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FLOW ASSURANCE FOR CROSS-COUNTRY PIPELINES WITH INTEGRATED BUNDLED TECHNOLOGIES

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Abstract

Flow assurance for material transfer pipelines has become a hot topic for producers, consumers, and environmentalists as the focal point in most cross-country pipelines is the necessity to locate and transport natural resources in a safe and economical manner; which is essential for the well-being of society as a whole. In particular, the challenge to transport heavy petroleum products over long distances has forced companies to implement new technologies in place of the invasive chemical injection of diluent chemicals into the pipeline to facilitate flow assurance. Often, the vast distance from the oil fields and/or petrochemical facilities to off-site refineries and terminal sites impedes the timely implementation of projects due to a multitude of reasons, especially in regards to environmental concerns and the basic transportation infrastructure such as roads and railways. While the use of cross-country pipelines has proven to be the most cost effective transportation solution, in many cases the safety, reliability, environmental and security concerns have limited the utilization of cross-country pipelines around the world. However, the most dramatic recent improvement in the safety and reliability of the heated cross-country pipelines is due to the role played by the integration of various thermal heat management and sensing systems, with a special emphasis on the fiber optic technology. Integrated bundled technologies also offer distributed temperature sensing, leak detection systems, third party intrusion monitoring and vibration protection systems to provide enhanced safety and reliability for these cross-country pipelines. This paper explores the flow assurance and risk management advantages of cross-country pipelines when early project planning includes adoption of various sensing technologies combined with a skin effect heat management system. The recent advancements in thermal insulation materials and application methods, new and efficient pipeline installation methodologies, and integrated state of the art fiber optic monitoring technologies can greatly assist in identifying and predicting failure conditions in pipelines. Bundling and integrating technologies have drastically enhanced the economic viability and environmental safety of cross-country transfer pipelines.

1. Introduction

It is widely believed that a reduction in the world's dependance on oil and gas as a major energy source is not expected any time in the near future. While energy conservation is increasingly considered a critical strategy and green energy looms as an ideal future solution, the rapid economic growth in emerging markets in Asia, Latin America and Africa has resulted in increased demand for oil and natural gas. It has become reality that conservation or renewable energy are not going to be the answer for a long time, if ever. As the demand for oil and gas reach record levels, the latest models in energy production economics present a new reality of what constitutes viable exploration and development methods in various regions around the globe. The renewed interest in exploration and development of oil fields with heavy, waxy (difficult to pump and transport) oil has offered a new lease on life for many energy starved countries throughout the world.

Some discoveries are classified as medium heavy with low sulphur and have high wax content. The Wax Appearence Temperature (WAT) could be 40-70 degree Celsius (°C) and pour points could be between 30-45°C., with a Wax Dissolution Temperature over 80°C. Transporting this heavy/waxy crude from the well head/gathering stations to distant places presents complex flow assurance issues. Even though road and rail methods of crude transport were

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common in the past, the volume and potential environmental risks quickly became apparent that cross-country pipelines are by far the best transportation method available. Tankers and pipelines are proven, efficient and economical means of connecting petroleum supply and demand. In USA, 170,000 miles of petroleum transmission lines are the primary means of moving crude oil, gasoline and other petroleum products. Most are buried and largely unseen. The oil and gas pipeline industry is currently facing a very serious challenge in assuring spill/accident free operations of the pipeline infrastructure that is distributed across many thousands of miles in both remote and populated areas. In many cases, to keep oil flowing, pipelines must be kept warm in every stage of its transportation, and the planned adoption of the latest "bundled technologies" can go a long way in making new pipelines safe and reliable to operate in the most sensitive of areas.

2. Safety and Risk Management through Flow Assurance

One of the primary reasons for the oil and gas industry to focus on flow assurance is a strong desire to operate their cross-country pipeline in a safe, reliable and economically viable manner over the lifetime of the asset. There is increasing awareness by governments and the general public that quality of life depends on environmentally friendly industrial infrastructure; in fact, recently there is a considerable focus on eliminating potential accidents and disasters caused by these cross-country pipelines. Additionally, other factors affecting the feasibility of a pipeline project may include cost, speed of construction and level of disruption to the indigenous populations. All of these factors come together to create a set of project objectives that must be satisfied. These key criteria can be met with a collaborative and integrated approach during the pipeline planning and design phases.

The oil and gas industry must evaluate what determines an acceptable risk to their business, to the environment and to indigenous populations. Every owner/operator can establish their own minimum acceptable "risk level" provided it meets minimum safety requirements established by governments and approval agencies. To establish a pipeline design which exceeds this minimum level of risk, a certain level of design engineering and technology integration must be considered as mandatory and requisite. For example, a crude oil pipeline transporting heavy oil with a pour point of 45°C needs either to be mixed with diluent to reduce the congealing temperature or to be supplied with external pipeline heating and proper insulation to maintain the liquid's temperature above its pour point temperature along the entire length of the pipeline. This Heat Management System (HMS) becomes a minimum mandatory investment and operational requirement as pumping the heavy crude against a "frozen" segment of the pipeline will result in pipeline rupture, and potentially cause an environmental and public relations disaster.

Beyond the minimum requisite technology, other complementary "incremental" technology investments can be specified to address other project objectives and gain acceptance by those affected along its route. These technology integrations might include things like temperature monitoring along the entire length of the pipeline, high/low temperature events on the pipeline, leak detection capabilities, SCADA mass balance, strain sensing and third party interference/security breach monitoring. The cost of integrating each additional "optional" technology, when bundled with other pipeline features, is usually a smaller initial investment than it would be as a standalone system. However, the full functionality benefit is returned with each additional technology, therefore making this additive approach economically attractive. There are many cost savings and design synergies that can be realized when taking such a holistic approach during early pipeline planning and front end engineering design (FEED). For example, if the level of intrusion to indigenous populations during construction is a concern, then pre-fabricated, pre-insulated pipe technology is an option for consideration to speed the initial pipeline construction and minimize the amount of field labor required to construct the pipeline.

The added benefit to the project in terms of a higher degree of flow assurance and management of risk with technology integration is illustrated conceptually in Figure 1 below. In this particular example, for a heavy, waxy crude oil pipeline, the critical technology addition is a pipeline heating and insulation system to facilitate the pumping of this high viscosity product. This basic requirement constitutes the minimum acceptable technology that should be incorporated into the pipeline Design Basis during its early planning phase. Additional incremental investments in various technologies are shown further to the right and are in arbitrary order of importance. As other technologies are added (bundled) the level of flow assurance increases; one can also think of this as increasing the level of confidence that the pipeline asset will behave as designed. It should be understood that both the selection of incremental technologies and the relative order of importance are determined early on by the owner/operator of the pipeline asset, based on the specific project objectives.

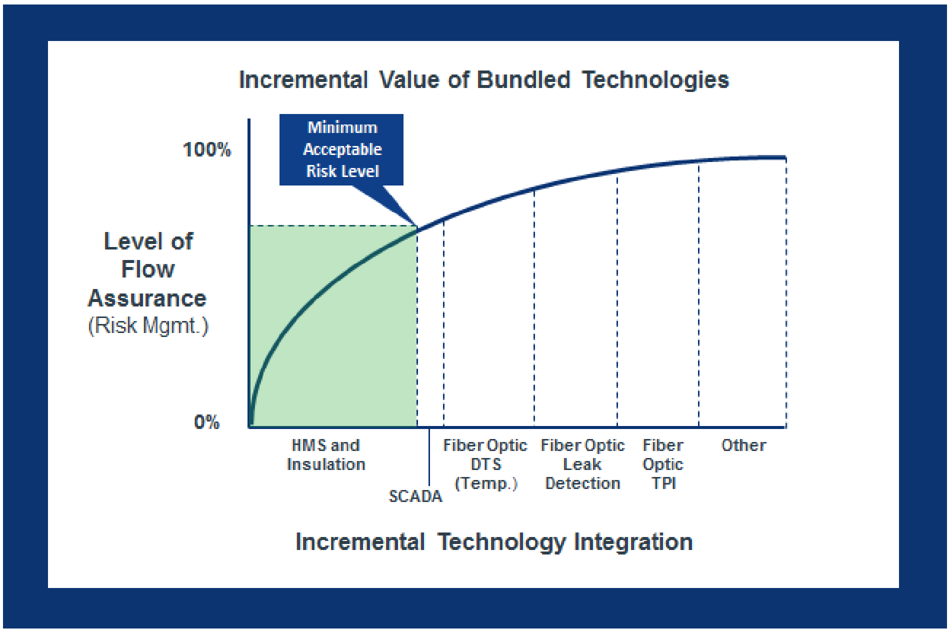

Figure 1. Chart Illustrating the Incremental Value Addition with Bundled Technologies

The capital investments associated with integrating various technologies for pipelines can be easily justified when considering the amount of lost revenue that may occur from events such as improper maintenance, pipeline spills, unintentional digging, nefarious illegal pipeline tapping, and intentional sabotage. A realistic and effective flow assurance program not only addresses capital expenditure, but considers the financial impact due to compromised safety and environmental risk during the life cycle of the asset.

3. Flow Assurance Using State-of-the-Art Technologies

A number of different flow assurance methods have been utilized in the past to keep oil flowing through transportation pipelines with varying degrees of success. The use of chemical additives or blending of various crude grades to improve the flow characteristics were early options. However, the emergence of long distance heated crude pipelines is becoming popular in many parts of the world as they represent an opportunity to evaluate and adopt new and emerging technologies. These technologies include thermal modeling techniques, optimized heat application methodologies, various types of pipeline monitoring such as distributed temperature sensing, leak detection, third party intrusion monitoring, and advanced mathematical analysis for crude oil heat up and cool-down scenarios under both steady state and transient conditions. The proper aggregation of bundled technologies can provide a winning combination for a project under consideration. A brief review of the state-of-the-art critical technologies is presented herein.

3.1. Hybrid Thermal Insulation Systems

The need for selecting an optimized thermal insulation system and the application methodologies to insulate the pipeline to result in a manageable homogenous heat loss is an important criterion. For underground pipelines, a one-hundred percent water-resistant moisture outer jacket is a primary requirement. A pre-insulated/pre-fabricated thermal insulation system employing a high temperature rated polyurethane foam (or other similar insulation material) can be very effective when applied under the controlled conditions in a manufacturing setting, resulting in a homogenous heat loss along the pipeline. Additionally, an outer jacket of extruded high density polyethylene (HDPE) (with suitable thickness to provide mechanical protection and prevent water ingress) creates an ideal thermal insulation envelope around the steel pipeline. These pre-insulated pipe spools (usually double random lengths) are transported to the project via truck, rail or barge, depending on the location of the manufacturing facility. They appear on the jobsite requiring a fraction of the field insulation effort versus conventional field construction methods; thus, the amount of time required to complete the project and the field labor requirement is greatly reduced. This can be especially attractive in remote locations where manpower and equipment logistics present a significant challenge.

3.2. Pipeline Heating Technology

Application of electrical heat on pipelines has been widely recognized as the most efficient way of heating long pipelines for flow assurance. A Skin Effect Heat Management System (SEHMS) as illustrated in Figure 2, utilizing a medium voltage wire (operating up to 5,000 volts) inside a carbon steel "heat tube" welded to the carrier pipe, has emerged as the ideal choice. The insulated conductor wire and the heat tube are connected together to make a circuit as long as 10 to 20 km. The relationship between the heat tube diameter, the conductor size and the applied voltage determines the output power (or, heat energy). The heat generation is based on the combined electrical phenomenon of Ohm's law, skin effect and proximity effect in ferromagnetic conductive materials under an alternating current (AC) of commercial frequency.

Like other conventional heat tracing cables, skin effect technology is very efficient since all of the heat is generated inside the thermal insulation envelope that encompasses the pipeline. The low impedance and high voltage capability of the skin effect heater enables it to operate over long circuit lengths at a relatively high power level. While the basis for the technology is sound and has been applied to many pipelines previously, every application requires unique design considerations.

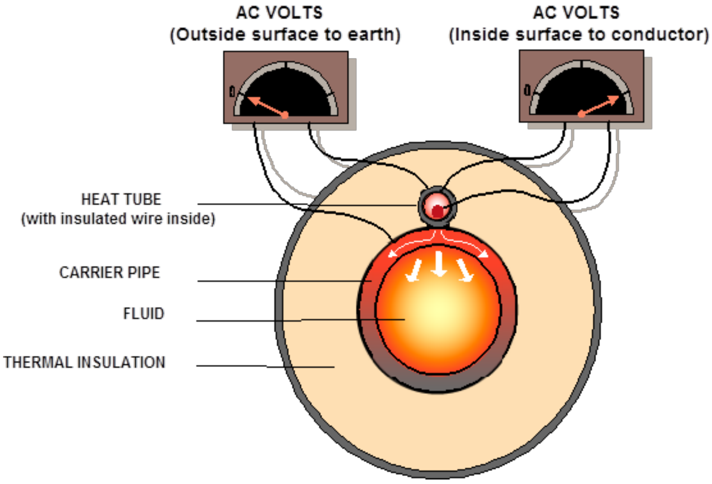

Figure 2. SEHMS Illustration

One can see from the schematic illustration in Figure 2 that safety is inherent in the SEHMS design, as no voltage potential is present on the outer surface of the heat tube; all current travels on the inside diameter of the heat tube, with no current or voltage on the outer surface of the heat tube. The safety and rugged reliability of the SEHMS system design are key reasons why it is an ideal system to heat cross-country pipelines.

3.3. Finite Element Analysis and Modeling

To establish an optimum power requirement for heated pipelines, Finite Element Analysis (FEA) is recommended to model thermal profile scenarios under steady state conditions. These FEA evaluations include prediction for cool down time for crude wax formation, and the required time to re-heat crude to a required temperature to enable flow by re-dissolution of the wax. Further, a more detailed Computational Fluid Dynamics (CFD) analysis can evaluate thermal profiles of the pipeline under various flow conditions. Transient analysis could also be performed to analyze the melting process of congealed crude and wax dispersal to resume flow in the pipeline.

3.4. Fiber Optic Technology for Pipeline Sensing

Many people know that fiber optic cables are ideal for transmitting telecommunication data, but they are equally effective for pipelines to detect temperature, leaks, strain, and third party interference because of the fiber's unsurpassed levels of sensitivity, long distance measuring capabilities and electromagnetic immunity. These attractive capabilities have led to unique solutions for critical detection and asset performance monitoring. The optical technologies today include Distributed Temperature Sensing (DTS), Fiber Brag Grating (FBG), Distributed Temperature and Strain Sensing (DTSS), Distributed Vibration Sensing (DVS) and Distributed Acoustic Sensing (DAS). Fiber optic monitoring systems continuously monitor the entire pipeline, registering small variations in sensing parameters to within a meter of an occurrence. While Distributed Temperature sensing (DTS) has been popular over the past ten years, some other optical monitoring systems are relatively new in deployment applications. For example, strain sensing can play a significant role in preventing pipeline mechanical failures (ruptures) by providing accurate information on pipeline movements due to high pipeline temperatures or earth movement events.

3.4.1 Raman Distributed Temperature Sensing (DTS) System:

DTS uses a fiber optic cable as a sensing element to measure temperature utilizing the Raman spectrum of light reflectivity. This system provides "thermal intelligence" by monitoring the temperature along the entire pipeline, giving operators a clear and visual understanding of the thermal profile of the pipeline and how the heating system is operating. It offers the capability to predict failure modes before the system fails and before losses are incurred due to pipeline failure. Further, it can significantly reduce downtime for the operating asset during planned maintenance events or unforeseen outages/restarts.

For distributed temperature measurement, a pulsed laser is coupled to an optical fiber through a directional coupler. Light is backscattered as the pulse propagates through the fiber core, owing to changes in glass density and composition as well as molecular and bulk vibrations. In a homogeneous fiber, the intensity of the sampled backscattered light decays exponentially with time. Because the velocity of light propagation in the optical fiber is well known, the distance can be calculated from the deterministic collection time of the backscattered light. Thus, the temperature and distance can be resolved simultaneously.

A major component of the fiber optic based measurement system is the interrogation electronics, or DTS unit. This is comprised of a light source (high intensity laser) and a specialized OTDR (Optical Time Domain Reflectometer) with software to analyse specific spectral signals for distributed or point temperature information. Systems can be multiplexed to collect signals from multiple external fiber optic cables.

Typical fiber optic cable deployment techniques include spooling or pulling the fiber inside a previously installed, dedicated encasement tube welded to the carrier pipeline, if possible at the 12 o'clock position. Figure 3 shows a typical DTS system GUI (Graphical User Interface) for pipeline temperature monitoring. Temperature profiles (data points) are correlated to physical landmarks along the pipeline alignment for easy reference to pipeline operators and maintenance personnel.

Figure 3. Fiber Optic DTS System Display

Simple and easily understood graphics are critical to any effective sensing or monitoring system, such as the DTS system shown above. The opportunity for operators to be able to quickly interpret and act upon the data presented makes such a technology investment pay large dividends.

3.4.2 Brillouin Distributed Temperature and Strain Sensing (DTSS):

A Brillouin scattering based fiber optic distributed sensing system is capable of accurately measuring every point over long distances (range up to 50 km) from a single interrogator. This reach is one of this technology's attractive advantages, as it is generally longer than other optical technologies. A Brillouin scattering based system exhibits a light wave frequency shift of around 10 GHz (0.1nm at 1.5 micron wavelength). This Brillouin shift is directly related to both local temperature and strain conditions. DTSS fiber optic distributed sensing systems are capable of accurately measuring every point over long distances (ranges over 50 km) from a single interrogator. The measurement is based on the analysis of back-scattered light when a laser pulse travels down the optical fiber. Standard single mode optical fiber is used as a sensor with high signal-to-noise ratio and long term stability due to stimulated Brillouin Scattering measurement. DTSS offers a spatial resolution of 0.5 m for temperature and strain and can offer a measurement resolution accuracy down to 0.1°C (temperature) or 2 microstrain (strain). Brillouin scattering can be stimulated to dramatically increase the magnitude of the Brillouin interaction while making it significantly more efficient for sensing purposes.

3.5. Distributed Vibration Sensing (DVS) System:

This technology is based on the fact that light waves propagating through a fiber optic cable are extremely sensitive to high frequency vibration waves (acoustic, ultrasonic) that may be generated in its nearby environment. These disturbances create microscopic stresses or vibrations that are mechanically coupled into the cable. These forces on the cable in turn generate highly sensitive optical phase changes and/or reflections within the fiber. The amount of optical phase change is determined by the strength of the amplitudes and frequencies as well as several other parameters which are detected. Specialized software associated with the control unit is used to interpret and classify these changes when a leak or security/safety event is detected; an alarm is triggered and displayed in the graphical user interface. This technology often involves fiber optic sensor configurations that utilize single mode optical fiber. One of the advantages of this technology is that the fiber does not need to be placed on the pipeline itself; for example, it can be laid in close proximity to the pipe in the trench backfill, for buried pipeline applications. The exact location in the pipe cross-section is determined by a number of factors, including the parameters to be sensed by the fiber.

4. Integrated Flow Assurance Solutions with Bundled Technologies

Various state-of-the-art technologies in pipeline monitoring, instrumentation and control, and heat management solutions have vastly improved the safety and reliability of flow assurance performance. However, the recent concept of bundling these technologies, integrated under single source responsibility, has revolutionized the risk mitigation and performance standards.

While skin effect based heating systems are the ideal choice for delivering heat to the pipeline, a combination of other applicable technologies could be bundled to enhance the performance of the pipeline and other assets. Flow assurance considerations shall address several issues such as temperature maintenance along the entire length of the pipeline, high and low temperature events on the pipeline, leak detection capabilities including early (small leak detection), third party interference (intentional or unintentional), and security breach. Proven technologies are available today to monitor, pinpoint and report abnormal temperatures, ultrasonic vibration events at any location of the pipe /asset movements with great accuracy and resolution. Distributed Acoustic Sensing (DAS) is one example of technology that could be used to detect digging and physical intrusion. Distributed Strain Sensing (DSS) systems are a new generation of technology employed to detect and prevent oil spills due to the ability to detect, locate and classify vibration caused by physical activities while simultaneously monitoring for early stage leaks along the pipeline.

These technologies today can play an important role in the safety and reliability of cross-country pipelines. Distributed temperature and strain detection technologies have certainly proven their value in the past 10 years, and various sensing technologies and systems can be integrated to provide continuous pipeline monitoring over vast ranges. Alarm events (system status, leak alarms, TPI alarms, flow, temperature security, fiber break sensing) can be routed to external controls systems (SCADA) via dry (voltage free) relay contacts or Ethernet (LAN) interface among other industry standard protocols. Figure 4 depicts an example where fiber optic Distributed Temperature Sensing (DTS) is combined with pipeline heating, a concept that is ideal for temperature sensitive fluids.

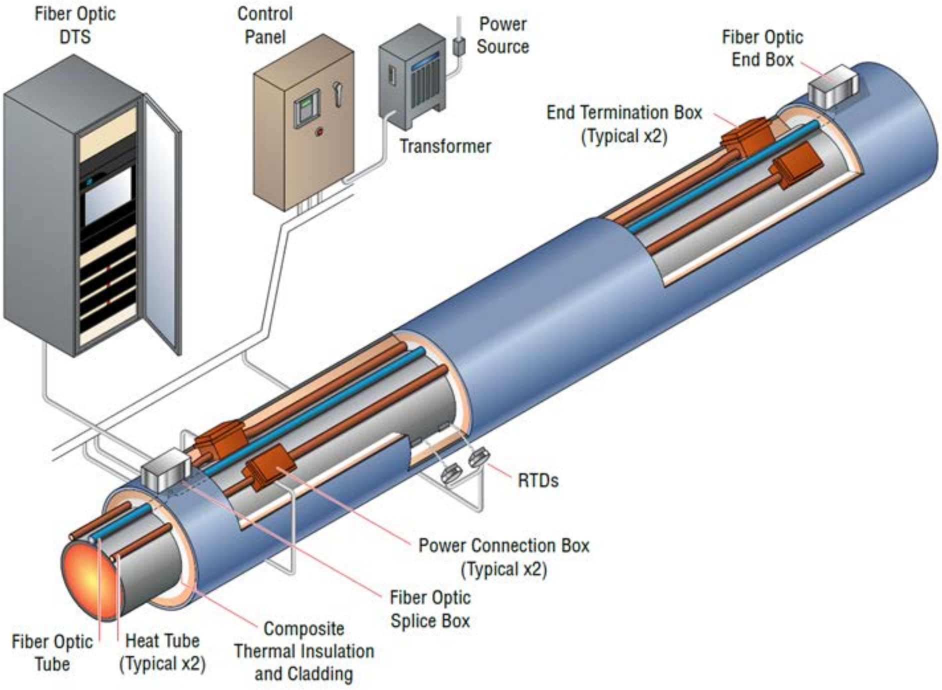

Figure 4. Fiber Optic System Configuration for Pipelines with Skin Effect Heating

The latest improvements in sensing technologies for the core alarming system, event classification algorithms and reduction in nuisance alarming have proven to be highly effective. Intuitive and simplistic user interface modules provide the alarm location information coordinates in real-time.

The execution of an integrated technology implementation strategy under single source responsibility to offer greater safety, security and optimum capital allocation at the conceptual stage is beginning to capture the attention of the solution providers and owners/end users.

5. A Success Story in Flow Assurance - Cairn, India 600 km Pipeline

In 2004 the largest onshore Indian oil discovery in 20 years was made when the Mangala Field was discovered within the Barmer Basin in the state of Rajasthan, North West India. With oil reserves estimated in excess of 1 billion barrels and potential production in excess of 200,000 barrels of oil per day it would equate to approximately 25% of India's domestic production. A pipeline was needed to transport the oil from the fields in northern central India to the western coast where a refinery hub and export terminal already existed.

There were many challenges relating to this discovery as the Rajasthan crude oil was non-conventional. Classified as medium heavy with low sulfur, it had a high wax content of up to 38% by weight. The crude exhibited properties that made pumping difficult, including a Wax Appearance Temperature (WAT) between 50-65 degrees Celsius (°C), a pour point between 32-42°C and a wax dissolution temperature between 80-82°C. These parameters mean that as the temperature of the crude drops below 65°C the wax begins to form a gel, and the crude becomes increasingly viscous as the temperature drops further. Below the pour point range, the crude is effectively a solid and it must be heated above 82°C to re-dissolve all of the wax.

It was obvious from the outset that transporting this waxy crude from the well to the refinery would present complex flow assurance issues. The crude would not flow unless it was kept warm in every stage of its transportation. This would require a unique solution, requiring the world's longest insulated and continuously heated pipeline. However in India, the availability of stable and reliable electric power is a major problem, especially in the remote regions. Furthermore, the utility power grid was not available along major portions of the proposed pipeline alignment. Thus, the primary power requirement for pipeline heating was met by gas-fired generators located at each pipeline station, spread approximately every 20 km along the pipeline route. The long circuit lengths afforded by skin effect heating allowed the number of power generation stations to be minimized, leading to an optimized and cost-effective project.

The Mangala Development Pipeline (MDPL) project was conceived with the objective to transport stabilized crude oil from a processing facility located close to the remote town of Barmer in Rajasthan to the coastal oil refining center of Jamnagar in Gujarat. Not only was the 600 km length a challenge, the pipeline crossed two states, including 270 towns and villages, involved 40,000 individual land owners, crossed hundreds of roads, railways, major rivers and canals and was buried a minimum of 1 meter below the ground.

Figure 5. Construction Team Laying Pre-Insulated Pipe for Oil & Gas Development

The MDPL project crude pipeline utilized a 24” diameter carbon steel pipe, with a wall thickness varying between 10.6-12.7 mm and a pressure rating of 90 Barg (1,305 Psig). The pipeline design included a Fusion Bonded Epoxy (FBE) corrosion coating, 90 mm Polyurethane Foam (PUF) insulation, and an outer shell of 5 mm high density polyethylene (HDPE) to protect the insulation and prevent water ingress.

The safety and risk management system included cathodic protection, third party intrusion detection along the entire length of the pipeline using fiber optic cable, and an integrated leak detection system whereby the pipeline is continuously monitored from a central control station utilizing a Supervisory Control and Data Acquisition (SCADA) system.

An 8” diameter gas supply pipeline was laid parallel to the crude pipeline to fuel gas-fired generators inside 35 stations along the pipeline route. With a budget of approximately US $900 million and a peak workforce of over 5,000, the fast track project was constructed in 23 months, with the first oil flowing in June 2010. The pipeline has been operating successfully since with a high degree of reliability.

Figure 6. Pre-insulated Pipe Spool System Laid in a Flooded Trench

Figure 7. Pre-insulated Pipe Spool System with Flotation for Subsea Deployment

A second phase of the project involved a 7 km section of heated pipe that was routed offshore to a loading buoy located in 30 m water depth and then returning back in a loop to the onshore terminal. The subsea portion of twin pipelines presented a new range of technical issues. Additional heat tubes were added for heating system redundancy. The insulation system design was modified with a 100 mm thick concrete coating to account for buoyancy issues and to take into consideration the mechanical requirement to withstand additional stresses during and after installation. In a carefully coordinated procedure, the buoyancy tanks were removed to sink the pipeline into a trench dredged into the seabed and then backfilled to protect the pipelines from wave action or shipping interaction.

6. Conclusions

An integrated and coordinated flow assurance program that incorporates state-of-the-art technologies and various modeling techniques offers significant advantages over the fragmented planning and design approach often practiced in the past. The bundling of individual design/construction features and smart technologies into a seamless comprehensive solution from a "single-source integrator" pays rich dividends in terms of safety and reliability in flow assurance. Key observations from this paper are:

- Every project's owner/operator must establish the minimum acceptable level of risk that meets or exceeds flow assurance requirements dictated by regulatory climate and/or compliance, and results in requisite design functionality. The bundled integration of additional state-of-the-art technologies further enhances flow assurance and improves the level of risk mitigation
- A bundled technology approach can yield significant flow assurance dividends, including safety, reliability and operational success if incorporated early in the project planning and Front End Engineering Design (FEED) phase. A strategy of "single source" responsibility by a single system integrator who can gain an understanding of the cost savings and design synergy often results in optimum technology performance and timely completion
- Skin effect based heating technology coupled with pre-fabricated, pre-insulated piping has proven to be a superior thermal management solution for long distance buried pipelines
- The availability of electricity through the grid and/or the use of fuel powered generators are often crucial issues relative to the viability of a heated pipeline project, which often traverses through remote areas; technology selection should take this into account
- The integration of various fiber optic based sensing systems is a critical component for the flow assurance in long cross-country pipelines. Often times, additional "technology investments" can result in a higher confidence level for the owner/operator when it comes to assuring continuous flow through the pipeline asset

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