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NEW FLOW ASSURANCE SYSTEM WITH HIGH SPEED SUBSEA FIBER OPTIC MONITORING OF PRESSURE AND TEMPERATURE

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ABSTRACT

Subsea production control systems are instrumented to constantly monitor flowline pressure and temperature at key locations to prevent plugging and introduce mitigating control strategies. New fiber optic sensors with ruggedized construction and non-electrical components are subjected to accelerated aging tests and deployed in several installations with long service life. An overview of current progress with fiber optic technology is provided for fatigue monitoring, temperature, pressure, and strain sensing. Recent developments include improved service life, novel bonding methods, pipeline sensor station improvements, sensor calibration, and long-term fatigue analysis.

The latest advancements are validated on multiple installations on a subsea tieback in the deepwater Mississippi Canyon of the Gulf of Mexico at 6,500 ft depth. A prior third-party sensor design experienced multiple non-recoverable sensor failures. A new sensor station design is employed on two Flowline Terminations to monitor pressure and temperature at a rate of 100 Hz. Subsea tiebacks are susceptible to flow assurance issues caused by plugging events such as hydrate formation. The system was originally designed to track pig location but transitioned to pressure and temperature sensing. An issue with the transition was the lack of calibration relating the fiber Bragg grating (FBG) strain levels to the actual process conditions. A novel method is presented for in situ adjustment of the sensor array calibration.

During the calibration procedure, the sensors produced unanticipated results during pipeline flow shut-in and later startup operations. The sensors helped uncover a configuration of the flowline and sensor locations that is valuable for detecting hydrate forming conditions at a key junction location. The sensors are located before and after the junction of two flowlines in the mixing zone of the pipeline streams. The novel contributions of this study are the high speed data collection, in situ fiber

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optic calibration, review of advancements in fiber optic sensing technology, and a field case study with multiple sensing arrays.

The developments are part of the Clear Gulf study, a collaboration between the offshore energy industry and NASA that was formed in 2010. The objective of the Clear Gulf study is to employ space technology and testing facilities for use in the upstream industry to advance subsea sensor technology. The highly sensitive monitoring systems developed as part of this study are used to give early warnings for flow assurance issues, structural failures, or catastrophic events.

NOMENCLATURE

BAR Barataria
D_{avg} Average pipeline diameter (m)
D_{in} Inside pipeline diameter (m)
D_{out} Outside pipeline diameter (m)
D Diameter
DCS Distributed Control System
E Young's Modulus (GPa)
EMI Electromagnetic interference
F_G Relation to photo-elastic constant
FBG Fiber Bragg Grating
$FLET$ Flow Line End Termination
FPS Floating Production System
ILS In-Line Sled, (Flowline)
L Pipeline length (m)
MC Mississippi Canyon
MPM Multi-Phase Meter
P_{in} Internal pressure (Pa)
P_{ex} External pressure (Pa)
P_0 Initial pressure (Pa)
SSC South Santa Cruz
T Temperature (K)
T_0 Initial Temperature (K)
TLP Tension Leg Platform
α_Λ Thermal expansion coefficient $\left(\frac{\mu\varepsilon}{K}\right)$
α_n Thermo-optic coefficient $\left(\frac{\mu\varepsilon}{K}\right)$
β Slope of pressure correlation
$\delta\lambda$ Change in wave-length from the nominal condition λ_0
ε Strain - ratio of deformation per original length $\left(\frac{m}{m}\right)$
γ Intercept of pressure correlation
λ_p Bragg wavelength (nm)
λ_0 Baseline wavelength
$\mu\varepsilon$ μ-Strain $\left(10^{-6}\frac{m}{m}\right)$
$\mu\varepsilon_{hoop}$ μ-Strain due to hoop oriented FBG
$\mu\varepsilon_M$ μ-Strain due to other mechanical forces
$\mu\varepsilon_Q$ μ-Strain due to thermal expansion of pipeline
$\mu\varepsilon_T$ μ-Strain due to fiber optic temperature changes

FLOWLINE OVERVIEW

Deep Gulf Energy developed a subsea tieback to the Blind Faith floating production system (FPS) deepwater platform in the Gulf of Mexico. It is located in the Mississippi Canyon (MC) Blocks 695 and 696. The South Santa Cruz (*SSC* in MC 563 at 6,550 ft water depth) and Barataria (*BAR* in MC 521 at 6,770 ft water depth) tiebacks to the Blind Faith FPS at 6,480 ft water depth utilize a 21.9 cm (8.625 inch) outer diameter with a 2.54 cm (1 inch) thickness on the inner pipe of a pipe-in-pipe configuration. The tieback extends 24 km (15 mi) with a flowline to transport production fluid and gas from the well heads to the platform [1] as shown in Figure 1. Production commenced in 2017.

Fiber optic monitoring of subsea equipment began 21 years ago on the Troika project in the Gulf of Mexico in 1997. The Troika project used FBG sensors with a prototype signal conditioning unit. This sensing system monitored the pressure, temperature, and strain in a pipe-in-pipe 22.5 km (14 mi) subsea tieback without pipewall penetration. Since the initial deployment, other deployments have monitored steel catenary risers, drilling risers, tension leg platforms (TLPs), umbilical installations, touchdown zones, slugging mitigation, and subsea tiebacks ([2–8]). Originally implemented in high temperature rocket motor applications, recent studies also extend this sensing technology to distributed monitoring of cryogenic liquified natural gas transfer pipelines [9].

For the Deep Gulf Energy application, pressure and temperature are key pieces of information to maintain flow assurance and event detection. Pig passage monitoring is also important for pipeline inspection and maintenance. This paper gives information about several monitoring stations installed during the initial construction and deployed for high-speed monitoring of conditions that predict potential flow assurance issues such as hydrate formation during startup and shut-in of the flowline. To obtain data from the fiber optic sensors, an umbilical was installed with fiber optic, hydraulic, and electrical lines. Only the fiber optic strands are used for the instrumentation and the sensors are non-penetrating into the flowline and non-electrical with no signal repeaters. Fiber optic sensors are appealing for deepwater applications because of ruggedness, immunity to electromagnetic interference, multiplexing capability, and low vulnerability to water.

For long tiebacks, signal degradation is anticipated and included in the design to ensure that signal strength is above a 1 decibel (dB) threshold for detection [7]. The source signal is in the range of 40-60 dB that is attenuated over splicing connections, through the fiber, and reflected for a round-trip journey. The umbilical includes fiber optic strands in a stainless steel tube. The tube void is filled with a hydrogen scavenging gel to reduce hydrogen embrittlement. The gel lessens hydrogen infusion by absorbing free hydrogen before it reacts with the silicon glass fibers. If hydrogen diffuses into the fiber it can cause attenuation

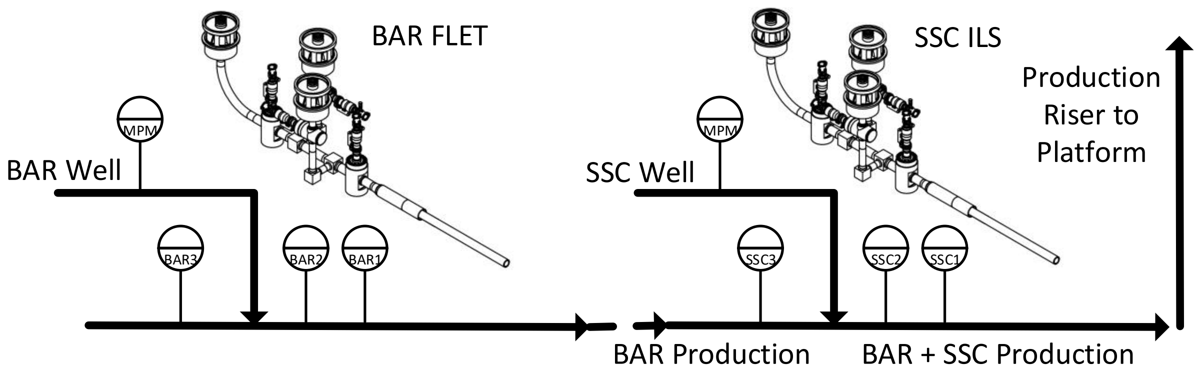


FIGURE 1: MONITORED MEASUREMENT STATIONS ALONG THE 24 KM (15 MILE) PIPELINE FROM WELL-HEAD TO PLATFORM PRODUCTION RISER TOP.

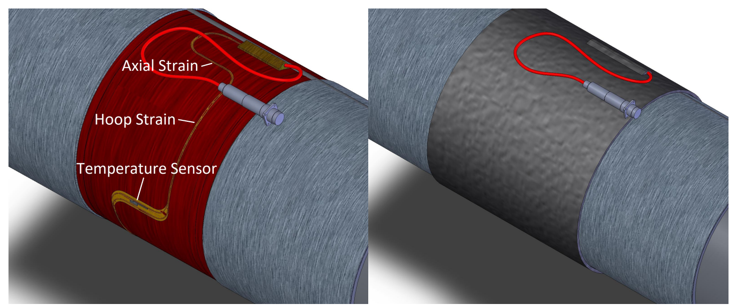
of the signal and decrease the signal to noise ratio. A standard long-distance fiber bundle from the telecommunications industry is used for this application. The fiber optic cable is integrated in the umbilical along with hydraulic lines and electrical cables. Many of the fiber optic lines are also used by other instruments near the wellhead for control and communications.

When attached to the flowline pipe, the fiber optic cables shielding is removed and the fiber is spliced in-line with specially designed Fiber Bragg Grating (FBG) sensors with reflective peaks in the range of 1510-1590 nm. The natural signal attenuation in this range is 0.177 dB/km (0.285 dB/mi). The light makes a round-trip journey to the sensor and back to the fiber optic interrogator. Consequently, the light travels twice the fiber cable distance. This double distance is important in estimating the light signal attenuation and the shift that occurs with distance as the reflected light signal is analyzed. To improve signal strength, a pressure balancing fluid with high viscosity is extruded over the fiber optic strands. This encapsulation is required for good performance in deepwater conditions where non-uniform pressure induces deformation of the glass. This high viscosity fluid is also used to avoid direct contact with the pipe surface that may have irregularities that may damage the fiber by notching or induce points of high stress.

Sensing Stations: Hoop, Axial, and Temperature Sensors

Each sensing station has 3 hoop sensors, 1 axial sensor, and 1 temperature sensor placed in series on a single fiber optic strand. A protective semitransparent polyurethane coating is cast around the bonded sensors to prevent damage to the sensor or the splicing connections as shown in Figure 2.

The sensors are routed to avoid areas of high-loss and have all required combinations for sensing of pig passage, temperature, and pressure. The sensors are bonded to a polished metal surface in the field and a protective polyurethane body is mould-injected to ruggedize the sensors. The entry point of the cable is also secured to the pipe to both immobilize and protect the egress point. This sensor station differs from prior work with post-installed sensors because the sensor station is custom-built on the pipe segment and not prefabricated with a clamp design.



(a) INTERNAL VIEW (b) EXTERNAL VIEW

FIGURE 2: (a) CUT-AWAY VIEW OF THE INTERNAL FIBER ROUTING AND FBG SENSOR PLACEMENT WITH HOOP, AXIAL, AND TEMPERATURE SENSORS. (b) RUGGEDIZED CONNECTOR AND PROTECTIVE POLYURETHANE FROM FIELD-CAST MOULD.

There are three sensing stations on each flowline termination as shown in Figure 3. The fiber is installed in a loop configuration so that all sensors can still be used if the fiber is broken in one location by sending a light signal down both ends. If the fiber is broken in multiple locations, the inner segment between two breaks is not visible to the optical interrogator and any sensors in that region are disabled. Due to the fiber ruggedization, sensor redundancy, and loop design the flowline termination sensing stations retained all needed sensor values for pressure, temperature, and pig detection.

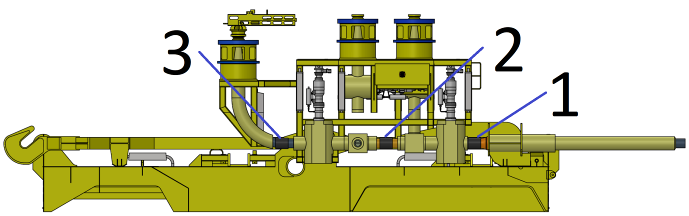


FIGURE 3: INSTALL LOCATIONS OF THE SENSING STATIONS. A TYPICAL *FLET* IS SHOWN.

INSTRUMENTATION METHODS FOR FLOW ASSURANCE

Monitoring the pressure and temperature is accomplished with individual point FBG sensors that are secured to the outside of the pipe in various configurations. Table 1 contains details of the working range for FBG sensors.

TABLE 1: FBG SENSOR RANGE.

Description	Typical Range
Sampling Rate	up to 5000 Hz
Range of wavelength	1460-1620 nm
Number of FBG sensors possible	
for a single fiber	up to 100
Accuracy	5 $\mu\varepsilon$
Resolution	1 $\mu\varepsilon$
Maximum fiber length	90 *km* (56 *mi*)
Fiber strain limit Temperature range	-40 to 300 ^{o}C

Conventional gauges are electrically powered and contain components that must be protected in subsea conditions. Fiber optic sensors are popular for subsea applications because they contain no electrical components with several advantages over conventional sensing systems. Some of the advantages are:

- Sensors are placed outside the pipeline, non-invasive
- Immune to electromagnetic interference (EMI)
- No electric power or metalic components
- Rapid real-time monitoring
- Multiple sensors (multiplexing) on a single line
- Little or no impact on the physical integrity of the containment structure
- Multifunctional sensors measure vibration, strain, pressure, and temperature
- Long service life
- Topside equipment requires 2U-4U server rack space
- High sensor sensitivity

These advantages make FBGs a natural fit for extreme environments such as deepwater flowlines.

As shown in Figure 4, there are many types of configurations for the fiber optic strain gauges. Hoop strain sensors are principally placed to monitor pipeline expansion or contraction due to pressure changes. Strain sensors along the axial dimension of the flowline are placed to measured vibration due to slugging and quantify the remaining fatigue life on risers. Sensors placed diagonally at a 45^o offset from the hoop and axial sensors are placed to measure torsion on the pipe. A fourth type of sensor is the unattached temperature sensor that is used for temperature compensation of the other sensors as well as provide a measurement of pipeline fluid temperature. When sensors are placed and analyzed in coordination, they provide real-time insight on bending moments, vibration frequencies, pig passage, hydrate buildup, and other events of interest to structural integrity and flow assurance. Figure 4 is an overview of possible fiber installation configurations for desired monitoring objectives.

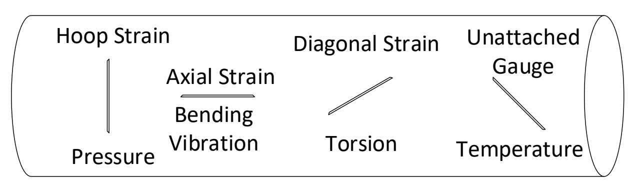


FIGURE 4: FOUR COMMON TYPES OF FBG SENSOR CONFIGURATIONS FOR FLOWLINES OR TENDONS.

The temperature sensors in this application have dynamic and steady state mismatch between the fluid temperature and the measured temperature at the exterior wall because of the thermal capacitance of the pipe and the heat loss to the surrounding seawater. However, heat transfer by conduction from the fluid in pipeline through the steel wall and to the fiber is fast compared to the slower dissipation of heat from the insulated Flow Line End Termination ($FLET$) or In-Line Sled (ILS) to the seawater. Therefore, the temperature sensor is used as a suitable approximation of the internal pipeline fluid temperature. This slight mismatch is compensated with a calibration to an existing nearby fluid temperature sensor that provides temperature, pressure, and other fluid properties. This sensor used for calibration is a Multi-Phase Meter (MPM) that is common in deepwater well monitoring and control. The MPM is electrically powered and requires a minimum flow limit to transmit data. The fiber optic sensors do not require subsea electrical power, provide sensing redundancy at a critical location, do not have a lower flow limit to begin transmitting, and provide measurements at a high sampling rate of 100 Hz. Once calibrated, the fiber optic sensors provide high speed sensing of the main flowline that can provide pig passage detection because of the non-penetration of the fiber optic sensor gauges.

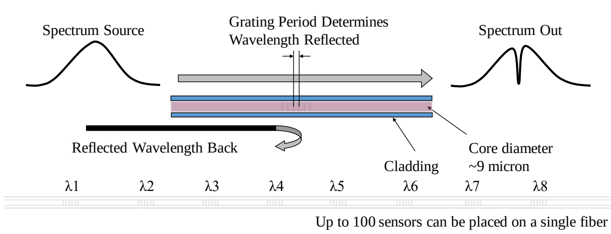


FIGURE 5: FBG SENSOR IN SERIES ON A SINGLE FIBER.

The fiber optic interrogator is set to sample at a frequency of 100 Hz although 1000 Hz is also possible for shorter distances. Individual measurements return as peaks in the light spectrum as shown in Figure 5. The individual peak values ($\lambda_1 \ldots \lambda_8$) are an illustration of 8 fiber optic sensors placed in series with different reflective peaks that are placed to not overlap expected sensor ranges. The peak location shifts lower under compression and higher under tension as strain is applied to the FBG. This peak location λ_p is compared to a baseline condition λ_0 to determine the shift from a nominal value. It is the fractional difference of the shift that is converted to a strain in typical units of micro-strain $\mu\varepsilon$ as shown in Equation 1.

$$\mu\varepsilon = 10^6 \left(\frac{\frac{\lambda_p - \lambda_0}{\lambda_0}}{F_G} \right) \tag{1}$$

Equation 1 is the basis for the temperature, axial, hoop, and pressure measurements.

Correlations for Pressure Measurement

Pressure from the fiber optic sensors is a combination of hoop strain and temperature compensation. The pressure inside the pipe P_{in} is the result of a balance of forces on the pipe cross-sectional area. The pressures difference between the pressure inside (P_{in}) and the pressure outside (P_{out}) makes the diameter of the pipe contract or expand from the starting and unstrained condition. The deformation of the pipe diameter is resisted by the elastic deformation of the carbon steel according to Young's Modulus (E). The inside pressure (P_{in}) is calculated by balancing the pressure forces with the resisting force from pipe elastic deformation as shown in Equation 2.

$$P_{in} = \frac{E\mu\varepsilon_{hoop}D_{avg} + P_{ex}D_{out}}{D_{in}} \tag{2}$$

The final form of Equation 2 is the basis for the empirical regression for calibration as shown in Equation 3.

$$P_{in} = \beta\,(\delta\lambda) + \gamma \tag{3}$$

where $\delta\lambda = \lambda_p - \lambda_0$, β is the slope, and γ is the pressure at nominal conditions. Note that $\delta\lambda$ is the shift in wavelength with the temperature compensation removed.

Correlations for Temperature Measurement

The fiber optic strain gauges have a positive increase in reflected wavelength peak with increasing temperature. In addition, the fiber optic sensor is typically attached to a metal tab that is disconnected from the pipe. This metal tab also experiences thermal expansion and contraction due to temperature. Equation 4 is the expected strain ($\mu\varepsilon_T$) due to the thermal expansion of the fiber. The temperature induced strain is related to the temperature change away from the nominal starting point ($T - T_0$).

$$\begin{aligned} \mu\varepsilon_T &= \tfrac{\lambda_p - \lambda_0}{\lambda_p F_G} - \mu\varepsilon_P \\ \mu\varepsilon_T &= (\alpha_\Lambda + \alpha_n)(T - T_0) \end{aligned} \tag{4}$$

The coefficient of linear thermal expansion (α_Λ) and the refraction index (α_n) relate temperature changes from the starting value of T_0 with $\mu\varepsilon_T$. The value of α_n is much larger than α_Λ for this application. Measured peak value (λ_p) as shown in Equation 5 on the temperature compensation gauges give an expression for T as shown in Equation 4.

$$T = \frac{\lambda_p - \lambda_0}{\lambda_p F_G\,(\alpha_\Lambda + \alpha_n)} + T_0 \tag{5}$$

Similar to the pressure correlation, Equation 5 is a linear correlation with constants that are either specified or calculated by regression for the purpose of calibration to existing measurements.

INNOVATIONS

An innovation of this project is the software analysis to provide real-time information on temperature and pressure in actionable form without overloading the data systems with the high data transfer rates as shown in Figure 6. The swept laser light source continuously interrogates the fiber optic line at a rate of 100 Hz (cycles/sec). Although the swept laser optical interrogator is capable, a high rate of 1000 Hz is not feasible for the long distances involved because the required light travel time and analysis of a swept laser does not permit the higher rate. A compression algorithm is deployed to deliver information on both pig passage (high speed required to detect passage) as well as continuous pressure and temperature measurements (lower sampling rates required). A multivariate regression [10] to existing sensors is used to fine-tune the temperature and pressure sensors measurements.

Topside software converts the shifted wavelength peaks into pressure and temperature readings that are transferred to the DeltaV Master Control Station. Frequent updates are provided in summary form to the Master Control Station via an Ethernet Modbus connection. The client has the capability to view DeltaV screens at the home office in near real-time.

This application on *SSC* and *BAR* is an advancement over earlier projects because it is the first application where there is active monitoring of the merging point of two flowlines. As mentioned previously, the sensors do not require direct contact with the production fluid. This allows sensors to be added or adapted without shutting in the production. The three sensor stations for each flowline termination were dry installed with fibers coated in a pressure balancing compound and tested as shown in Figure 7.

After the sensing stations are completed, the flowline termination is painted and prepared for insulation casting as shown in Figure 8. One notable aspect of this project is that the design of the flowline termination was not modified to fit the sensors. The sensors were custom built on bare flowline pipe sections. Typical installation requirements are at least 20 cm (8 in) of exposed pipe surface either in the radial or axial direction, depending on the type of sensor.

SENSOR CALIBRATION AND FIELD PERFORMANCE

A test article was constructed in the lab for the purpose of testing the calibration methods to correlate FBG sensor readings to known temperatures and pressures in the case of no available temperature compensation. In this case, an axial and hoop strain sensor were placed on a 5 cm (2 inch) section of pipe that was liquid filled and capped at both ends with a check valve to inject additional liquid and raise the pressure. The purpose of this study was to investigate the calibration in the event of a temperature compensation sensor failure. The results of the calibration exercise are shown in Figure 9. The pressure and temperature show good agreement over the range of operation. This calibration exercise suggests that tempeature compensation sensors are valuable, but not required if there are at least hoop and axial sensors present.

After umbilical installation and connection to topside servers, the sensors were calibrated to the available nearby measurements. Although sensors readings were taken on-shore during installation, calibration was required under hydrostatic pressure at water depth. Periods of start-up and shut-in data were available to link the fiber optic peak wavelength positions to temperatures and pressures. A multi-variate regression was performed to align measurements during endpoint conditions as well as transient operations with many thousands of data points [11]. If calibration data were not available from instruments, only the seawater temperature would be used for the lowest temperature point and known correlations for any deviation. During the calibration phase, many days of historical temperature and pressure data were simultaneously recorded with the FBG sensor values.

Sensor Performance

The pressure and temperature are monitored for individual sensor stations as well as average values that are reported for the termination assembly. The specific location of the three sensors were previously shown in a simplified process flow diagram in Figure 1. Fiber optic sensor station BAR_3 is isolated from the flowline by a pipeline blind and is intended for future capacity expansion. Sensor stations BAR_1 and BAR_2 are close to the wellhead and give an accurate temperature of the produced fluids before there is heat loss to the surrounding water. Sensor station SSC_3 measures the temperature and pressure at the end of the *BAR* tieback before it co-mingles with *SSC* production. Even at full-rates, this temperature enters the *SSC ILS* much cooler than recorded near the wellhead. Sensor stations SSC_2 and SSC_1 measure the mixture of *SSC* and *BAR* flow.

The sensors on the $BAR\ FLET$ and $SSC\ ILS$ were tested during well start-up following a prolonged shut-in period. The start-up schedule had both wells coming online at the same time but there was an issue that prevented *BAR* from starting for a couple additional days. *BAR* began flowing at 0.5 hr, just long enough to raise the temperature of the $FLET$ to 55 ^oF before shutting down again as shown in Figure 11.

Figure 11 has many other details of the performance of the sensors during start-up and ramping to full-production. One of the notable items is the excellent agreement between temperature of the MPM and FBG sensors as production starts first on the *SSC ILS* and $BAR\ FLET$. The deviation on *SSC* at 4.5 days

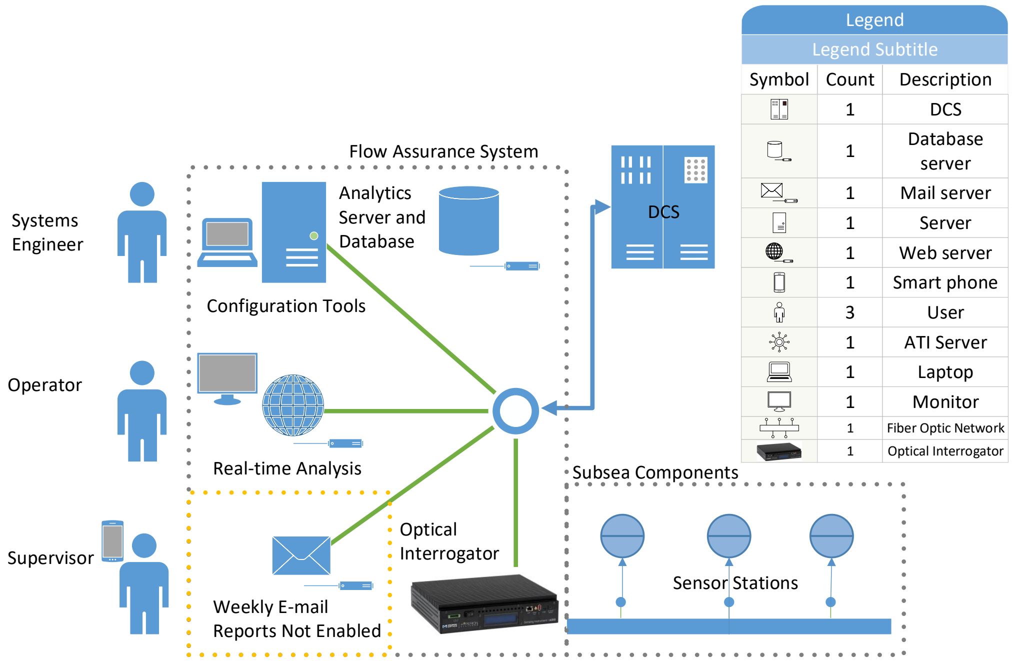


FIGURE 6: SOFTWARE SENSING INTEGRATION WITH THE DISTRIBUTED CONTROL SYSTEM.

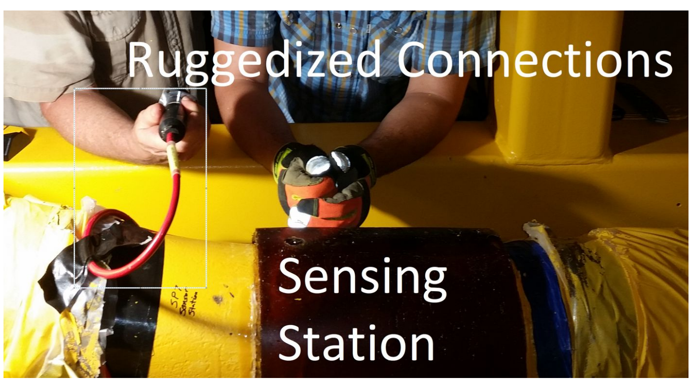


FIGURE 7: *FLET* MEASUREMENT STATION TESTING.

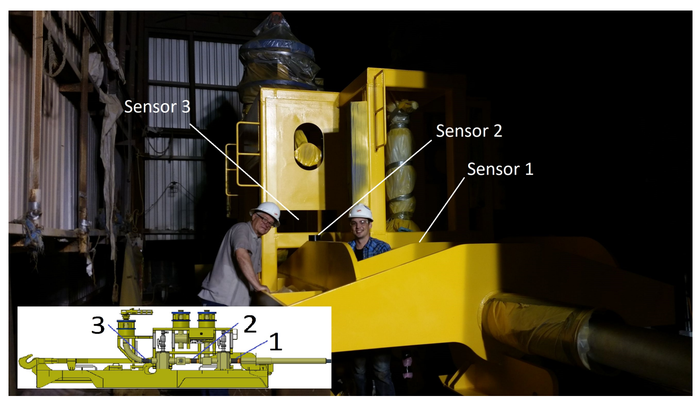


FIGURE 8: FLOWLINE TERMINATION MEASUREMENT STATION TESTING PRIOR TO INSULATION.

is due to the 11 km (7 mi) cold slug of fluid at $\sim$38 ^oF that is stagnant in the pipeline between *BAR* and *SSC*. When *BAR* starts flowing, the cold slug is pushed onward and co-mingles with the *SSC* production. While the temperature performance is excellent for both *BAR* and *SSC*, there is more disagreement between the pressure of the MPM and *FLET* or *ILS* sensors. The difference in pressure, particularly at *SSC*, may be due to a number of issues that are not conclusively diagnosed. Because the sensor stations are at different locations than the MPM meters as shown in Figure 1, all sensors may be correct if there are fluid velocity or hydraulic head differences due to elevation of the flowlines at those particular points.

Individual sensors give additional insight on the co-mingling that takes place at the *SSC ILS* as shown in Figure 11. The sensing station SSC_3 measures the production from *BAR* that has dissipated heat to the surrounding seawater over 11 km (7 mi). At 0.5 days, *BAR* attempts start-up but then has 4.0 more days of

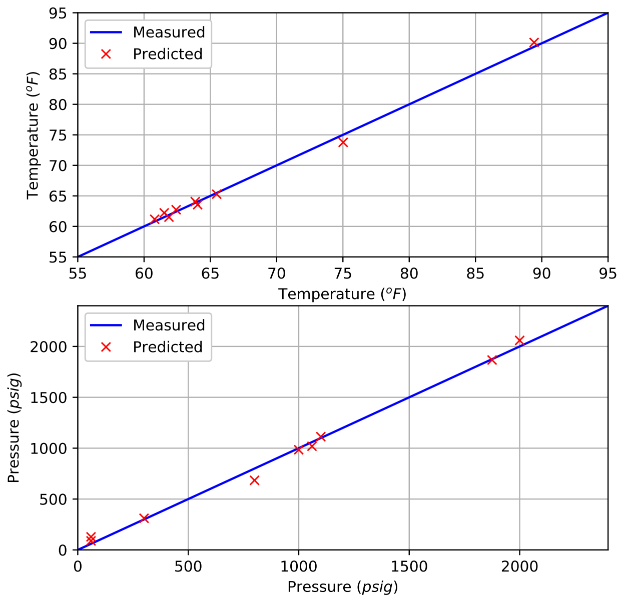


FIGURE 9: CALIBRATION RESULTS WITH ONLY HOOP AND AXIAL SENSORS.

shut-in. The *BAR FLET* cools to seawater temperature after 1.5 days. When *BAR* starts again at 4.5 days, the *FLET* T_1 (BAR_1) and T_2 (BAR_2) sensor stations are in agreement with the production fluid temperature. The third sensor station T_3 (BAR_3), also rises but is behind a blind so the effect is due to heat conduction through the pipe and stagnant fluid behind the blind.

The *SSC* sensor stations (SSC_1, SSC_2, and SSC_3) give a detailed view of the mixing zone of the *SSC ILS*. The *ILS* T_3 is the temperature of the produced fluids just before it is mixed with the warmer *SSC* production. The cold slug of fluid from *BAR* is recorded by *ILS* T_3 from day 4.5 to 5.2 as the line is replaced with warm reservoir fluids. The temperature steadily climbs starting at the time of 5.3 days as the production fluid heats the steel pipeline and approaches a steady state temperature of 70-80 ^oF. This outlet temperature depends on the flow rate with a higher temperature as the flow increases. The normalized flow from original units of barrels per day is shown in the bottom subplots along with the fractional flow from *BAR* and *SSC* that is joined in the mixing zone. *ILS* T_2 is closer to the mixing point and more closely aligns with *SSC* production temperature due to incomplete mixing of the fluids and the specific location of the fiber optic sensors on the top of the pipe. *ILS* T_1 is further from the mixing zone and more accurately represents the combined fluid temperature. These temperatures and pressures are important for detecting flow assurance issues, particularly during shut-ins and start-ups when cold fluid is expected from the *BAR* line.

STRUCTURAL MONITORING AND FLOW ASSURANCE

There has been significant advancement in instrumentation for deepwater offshore in the past couple decades. Fiber optic technology has developed from an immature technology to low-risk, reliable, and predictable technology. The additional instrumentation is a shift in the industry towards Intelli-fields [12] that automatically sense and respond to events with immediate and small adjustments instead of reactionary methods that often require more drastic mitigation such as hydrate remediation.

Monitoring temperature and pressure is particularly important for flow assurance. Critical areas of flow assurance include pressure management, start-up sequences, multiphase flow characterization, thermal management with active heating or passive insulation, hydrate mitigation, wax deposition, asphaltene buildup, scales, emulsion, erosion, and internal corrosion. Flow assurance has developed in deepwater applications from pressure management and pipe sizing to a holistic strategy to prevent, detect, and mitigate flow assurance issues. Fiber optic sensors are only one of the many technologies being applied for active monitoring of flowlines and integrate well with other sensors. In this case, high frequency data (100 Hz) is another tool to better characterize flow assurance. This particular installation is of special interest because of the active monitoring at a co-mingling point on an *ILS*.

Long-term development with Clear Gulf JIP

The Clear Gulf Joint Industry Project (JIP) was founded in 2010 to address technology developments for deepwater applications. The Clear Gulf JIP relies on oil and gas industry experts as well as test facilities at NASA. While the sensors on this project were dry-installed, the post-installed clamp design and adhesion to the pipe is recently improved with fundamental research and testing conducted by NASA Johnson Space Center [13, 14] for long-term service life verification. The new clamp design is shown in Figure 12 with several enhancements over the prior clamp design [4, 5].

NASA provides unique test facilities for extreme environments. The Johnson Space Center is located in Houston to collaborate with several energy companies. Developments and testing at NASA is currently being applied on this and other projects as part of the JIP.

CONCLUSIONS

This work details the design, installation, calibration, and operation of sensors on a deepwater flowline for structural integrity assessment, pig detection, and flow assurance evaluation.

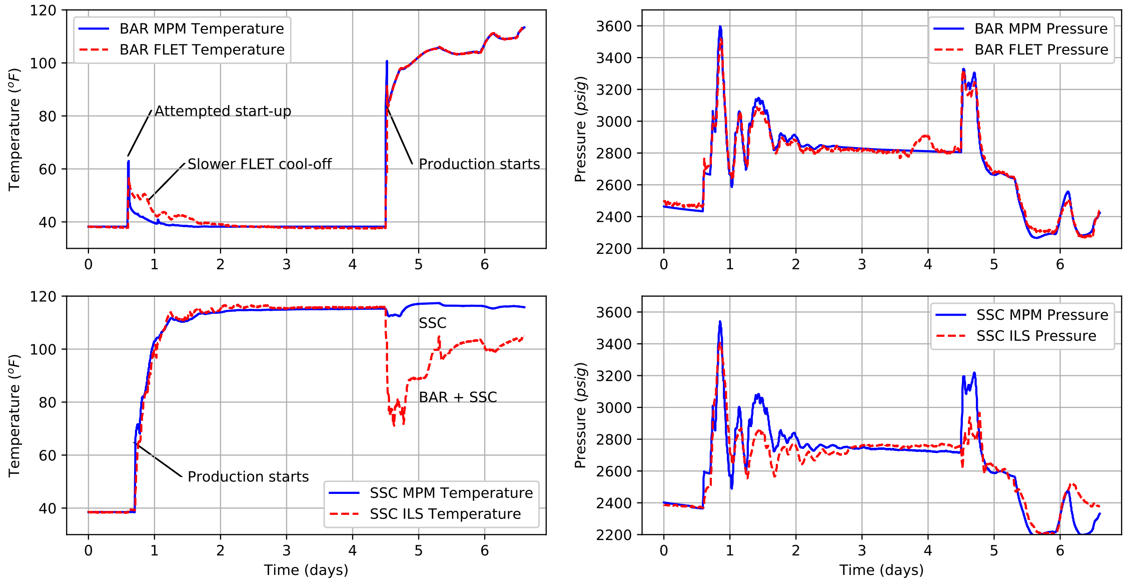


FIGURE 10: FIBER OPTIC SENSORS ON *FLET* AND *ILS* COMPARED TO THE MULTI-PHASE METER (MPM).

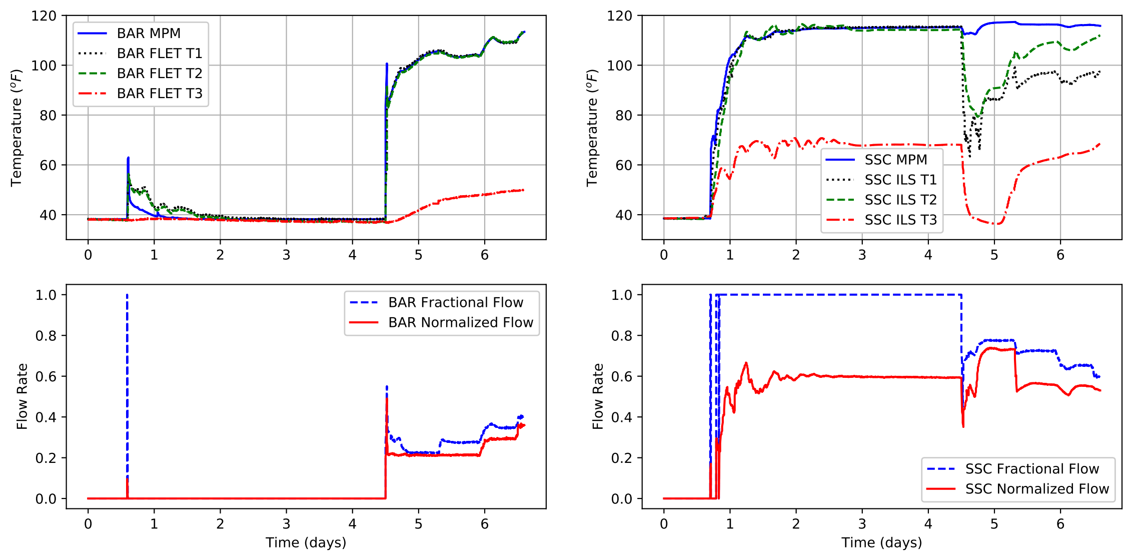


FIGURE 11: INDIVIDUAL SENSORS WITH *BAR* AND *SSC* CO-MINGLED STREAMS.

Key innovations of this project include high frequency data acquisition at 100 Hz, novel in-situ calibration methods, calibration without temperature compensation using only axial and hoop sensors, co-mingling zone evaluation on an *ILS*, and detailed data

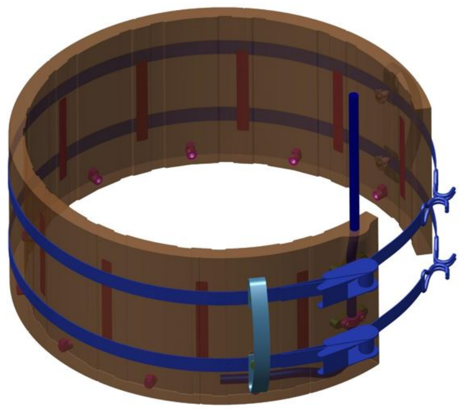


FIGURE 12: CUT-AWAY DIAGRAM OF THE MEASUREMENT STATION CLAMP FOR INSTALLATION ON EXISTING SUBSEA PIPELINES.

of the installed performance compared to a conventional gauge. Possible future work is the automated high speed detection of hydrate formation events, flow estimation from successive sensor arrays that measure pressure drop, automated re-calibration for pipeline wall thickness changes (erosion), and improved fiber diagnostics from the optical interrogator to detect line breaks, and enhanced multiplexing to increase the limit of sensors along a single fiber strand. Concurrent improvement efforts are also being conducted on sensor clamp and adhesion design, particularly for post-installed fiber-based monitoring systems.

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