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Using Advanced Materials and Techniques to Repair and Maintain Aging Wellbore

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Abstract
For more than 100 years, engineers and scientists have worked to improve and leverage groundbreaking new materials in the construction of wells. Innovations in material properties, analytical evaluation, and deployment techniques have yielded high-quality wells able to survive effectively through well lifetimes. With improvements in data acquisition and analysis, this review examines how operators and engineers address the critical question: "How well do we really know our wells particularly when planning maintenance, repair, or well abandonment. This review analyzes the performance risks associated with improper repair, maintenance, and life-planning of wells, including considerations of time, safety, environmental impact, and cost factors comparable to initial construction expenses. In subsea wells specifically, proper monitoring and repair has become increasingly critical due to reduced monitoring margins and the significant perceived costs of production interruption. These factors are driving operators toward improved surveillance standards and the adoption of advanced materials and techniques. To ensure the longevity of well equipment and systems in aggressive conditions, the industry continues to develop enhanced surveillance approaches alongside innovative materials and techniques that can withstand challenging operational environments.
Keywords*: wellbore integrity, advanced materials, composite repair, monitoring, self-healing, corrosion, aging wellbore.*

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I. Introduction

Some operators are completing wells with synthetic completions, running optical fiber, and using multi-interval refracturing and producing operations to ensure adequate hydrocarbon flow (Edouard et al., 2022). Others have installed downhole monitoring equipment, packers, chokes, and downhole valves to optimize contributions from multi-interval wells (Golenkin et al., 2020). This requires understanding production from various zones, avoiding premature water or gas coning, and stimulating or isolating undesired or nonproductive zones (Kortukov et al., 2020). To aid production of multiple reservoir intervals, operators routinely run optical fiber inside synthetic casing strings, providing sensing mechanisms to monitor production in real time (Hartog, 2020). The main advantage of these high-resolution downhole systems is their ability to optimize the productive life and output of a reservoir (Sun et al., 2021). For refracturing applications, optical fiber can also be extended to improve stimulation treatment design (Hajiyev, 2021). The goal of using consistent tools and completions across multiple producing zones is to increase the well's load factor (Johny et al., 2021). In multi-intervention scenarios, the advantages are numerous regardless of the intervention objective (Scheffler, 2021). Intervention supply costs can be dramatically decreased, and operational support can be prepared with surprising precision (Du et al., 2022). When problems occur during operations, rapid response becomes possible because rebuilding the bottom hole assembly for repeat operations saves significant time and money (Gevorkyan et al., 2022). In challenging situations requiring fishing or sidetracking operations, the ability to pull near the top of the hole, sidetrack the well, discard potential cuttings appropriately, and lay down surface hole or heel equipment can be a tremendous operational advantage (Hmadeh, 2021). If a second HY-Intervention can be completed in just over one day, costs decrease significantly, dramatically improving the economics of refracturing projects (Ashfaq, 2023).

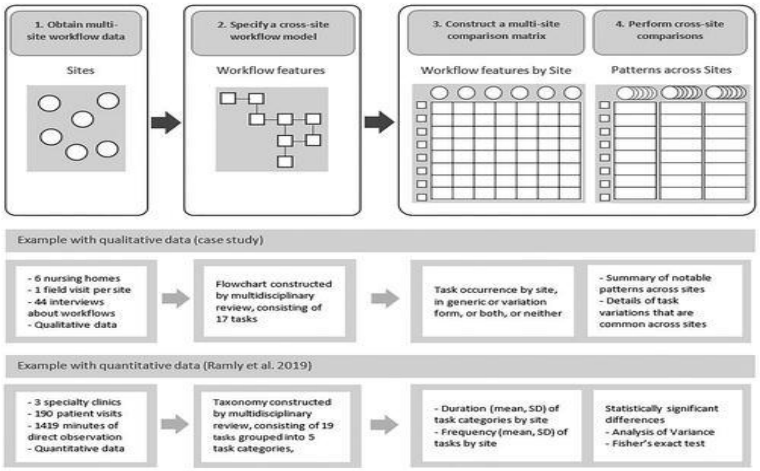

Figure 1: Multi-intervention workflow comparison (Ramly et al, 2021)

Understanding Aging Wellbores

Oil and gas wellbores can suffer similar issues associated with the structural integrity of other concrete structures in harsh environments. Corrosion, thermal movements, hydraulic movement, and microcracks can induce stress up to the ultimate stresses (Zhang et al., 2023). Wellbores differ from other inverted pipe structures in that they are exposed to higher stresses due to internal and external loading existing from the presence of tool motions, casing, and tubing and external parameters including voltage levels, well fluid pH, temperature, and salinity (Wang et al., 2021).

Additionally, aging effects due to the loss of properties of concrete wellbores will occur over time (Nguyen et al., 2022). Acid attack and mechanical abrasion can contribute to properties loss; however, these can be reduced or alleviated through proper cement formulations and casing-cement bonding designs (Xu et al., 2023). Over time, electrochemical corrosion and thermal cycling will still contribute to the aging of the wellbore (Liu et al., 2021).

Narrow self-repairing patching and grouting materials are one set of materials that can be used to arrest the aging process, as well as help to repair damaged areas (Sankaran & Ammasi, 2024). Despite the advancements in these patching and grouting materials, issues continue to exist in applying these materials in elements such as full wellbores, where tube spacing and material placement are likely issues (Rajadesingu et al., 2024).

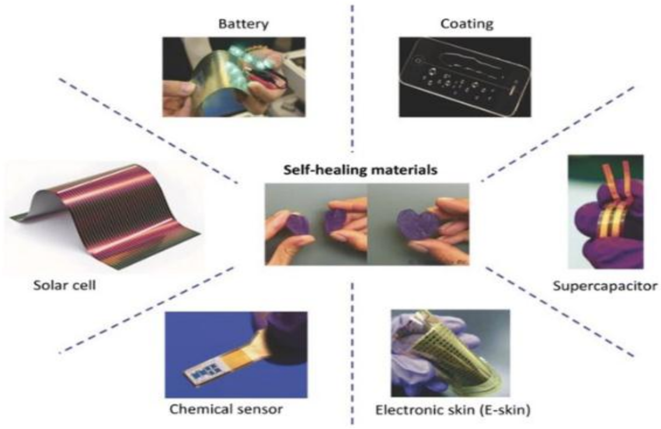

Figure 2: Application challenges of self-repairing materials in wellbore environments (Zhang et al, 2020)

These materials are designed to flow freely into limited void spaces, achieving placement of the material and bonding to the surrounding substrate as a result of shear-thickening (Li et al., 2024). This flow-throttling mechanism, allowing uncured material to conform to the dimensions of the void and then bond to the surrounding substrate upon curing, aids in the self-repairing capabilities of the material (Rb & Kennedy, 2024).

Definition and Characteristics of Aging Wellbores

A wellbore can be referred to as an aging wellbore when it is no longer able to achieve its goals and functions in a safe, efficient, and suitable manner (Al-Rbeawi, 2023). Aging wellbores have been viewed as a concept of paramount importance and urgency, driven by numerous described concrete issues and challenges encountered over and over again by the upstream oil and gas sector (Feng, 2024).

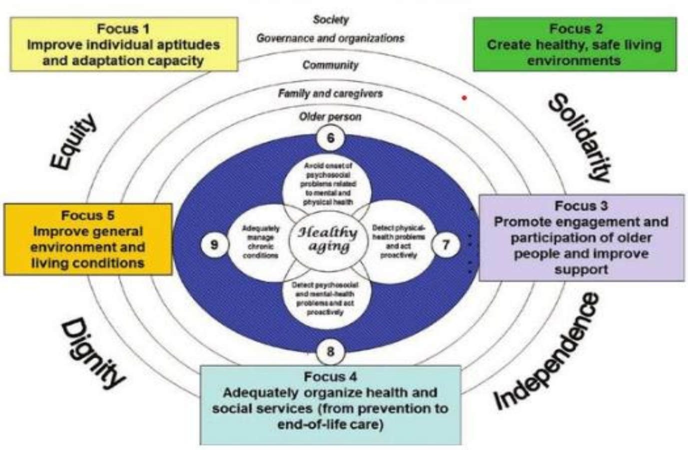

Figure 3: Conceptual diagram of aging wellbore challenges (Dubuc et al, (2013).

Aging wellbores are characterized by a good number of issues and problems, contributed and aggravated by a large number of failure mechanisms and degradation factors, which are capable of making long-term operation of a wellbore both unsafe and uneconomical (Hussain et al., 2022). The prevention and recovery of aging wellbores thus constitute a strenuously urgent task, which does not only require systematic interdisciplinary studies and investigations, as well as the searching for ever more reliable and effective novel materials, but also supplementary advanced techniques and approaches (Fernandez et al., 2024).

The wellbore is a small-diameter drilled hole that penetrates the surrounding stratum, with numerous degrees of slope and direction, and provides a passage for both drilling fluid and gas and oil return from the reservoir to the ground (Toczek & Wisniowski, 2024). It is an essential infrastructure piece for both drilling, oil and gas production, and geological storing of carbon dioxide (Wang et al., 2023). Thus, there can be from one to dozens of thousands of wellbores in a gas field development plan, from a wellhead platform in offshore plant to a processing plan (Batirova et al., 2023).

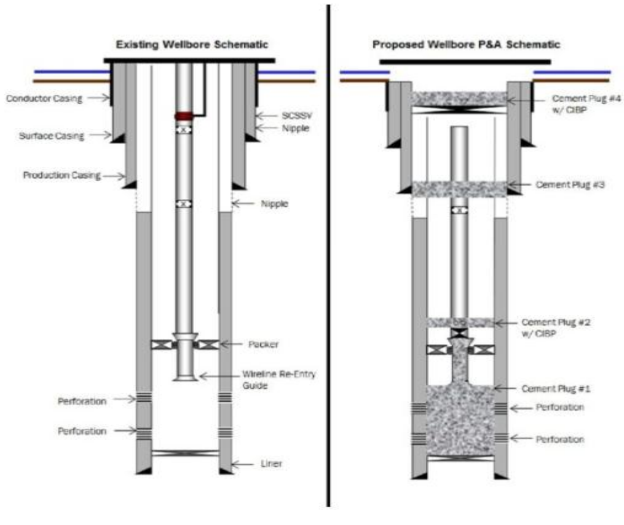

Figure 4: Typical wellbore configuration in an offshore field (Zhang et al, 2020)

It plays a significant role in the investigation and development of energy and protecting the environment (Ahmed, 2022). Gas resources include both natural gas and coal-bed methane, both of which have lean, rich, and dry gas (Liu et al., 2022). To increase the oil recovery ratio, a great number of workovers, perforation, acid fracturing, and infrared fracturing come into play (Lyons et al., 2020).

Causes of Wellbore Aging

In order to comprehensively address and effectively combat the challenges associated with wellbore aging, it becomes imperative to initially acknowledge the fundamental causes that give rise to such issues (Peng et al., 2024). It is worth noting that nearly all instances of wellbore damage stem from interconnected or individual chemical reactions taking place at the surface of the rock. These reactions involve the indigenous formation brine in conjunction with the drilling and producing fluid, or they induce damage at the micro level (Viswanathan et al., 2022). Several intrinsic downhole factors contribute to the deterioration and aging of modern wells. Some of the most prevalent causes include acidization of carbonated permeable formations, the precipitation of gypsum in anhydrite formations, the occurrence of naturally-formed fractures and fissures retaining trapped mud filtrate, and similar scenarios (Wei et al., 2022).

Moreover, it is crucial to acknowledge the detrimental impact of drilling and completion fluids employed during the construction and operation of production wells (Abdideh & Mafakher, 2021). They also serve as a common catalyst for wellbore damage and the aging process. Subsequently, after the implementation of drilling or construction procedures, the primary form of wellbore damage or aging arises due to water content or the carrying capacity of the host rock for chemicals that facilitate reductive processes (Yousuf et al., 2021). Such damage can manifest during drilling, workover operations, or even during the production phase, particularly in hydratable formations such as anhydrite, natural halides, or soluble matrix formations (Renard, 2021). The pervasive and extensive nature of this damage should not be underestimated, especially before the onset of water production. Therefore, it necessitates prompt treatment and remediation to prevent the chemical alteration of the rock, which could potentially lead to contamination of the produced fluids and failure of the production equipment (Ibrahim, 2021).

Advanced Materials for Wellbore Repair and Maintenance

Engineers and materials scientists have long sought to produce improved wellbore materials. The aim has been to engineer enhanced properties such as increased resistance to corrosion due to completion and production fluids, high strength to maintain wellbore stability, and resistance to erosion/abrasion and cavities (Liu et al., 2023). Some of the desired properties have historically been mutually exclusive. For example, strong materials would inevitably be brittle and then prone to early fractures. But advanced manufacturing techniques now make it possible to design and fabricate materials with unprecedented properties (Parmar et al., 2022). Benefits include reduced wellbore maintenance, less downtime, and reduced cost (Yuan et al., 2021).

Advanced materials for wellbore structures and equipment can be manufactured with a designed/precise micro-architecture at multiple length scales ranging from molecular to macroscale (Zhu et al., 2024). A wide range of materials is being developed for use in different wellbore applications. These materials include advanced polymers, advanced composites, ceramics, and metallic materials (Wang et al., 2024). Additive and powder metallurgy techniques offer manufacturing techniques that produce materials conforming to the desired arbitrary micro-architecture (Konstantinou & Wang, 2023). Using the principles of mechanics of materials and materials science, these techniques are used to fabricate components with the desired properties to address the specific challenges that arise during wellbore exploitation (Harran et al., 2023). TOF-SIMS results are presented for chemical analysis; by depth profiling, reveals critical aspects of the used material, versus residual solvents, crosslinking or degradation, adhesion of one material to another, as well as material defects at the wellbore wellhead. Full mechanical tests data using tensile testing and nanoindentation are also presented in the paper, evaluating the tensile strength and the deformation mechanism of the materials, the elastic and the transition behavior of the materials from the thin to bulk states (Wang et al., 2023).

Nanomaterials

Nano-materials are a contemporary addition to foundations and drilling fluids. Nanotechnology is the research tool that deals with the manipulation of matter and materials to create a device with characteristics. This sort of work is often performed on scales smaller than 100 nanometres (Dehghani et al., 2024

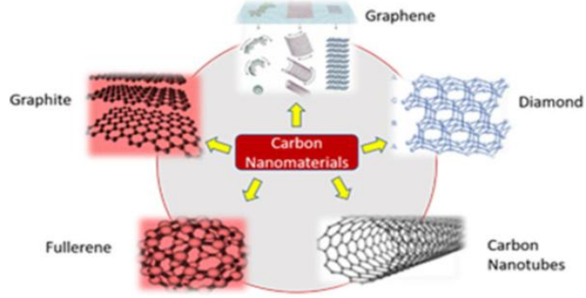

Figure 5: Nanoscale materials used in wellbore applications (Ospanov et al,2024)

The major substance additions to wellbore repair and maintenance systems include: Nano-clay is a type of clay that is used in the repair and maintenance of wellbores (Mahmoud et al., 2024). Nano-additives gained from conventional drilling fluids can be further modified to impart lost circulation and shale stabilization properties (Lysakova et al., 2024). By facilitating the cross-linking process, nanosilica aids wellbore repair cements (Lalji et al., 2023). Carbon nanotubes act as multifunctional additives in the drilling and production process, providing a significant shift in physical and mechanical characteristics to fluids (Medhi et al., 2024).

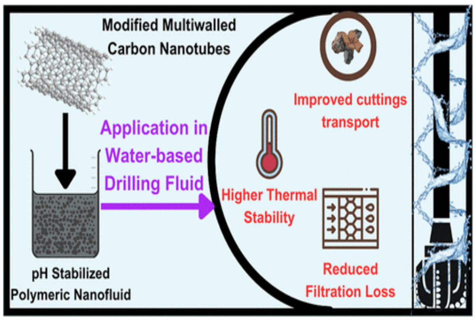

Figure 6: Carbon nanotube structures and applications in wellbore fluids (Anirudh et al 2024)

They have a range of unique characteristics and exhibit considerable promise for improved drilling fluids due to their potential for reinforcing and durable usage (Zhao et al., 2022).
Functionalized carbon nanotubes are obtained by incorporating some form of structural disruption or other reactive group, making it easier to create a covalent bond between the nanotube walls and a matrix material (Díez-Pascual, 2021). A wide array of organic functional groups can associate with the carbon nanotube walls by means of a sidewall polymerization technique (Hassan et al., 2021). The functionalization of carbon nanotubes allows better dispersion of the nanoparticles within the nanocomposites and increases interaction within the matrix, all at strengths well above the current resolution (Dubey et al., 2021). Common carbon nanotube functional components are as follows: –COOH, $-C_2H_4$, $-C_2H_3$, $-NH_2$, –NHCHO, –CHO, $-C_6H_5$, and $-CH_2OH$ (Uthaman et al., 2021).

Composite Materials

Composite materials are either natural or synthetic materials that are made up of two or more different components with significant differences in chemical and/or physical properties (Bunsell et al., 2021). The components in the polymer composites are reinforcing fillers and a polymer matrix. Reinforcing fillers are available in different fibers such as glass, graphite, aramid, and carbon (Lunetto et al., 2023).

Figure 7: Various reinforcing fillers used in composite materials for wellbore applications (Mulla et al,2023)

Ceramic filler materials such as SiC, TiB2, B4C, and SiN have also been integrated into simple composite materials (Barbero, 2023). The two chemicals that easily and dramatically affect the quality of a composite material are mechanical properties (tensile strength, compressive strength, interlaminar shear strength, and flexural strength) and physical properties (thermal expansion coefficient, modulus of elasticity, density) (Papathanasiou & Bénard, 2021).

Therefore, chemical treatment of fillers can help modify the mechanical and physical properties of flexural properties of filled polymer composites (Ramesh et al., 2022). The chemical filler treatment aims to improve the surface characteristics and properties of the treated filler in order to enhance them (Raja et al., 2022). The overall result of chemical modification is a beneficial effect on the flexural properties of the filled polymer composites. Improvements in adhesion to the matrix, wettability, and compatibility of the composite can be achieved by this process (Jagadeesh et al., 2022). These improvements have caused an increase in flexural properties with chemical modification of the filler. As a rule, better dispersion of the filler in the matrix can be achieved, which reduces localized stress concentrations around the broken crystals (fracture area) (Cazan et al., 2021). The void content in the matrix will be reduced by solving in the interface. These evidently support the increase in flexural properties of the composites (Sathish et al., 2022).

Smart Materials

The concept of self-healing materials consists of an autonomous reparative ability for materials via some pre-designed initiation mechanism of the repair process. This process comes from an inspiration of healing systems in nature, such as biological tissues (Shinde et al., 2022). Recent advances in polymer-making have gained significant achievements in the development of self-healing polymers, which show good prospects in several specific applications such as aerospace, automotive, civil construction, and infrastructure protection (Xia et al., 2021). We associated the concepts of smart and self-repair materials with the inspection process of petroleum and natural gas reservoirs. These two properties should be effectively combined with the primary role of the wellbore seal - isolating the petroleum or natural gas production wells, and for temporary storage of some functional mixtures and phosphorus mining rills, offering a solution to accidental annular fluid loss and pollution events that have recently occurred (Qiu et al., 2024).

Smart materials are usually made of composite materials, and they can respond to environmental factors such as pH, temperature, or pressure to produce self-healing effects (Shah & Huseien, 2020). Traditional self-healing materials need additional damage probes and healing catalysts. Consequently, the development of smart materials adds additional sensing components such as core-shell vesicles and transparent microspheres, therefore creating an autonomous self-repairing capability (Khatib et al., 2021). Statistics show that most self-healing polymers are based on fluorescent dyes, found within their unique route towards photo-triggering, leading to the voice signal for the self-healing process. These optical response smart polymers have successfully been applied in astronautic constructions (Lugger et al., 2021). A self-repairing epoxy with the ability to transport and repair carbon fibers has also been developed (Wang & Urban, 2020).

Innovative Techniques for Wellbore Repair and Maintenance

Oil and gas drilling all over the globe is a huge industry, which can be both very profitable and also environmentally damaging. It's very important that the drilling process is done in the most effective way to avoid as much environmental damage as possible, while maintaining a high profit margin. Unfortunately, more than 8% of oil and gas wells have wellbore stability problems (Liu et al., 2022). Wellbore collapse because of the high overburden stress or other mechanical, chemical and flow-assisted mechanisms leads to a bad environment below the earth, and if the problem is not well solved, the downhole instruments may be destroyed, the drilling process will be failed, which will lead to huge waste of the resources, as well as money (Wang et al., 2022). Therefore, maintaining the stable wellbore to obtain accurate resource information for the drilling process, which are related to the profits of the oil and gas, the application value is very large in the oil and gas industry (Li et al., 2022). Due to the growing number of small scale deepwater projects in the global offshore oil executives regarding the possibility of acquiring an old and decayed well, there are an increasing importance in the development of new repair and maintenance methods to keep a satisfactory state of the wellbore (Jello & Baser, 2023). Consequently, there are numerous engineering techniques yielding well integrity, but some of them are found to cause some level of damage to the wellbore; others are also very expensive or hard to effectively access certain well areas. The fact is that the need to repair and maintain these wells has motivated research groups around the world to seek new materials and technology that can effectively solve the challenges posed by these old and decayed wells, mainly to take advantage of the old known wellbore (Gianoutsos et al., 2023).

Therefore, this section presents a literature review on innovative techniques that are being developed and that address these challenges. Some repair and maintenance techniques are based on the application of advanced materials, while others result from the application of innovative technology. It is noteworthy that several types such as wellbore cleaning, isolation and repairing of defects, erosion and corrosion regions, radial drilling, re-cementing, re-locks, scale formation and production enhancement, will be discussed which have found innovative and synergistic solution through the techniques and technologies discussed in this section. The most innovative materials and advanced technologies for wellbore repair and maintenance are analyzed and discussed, aiming to highlight some of the challenges and prospects for future research, considering also cost-benefit and technological development research. The importance of these techniques is related to the enormous amount of old wells that may be recovered with these advanced materials and technology in a near future (DiGiulio, 2024).

Robotics and Automation

As drilling technology continues to advance and horizontal wells become longer and more complex, technologies that enhance the safety and efficiency of drilling are becoming increasingly vital. Challenges to health, safety, and the environment in drilling arise due to the rigors associated with the harsh downhole environment and the hazards of the complications of the machinery and rotating equipment, large manual labor engaged in the transfer of drill string and casing, as well as the risk of falling equipment, fires, and explosions (Samokhvalov, 2023). Solutions have been developed to deal with these risks, such as managed pressure drilling (MPD) that allows continuous control during drilling to remain at the margin between the maximum and minimum values of bottom hole pressure (Muhammad and Tariq, 2023). Other systems are the nuclear magnetic resonance sensors used to minimize the risk related to the mud log at the start of drilling, but do not address the need to activate resilient tools, access the drill string, deliver chemicals to the bit, rotate and slide drill pipe anchors, activate trilateral tools, deliver high torque necessary to break the drill rod, and optimal material resistance when cutting or sliding the column shelf (Najjarpour et al., 2022).

In this context, the areas of robotics, automation, and controls applied are essential. The use of robotics in drilling operations can involve work with machines in remote or dangerous activities, improving safety, handling toxic substances, reducing processing time and geographical scope in pipeline construction, pipeline integrity monitoring, and linking storage centers or ultimate destination terminals (Olajiga et al., 2024). One of the strongest trends for the replacement of human labor by robotics in drilling of foundations is the use of machines controlled by remote control of the existing excavator class, which are gradually gaining a larger area of participation in the market (Lei et al., 2024). The machines have 6 degrees of freedom, have feedback data with the aid of high-definition cameras, and are more flexible and with increasingly reliable and efficient movements with a range of actions ranging from drilling, cutting, and grouting. The handling and driving of direct push trucks through remote control is focused on areas without access to large size drill rigs (Alzarok et al., 2020).

Laser Technology

Carbon dioxide (CO2) lasers produce light in the mid-infrared region of the electromagnetic spectrum. High-quality closely fitting joints can be obtained very rapidly. This technique is useful for a variety of joints, but is particularly effective for welding thick, carbon-containing materials since the laser beam couples into the material very easily; the high power output provides high power density (Li et al., 2023). The advantages of using a CO2 laser are listed as follows (Budden et al., 2021):

1. The power output of gas lasers is usually high.
2. Laser welding in an inert gas (e.g. He, Ar or N2) is possible.
3. The heat-affected zone (HAZ), which is narrow and shallow, has a high cooling rate.
4. The welding speed is high, and so the heat-affected zone is small.
5. Many materials which are barely transparent to visible light can be easily transmitted by high-power IR light because it couples well with the vibration of lattice ions.
6. High-power lasers from CO2 can use non-lens optic systems for focusing.
7. The power sources of CO2 lasers are relatively robust.

The use of pulsed lasers in high-speed laser welding is important since it enables the control of the cooling rates of the molten pool by controlling the pulse repetition rate (Xie et al., 2023). Furthermore, the use of a high-repetition-rate, pulsed laser significantly reduces the amount of the fusion zone, especially if the welding speed is kept small. For certain combinations of remote distance (between the workpiece and focusing lens) and easily accessible-to-laser focal point, non-contact laser welding could be applied. Such a process has already attracted interest in several industries, especially in the welding of aluminum and copper, in which good-quality welds can be made (Ma et al., 2021).

3D Printing

3D printing, also known as additive manufacturing, is a fast-growing technology being used in the oil and gas industry. This technology is impactful for manufacturing just about any item, from spare parts and driller bits to printed structures and components derived directly from 3D scans and used for maintenance (Joseph et al., 2023).

Despite the benefits of 3D printing methods, urgent regulatory concerns have arisen regarding the application of this technology, mainly due to the possibility of using counterfeit materials for printing components meant for safety-critical applications in the sector (Ostolaza et al., 2023). Efforts have been dedicated to developing metal-based printing with designs that are a hybrid of various metal powders, with the intention of avoiding the risk of counterfeit materials and ensuring that materials can fully comply with safety certification precautions (Martins et al., 2023).

The first steps in this particular direction are very promising and demonstrate substantial potential. Although conventional fabrication is non-existent in underground and marine well applications, new additive manufacturing methods and materials, which include metallic printing, allow for new possibilities that could eliminate most of the problems related to T11/T22 tubular material failure subjected to the demanding supercritical conditions associated with the generation IV nuclear power plants (Leon et al., 2023). The successful demonstration of a compliant 3D printed Inconel 625 feature within a full-scale assembly form is already giving impressive results (Anyaezu, 2023).

With these innovative materials, a range of downhole equipment, such as drilling assemblies, packers, and safety equipment, can be developed today, allowing for long-intervention deployments and the use of higher downhole safety, corrosion, and abrasion-resistant standards than those typically afforded by the harsh operating conditions in the drilling, production, or conveying stages (Horton, 2024).

Case Studies and Applications

Published cases serve to illustrate the operating principles, limitations, and potential refinements of any new process. In the new area of geosystems engineering, examples from the growing list of actual applications of swelling elastomers to problems of primary and secondary oil and gas recovery, in situ shale hardening and cracking for wellbore stability, and prevention of communication in thermal production are presented (Yang et al., 2023). These include major commercial field trials as well as small-scale laboratory investigations of such specific problems as evaluating possible expanded applications. Other examples illustrate the significant economic impact of instrumentation and automated controllers on the optimization of core flood laboratory experiments (Zhou et al., 2024).

The number of examples is finite and will become outdated with the continued expansion of the technology. Meanwhile, these applications have a meaning far beyond the showing of some interesting well completion and reclamation to primary and secondary oil and gas recovery, together with the application of controlled versions of the oil production geosystems for marketing elements of the present work are anticipated for enhanced coal-bed methane recovery (Jello & Baser, 2023). Recent applications to the prevention of transient hydraulic communication in the central processing of thermal recovery are described. (Feng, 2024).

Offshore Wellbore Repair

Wellbore integrity is a key priority for safe operations and is essential to effective production. Aging wellbore damage occurs in many forms, including corrosion, scaling, and physical damage to cement or steel. Technologies have been developed to repair damage and prolong the life of the wellbore. These repairs are as varied as the damage but need to be both simple and reliable. Ideally, repairs should be implemented with minimum well intervention. These challenges are usually magnified and complicated in subsea wells where work is more expensive and maintenance operations are more disruptive to routine operations (Zhang et al., 2024).

Recent repair development has focused on reliability and ease of use, cementing techniques that have proved very successful in drilling and well construction, and developing new materials and long-term solutions to physical damage caused by corrosion and mechanical factors (Cordella et al., 2021). Many repair technologies depend upon accurate operations to operate correctly, and it is essential to develop tools and techniques to ensure that guidance information is accurate and reliable. Various technologies have been developed to allow structural defects, such as annulus holes, and mud/gas ingress, to be sealed and returned to a safe state. These technologies are usually deployed by wireline (slickline or electric line), coiled tubing, or capillary tubing and are designed for minimal intervention. They are also designed to give a long service life with full performance being available over many years (Hernandez et al., 2020).

In the subsea environment, however, these types of repair may be implemented by intervention vessels or workover rigs. The distance from the platform to the well and the water depth make this service expensive and difficult. Offshore downtime is also very disruptive to production, and every attempt is made to ensure that work is carried out quickly, efficiently, and correctly the first time. Early work on scaling both the annulus and the tubing has focused on developing a series of inflatable packers that can be used in both damage and non-damage situations (Zhang & Song, 2024). These packers employ centralizers to ensure good pipe centralization and a metal pan that can be advanced in the debris to allow successful operation. Early hardware has already shown good performance, and a family of these tough elastomer packers that employ radial reinforcement has now been developed. The synthetic elastomers are being evaluated for oil-based drilling mud applications to ensure a broad depth of operating temperature, though these packer systems remain sensitive to spalled and poorly adhered scale (Rinaldi et al., 2021).

Onshore Wellbore Maintenance

Tubing wear, coupled with sand production, water breakthrough, liquid loading, scale deposition, paraffin deposit, erosion, corrosion, and hydrate formation in leaking wellbores, are some of the maintenance challenges that need to be overcome when wellbores age. The maintenance methods currently used are not sustainable on wells. The pressure difference needed to transport sand and sand screen damage limit the life of onshore wellbores (Yu et al., 2021). Because onshore wellbores are not deep, it would be possible to regularly repair them using formed tubulars that are capable of carrying high pressures, as well as some chemically bonded composite materials and coatings tailored to preserve good tube geometry. Such recompletions are prohibitively expensive in resource wells, which are not permanent. Those resource wells are mothballed and redug. The Irish National Roads Authority compared the lifetime integrity of controlled traffic roads and resource roads and found that resource road maintenance is more expensive on a per-day basis. Given that designs have kept traffic off inappropriate roads since original construction, the finding is not unexpected (Roy et al., 2023).

As long as an open wellbore has pressure or seeps are evident, the only cost-effective solution for bypassing a battle with sanding and/or surges is a set of liners, followed by subdivision and/or full production conversion renewed tubing (Bridges et al., 2021). When part of the sanding mechanism is working, time may be available to add a cement shear plug to sustain the bypass without running full production conversion produced tubing. Using a shear plug is the best option for fast bypass because having that plug will stop any further erosion in progress during uplift until a pipe string washing fluid can be circulated. Unlike oil and gas recovered from underground reservoirs, sand washing fluid can be gathered and processed within the same workday. Allowing continuous gas sand production can erode surfaces and help to exclude future bypass operations as a potentially viable solution. Given that the current industry focus is on how to maintain an operation, more thought should be given to using refreshing sand bypass as a form of formation stimulation (Huang et al., 2022).

Challenges and Future Directions

Research in the area of well repair and maintenance is presently underway using advanced designs and materials. The goal is to provide an extending service life, but there are technological barriers in order to implement these new designs in actual repair and maintenance operations (Armstrong et al., 2020). These barriers must be broken for these new ideas to become a positive reality (Hu et al., 2022). This section discusses the technological challenges and where future research should be directed to overcome these barriers (Li et al., 2021; Zhai et al., 2021).

Industrial Challenges

As the oil industry moves toward more challenging prospects, deeper water, and the likelihood of significant co-developments within spurs, the need to advance state-of-the-art intervention, repair, and maintenance technologies becomes critical (Wan & Leirmo, 2023). Challenges will center on the inherently high costs of interrupting production from a multitude of wells, with consequent escalated returns on investment (Powell et al., 2022). The overall strategy will be to pursue technologies that can reduce intervention time or frequency, reduce repairs or maintenance frequency, or both (Silvestri et al., 2020). Of course, maximizing the usable life of, or access to, existing wells is a strong incentive to use these developing technologies, in addition to avoiding high costs and operational inefficiencies (Ren et al., 2021).

Future Research

An overall resolution of the key above challenges requires focused, long-term investment in research and development (Koroteev & Tekic, 2021). Much can be achieved by solving small, modular problems systematically and incrementally: persuade the worldwide industry to invest and collaborate in pursuit of appropriate, tested, standardized solutions, avoid bespoke mission-specific developments and embrace standardization and simplification (He et al., 2023). High cost, one-off, specialized developments must be avoided if broad and rapid uptake (with acceptable insurance premiums) is to be ensured (Ukato et al., 2024). Thus, today's research should be a forerunner of tomorrow's generic, industry-wide application.

Environmental Considerations

Our industry is often faced with ever-present challenges to address issues associated with wellbore integrity, well construction, and rehabilitation. Many wells have been in existence and operation for over 20 years. Aging and abandonment of these wells can pose a huge economic burden and potential environmental risk (Hermesmann & Müller, 2022). Particularly, some abandoned wells within shallower intervals or loosely consolidated coal formations and coal bed methane can act as a conduit and threaten potable aquifers or surface water through natural pathways (Andrade et al., 2021). Where economic conditions exist, it may be advantageous to rehabilitate or re-complete these older wells, rather than to drill new ones (Muhammed et al., 2022).

Careful planning and comprehensive calculation of cement slurry properties are required during workover and completion processes to ensure durability and integrity of the wells (Gaurina-Međimurec et al., 2021). During the construction of a new well, predicting the frictional pressure loss in the annulus is critical (Yang et al., 2024). Many of the problems associated with wellbore hole instability, production decline, and workover remain related to the cements used, how well they are mixed and pumped into the boreholes, and how quickly and uniformly they cure (Khan et al., 2023). As wells age, there is a risk that cement barriers and seals can fail due to shrinkage, chemical action with corrosive or reactive fluids, or as a result of shear separation between cement and casing during establishment of the pressure gradient (Wolterbeek and Hangx, 2023). There is a real need to minimize such problems by developing wellbore cements with improved resistance to stress. Together with this, it is also necessary to develop more advanced techniques and tools to verify the integrity of these pressure containment barriers on a more frequent basis (DeBruijn & Whitton, 2021).

Regulatory Compliance

There are numerous governmental and industry standard regulations in place regarding wellbore repair and treatment operations. One aspect of maintaining regulatory compliance during well operations is to constantly exercise the installation and execution of a response plan. The regulatory framework can be as unique as states or even more localized jurisdictions addressing specific issues (Zhang et al., 2024). It is not uncommon to have different state regulations even within the same country. Therefore, regulators, law, and enforcement often lead in the development of drilling materials (Wood, 2024). They may place specific restrictions that a commodity provider must adhere to. Additionally, operators often buy specific technologies to meet a specific reservoir requirement (Jaculli et al., 2022).

In particular, the technology that is being presented in this paper must be able to meet the following challenges:

- Produce low leachate levels in order to pass environmental hazards tests.
- Low density in order to provide operators choices in developing specific fluid densities.
- Control particle size (specific particle distribution) to meet environmental regulations, lost circulation requirements, provide for an immediate seal, and achieve strong bonding with the formation wall.
- Retain strength (durability) to carry out testing that is essential for high angle and horizontal drilling to check for hole geometry.
- Excellent control of free fluid levels to meet operator specific well requirements in avoiding formation reactivity.

Future Trends in Wellbore Repair and Maintenance

The trend in using advanced materials and techniques to repair and maintain aging, as well as newly designed and constructed wellbores, is on the upswing pace. The rationale is the need to extend the longevity of existing wells by maintaining their integrity, thereby ensuring safe and efficient production of hydrocarbons (Davoodi et al., 2024). Because of such requirements, numerous alternatives for wellbore repair and maintenance, including using new materials and technologies, and researches are being conducted. These include metallic repairs using steel bands and wraps to restore tensional strength to the wellbore, forward modeling for designing tensile repair, and studies conducted for life and longevity to understand the prevention and remediation of fatigue and moisture (Shi et al., 2022). Polymeric repairs, such as mechanically bonded composite repairs and resin-based mechanical alloy repairs and more, have been used and investigated, with sophisticated models developed for repair design (Jafariesfad et al., 2020).

The present trend, and the one to continue in the future, is using composite-based repairs. As more research results and repair solutions have been presented using this technology in recent years than those using metallic-based solutions (Bilvatej et al., 2024). The current trend in wellbore repair and maintenance is using repairs for short-term maintenance (or temporary purpose) and life extension/longevity. Those for the latter category are non-intrusive, un-bonded, non-load bearing, non-stressed, sub-scale structures fabricated on the well (Ilyas et al., 2022). Also, those for short-term purposes are stress-bearing, emergency designs, re-establish full tensional capability, and cost-effective solutions for short-term repair stability. Using hot taping as a repair technology is also gaining interest due to its fiber-placing speed and installation, while external clamp-on casing repairs can be performed safely and economically (Almushaikeh et al., 2023). These trends are directed towards improving the operation and management of wellbore integrity using advanced materials and techniques (Akbarzadeh et al., 2024).

II. Conclusion

In conclusion, the repair, maintenance, rehabilitation, and modification of aging wells are of utmost importance in order to minimize environmental and safety hazards, as well as to prevent unnecessary loss of energy resources. A thorough understanding and assessment of the integrity of the well is integral to planning successful well repair or maintenance operations. Advanced materials and techniques, such as carbon fiber-reinforced polymers, advanced cement-based materials, chemical-based repair systems, and using intelligent wellbore tubulars have already proven effective in the field. However, with the growing concerns arising from increasing numbers of aging wellbore structures, more research and innovation in the development of fast-track and cost-effective materials and repair techniques are highly sought. The commercial availability of these new materials and systems is another challenge that is yet to be met.

It is also worth noting that the life span of the various materials come into the picture during planning, especially when dealing with well repair operations. Material selection during the planning phase can potentially reduce problems encountered later on, thus ensuring the longevity and optimal performance of the structures. Where possible, government bodies and professional associations should develop guidelines to consider the accelerated aging issue from the onset of the design of this type of construction in order to prevent significant serviceability problems to all stakeholders involved, including those of the environment.

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