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# Research Progress and Advances in Monitoring the Integrity of Oil and Gas Wellbores

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## Abstract

**Maintaining the integrity of wellbores is crucial for the success of oil and gas production, especially for carbon capture and storage (CCS) and geothermal projects. This review discusses current research efforts and advancements in methods aimed at monitoring wellbore integrity. The review critically examines current monitoring practices, identifies challenges, and compares various techniques. Advancements in sensing technologies, including fiber-optic and acoustic sensors, are explored, supported by case studies showcasing successful applications. Real-time monitoring systems, incorporating data analytics and machine learning, are scrutinized through case examples demonstrating their effectiveness.**

## Keywords

**Wellbore Integrity Monitoring; Fiber Optic Sensing; Permanent Downhole Gauge.**

## 1. Introduction

Ensuring wellbore integrity is a critical aspect of the entire lifecycle of oil and gas operations, ranging from exploration to mature developments. The Subsurface Containment Assurance Program[1] emphasizes the containment of produced or injected fluids within their designated wellbores or geologic zones. This containment is deemed crucial for both conventional and unconventional prospects and reservoirs, highlighting its fundamental role in exploration and production activities.

Wellbore integrity monitoring spans the evolution of techniques from the early exploration period, where the focus was on reaching hydrocarbon reservoirs with limited monitoring tools, to the introduction of well logging tools in the 1920s and 1930s, providing basic measurements for assessing wellbore conditions. Advancements in cementing practices during the 1940s and 1950s improved zonal isolation. The 1960s and 1970s saw the introduction of downhole pressure and temperature monitoring as drilling moved into challenging environments. Acoustic and seismic monitoring emerged in the 1980s and 1990s, enabling the detection of anomalies and structural issues. The 21st century witnessed a significant leap with the integration of fiber optic sensing technologies, particularly Distributed Fiber Optic Sensing (DFOS)[2-4], enabling real-time monitoring along the entire wellbore length. Recent years have seen a focus on digitalization, data analytics, and machine learning for predictive maintenance[5-7], as well as the integration of data from various sources for a comprehensive assessment[8, 9]. Advances in remote monitoring, automation, and Industry 4.0 principles have further enhanced wellbore integrity management. The present era emphasizes the adoption of Digital Twins (DT), enabling a virtual representation of the wellbore for real-time monitoring and analysis. Throughout history, the industry's pursuit of accurate, real-time, and comprehensive monitoring techniques reflects a commitment to ensuring the safety, efficiency, and sustainability of oil and gas operations.

The purpose of this paper is to provide a comprehensive overview of current advancements, challenges, and future directions in wellbore integrity monitoring within the oil and gas industry. By offering insights into the state-of-the-art practices, the paper intends to depict the current landscape of wellbore integrity monitoring and stimulate discussions on future developments and research directions.

## 2. Permanent Downhole Gauges

Permanent Downhole Gauges (PDGs) are critical tools in the oil and gas industry for continuous real-time monitoring of downhole conditions in wells. They are permanently installed in wells to measure and record key parameters such as pressure, temperature, and sometimes flow rate. Unlike conventional gauges that are deployed temporarily for specific well testing operations, PDGs remain in place throughout the well's lifecycle, providing ongoing insights into reservoir behavior and well performance. The West Erregulla gas field, located in the northern part of the Carnarvon Basin offshore Western Australia, achieved its first natural gas production in mid-2017. All seven wellhead producers are equipped with Permanent Downhole Pressure Gauges (PDHG) for real-time pressure monitoring[10]. As of 2006, the number of permanently installed gauges is probably in excess of 10,000 worldwide[11].

Permanent Downhole Gauges (PDGs) employs a sophisticated array of technologies for precise and continuous monitoring of downhole conditions. One fundamental category within PDGs encompasses various sensing technologies, each serving a specific purpose in the comprehensive monitoring system.

Pressure sensors, such as Quartz Crystal Gauges (see Figure 1), play a pivotal role in accurately measuring downhole pressure. Quartz Crystal Gauges leverage the piezoelectric effect and the hardness of quartz, making it an ideal material for constructing precision sensors. It's should be noted that that only single crystal alpha quartz is suitable for creating these sensors.

**Figure 1.** Quartz pressure sensor of Quartzdyne

Fiber Optic technology can be utilized for strain and temperature gauges, which measure the deformation or strain in downhole components. Fiber Optic Strain Gauges are known for their resilience in harsh downhole environments. A specific type of fiber optic sensor employed in PDGs is the Fiber Bragg Grating (FBG) sensor (see Figure 2). FBG consists of a fiber segment where the refractive index is periodically altered. This periodic alteration causes specific wavelengths of light to be strongly reflected, while allowing others to pass through. In the context of PDGs, FBG sensors are used to measure both temperature and pressure downhole. The ability of FBGs to operate in high-temperature and high-pressure environments makes them well-suited for downhole applications[12].

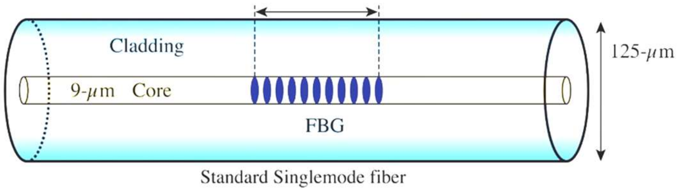

**Figure 2.** FBG sensor

Communication and data transmission systems, whether wired or wireless, facilitate real-time data transfer and integration with Supervisory Control and Data Acquisition (SCADA) systems for centralized monitoring. Power supply and energy management are crucial, with battery-powered systems and efficient power management ensuring sustained operation in harsh downhole environments. The materials, encapsulation, and sealing category focus on the robustness of PDGs, incorporating hermetic sealing, corrosion-resistant materials, and sturdy casings to protect internal components from extreme pressures, temperatures, and corrosive fluids. Halliburton's downhole flow measurement has evolved from very large printed circuit board technology to hybrid electronic technology, a significant driving factor being the ability to withstand higher temperatures. The company has improved the flow control valve (ICV) in its SmartWell system to adapt to high-pressure environments, with pressure differentials reaching up to 15,000 psi.

The installation of downhole monitoring instruments imposes elevated demands on field operations, necessitating the customization of wellheads and casings (see Figure 3), as well as the design of specially adapted short sections for Permanent Downhole Gauge (PDG) installations. The deployment process involves the careful insertion of optical cables, hydraulic lines, and electrical cables, and it is most suitable for wells with slight inclinations. Each procedural step must be meticulously executed to ensure the integrity of the instrument equipment. Moreover, the well completion and cementing cycle for such installations is twice the time required for conventional wells, adding complexity to the overall operational timeline. However, despite these challenges and extended timelines, the benefits derived from enhanced reservoir monitoring and optimized production strategies often outweigh the drawbacks, justifying the investment in these advanced downhole monitoring technologies.

**Figure 3.** (a)Customed wellhead (b) Customed Joints (c)Example of casing-conveyed downhole gauge Installation

Transient identification methods are techniques used to identify and analyze transient events in pressure measurements obtained from permanent downhole gauges (PDG) installed in wells. Traditional transient identification methods involve manual processing and analysis, but with advancements in well surveillance technology, there is a need for automated transient identification. Several methods have been proposed in the literature for transient identification, including wavelet decomposition methods and pressure data trend methods. These methods vary in their detection algorithms, testing results, and overall performance and application[13].

The influx of data from PDGs has led to the integration of data analytics and machine learning algorithms. These tools help operators extract valuable insights from large datasets, identify patterns, and predict potential issues. Predictive analytics contribute to proactive well and reservoir management. Khazali[14] employ least square support vector machines (LS-SVM) as a machine learning method for analyzing data from PDGs.

In gas lift wells, the gas flow rate can be used to determine downhole pressure which is the most important variable to describe the dynamics of an oil well[15]. This is also called soft sensors, a set of computational models or algorithms that estimate or predict physical quantities or process variables within a system[16]. They are termed "soft" to distinguish from traditional "hard" downhole gauges. It relies on mathematical models, algorithms, and data-driven techniques to infer downhole pressure. The use of soft sensors is particularly advantageous in situations where installing and maintaining physical sensors may be challenging or cost-prohibitive[17].

## 3. Fiber Optic Sensors

The utilization of fiber optic sensing in the oil and gas industry has undergone significant expansion in the last two decades. Baldwin[18] offers a historical perspective, tracing the evolution of fiber optic sensing in the industry from its initial applications to its current diverse uses. Beyond wellbore applications, fiber optic sensors are extensively employed for flowline and pipeline monitoring, as well as riser integrity monitoring. Some applications push the boundaries with operating temperatures reaching 300°C and pressures exceeding 137.9 MPa. Xue[19] introduces a method for monitoring caprock and wellbore integrity at CO2 storage sites through Distributed Fiber Optic Sensing. DFOS possesses a unique advantage in measuring temperature and strain at any point along an unprocessed optical fiber, contrasting with conventional methods like Fiber Bragg Grating (FBG), which measures at discrete points. Sun [20] further investigates the application of DFOS in CO2 geological storage (CGS) through field trial wells in Japan. Raab[21] explore the application of fiber-optic distributed-acoustic-sensing (DAS) technology for real-time well-integrity monitoring by acquiring dynamic axial-strain changes caused by elastic wave propagation along the wellbore structure. White[22] present a case study highlighting unexpected casing erosion during hydraulic fracturing, leading to the loss of inter-stage isolation, as detected through fiber optic signals. Additionally, Lipus[23] demonstrate the diverse applications of fiber-optic distributed acoustic sensing (DAS) data in wellbore monitoring, including flow monitoring, formation evaluation, and well integrity studies.

In wellbore monitoring, three primary deployment methods are utilized to position and secure fiber optic sensors, ensuring accurate and reliable data acquisition(see figure 4). The first method involves deploying the sensor inside the tubing of the wellbore. The second method entails placing the sensor outside the tubing, utilizing a clamping mechanism to secure it in the annular space between the tubing and the casing. The third method, for deployment outside the casing, employs both clamping and cementing for enhanced stability. The choice of deployment method depends on factors such as wellbore configuration and monitoring objectives.

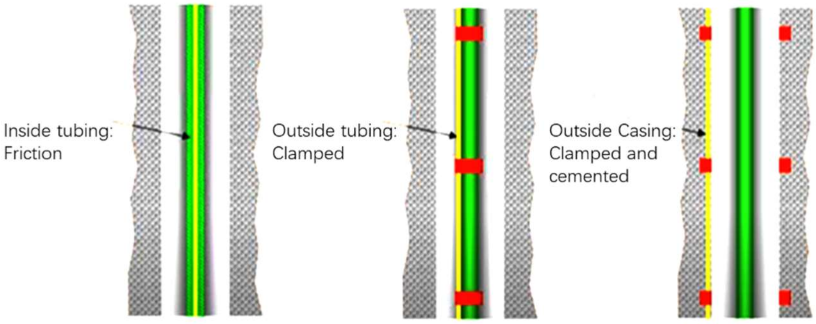

**Figure 4.** Inwell Deployment Methods

Scattering phenomena in optical fiber play a crucial role. When light propagates along an optical fiber, various scattering phenomena contribute to distributed sensing (see Figure 5). Rayleigh scattering[24], characterized by interactions with microscopic variations in the refractive index, is utilized for acoustic, strain, and temperature sensing. Brillouin scattering[25], involving interactions with acoustic phonons, enables simultaneous strain and temperature measurements. The Brillouin frequency shift, influenced by both temperature and strain, provides comprehensive sensing capabilities. Raman scattering[26], another significant process, contributes to temperature sensing by analyzing the frequency shift in the scattered light. This integrated suite of scattering mechanisms, including Rayleigh, Brillouin, and Raman scattering, allows for versatile and simultaneous monitoring of acoustic signals, strain, and temperature variations along the optical fiber.

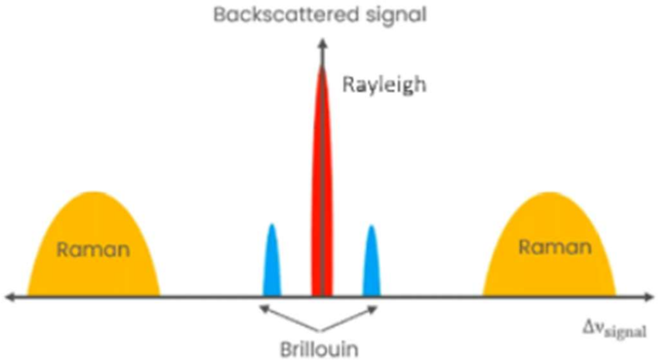

**Figure 5.** Scattering phenomena in optic fiber

Distributed Acoustic Sensing (DAS) is a fiber optic sensing technique that utilizes the entire length of an optical fiber as a continuous sensor to detect acoustic signals or vibrations. DAS relies on the principle of Rayleigh scattering, a phenomenon where microscopic variations in the refractive index of the glass along the optical fiber cause scattering of light. The entire optical fiber becomes a distributed sensor, with each segment acting as a virtual microphone. When acoustic waves or vibrations travel along the optical fiber, they induce changes in the backscattered light patterns due to the modulation of Rayleigh scattering. These changes in the scattered light are detected and analyzed by the DAS system. By interpreting these patterns, DAS can provide real-time information about the location, intensity, and frequency characteristics of acoustic events along the length of the fiber.

Distributed Temperature Sensing (DTS) is a fiber optic sensing technique that monitors temperature variations along the entire length of an optical fiber. DTS systems are mostly based on the principle of Raman scattering, an inelastic scattering phenomenon. Unlike Rayleigh scattering, which is commonly used in other fiber optic sensing techniques, Raman scattering involves a change in the energy of the scattered photons. In DTS, a laser pulse is injected into the optical fiber, and as the pulse travels along the fiber, it interacts with the molecular vibrations of the fiber's material. The scattered light, which undergoes Raman scattering, experiences a frequency shift proportional to the temperature of the fiber at that point. By analyzing the frequency shift in the Raman-scattered light, DTS systems can provide continuous and real-time temperature profiles along the entire length of the optical fiber.

Distributed Strain Sensing (DSS) is used to monitor and measure strain along the entire length. It relies on the changes in the fiber caused by strain. The strain-induced changes affect the properties of the optical signal traveling through the fiber. One common method for DSS is the use of Fiber Bragg Grating (FBG) sensors embedded or inscribed in the optical fiber. The Bragg wavelength of the FBG changes when the fiber experiences strain. In some cases, distributed strain sensing can be integrated with Distributed Temperature Sensing (DTS) for comprehensive monitoring of both strain and temperature along the same optical fiber. Brillouin-based DTSS involves utilizing Brillouin scattering to simultaneously measure temperature and strain variations at different points along the optical fiber. DAS can also detect strain change, and it offers superior time sensitivity, making it particularly effective for capturing rapid changes and dynamic events, but its resolution is constrained by the impact of minor vibrations on Rayleigh scattering, making it particularly suited for monitoring sound waves and vibrations. Brillouin-based DSS demonstrates higher spatial sensitivity to small strain changes, as Brillouin scattering's frequency shift is linearly related to strain. It is advantageous when high spatial resolution and accuracy in pinpointing strain locations are paramount. Wu[27] developed real-time and in-situ monitoring of the cement-casing bond using a fiber optic DTSS system. The helical wrapping installation enables circumferential measurements of temperature and strain changes in the entire cement annulus. Additionally, some researchers[28, 29] delve into pH sensing capabilities using sol-gel-coated titanium oxide (TiO2) fiber optic sensors in wellbore cement conditions.

Single-mode fiber (SMF) and multimode fiber (MMF) (see Figure 6) are essential in downhole monitoring. In downhole monitoring and sensing, single-mode fiber (SMF) is often preferred due to it is suitable for longer-distance transmissions, which is crucial when deploying sensors or communication systems deep into the wellbore. The low dispersion and attenuation of SMF help maintain signal integrity over extended distances. Multimode fiber (MMF) is commonly used in local area networks (LANs) within oil and gas facilities or shorter wellbores. It is cost-effective for shorter-distance applications. Attenuation is a critical factor in optical communication systems, as it determines the maximum distance over which the signal can be transmitted before the signal becomes too weak to be reliably detected. Ultra-low loss fibers are engineered, and Manufacturers continually work on developing fibers with lower attenuation characteristics to improve the efficiency and reach of optical communication systems.

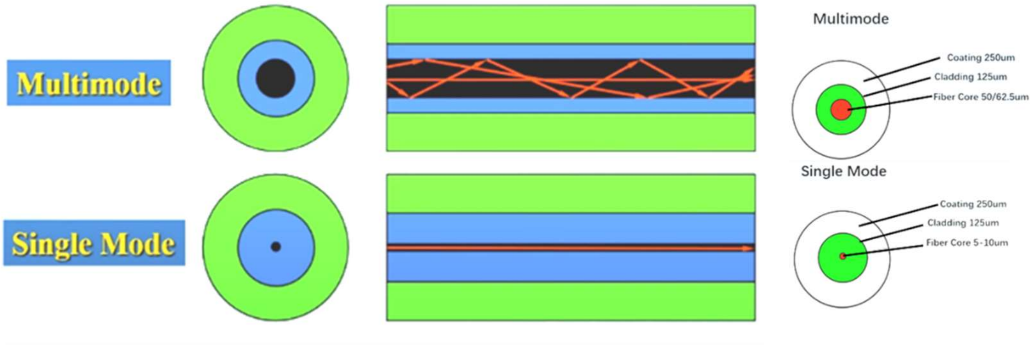

**Figure 6.** Single mode and multimode fiber

## 4. Downhole Corrosion Monitoring

The oil and gas industry grapples with corrosion-related challenges, leading to equipment degradation and eventual failure. Corrosive impurities in crude oil, including carbon dioxide (CO2), hydrogen sulphide (H2S), and free water, contribute to internal component corrosion, posing a significant threat to the integrity of wellbore tubing and equipment. Various forms of corrosion, such as CO2 corrosion, H2S corrosion, O2 corrosion, galvanic corrosion, crevice corrosion, are prevalent in wellbores. Monitoring the corrosion of materials and structures in downhole conditions is crucial, and traditional techniques like weight loss and electrochemical methods are commonly employed.

Currently, the oil and gas industry primarily uses electrical resistance (ER) and ultrasonic probes for corrosion monitoring. ER sensors (see Figure. 7) use metallic electrodes to measure the change in resistance. The sensor element is made of a material with a composition similar to that of the structure to be monitored. Thin probes are used for environments where the expected corrosion rate is relatively low, while probes with larger cross-sectional area are used for more aggressive media. The probe should be energized with a constant current, the changes of voltage is measures. The ultrasonic probe (see Figure. 8) involves a transducer and a probe, where the transducer emits ultrasonic waves that travel through the material to be measured. The probe detects echoes as the waves reflect back. The time taken for this round trip is measured, and, knowing the speed of sound in the material, the thickness is accurately calculated. Calibration is essential for accuracy, some advanced ultrasonic thickness gauges incorporate multiple transducers and signal processing techniques for enhanced precision. It is renowned for its non-destructive nature and real-time measurement. Despite their widespread use, these sensors have drawbacks, such as slow response time, lower reliability, high cost, and specificity to particular chemical species.

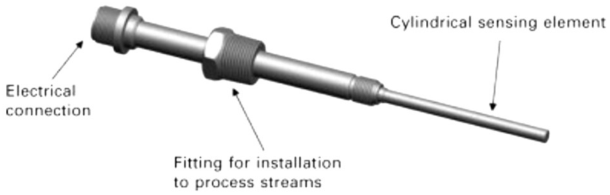

**Figure 7.** Typical ER probes[30]

**Figure 8.** Typical commercial downhole ultrasonic sensor

Several innovative downhole corrosion monitoring devices and systems have been proposed.

Al-Ajmi et al.[31] introduced a risk-based methodology for predicting downhole casing leaks using advanced casing corrosion logs. Leal et al. [32] shared insights from long-duration batch treatment using corrosion inhibitors in deep sour gas wells, monitored with a new downhole corrosion and scale monitoring tool. Chanchlani et al.[33] contributed to improving the mean time before failure (MTBF) in rod-pumped wells through a corrosion decision tree for risk assessment and corrosion management.

The application of novel materials, such as ZnO nanosheets[34] and boron-doped diamond electrodes[35], has been explored for corrosion monitoring in downhole environments. These materials enhance the sensitivity and durability of sensors, contributing to more reliable data collection. Moreover, the study of corrosion behaviors under dynamic conditions, such as those induced by $CO_2$ or in simulated oilfield brines[36, 37], has provided deeper insights into the factors influencing downhole corrosion.

Furthermore, research has extended beyond traditional metallic structures to include monitoring techniques for non-metallic components in downhole environments. For instance, corrosion monitoring in concrete structures, which are commonly used in well construction, has been addressed through the development of embeddable potential sensors[38]. These sensors offer a non-destructive approach to assess corrosion within concrete, contributing to the overall integrity of the well infrastructure.

In the realm of downhole corrosion monitoring, advancements in sensor technology have paved the way for a more comprehensive understanding of corrosion processes. The integration of these monitoring techniques not only ensures the longevity of well infrastructure but also contributes to the overall safety and efficiency of oil and gas operations. Ongoing research continues to explore new materials, sensor designs, and monitoring strategies to further enhance the accuracy and reliability of downhole corrosion assessments.

## 5. Outlook and Conclusion

The field of wellbore integrity monitoring in the oil and gas industry has witnessed significant evolution, progressing from early well logging tools to the integration of technologies like Distributed Fiber Optic Sensing (DFOS). This comprehensive review highlights the historical developments and current state-of-the-art practices in wellbore integrity monitoring, emphasizing the industry's commitment to safety, efficiency, and sustainability. Permanent Downhole Gauges (PDGs) play a pivotal role in continuous real-time monitoring, utilizing advanced technologies such as Quartz Crystal Gauges and Fiber Bragg Grating sensors. The deployment of PDGs involves sophisticated customization of wellheads and casings, contributing to enhanced reservoir monitoring and optimized production strategies. Additionally, the integration of data analytics and machine learning algorithms has become imperative for extracting valuable insights from the influx of PDG data. Fiber optic sensing technologies, including Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS), have become integral for wellbore monitoring. Downhole corrosion monitoring techniques contribute to a deeper understanding of downhole corrosion processes.

In conclusion, the outlook for wellbore integrity monitoring is promising, with ongoing research focusing on refining materials, sensor designs, and monitoring strategies. The industry's continuous pursuit of accuracy, real-time monitoring, and comprehensive assessments reflects its dedication to overcoming challenges and ensuring the long-term viability of oil and gas operations. The integration of advanced technologies, coupled with a proactive approach to risk assessment and corrosion management, positions the industry for sustained success in maintaining wellbore integrity.

## References

[1] Schultz RA, Summers LE, Lynch KW, Bouchard AJ. Subsurface containment assurance program-Key element overview and best practice examples. Offshore Technology Conference Asia: OTC; 2014. p. OTC-24851-MS.

[2] Ashry I, Mao Y, Wang B, Hveding F, Bukhamsin AY, Ng TK, et al. A review of distributed fiber–optic sensing in the oil and gas industry. 2022;40(5):1407-31.

[3] Bao X, Chen LJs. Recent progress in distributed fiber optic sensors. 2012;12(7):8601-39.

[4] Baldwin CS. Applications for fiber optic sensing in the upstream oil and gas industry. Fiber Optic Sensors and Applications XII: SPIE; 2015. p. 69-78.

[5] NIZAR M. Digitalization and Data Automation: The Path for a More Efficient Well Integrity Data Management and Cost-Effective Responses. Abu Dhabi International Petroleum Exhibition and Conference: SPE; 2022. p. D022S164R002.

[6] Thomas T, Norman B. Quantifying Well Integrity Risk at Scale: A Repeatable & Data Driven Analysis of Well Integrity in Unconventional Gas Fields. SPE Annual Technical Conference and Exhibition?: SPE; 2023. p. D031S4R04.

[7] Al-Shehri DAJS. Oil and gas wells: Enhanced wellbore casing integrity management through corrosion rate prediction using an augmented intelligent approach. 2019;11(3):818.

[8] Gasda SE, Wang JZ, Celia MAJEP. Analysis of in-situ wellbore integrity data for existing wells with long-term exposure to CO2. 2011;4:5406-13.

[9] Duguid A, Carey JW, Butsch RJEP. Well integrity assessment of a 68 year old well at a CO2 injection project. 2014;63:5691-706.

[10] Xia Z, Haynes A, Ong C-S. Pressure and Rate Transient Analysis via Permanent Downhole Gauges–Application and Challenges at Wheatstone Field. SPE Asia Pacific Oil and Gas Conference and Exhibition: SPE; 2020. p. D023S11R01.

[11] Chorneyko DM. Real-time reservoir surveillance utilizing permanent downhole pressures-an operator's experience. SPE Annual Technical Conference and Exhibition?: SPE; 2006. p. SPE-103213-MS.

[12] Zhong ZY, Zhi XL, Yi WJ. Oil well real-time monitoring with downhole permanent FBG sensor network. 2007 IEEE International Conference on Control and Automation: IEEE; 2007. p. 2591-4.

[13] Cui B, Chen L, Zhang N, Shchipanov A, Demyanov V, Rong CJE. Review of Different Methods for Identification of Transients in Pressure Measurements by Permanent Downhole Gauges Installed in Wells. 2023;16(4):1689.

[14] Khazali N, Sharifi MJJoPS, Engineering. New approach for interpreting pressure and flow rate data from permanent downhole gauges, least square support vector machine approach. 2019;180:62-77.

[15] Nygaard G, Nævdal G, Mylvaganam S. Evaluating nonlinear kalman filters for parameter estimation in reservoirs during petroleum well drilling. 2006 IEEE Conference on Computer Aided Control System Design, 2006 IEEE International Conference on Control Applications, 2006 IEEE International Symposium on Intelligent Control: IEEE; 2006. p. 1777-82.

[16] Teixeira BO, Castro WS, Teixeira AF, Aguirre LAJCEP. Data-driven soft sensor of downhole pressure for a gas-lift oil well. 2014;22:34-43.

[17] Aguirre LA, Teixeira BO, Barbosa BH, Teixeira AF, Campos MC, Mendes EMJCEP. Development of soft sensors for permanent downhole gauges in deepwater oil wells. 2017;65:83-99.

[18] Baldwin CS. Brief history of fiber optic sensing in the oil field industry. Fiber optic sensors and applications XI: SPIE; 2014. p. 909803.

[19] Xue Z, Hashimoto TJEP. Geomechanical monitoring of caprock and wellbore integrity using fiber optic cable: Strain measurement from the fluid injection and extraction field tests. 2017;114:3305-11.

[20] Sun Y, Xue Z, Hashimoto T, Lei X, Zhang YJWRR. Distributed fiber optic sensing system for well-based monitoring water injection tests-A geomechanical responses perspective. 2020;56(1):e2019WR024794.

[21] Raab T, Reinsch T, Aldaz Cifuentes SR, Henninges JJSJ. Real-time well-integrity monitoring using fiber-optic distributed acoustic sensing. 2019;24(05):1997-2009.

[22] White M, Friehauf K, Cramer D, Constantine J, Zhang J, Schmidt S, et al. One Stage Forward or Two Stages Back: What Are We Treating? Identification of Internal Casing Erosion during Hydraulic Fracturing-A Montney Case Study Using Ultrasonic and Fiber-Optic Diagnostics. 2021;36(02):383-97.

[23] Lipus MP, Schölderle F, Reinsch T, Wollin C, Krawczyk CM, Pfrang D, et al. Dynamic motion monitoring of a 3.6 km long steel rod in a borehole during cold-water injection with distributed fiber-optic sensing. 2021;2021:1-26.

[24] Palmieri L, Schenato LJTOOJ. Distributed optical fiber sensing based on Rayleigh scattering. 2013;7(1).

[25] Kobyakov A, Sauer M, Chowdhury DJAio, photonics. Stimulated Brillouin scattering in optical fibers. 2010;2(1):1-59.

[26] Li J, Zhang MJLS, Applications. Physics and applications of Raman distributed optical fiber sensing. 2022;11(1):128.

[27] Wu Q, Nair S, van Oort E, Guzik A, Kishida K. Behavior and properties of cement-embedded fiber optic sensors for zonal isolation monitoring. International Petroleum Technology Conference: IPTC; 2019. p. D021S30R04.

[28] Gomes BR, Araújo R, Sousa T, Figueira RBJC. Sol-gel coating membranes for optical fiber sensors for concrete structures monitoring. 2021;11(10):1245.

[29] Shumski A, Diemler N, Wright R, Lu F, Ohodnicki P, Su Y-D. TiO2 coated optical fibers for distributed real-time pH monitoring in wellbore conditions. Fiber Optic Sensors and Applications XVIII: SPIE; 2022. p. 95-103.

[30] Yang L, Chiang K. On-line and real-time corrosion monitoring techniques of metals and alloys in nuclear power plants and laboratories. Understanding and Mitigating Ageing in Nuclear Power Plants. Elsevier; 2010. p. 417-55.

[31] Al-Ajmi MD, Al-Shehri D, Mahmoud M, Al-Hajri NMJJoERT. Risk-Based Approach to Evaluate Casing Integrity in Upstream Wells. 2018;140(12):122901.

[32] Leal J, Ramachandran S, Wang Q, Espinosa M, Elharakany M. Successful long duration batch treatment of gas well to prevent corrosion challenges and solutions. International Petroleum Technology Conference: IPTC; 2020. p. D021S7R03.

[33] Chanchlani K, Khanduja N, Gunwant D. Improving Mean Time Before Failure MTBF in Rod Pumped Wells by Analyzing Corrosion Barriers. SPE International Oilfield Corrosion Conference and Exhibition: OnePetro; 2021.

[34] An Q, Xin Y, Huo K, Cai X, Chu PKJMC, Physics. Corrosion behavior of ZnO nanosheets on brass substrate in NaCl solutions. 2009;115(1):439-43.

[35] Nie M, Neodo S, Wharton J, Cranny A, Harris N, Wood R, et al. Electrochemical detection of cupric ions with boron-doped diamond electrode for marine corrosion monitoring. 2016;202:345-56.

[36] Laumb JD, Glazewski KA, Hamling JA, Azenkeng A, Watson TLJIJoGGC. Wellbore corrosion and failure assessment for CO2 EOR and storage: Two case studies in the Weyburn field. 2016;54:479-89.

[37] Li H, He J, Meng Yap K, Kus S, Srinivasan S. On-line, Real-time Corrosion Monitoring Techniques under CO2-Brine Environment-Comparative Study. NACE CORROSION: NACE; 2017. p. NACE-2017-9040.

[38] Cvetic P, Wright R, Spaulding R, Moore J, Crandall D, DiCarmine P, et al. Cement properties with embedded sensors for wellbore integrity monitoring. Smart Structures and NDE for Industry 40, Smart Cities, and Energy Systems: SPIE; 2020. p. 40-51.