.

A detailed discussion on the limitations of various types of conventional heating cables is beyond the scope of this paper. However, a basic understanding of reliability issues related to the housing of heating cable inside the conduit illustrates the need for a new approach to deliver optimum heat for the frost heave prevention systems for cryogenic tanks.

V. Skin Effect Heat Management For Frost Heave Prevention

A. 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, there by 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. Fig. 6 displays a cross section of a concrete slab with skin effect heating.

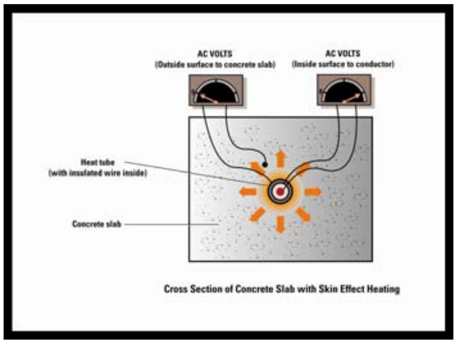

Fig. 6. Cross Section of Concrete Slab with Skin Effect Heating

The heat is generated on the inner surface of a ferromagnetic heat tube by I2R loss 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 I2R 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.

Fig. 7 graphically depicts an example of a skin effect system configuration for frost heave prevention. 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.

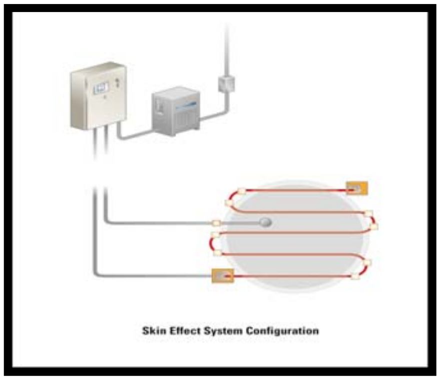

Fig. 7. Concrete Slab with Skin Effect Heating

B. Advantages Of Skin Effect Heating For Frost Heave Prevention Applications

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 tank. 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.

VI. FIBER OPTIC TEMPERATURE MEASUREMENT TECHNOLOGY

Distributed fiber optic temperature sensors contribute significant improvements in the accuracy and reliability of Frost Heave prevention systems. Compared to the traditional RTD or thermocouple based systems, the fiber optic temperature monitoring systems have some significant advantages. First of all, they are unaffected by Electro Magnetic radiation. Secondly, these systems offer a very attractive spatial resolution (often less than one meter) over the length of the fiber. This feature offers the capability to monitor the thermal profile in the entire foundation. Present temperature sensing systems offered by the heating system suppliers use a small number of RTDs (often less than 10 RTDs), randomly placed in the concrete slab, to monitor and control the heating system. This type of temperature sensing design could result in "frozen zones" as the physical location of these RTDs are selected randomly and may fail to identify these cold zones, leading to tank failure. One answer to the problem is distributed temperature sensing using a fiber optic temperature monitoring system.

Fiber Optic temperature monitoring makes use of a natural light scattering phenomena associated to the propagation of light in an optical fiber. Due to the interaction of light with the propagation medium, different scattering components which show a frequency shift compared to the light causing the interaction are generated. These are shown in Fig. 8. Three components can be distinguished: the Rayleigh, Raman and Brillouin component. The characteristics of the later two components are temperature dependent and can hence be used for temperature monitoring[3]. For the Raman components, the temperature information is contained in the intensity of the Raman peaks while for the Brillouin components the temperature information is contained in the Brillouin frequency. A peak shift of the Brillouin frequency can be observed when the temperature is changing, see Fig. 9. Both these technologies are considered for temperature monitoring. For the purpose of this paper, the Brillouin technology is considered for distributed temperature sensing.

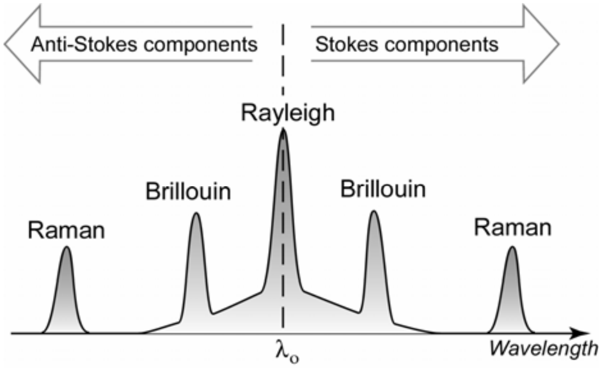

Fig. 8. Scattering Components in Optical Fiber Generated by Incident Light Beam at Wavelength, λ_0

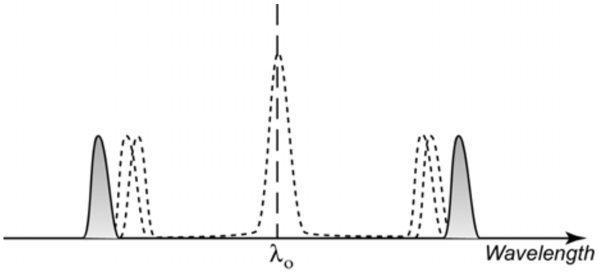

Fig. 9. Brillouin Response as a Function of Temperature

The measurement principle of the Brillouin sensing technology is based on the Optical Time Domain Reflectometer (OTDR) technology. This is a "modified radar concept": a very short optical light pulse, also called pump pulse, is launched in the sensing fiber. This pulse will propagate through the fiber where it will generate scattered Brillouin components over the complete fiber length. A proportion of the scattered light falls within the cone of acceptance of the fiber and is guided back towards the source. The returning signal is sent to a highly sensitive receiver where the Brillouin frequency is analyzed as a function of time. Based on the time delay between the pulse launch and the detection time, the location of the interaction can be defined. The further the interaction takes place in the sensing fiber, the longer will be the time delay between the pulse launch and the detection of the interaction. One single fiber could therefore replace thousand of point sensors thanks to the distributed sensing concept such that distributed temperature information along the complete length of the fiber can be obtained.

Recent developments take advantage of Stimulated Brillouin Scattering5 (SBS) as opposed to spontaneous Brillouin scattering. The SBS system is based on the measurement of the Brillouin Scattering characteristics in combination with a Continuous Wave (CW) signal to increase the Brillouin gain in the fiber. Fig. 10 shows a schematic representation of the SBS configuration. The SBS technology offers high signal to noise ratio, high accuracy, extended range, high resolution and short acquisition times.

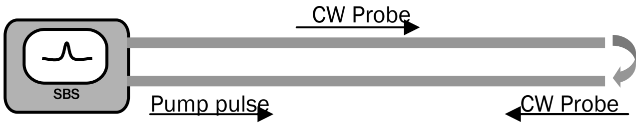

Fig. 10. Principle Stimulated Brillouin Scattering (SBS)

VII. Fiber Optic Temperature Sensors For Frost Heave Prevention Systems

Distributed fiber optic sensors contribute significant intelligence to understand the thermal profile of the tank foundation. These sensors are placed inside the concrete slab 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. One end is used to launch in the CW signal and the other end is used for the pump pulse causing the Brillouin components. Alternatively, a single fiber end configuration is also used for this application. The sensing cable exists of a stainless steel tube housing the optical sensing fiber. The tube 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 range up to 25 km.

VIII. Conclusions

The use of conventional heating cable inside conduit for frost heave prevention 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 tank foundations. The combination of skin effect heat management and fiber optic temperature sensing and control systems offers a major improvement in the reliability and efficiency of the frost heave prevention application.

IX. References

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X. Biographies

Franco Chakkalakal received the BS degree in EE from Kerala University, India, the MS degree in EE from St. Louis University, St. Louis, MO and 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.

Johan Vlekken received his Master degree in materials science from the Catholic University of Leuven (Belgium) in 1993 and received in 1998 his PhD degree in material science at the institute for Material research in Diepenbeek (Belgium).

Johan worked as a Post-doctoral fellow at the Institute for Material Research from 1999 to 2001. In 2001 he joined I.D. FOS Research, a research company focused on fibre optical sensing, where he became R&D Director in 2002. In 2003 he became Vice President of FOS&S, a company specialized in the development and implementation of fibre optic sensors and sensing systems.

Benjamin Primm received a BS in Mechanical Engineering from Purdue University in 2001. Mr. Primm joined Tyco Engineered Products and Services through their leadership development program and then was placed with Tyco Thermal Controls in 2002.

Ben helped to implement Tyco Thermal Control's Finite Element Analysis capabilities. At present he is the lead Finite Element Analysis Application Engineer for TTC and also involved in developing new applications for skin effect heat management systems.