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Review

A Review of Well Life Cycle Integrity Challenges in the Oil and Gas Industry and Its Implications for Sustained Casing Pressure (SCP)

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Abstract: Sustained Casing Pressure (SCP) is a condition in oil and gas wells where continuous pressure buildup in the well casing over a long period of time occurs. Several factors might be responsible for this, including the influx of formation fluids, the leakage of fluids from the well, and other possible sources. SCP is a serious concern as it can indicate well integrity issues and lead to catastrophic failure. This paper covers the multifaceted integrity challenges that arise over the whole life cycle of a well, the capture and storage of carbon dioxide, and the storage of hydrogen in depleted reservoirs. The review study suggests that inadequate cement coverage, weak bonding, and inadequate gas or water movement routes could lead to connection issues, leakage, and equipment malfunction. Implementing safety barrier systems correctly is the solution to preventing sustained casing pressure and ensuring the stability of well integrity. It is revealed that more than 45% (6650 wells out of 12,927) of Gulf of Mexico wells had SCP difficulties, whereas 35% of UK North Sea wells have at least one problem. Ten per cent of the 6137 wells studied on the United Kingdom Continental Shelf had either a barrier failure or a well integrity failure.

Keywords: well integrity; sustained casing pressure; abandonment; well life cycle; oil and gas; carbon dioxide capture and storage; hydrogen storage

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1. Introduction

Well integrity refers to the ability of a wellbore to effectively contain the fluids and gases that are being produced or injected while also preventing unwanted fluids or gases from entering the wellbore. In the oil and gas industry, well integrity is crucial to ensure the well's safety and reliability and protect the environment. It involves a combination of design, construction, maintenance, and monitoring measures to ensure the well remains secure throughout its lifespan. Typically, well integrity involves a multi-layered approach, starting with the design of the well casing and cementing materials used to seal the wellbore. Proper wellhead equipment installation and maintenance, including valves and safety devices, are also critical to maintaining well integrity. Furthermore, regularly monitoring and testing the well for leaks, pressure changes, and other signs of potential issues is important to identify any problems early on and take appropriate remedial actions. Overall, well integrity is essential to ensure safe and sustainable operations in the oil and gas industry and minimise environmental and safety incident risks. The comprehensive management of the well structure in such a way that the wellbore fluids do not communicate with the environment is referred to as well integrity.

Well integrity was defined by NORSOK Standard D-010 as "the use of technical, operational, and organisational solutions to limit the risk of uncontrolled release of formation fluids throughout the life cycle of a well" [1]. The American Petroleum Institute (API) definition is similar to the NORSOK Standard D-010 definition. On the other hand, API incorporates safety, groundwater protection, and superior hydraulic fracturing execution without harming the environment with the produced fluids [2]. SCP is a key indicator of potential well integrity problems, suggesting that the casing may be compromised and unable to contain reservoir fluid. It can occur due to casing or cement failure and gas migration. It can also cause damage to the well casing and surrounding rock formations, requiring costly repairs. Regular monitoring and maintenance of well integrity are necessary to prevent SCP. This includes monitoring pressure changes and conducting inspections of the casing and surrounding formations. Well integrity is crucial in preventing environmental contamination and blowouts. The industry is increasingly focused on well integrity due to the high number of well failures reported worldwide.

Throughout the history of the oil and gas industry, accidents have changed how everyone thinks about safety. Major accidents have caused people to think about safety differently. Many oil and gas accidents happen because the barrier materials are degraded and have lost integrity in handling the wellbore pressure. Wellhead movement, leakage of wellhead and X-tree safety-critical elements, scale formation, corrosion of the casing and completion string, and SCP are the most common of these problems [3]. The Aliso Canyon incident in 2015 highlighted the potential consequences of gas leaks, emphasising the importance of well integrity. SCP occurs when pressure continues to build up after multiple bleed-down operations.

Industry stakeholders aim to achieve a high return on investment while avoiding the failure of structural/elemental wellbore constituents. Several variables, however, endanger the integrity of these vital wellbore elements. This paper investigates the multifaceted challenges that arise over the whole life cycle of a well.

Cause and Management of Well Integrity

The wellbore must be built according to the specifications of the governing regulations and have two protective barriers. These barriers will prevent hydrocarbon fluids from contaminating water-bearing aquifers. The same applies at the surface, where a wellhead and a Christmas tree trap hydrocarbon fluid. The technical integrity of a well is related to its tightness. A well's tightness is "the highest permissible leakage rate across the system or using other well integrity parameters" [4]. No mechanism could attain 100% tightness.

However, the wellbore may fail its integrity test due to various circumstances driven by chemical, mechanical, and operational concerns [5]. Smith and Milanovic [6] painted a full picture of the problems with well integrity for the whole wellbore and pointed out that well integrity problems are different in different parts of the world. The image they painted shows that each wellbore has a distinct integrity concern from another, and how these issues are treated varies between operators worldwide.

Still, the job of keeping the wellbore integrity intact is becoming more and more important in the sector. It is important throughout the whole life cycle of a well, beginning with drilling and ending with plugging and abandonment [5,7]. Also, well integrity is important in carbon dioxide (CO_2) sequestration [8,9]. Davies et al. [7] and Miyazaki [10] discovered that well integrity could be lost at any step of the well life cycle. According to Watson and Bachu [11], well integrity failures occur owing to the loss of one or all of the barrier elements in the well, resulting in fluid leakage from the formation to the surface. Fluids travel via porous cement, cracks or fractures in cement, mud cake voids generated during drilling operations, and cement shrinkage.

In their study, Conley et al. [12] provided empirical evidence demonstrating that the Aliso Canyon natural gas leak released a total of 97,100 metric tonnes of CH_4 and 7300 metric tonnes of C_2H_6 into the atmosphere during a period of 112 days. This particular release is responsible for roughly 24% of the yearly methane (CH_4) emissions and 56% of the yearly C_2H_6 emissions originating from all other sources within the geographical area of the Los Angeles basin. The emission of methane (CH_4) under consideration represents the second-highest recorded level in the United States.

SCP is a phenomenon that occurs when there is pressure buildup in the annulus between the production casing and the wellbore, which can lead to well integrity issues [13]. Some of the major causes of SCP include the following:

- Casing and cement degradation: The degradation of the casing and cement could lead to cracks, leaks, micro-annuli and other structural failures that can compromise the integrity of the well [11,13,14];
- Gas migration: Gas migrates from the formation into the annulus, leading to increased pressure and the potential for gas to escape into the environment [11,13];
- Corrosion: The corrosive activity of casing and cement weakens the well structure and can cause potential leaks [11,14,15].

Overall, SCP is a significant concern in the oil and gas industry, and proper monitoring and management are essential to maintain well integrity and prevent potential hazards.

Figure 1 shows how hydrocarbon fluids can leak out of the well and reach the surface in a typical well. During the drilling, production, and abandonment phases, every wellbore design tries to limit fluids with barrier systems that protect against bad pressure, temperature, corrosion, and exposure. Cement, casing, elastomeric seals and valves are common barrier methods. The barrier mechanisms, positioned in zones penetrated by the wellbore, protect the soils, rock layers, groundwater, and surface water from contamination [13]. Well integrity failure is defined as the failure of all or some of the well barriers, which allows fluid leakage into the environment, and barrier failure is the failure that does not result in an identifiable leak into the atmosphere. Single or several well obstacles might cause this failure.

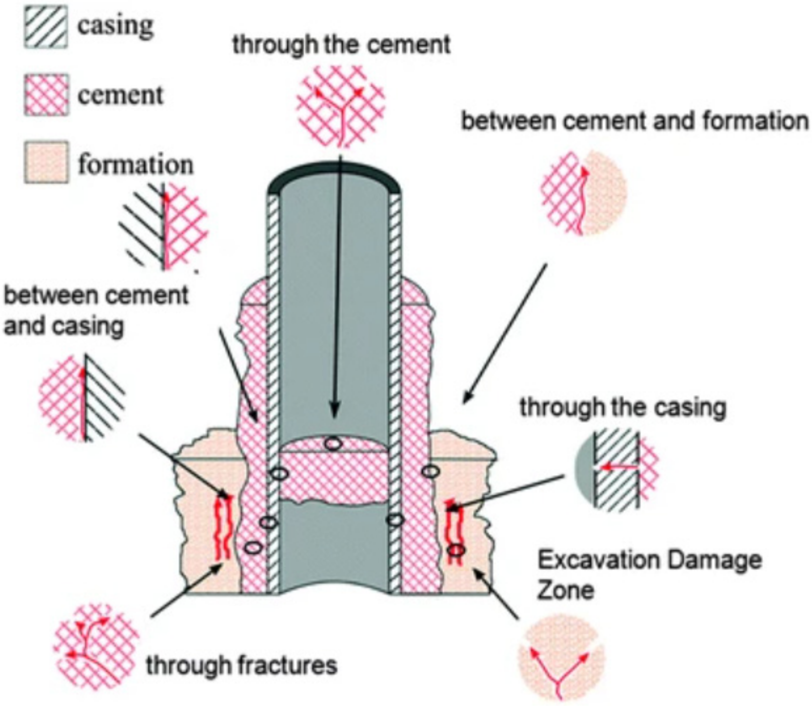


Figure 1. Leakage pathways [4].

Normally, the casing is pressure-tested from the surface. There is SCP when this test is positive. It does not reveal the location of the failure or the failing barrier [11]. Consequently, the only way to assess the integrity of the casing is by surface pressure testing. If a positive pressure test is successful, it signifies the existence of a leak, thus confirming the presence of SCP. Although a surface pressure test may detect the presence of SCP, it cannot pinpoint the exact position of the failure inside the wellbore or identify the precise barrier that has been breached.

The contributions listed above provide an overview of the well integrity issues consistent with the industry's current state. However, this study will focus on the challenges/problems encountered during production that prevent the well from reaching its maximum estimated production life expectancy. It is a problem with SCP, which researchers have defined as the failure of pressure at the casing head to remain at 0 psi but continually rise after each bleed-down action [16].

The well integrity/risk assessment (RA) model was used by Dethlefs and Chastain [17] to figure out how a well or group of wells could fail. The RA discussion assesses each well type against potential failure scenarios for well-barriers. Each failure mode refers to a specific type of barrier failure in the well's mechanical structure. The model assumes only one failure occurs at a time but can be categorized into specific categories. The facilitator guides the discussion, asking what would happen if a barrier failed. The failure modes vary depending on the well's design and operational conditions, and a detailed list of failure modes is compiled for each type of well. The different failure modes were identified. Among them are leakages below and above the lower master valve, below and above the subsurface safety valve, and Parker issues leading to communication between the A Annulus and the tubing. This evaluation is useful for any well where the methodology utilised in their research is used. Dethlefs and Chastain [17] claimed that the operators do not keep proper records and have integrity problems. Following their model will necessitate extensive expertise and experience from the risk assessment staff to sort out the failures on their wells. However, it is not impossible to have more than one failure mode occur simultaneously in the real world in the oil and gas industry.

Most research has focused on post-SCP predictions, which aim to find solutions to already escalated integrity issues, thereby providing integrity maintenance and escalation mitigation [16,18–25].

2. Integrity Challenges in Different Types of Wells

Integrity concerns are not restricted to a single type of well. It affects all types of wells and can be seen at all phases of the well-life cycle, from drilling through abandonment. The severity of integrity failures comes from poorly constructed wells. Factors such as the quality of the casing, its stability, pressure control, geological characteristics, operating parameters, maintenance, human error, environmental conditions, and compliance with regulations are of utmost importance. Regular inspections, implementation of error prevention measures, and adherence to industry standards mitigate the severity of failures and guarantee the integrity of oil and gas wells.

The following section examines integrity problems in the different classes of wells.

The two main types of wells drilled in the industry, conventional and unconventional, are vertical and deviated or directional wells, depicted in Figure 2. Figure 3 shows sidetrack wells, multitarget infill or designer wells, and multilateral wells classified based on their usage and purpose.

While several types of wells exist, the reasons for integrity issues are mostly consistent across all well types. These include incorrect casing design, improper cementing, and formation damage, which can lead to leaks in wellbores, compromising safety and environmental protection. Long-term exposure to corrosive fluids, erosion, formation damage, equipment malfunctions, reservoir pressure, temperature variations, external pressures, and inadequate maintenance can exacerbate integrity issues. Nevertheless, precise reasons for well integrity challenges are unique to the well's design. Table 1 summarises the well integrity failure mechanisms and their causes.

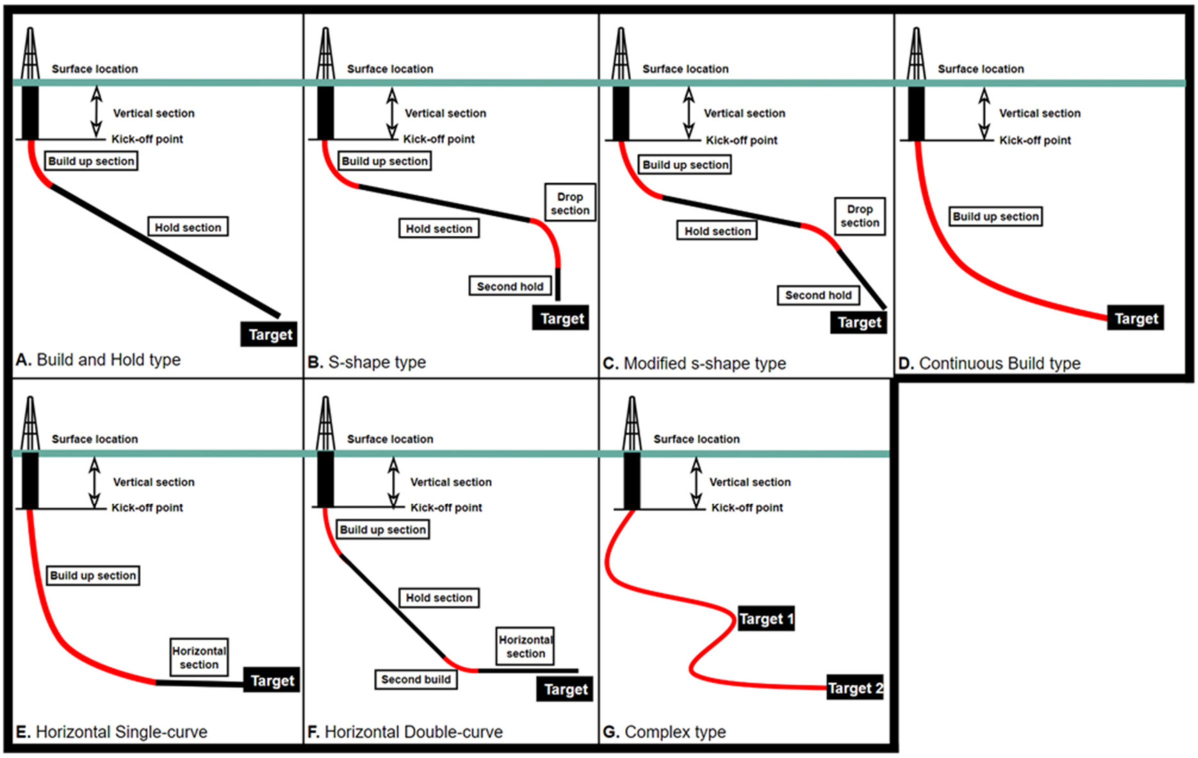


Figure 2. Directional Drilling well types [26].

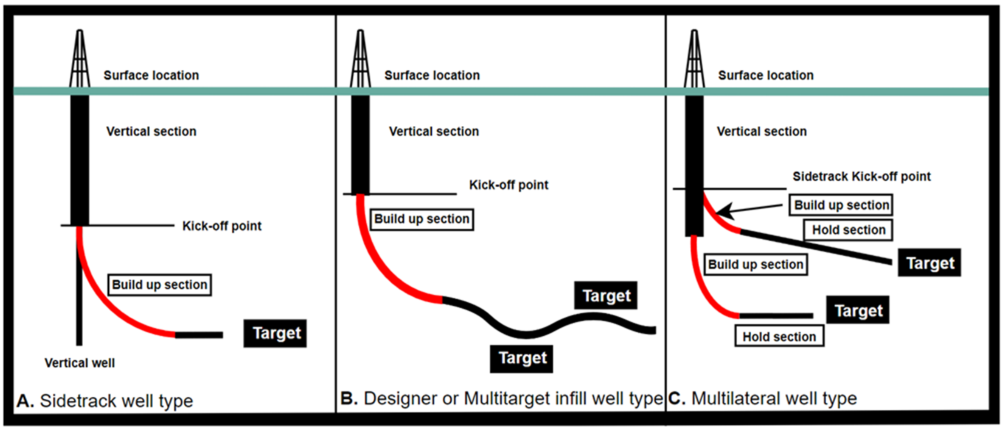


Figure 3. Other well types.

Table 1. Summary of Well integrity failure mechanisms and causes.

Failure Mechanisms	Materials	Causes	References
Corrosion	Casing and Tubing	Formation and Production Fluids—brines or acidic solutions like hydrogen sulfide (H2S) or carbon dioxide (CO_2). Hydrogen Damage. Wellbore Contaminants—salts, solids, and other impurities. Microbial Activity—sulfate-reducing bacteria (SRB) and acid-producing bacteria. Oxygen Exposure—oxygen ingress due to improper well sealing damaged protective coatings. Temperature and Pressure elevation. Galvanic Corrosion. Improper Material Selection. Cementing Issues. Mechanical Damage. Lack of Corrosion Inhibitor. Improper Well Maintenance.	[4,13,14,27–31]

Table 1. *Cont.*

Failure Mechanisms	Materials	Causes	References
Wear	Casing and Tubing	Sand and Abrasives. Friction with Downhole Tools. Wellbore Deviation. Chemical Reactions. Fluid Velocity. Scaling. Hole Cleaning Operations. Improper Centralization. Casing Expansion and Contraction. Vibration and Impact. Corrosion-Induced Wear. Debris in the Wellbore.	[4,13,14,27,28,30]
Fatigue	Casing and Tubing	Pressure Cycling. Temperature Cycling. Mechanical Vibrations. Resonance effects. Wellbore divisions. Casing and Tubing Movement. Downhole Vibrations. Improper Design or Installation. Material Quality. Corrosion. Well Conditions. Operating Practices.	[4,5,13,14,27,28,30,32–34]
Collapse	Casing and Tubing	High Formation Pressure. Inadequate Casing Design. Hydrostatic Pressure. Wellbore Temperature. Fluid Density and Mud Weight. Geological Factors. Poor Cementing. Barite Sag. Annular Pressure Buildup. Buckling and Mechanical Damage. Corrosion and Material Degradation. Shifting or Subsidence of Geological Strata.	[4,13,14,28,30,35]
Leakage	Casing and Tubing	Poor Cementing. Casing or Tubing Damage. Casing or Tubing Corrosion. Casing or Tubing Connection Failures. Annular Seal Failures. Faulty Wellhead or Christmas Tree. Pressure Buildup. Formation Integrity. Migration of Formation Fluids. Chemical Interactions. Geomechanical Effects. Improper Well Construction. Corrosion of Wellhead Equipment.	[4,13,14,28,30,35]
Bond Failure	Cement	Poor Cement Quality. Improper Cementing Practices. Cement Slurry Properties. Cementing Additives. Contaminants in the Wellbore. Casing Movement. Cement Set Time. Cement Sheath Integrity. Pressure Differential. Wellbore Geometry. Casing Centralization. Gas Migration. Temperature Effects. Pressure Testing Procedures. Geological Factors. Insufficient Annular Space.	[4,14,28,29,33,36–41]
Wellhead and Christmas Tree Failure	Wellhead and Christmas Tree	Corrosion. Material Degradation. Pressure Surges. Temperature Extremes. Mechanical Damage. Hydraulic Fluid Leaks. Seal Failures. Valve Failures. Corrosion of Control Lines. Instrumentation Failures. Improper Installation or Maintenance. Design Flaws. Well Interventions. Wellbore Debris. Subsidence or Ground Movement. Environmental Factors.	[13,42,43]
Packoff Failure	Seals	Inadequate Installation. Improper Sizing. Material Degradation. Corrosion. Mechanical Damage. Pressure and Temperature Extremes. Chemical Exposure. Vibration and Movement. High Flow Rates. Wellbore Debris. Sealing Interface Issues. Design Flaws. Packoff Age. Stress due to well interventions. Formation Movements. Improper Pressure Management.	[4,14,44,45]
Annular Pressure Buildup	Casing and Tubing	Gas Migration. Formation Fluid Influx. Wellbore Blockages. Gas-Lift Operations. Cement Failure. Incomplete Well Control. Reservoir Compaction. Temperature Changes. Leakage at Wellhead or Connections. Formation Movement. Poor Cement Bond. Zonal Isolation Failures. Annular Fluid Properties. Reservoir Dynamics. Completion or Workover Operations.	[4,13,14,28,30,35,46]

Table 1. *Cont.*

Failure Mechanisms	Materials	Causes	References
Geomechanical Failures	Formation	Formation Depletion. Formation Swelling. Faults and Fractures. Unconsolidated Formations. High Drilling Mud Weight. Fluid Invasion. Pressure Imbalance. Wellbore Tortuosity. Lost Circulation. Wellbore Deviations. Wellbore Interactions. Formation Compaction. Well Stresses. Formation Properties. Seismic Activity.	[14,28,38,39,47–51]
Chemical Compatibility Issues	Casing, Tubing, formation and Cement	Chemical Incompatibility. Corrosive Agents. Scale Formation. Emulsion Formation. Precipitation. Fluid Phase Changes. Inhibition of Chemical Treatments. Reservoir Fluid Incompatibility. Environmental Conditions. Biological Growth. Contaminants. Material Selection. Transportation and Mixing of Chemicals. Additive Interactions. Operational Changes.	[4,31,52–57]
Thermal Stress	Casing, Tubing and Cement	Temperature Fluctuations. Wellbore Operations. Fluid Temperature Changes. Start-Up and Shutdown. Well Production. Pressure–Temperature Effects. Heat Transfer. Insulation or Cooling. Geothermal Gradients. Material Properties. Poor Material Selection. Welding and Fabrication. Mechanical Constraints. Equipment Misalignment. Cyclic Loading. Severe Temperature Extremes.	[4,13,14,28,30,35,36,39,46,51]

2.1. Well Life Cycle Phases

The well life cycle consists of the following phases: (1) design, (2) construction (drilling, completion, and assessment), (3) production, (4) intervention, and (5) plug and abandonment [58]. Figure 4 depicts the many stages of the well integrity life cycle.

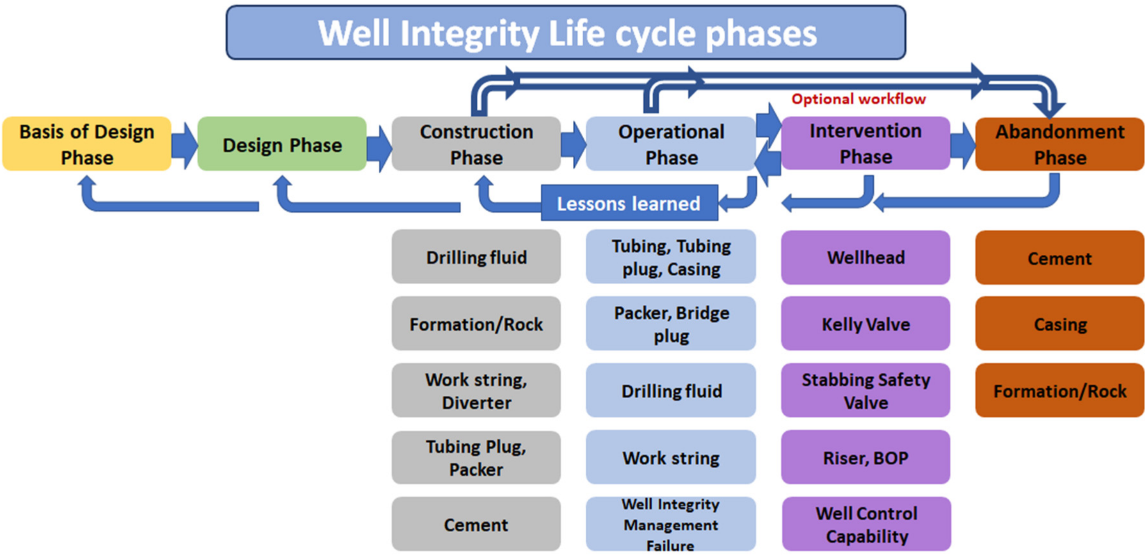


Figure 4. Well integrity life cycle phases (ISO16530-1 2017 [59]) (Adapted from [3]).

The NORSOK Standard requires that two well barriers be used during well operations to prevent a catastrophic calamity, such as a blowout, which could cause environmental damage and human deaths [1].

2.1.1. Design Phase

Kiran et al. [5] emphasised the significance of the design phase of the well construction by mentioning the interdependence of the circumstances that lead to well integrity failures. Certain factors, such as temperature, pressure, corrosion, and chemical fluctuations, influence wellbore integrity. For example, changes in chemicals or temperature alter the corrosion damage on metals. These changes can weaken the structural integrity of the wellbore, leading to potential leaks or failures. Additionally, the authors highlight that proper design considerations during the construction phase can help mitigate these risks and ensure long-term well integrity. As a result, a suitable casing with sufficient metallic qualities suited for the well must be chosen to ensure the well's integrity when constructed.

It is vital to note that cement design is important in ensuring the well's strength, durability, and integrity during the design phase. Fourmaintraux et al. [60] proposed a five-step solid cement sheath design procedure. The well is a collection of components defined by their shape and material. The operational phases further divide the well life. Response curves that connect a deformation variable and a load variable at one point on a component demonstrate how each elementary action impacts it. The impact of every operational activity on any component is shown by a collection of response curves that are a function of the response curves for each elementary action; the intersection of neighbouring component response curves determines equilibrium.

During the design phase of a well, various well integrity issues should be considered to ensure the well is designed and constructed to maintain its integrity throughout its lifespan. Well design is influenced by various factors such as formation type, depth, pressure, temperature, fluid properties, and potential dangers. Reservoir engineering aims to maximise hydrocarbon recovery while minimising production difficulties. Reservoir modelling and analysis help determine optimal locations, completion processes, and production strategies. Wellbore stability and integrity are influenced by rock mechanics, drilling fluid characteristics, and casing design. The selection of drilling rigs, bits, casing, tubing, packers, and completion equipment is influenced by well depth, formation hardness, trajectory, and environmental conditions. Safety and environmental protection are crucial in well design, with safety barriers, blowout prevention systems, emergency response plans, and environmental protection measures. Performing Failure Mode, Effects, and Criticality Analysis (FMECA) is a methodical approach used to discover possible failure modes of components or systems, evaluate their impacts, and prioritise crucial failure modes for risk reduction. Conducting FMECA during the design phase enables the identification of potential failure modes and their associated repercussions. This allows engineers to integrate preventative measures into the design in order to mitigate potential risks. Figure 5 depicts the integrity deterioration of well structural materials when exposed to various environmental conditions over time.

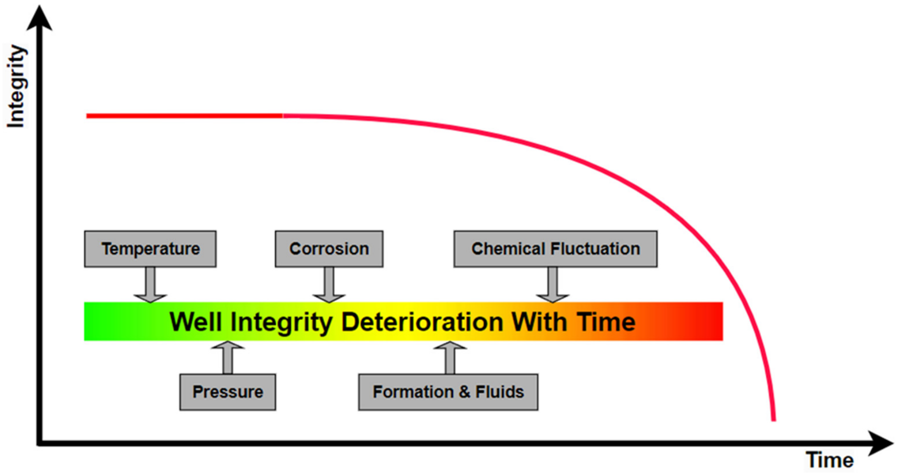


Figure 5. Typical graph showing Integrity versus Time.

Some of the key well integrity issues during the design phase include the following:

Failure to account for the geomechanical characteristics of the subsurface formations can lead to wellbore instability, including issues such as wellbore collapse, formation damage, or fluid influxes. Proper geomechanical analysis is crucial to designing wellbore paths that can withstand the anticipated stresses and pressures [61,62].

Also, poor design of casing and tubing strings can result in integrity issues [63,64]. The structural integrity of a well can be compromised due to factors such as insufficient casing wall thickness, improper material selection, or inadequate centralisation [40,41,65–67]. Additionally, selecting the appropriate casing and tubing sizes to handle anticipated pressures and loads is essential.

In addition, proper cementing is crucial for achieving zonal isolation and preventing fluid migration. Inadequate cement coverage, poor cement bonding, or failure to address potential gas or water migration paths can lead to communication between different formations or zones, compromising well integrity [68–70].

The integrity of a well is contingent upon the careful design and selection of its wellhead equipment and casing hangers. Inappropriate wellhead design, inadequate sealing mechanisms, or insufficient load-bearing capacity can lead to leaks, equipment failure, or loss of well control [71,72].

During the design phase, it is imperative to incorporate suitable measures to avert kicks, which refer to the uncontrolled influx of formation fluids into the wellbore, and blowouts, which denote the uncontrolled discharge of fluids to the surface. The task at hand pertains to developing proficient well control mechanisms, encompassing blowout preventers (BOPs) and related apparatus, capable of managing projected pressures and flow rates.

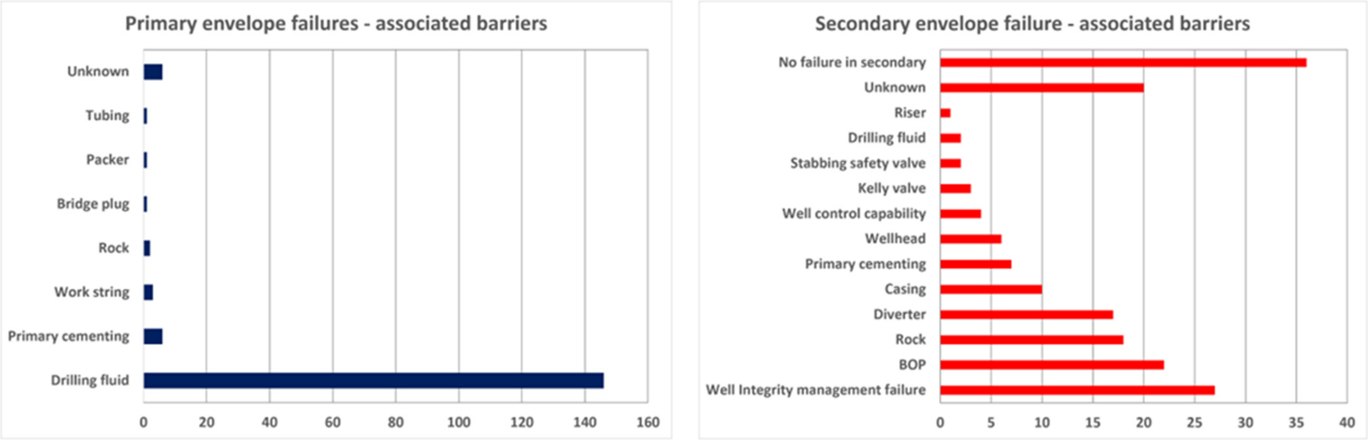
The failure to take into account the potential risks of corrosion and to make informed decisions regarding material selection may result in issues related to the integrity of the system or structure. The process of corrosion has the potential to cause a reduction in the strength of the casing, tubing, or surface equipment, which may result in leaks or structural failure [73]. The risks of corrosion can be better mitigated by the selection of corrosion-resistant materials for equipment and infrastructure, involving alloys like stainless steel or corrosion-resistant alloys. Protective coatings and linings can offer additional defence against corrosion. Cathodic protection uses metal surfaces as cathodes of electrochemical cells, while corrosion inhibitors create barriers on the metal surface. A comprehensive inspection and maintenance program is essential for identifying and preventing corrosion. Corrosion monitoring devices can help measure rates and identify potential issues. Water and fluid management is essential for minimizing corrosion hazards. Adhering to temperature and pressure limits is crucial for equipment use. Staff training on corrosion awareness and preventative strategies is essential. Compliance with industry norms and standards is vital for safety and soundness in oil and gas operations.

Therefore, implementing rigorous design verification and quality assurance processes is paramount during the design phase. The practice mentioned above guarantees that design specifications and standards are duly adhered to and that any potential risks to the integrity of the project are identified and resolved prior to the commencement of construction. By addressing these well integrity challenges during the design phase, operators can enhance the overall integrity of the well, reduce the risk of costly failures, and ensure safe and efficient well operations throughout its life cycle.

2.1.2. Drilling Phase

The well's life cycle begins with the drilling of the well as defined in the drilling programme. The well can be drilled onshore or offshore [74,75]. A typical well is drilled in stages using a drill bit size of 36 inches to reach the casing setting depth, where the 30-inch casing is run and cemented. Before pumping cement into the annulus behind the casing, the wellbore is thoroughly circulated and cleaned, and the casing well is centred. The casing keeps formation fluid out of the well and prevents it from collapsing. This operation is repeated until the final size is drilled and cased off. Pressure tests and bond logs are performed to determine the cementation quality. The well is prepared for production by running tubing into the cased well, followed by the Xmas Tree installation.

NORSOK Standard D-010 [1] defined two types of well barriers that must be present during drilling operations: primary and secondary well barriers. The fluid column is the principal well barrier, whereas the secondary well barriers are the wellhead and blowout preventer (BOP), riser, cemented casing, and uncemented casing. The global oil and gas industry is united in preventing blowouts during well development. As a result, numerous laws and guidelines are put in place to ensure safe drilling and well completion. Jaculli et al. and Holand [3,76] examined data from the Gulf of Mexico and the North Sea and concluded that drilling fluid accounts for the highest percentage of failure among the barrier elements that comprise the primary well envelope. According to their perspective on the secondary envelope, "well integrity management failure" is the primary source of well integrity difficulties. For more information, see Figure 6. This observation is correct because the formation tends to release fluid into the wellbore when the hydrostatic head of the mud column decreases and receives drilling fluid when the weight is too high.



(**a**) (**b**)

Figure 6. Failure modes of barrier elements within the primary (**a**) and secondary (**b**) envelopes (Adapted from [3]).

Numerous operational modifications are implemented during the well construction process to ensure the well's structural integrity. According to Petersen et al. [77], the accomplishment of this task requires the utilisation of advanced technological equipment and a robust system of integrity that is closely monitored. The implementation of safety barriers involving casing running and cement setting can effectively mitigate operational risks by preventing well collapse and the influx of formation fluids into the wellbore [78]. According to the statement, a safety barrier refers to a set of structural components that possess the ability to prevent undesirable occurrences along a particular route connecting the system under investigation and the surrounding environment. The final component of the research conducted by Miura et al. [78] involved the implementation of the Quantified and Dynamic Risk Assessment (QDRA) methodology, which is founded on the concept of Barrier Integrated Sets (BIS). The BIS modelling approach employs a graphical methodology to assess a system's safety level by quantifying the integrated barriers between the system in question and its surrounding environment.

Several well integrity challenges can arise during a well's drilling phase [17,79–81]. These issues can significantly affect the well's integrity and require immediate attention and mitigation [14]. Some key well integrity issues during the drilling phase include the following:

- Fluid influx or kicks: Drilling into pressurised formations can result in fluid influx or kicks, which are uncontrolled flow of formation fluids into the wellbore. Failure to detect and control kicks can lead to well control problems, blowouts, or loss of well integrity [52,82];
- Wellbore stability: Drilling through different formations involves managing wellbore stability to prevent collapses or hole enlargement. Failure to control wellbore stability can lead to wellbore instability, differential sticking, lost circulation, or formation damage [61,62];
- Lost circulation: While drilling, lost circulation occurs when drilling fluids are lost into permeable formations instead of returning to the surface. Lost circulation can compromise well control, hinder drilling progress, and lead to formation damage [83];
- Formation damage: Drilling activities, such as mud invasion, can cause damage to the reservoir formation. Excessive mud filtrate invasion, mud weight imbalances, or improper drilling practices can negatively impact well productivity and integrity [84,85];
- Formation fluid contamination: Contamination of drilling fluids or mud with formation fluids can occur due to poor wellbore stability or inadequate well control. Formation fluid contamination can impact drilling operations, damage equipment, and compromise well integrity [86];
- Casing and cementing issues: Improper casing and cementing operations during drilling can result in inadequate zonal isolation and compromised well integrity [81]. Poor cement bonding, inadequate centralisation, or insufficient casing support can lead to fluid migration or communication between different zones. Appropriate centralisation of casing coupled with the selection of good centralisers would improve formation-casing-cement bonding [40,41];
- Well control equipment failure: Equipment failures during drilling, such as malfunctioning blowout preventers (BOPs) or inadequate well control systems, can pose a significant risk to well integrity [17]. It is crucial to have properly functioning well control equipment to prevent blowouts or uncontrolled flow;
- Corrosion and material degradation: In the oil and gas industry, exposure to corrosive environments or incompatible fluids can lead to material degradation and corrosion during drilling [87–89]. Corroded drill pipes, casing, or surface equipment can compromise well integrity and require remedial actions [90].

It is essential to address these well integrity issues during the drilling phase by implementing proper drilling practices, well control measures, wellbore stability management, and regular monitoring. Early detection and mitigation of these issues can help ensure the overall integrity of the well and prevent costly incidents or failures.

2.1.3. Production Phase

This phase begins when the well's activities are completed. The well is perforated to allow formation fluid access to and control over the wellbore. Natural or assisted oil well output is possible. Spontaneous production generates enough pressure within the deposit for hydrocarbons to flow naturally into the wellbore [91,92]. In contrast, assisted production would necessitate the use of pumps and other methods to get the oil to the wellbore and then to the conductor pipes on the surface [93].

During well production, several well integrity concerns may arise, which have the potential to undermine the secure and effective extraction of hydrocarbons [79]. Corrosion is a phenomenon that can potentially impact wellbore tubular surface equipment and infrastructure. Corrosive fluids, contaminants, or inadequate corrosion protection measures can lead to material degradation, leaks, and structural failure [94,95]. The scaling phenomenon arises due to the precipitation and deposition of minerals, e.g., iron sulphides (FeS), calcium sulphates ($CaSO_4$), etc., from the formation fluids onto the wellbore tubular, leading to scale buildup and, consequently, decreased production rates and possible flow obstruction [95,96].

In reservoirs with unconsolidated formations, sand production can occur during production operations [97,98]. Sand influx can erode wellbore tubular, damage surface equipment, and hinder production [95,98]. Implementing sand control tubular is important to mitigate these issues. The integrity of oil and gas equipment, such as wellheads, valves, and piping, is contingent upon appropriate maintenance measures. The occurrence of leaks, containment failure, or uncontrolled flow can be attributed to equipment malfunction or deterioration [95,98,99].

Over time, fluids can migrate through the well annulus, leading to annular pressure buildup. Exceeding the design limits of pressure differentials can result in casing deformation, casing failure, or compromised zonal isolation [100,101]. Flow assurance issues, such as hydrate formation, wax deposition, or asphaltene precipitation, can restrict fluid flow and hinder production. Effective management and mitigation strategies are necessary to ensure the integrity of wells and maximise production rates [95,102]. Regular well integrity monitoring is of utmost importance during the production phase. Monitoring parameters such as casing and tubing pressures, temperatures, corrosion rates, and production data helps detect integrity deviations or anomalies, allowing for timely interventions [95,101].

Additionally, monitoring sustained casing pressure in ageing wells faces several challenges. Many older wells lack the necessary downhole equipment for accurate pressure and temperature readings in the annulus, requiring costly retrofits. The cement sheath often degrades over time due to chemical exposure, temperature changes, and mechanical stress, making reliable SCP measurements difficult [37]. Interpreting the collected data also proves challenging due to limited historical information, uncertainties about wellbore conditions, and the potential presence of multiple fluids in the annulus [103]. Adopting advanced technologies and approaches is crucial to improve SCP monitoring accuracy in these wells. This includes utilising sensitive fibre optic sensors for more reliable downhole measurements, employing sophisticated data analytics to interpret complex data considering wellbore specifics, and exploring non-intrusive monitoring techniques that do not require downhole equipment.

Fluid losses and leaks are potential occurrences within the production system, which may transpire at different junctures, such as wellheads, seals, valves, or connections. Depletion of fluids may lead to reduced productivity, ecological pollution, or jeopardised safety [95]. The timely detection and remediation of leaks play a crucial role in maintaining the integrity of a well. Implementing proactively well integrity management practises, such as regular inspections, maintenance, and monitoring programmes, is crucial to effectively address potential issues during the production phase. By doing so, operators can ensure the continued integrity of the well, maximise production efficiency, and minimise risks to personnel and the environment.

2.1.4. Intervention Phase

The well's oil and gas production should be maintained so that the well may be accessed to undertake essential repairs. Different maintenance actions could be taken depending on the well's condition and how well it works.

Well intervention refers to a set of procedures performed on an already existing well to achieve diverse objectives, including but not limited to maintenance, production optimisation, well diagnostics, and well integrity management. The management of well integrity is a critical aspect of the well's life cycle, and the intervention phase plays a pivotal role [104]. The interventions that can be implemented comprise integrity assessments, inspections, and maintenance activities to detect and resolve integrity concerns, such as corrosion, casing or tubing failures, cement degradation, or annular leaks [79].

The phase of intervention holds significant importance in the life cycle of a well, following the primary stages of drilling and completion. Intervention involves maintenance and servicing operations carried out to sustain the productivity and operational reliability of the well [105]. This intervention may include maintenance, refurbishment, or replacement of faulty equipment, substituting deteriorated parts, or resolving wellbore complications [106,107].

The process of production optimisation involves conducting interventions aimed at improving the productivity of a well [105,107]. Various techniques, such as well stimulation, acidising, hydraulic fracturing, or artificial lift installation, can enhance reservoir connectivity, mitigate formation damage, or augment flow rates. Maintenance and servicing are integral components of interventions to assess well performance, diagnose production issues, or evaluate reservoir characteristics. Various techniques such as production logging, pressure testing, well testing, and downhole imaging are employed to collect data and acquire knowledge regarding the behaviour of wells and reservoirs.

During the final stages of a well's lifespan, it may become necessary to perform plugging and abandonment operations as part of the intervention process. It is imperative to implement appropriate protocols and measures for well abandonment to guarantee the safe and irreversible discontinuation of production, minimise ecological hazards, and sustain the enduring integrity of the well [108,109]. The implementation stage holds considerable importance in optimising the longevity and efficacy of a wellbore [79,110]. This technology facilitates the optimisation of production, the extension of the well's productive lifespan, the assurance of safe operations, and the operators' management of well integrity concerns [111]. Efficient interventions have the potential to enhance production rates, optimise reservoir management, minimise downtime, and enhance overall operational efficiency over the entire lifespan of the well.

Throughout the intervention phase, there is a possibility of encountering well integrity concerns. The integrity of tubing and casing is paramount in effectively operating a well. Any form of corrosion, mechanical damage, or insufficient cementing can compromise well integrity, thus posing a significant challenge. The above-mentioned can lead to potential occurrences of leaks, cross-flows, or compromised well control [37,112]. The degradation of annular seals, located between casing strings or between casing and formation, can deteriorate zonal isolation over time. This phenomenon facilitates the movement of fluids across distinct geological strata or their upward release to the Earth's surface [113]. Maintaining the control of appropriate pressure is of utmost importance during intervention activities. The integrity of a well can be compromised due to uncontrolled flow or pressure buildup, which may result from equipment failures, inadequate barriers, or incorrect procedures [7,37,112]. Preserving wellhead components, valves, and surface equipment integrity is crucial for ensuring secure intervention operations. The potential consequences of component degradation, damage, or malfunction include equipment failure, uncontrolled releases, and leaks [7,37]. Intervention activities, including perforation, stimulation, or fluid injection, can potentially induce formation damage or fluid migration [114]. The integrity of cement is crucial for zonal isolation and well support, as inadequate management can lead to decreased reservoir productivity and unwanted fluid displacements [114]. The efficacy of the cement barrier can be compromised due to various factors, such as inadequate bonding, channelling, or degradation of cement, which can result in the migration of fluids or communication between different zones [115]. The stability of the wellbore may be compromised during interventions, such as milling, fishing, or reaming, thereby posing potential risks. Insufficient support, wellbore failure, or reservoir impairment may arise, posing risks to the integrity of the well. It is, therefore, imperative to tackle the well integrity concerns to guarantee secure and effective operations while reducing the likelihood of harm to the environment or personnel.

2.1.5. Plug and Abandonment Phase

When a well cannot produce as much hydrocarbon fluid, and all attempts to improve recovery have failed, the well is plugged and abandoned. The primary goal of plug and abandonment is to restore the well's original state with restored cap rock integrity. It entails removing crucial pieces as well as cutting or pulling the completion string. Cement plugs are installed in high-risk regions of the wellbore to prevent fluids from escaping into the environment [113]. As a result, barriers are formed against the possible passage of fluids from the reservoir part. Figure 7 portrays a typical well production architecture before and after well abandonment, with plugs placed in zones of interest in the well.

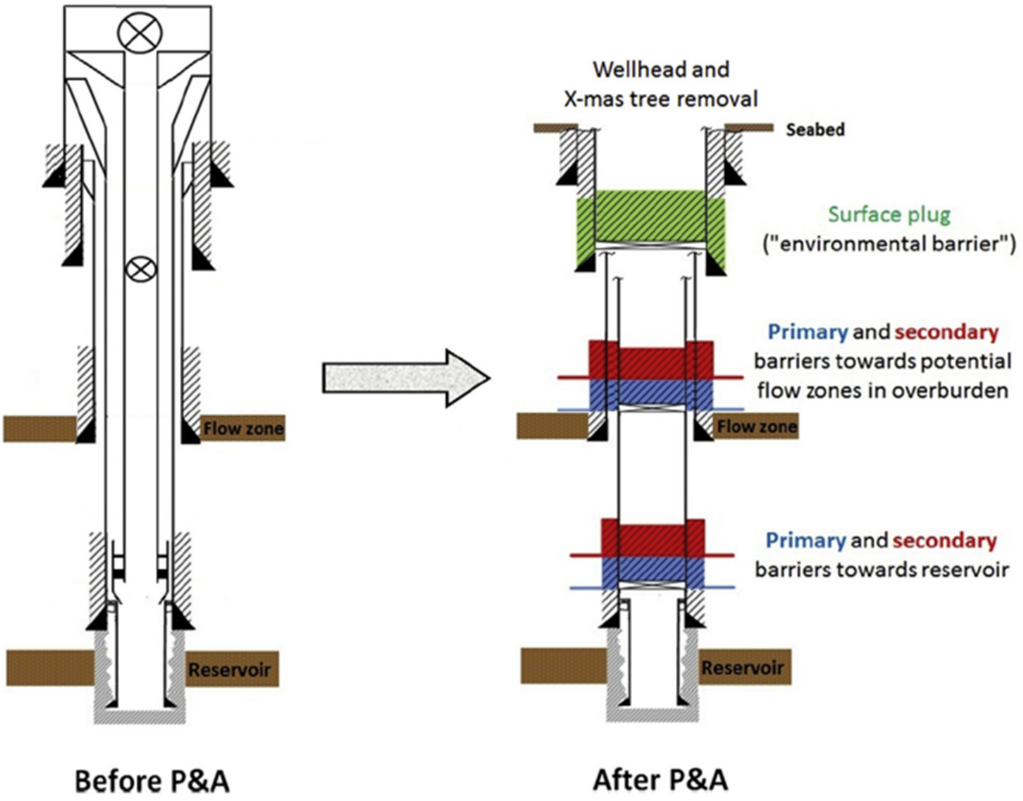


Figure 7. Typical production well before and after plug and abandonment [113].

Wellbores are plugged when they are redundant and of no use [4]. The plugging efforts must adhere to regulatory procedures. Cement is pumped and put in areas prone to leakage and at intervals within the well to seal off the formation fluid. If cement bond logs show a lack of cement behind the casing, a cement squeeze is undertaken after the casing is perforated. Before covering the casing, it must be cut 3 m below the mud line or surface.

Various concerns regarding well integrity may arise in a well's plug and abandonment (P&A) stage due to the permanent discontinuation of production and the decommissioning procedure. These issues must be managed carefully to ensure the well's safe and environmentally sound abandonment [113]. Several significant well integrity concerns arise during the plugging and abandonment phase, including the following:

- Cement and barrier integrity: Proper placement and integrity of cement plugs and barriers are critical during well abandonment. The efficacy of barriers may be compromised due to insufficient cement bonding, channelling, or degradation over time, which may result in fluid migration or communication between distinct zones. The maintenance of well integrity necessitates the monitoring and control of annular pressures. The management of annular pressures is of utmost importance as production ceases and the pressure of the reservoir undergoes alterations. Pressure differentials across wellbore barriers can lead to casing deformation, failure, or zonal isolation breaches. Preserving tubing and casing integrity is imperative during the plugging and abandonment process. Corrosion, mechanical damage, or inadequate cementing can compromise their integrity, potentially resulting in leaks, cross-flows, or loss of well control [7,37,112];
- Wellhead and surface equipment integrity: Wellhead components, valves, and surface equipment must be properly inspected and maintained during the P&A phase.

The potential outcomes of component deterioration, damage, or malfunction include uncontrolled releases, equipment failure, and leaks. Fluid migration, which can compromise well integrity, may occur due to reservoir pressure differentials, permeable zones, or breaches in barriers. The prevention of fluid migration between various zones or to the surface is of utmost importance during the plugging and abandonment phase, as it ensures adequate zonal isolation. This is essential in the context of formation fluid migration [7,37,112].

Selecting suitable plugging materials holds significant importance in ensuring the longevity of well integrity. The materials must exhibit appropriate characteristics to establish durable and efficient barriers, endure subsurface conditions, and impede fluid migration [109].

Well integrity assessment is crucial during the P&A phase, so regular monitoring and verification activities are necessary. The activities above may encompass monitoring pressure, logging of cement bonds, or sampling fluids to detect any potential issues with the integrity of the well and verify the efficacy of the abandonment procedures. Therefore, effective management of well integrity issues during the P&A phase necessitates meticulous planning, strict adherence to regulatory mandates, and the implementation of industry-leading methodologies. By addressing these concerns, operators can ensure the safe abandonment of the well and minimise potential risks to the environment and surrounding resources.

2.1.6. Carbon Dioxide Capture and Storage

The Carbon Dioxide Capture and Storage (CCS) technique is a process that mitigates the emission of carbon dioxide (CO_2) by capturing the greenhouse gas from industrial sources and subsequently concealing it underground. Although CCS has the potential to aid in mitigating climate change, it also poses certain concerns regarding well integrity that require attention. Researchers are becoming more interested in carbon dioxide capture and storage (CCS) to slow climate change caused by rising greenhouse gas emissions and carbon footprints [116–119]. Similarly, as the world strives to reduce greenhouse gas emissions to zero, integrity is becoming increasingly crucial in the oil and gas business. The integrity of wells is critical to operational performance in CO_2 collecting and storage [120,121]. According to Iyer et al. [52], wells with integrity difficulties are more likely to allow the release of collected CO_2 and hydrocarbon fluids from the formation into the environment. These fluids pollute groundwater and surface air, increasing the greenhouse impact [122,123]. According to the literature, not all well integrity leaks have been documented [124]. Leakages account for a small proportion of reported well integrity losses in the oil and gas industry. Because these leaks do not constitute a risk to humans or the environment, they are managed or fixed at the wellhead [11,52,124,125]. There have been a few instances where well integrity loss has resulted in catastrophic damage to human life, environmental degradation, and groundwater contamination [50,126,127].

The term "Caprock" pertains to the impermeable layer above the zone where CO_2 is stored, serving as a barrier to prevent leakage. The containment of CO_2 may be compromised and pose potential hazards to human health and the environment due to Caprock faults, fractures, or insufficient sealing properties. Maintaining the integrity of the caprock is of utmost importance to prevent any potential leakage of CO_2 to the surface.

Preserving wellbore integrity is of utmost importance in carbon dioxide injection and storage. Leaks or breaches in the wellbore can be attributed to corrosion, cement degradation, mechanical damage, or inadequate cementing. These factors have the potential to facilitate the escape of CO_2. Ensuring the integrity of the wellbore requires appropriate construction techniques and continuous monitoring. Wellbore completions and abandonments in the field impact corrosion and wellbore integrity. Inadequate cementing practices can increase corrosion probability, making a comprehensive assessment crucial for predicting and safeguarding against corrosion [29,79,128].

The migration of CO_2 through potential leakage pathways, such as abandoned wells, fault zones, or natural fractures, is a significant concern. Identifying and evaluating these pathways are crucial in mitigating the potential risk of CO_2 leakage and ensuring long-term storage integrity. The subsurface may undergo geochemical reactions due to CO_2, which could affect the integrity of wells. The reactions mentioned above have the potential to result in mineral dissolution, scale formation, or corrosion, thereby impacting the soundness of wellbore tubular, cement, or sealing materials [129].

Managing reservoir pressure is crucial to CO_2 injection, as it prevents overpressurisation and ensures the well's integrity. Elevated pressure levels have the potential to induce wellbore failure, casing deformation, or breaches in the sealing strata, thereby augmenting the likelihood of CO_2 leakage [79].

Implementing appropriate site abandonment and closure protocols is crucial to guarantee the sustained integrity of a site following the cessation of CO_2 injection. The activities mentioned above include sealing wells, cessation of site operations, and persistent surveillance to ensure the perpetual confinement of carbon dioxide and preclude any prospective discharge [130].

Effective management of well integrity concerns related to Carbon Capture and Storage (CCS) necessitates the implementation of rigorous risk evaluation, meticulous well construction and monitoring protocols, and compliance with regulatory mandates. An all-encompassing strategy that considers the complete life cycle of carbon capture and storage (CCS) initiatives, ranging from the selection of sites to their eventual closure, is imperative to guarantee secure and efficient carbon dioxide sequestration [119].

Assessing the integrity of active and decommissioned wells is crucial for effective CO_2 containment. Researchers have focused on identifying integrity failures, setting standards, and evaluating methods. Degradation of well integrity can be attributed to mechanical loading and chemical corrosion. Research has focused on selecting materials for new wells or well plugging to ensure well integrity and safe operation in Carbon Sequestration with Enhanced Gas Recovery (CSEGR). Evaluation methods include cement bond logs (CBLs) and variable density logs (VDLs), but there is a lack of logging tools for accurately identifying and quantifying corrosion within the cement [15].

The storage of CO_2 in depleted reservoirs can no doubt mitigate carbon emissions, although it presents challenges to wellbore cementation. Fluctuations in temperature and pressure conditions can induce thermal stresses, corrosion, and fatigue in cement and casing. Dissolved CO_2 in formation water produces carbonic acid, which damages the cement sheath and jeopardises its long-term zonal isolation potentials. To maintain long-term integrity, it is crucial to consider these factors during the design and implementation phases: selecting cement formulations resistant to CO_2 attack, utilising corrosion-resistant alloys for casing, and establishing comprehensive monitoring programs to identify early wellbore integrity concerns.

2.1.7. Hydrogen Storage in Depleted Reservoirs

Hydrogen's future relies on large-scale storage systems facilitated by geological formations like depleted oil and gas reservoirs, caverns, and aquifers. These solutions manage demand and supply fluctuations, making depleted natural gas reservoirs economically efficient and reliable. Native residual gases reduce cushion gas use, but there is a lack of understanding. Hydrogen is gaining recognition as a low-carbon energy source that can reduce carbon emissions in power generation, heating, transportation, and businesses requiring significant fuel consumption [131].

With the increasing worldwide need for sustainable energy solutions, there is a growing interest in using depleted hydrocarbon resources for hydrogen storage. This has become a lucrative area of study and investigation. Hydrogen, known for its substantial energy density and eco-friendly byproducts, has been recognised as a feasible substitute for conventional fossil fuels [132–134].

Nevertheless, the efficient storage and delivery of hydrogen is a substantial obstacle [135]. Hydrogen has a very low energy density when measured by volume, especially at normal atmospheric pressure. Therefore, compression is required in order to increase its energy density [136]. In order to tackle this problem, many hydrogen storage systems have been created and assessed, such as high-pressure compression, liquefaction, and solid-state storage using metal hydrides or porous materials [133–136].

This technique has the potential to provide a high amount of energy per unit volume, the ability to store energy for a long period of time, and the possibility of being used on a big scale [135]. Recent research has emphasised the benefits of this method, including the capacity to use already established infrastructure, the possibility of storing massive amounts of hydrogen, and the potential for storing hydrogen in a stable manner over a long period of time [134]. These studies have also indicated other technical issues that need to be resolved, including guaranteeing the integrity of the storage reservoirs, handling possible gas leaks, and improving compression and injection operations [137,138].

Recent studies have examined the practicality and possible advantages of this method. The sealing mechanisms and well designs of depleted reservoirs have the capacity to facilitate the compression of hydrogen to high pressures. This compression process has the potential to greatly enhance the volumetric energy density of stored hydrogen. Moreover, the geological barriers and confinement qualities of these exhausted reservoirs may provide a significant level of safety and protection for the stored hydrogen [139,140].

Compression is still an essential element of this storage technique since achieving the requisite energy densities requires high-pressure compression. The study has examined compression techniques used in stationary and automotive applications, focusing on their current performance and continuing research efforts to enhance efficiency, reduce costs, and increase safety [134–136].

Concurrently, there have been endeavours to create sophisticated hydrogen storage materials, such as tailored carbon fibres with hollow porous structures, which may augment the capacity for storing hydrogen [133]. By harnessing the potential of depleted reservoirs together with these materials, we may make significant progress towards overcoming the "hydrogen grand challenge" and establishing a sustainable hydrogen economy.

However, it is worth noting that storing hydrogen in depleted reservoirs does not go without its challenges when aiming at the long-term integrity of the cemented wells. One such challenge is hydrogen embrittlement, where hydrogen atoms diffuse into the casing and the cement, thus reducing their ductility and fracture toughness. This embrittlement can lead to cracking and premature failure under stress, especially at lower temperatures often associated with hydrogen storage [141]. Additionally, dynamic temperature and pressure fluctuations during hydrogen injection and withdrawal cycles can induce thermal stresses and fatigue in the cement sheath, further increasing the risk of degradation [142]. Therefore, ensuring the long-term integrity of cemented well treatments for hydrogen storage will be an excellent practice. This will be achieved by carefully considering material selection using hydrogen-resistant casing materials and specialised cement formulations, coupled with robust monitoring and maintenance programme implementation.

2.2. Sustained Casing Pressure

The occurrence of sustained casing pressure (SCP) is a significant challenge for oil and gas operators. Well integrity issues can manifest at any phase of the well history. However, SCP shows up after wellhead installation and can last throughout production activities if not addressed promptly. The observed behaviour can be ascribed to gas migration within the annular region, leading to increased pressure at the wellhead. Wojtanowicz [143] posits that the occurrence of gas migration in the annulus can be ascribed to the decrease in hydrostatic pressure within the cement column and changes in the volume of the annular space. The failure of annular seals, which allows for the upward migration of gas, can be ascribed to two primary factors: channelling that takes place during the process of cement setting and insufficient cement bonding.

Wojtanowicz [143] and Bourgoyne, Scott, and Manowski [144] identified substantial integrity challenges within the oil and gas sector in relation to SCP. It has been revealed that a total of 8122 wells located in the Gulf of Mexico (GOM) are currently facing issues about well integrity in relation to SCP. Johns et al. [145] reported that a considerable percentage of wells in the Gulf of Mexico (GOM) had issues related to sustained casing pressure, impacting approximately 45% of the wells. Based on the research conducted by Wojtanowicz [143], it has been observed that there have been occurrences of well integrity issues associated with SCP in several geographical areas, such as India, South Louisiana, Tunisia, and the San Juan Basin of New Mexico. However, a comprehensive assessment of the number of wells affected by SCP in these areas was not carried out. Although it is really accurate that a significant proportion of instances involving SCP are of a modest nature and can be effectively mitigated through the casing's structural integrity, it is imperative to proactively tackle the issue rather than opting for well abandonment. Failure to do so may lead to significant repercussions. Wojtanowicz [143] asserts that a significant majority, specifically around 90%, of SCP issues can be classified as minor concerns. The wells situated on the outer continental shelf of the Gulf of Mexico have seen the effects of persistent casing pressure, as illustrated in Figure 8. The data suggest a positive correlation between the duration of well operation and the frequency of SCP concerns.

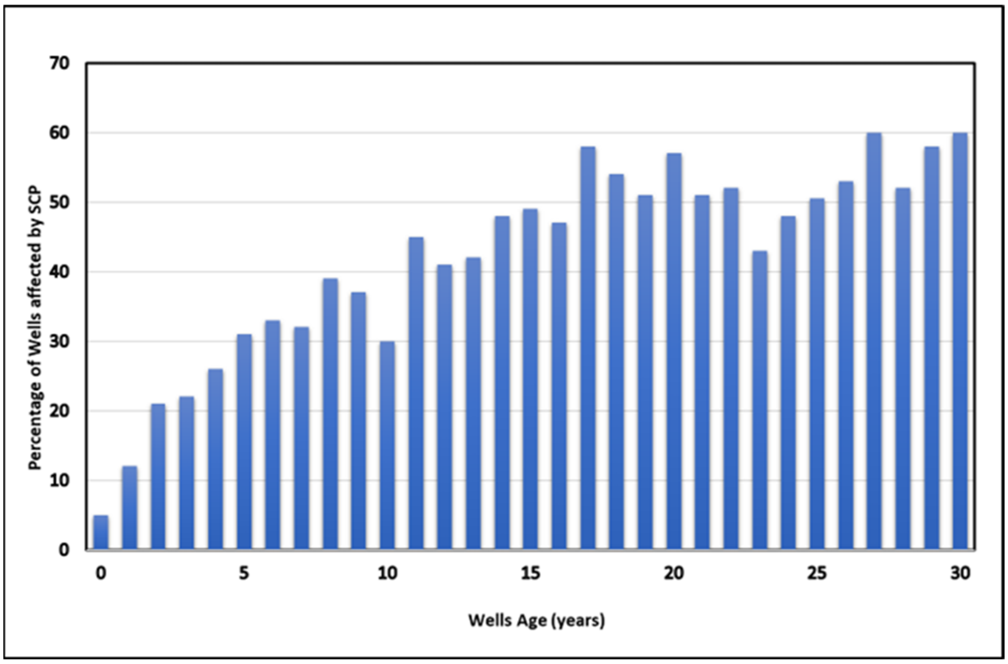


Figure 8. Percentage of Wells affected by sustained casing pressure (SCP) versus age of wells (Adapted from [146]).

The objective of the study conducted by Rocha-Valadez et al. [103] was to assess the magnitude of SCP within the annular space of wells. The study's results demonstrated that the introduction of gas leakage into the annulus led to a rise in the casing pressure. The model that has been built provides a systematic approach for designing transport protocols to manage persistent casing pressure. This is achieved by employing analytical solutions and linear differential equations. The results suggest that the model exhibited a high degree of agreement with the actual data collected in the field, revealing an increase in casing pressure within the annular space. The proposed model is based on certain assumptions, which may reflect an ideal situation rather than a practical and realistic condition. The occurrence of SCP within the annular space can be attributed to the release of gas originating from the cement sheath. The objective of the study conducted by Rocha-Valadez et al. [103] was to reduce the length of time required for pressure buildup to attain the Maximum Allowable Wellhead Operating Pressure (MAWOP) and establish a stable casing pressure. In order to accomplish this objective, the researchers employed preliminary data on SCP buildup to formulate a model that presents an inherently safer methodology for conducting SCP tests. Based on their claim, the model possesses the capacity to predict the accumulation of gas in the annulus, permeability, and distribution of pressure. The utilisation of just two case studies in this research is worth mentioning, as it may impose limitations on the applicability of the established model to a broader spectrum of wellness habits. Assumptions can potentially emerge due to a lack of readily available knowledge. The failure to recognise the lack of relevant information that could have prevented such assumptions was evident. The occurrence of SCP is frequently ascribed to the accumulation of pressure within the annular gap between the production casing and tubing. The observed rise in pressure can be mostly ascribed to the occurrence of tubing leakage, which has been identified as a primary contributing element to the phenomenon known as SCP. The distribution of tubing and annulus is subject to the influence of the leakage point in the tubing, as determined by a model that incorporates the impacts of pressure and temperature. In their study, Wu et al. [20] performed three key calculations. These calculations involved estimating the depth of the leaking location, evaluating the temperature and pressure of the annulus at the point of leakage, and analysing the maximum annular pressure (MAP) at the wellhead. It is important to highlight that certain assumptions were made despite the use of offshore platforms for data collection from a gas-producing well in order to develop the model. The model's effectiveness is constrained when applied to wells with significant variation. Additionally, their research efforts mostly focus on addressing concerns that come after the beginning of the SCP rather than those that arise before the SCP.

Theoretical models establish the basis for understanding SCP; nevertheless, actual oil and gas reservoirs sometimes display considerable geological heterogeneous conditions that must be acknowledged. Precisely forecasting SCP in such contexts necessitates a more sophisticated methodology. This entails the integration of high-resolution three-dimensional (3D) geological models obtained from seismic surveys, well logs, and core data to accurately represent changes in characteristics such as porosity and permeability [147]. Advanced numerical simulation approaches, including finite element and finite difference methods, resolve fluid flow and heat transfer equations within these complex geological frameworks [148]. These models must consider multi-phase flow dynamics and incorporate geomechanical coupling to clarify the relations between pressure variations and rock deformation [149]. Data integration techniques, including history matching, are essential for calibrating model parameters to ensure forecasts correspond with observed reservoir behaviour.

The graphic illustration in Figure 9 provides a visual representation of the occurrence of sustained casing pressure across different casing diameters in the wellbore. The intermediate casing, which had a diameter of 10 ¾ inches, displayed the highest frequency of SCP issues. The 13 $^{3}/_{8}$-inch surface casing, 9 $^{5}/_{8}$-inch intermediate casing, and 7-inch production casing were found to possess the second highest ranking, whereas the 20-inch and 16-inch conductor casings were assigned the third rank. Based on the research conducted by Xu and Wojtanowicz [102], it has been determined that the 11 ¾″ surface casing holds the fourth rank in relation to potential difficulties related to the SCP. Nevertheless, there is a lack of evidence about any potential problems related to SCP with respect to the 16-inch surface casing, 8 $^{5}/_{8}$-inch intermediate casing, and 7 $^{5}/_{8}$-inch and 6 $^{5}/_{8}$-inch production casings.

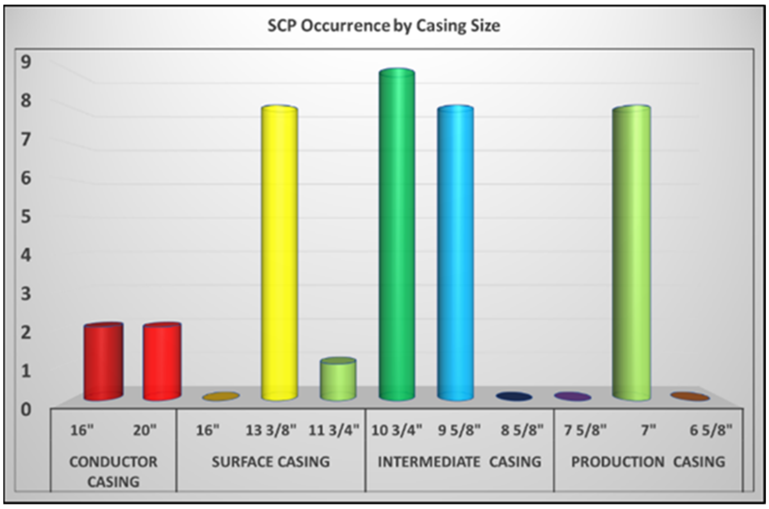


Figure 9. SCP Occurrence by Casing Size (Adapted from [102]).

3. Challenges, Opportunities and Future Perspectives

The challenges posed by well integrity and sustained casing pressure in the oil and gas industry cannot be overemphasised. SCP poses significant threats to oil and gas wells, causing deformation, corrosion, and failure. This undermines the well's structural stability, increasing the risk of leaks and other safety risks. Inadequate management of SCP can lead to unregulated hydrocarbon discharges, explosions, fires, and poisonous gases, causing injuries, fatalities, and significant harm to property and the environment. In the run-up to attaining a net zero economy by 2050, there is a challenge to achieving this aim should SCP issues not be dealt with. This could lead to leakage of stored CO_2 or hydrogen from the reservoir due to compromised integrity. Operators must follow safety rules, monitor the situation, and take proactive measures to reduce incidents. SCP can also lead to significant financial losses for oil and gas producers, requiring significant equipment, resources, and workforce expenditures. Environmental impacts include soil, groundwater, air quality, and human health. SCP management must adhere to strict regulatory criteria, avoiding fines, penalties, legal responsibilities, and damage to reputation. Efficient SCP management can minimise operating risks, protect staff and the environment, and ensure long-term operations viability.

Opportunities abound in the optimisation of SCP management through advanced monitoring systems, integrated data analytics, remote monitoring and control systems, predictive maintenance solutions, and stakeholder collaboration. Technological advancements like distributed temperature sensing, fibre-optic sensors, and wireless sensor networks enable real-time monitoring of pressure and other variables in wellbores, enabling early identification of pressure abnormalities and prompt management to reduce hazards. Big data analytics platforms equipped with machine learning algorithms provide insights into SCP trends, correlations, and risk factors, allowing operators to make informed decisions. Remote monitoring systems minimise on-site staff requirements and improve operational effectiveness. Collaboration among operators, service providers, and technology suppliers fosters advancements in SCP monitoring technologies, intervention approaches, and predictive analytics capabilities. Machine and deep learning technologies offer advanced surveillance and predictive analysis in managing SCP, automating hazard evaluation in supply chain planning, enabling intelligent resolution of SCP-related problems, and extending the lifespan of well infrastructure.

Future perspectives on SCP management should emphasise integrated risk management systems that consider geological, operational, and regulatory issues. Operators need to implement comprehensive risk assessment procedures, including monitoring data, well integrity evaluations, reservoir modelling, and environmental risk analysis. The use of data analytics and artificial intelligence (AI) would drive decision-making processes, enabling operators to make informed decisions and optimize strategies for supply chain disruptions. Strategies would minimise the ecological footprint and ensure long-term sustainable practices. Operators would use digital twin models, IoT sensors, and cloud-based platforms to generate virtual representations of well assets and simulate scenarios. Regulations may enforce stricter monitoring and reporting obligations, and it is crucial for operators to adapt to these changing requirements. Knowledge dissemination, collaborative research, and technology transfer should be prioritised to enhance SCP monitoring technologies, intervention strategies, and best practices.

Below are some suggested study paths for future advancement in the areas of well life cycle integrity and sustained casing pressure:

- Predictive Modeling for Sustained Casing Pressure: Enhance the complexity of prediction models, maybe using machine learning, to anticipate the probability and intensity of persistent casing pressure incidents. This may include integrating real-time data from sensors, geological data, and previous well data. Predictive algorithms can help oil and gas industry operators identify well pressure trends, take preventive actions and avoid costly repairs. They also mitigate blowout risks, improve decision-making, and reduce maintenance costs. Predictive models prioritise wells with higher SCP risks, reduce environmental impact, and improve operational efficiency. Integrating predictive models into real-time monitoring systems ensures optimal well performance;
- Advanced Materials for Wellbore Integrity: Examine the use of innovative materials that possess improved strength, resistance to corrosion, and ability to contain pressure. These innovations may include improvements in casing materials, cementing technology, and wellbore coatings. Advanced materials enhance oil and gas well integrity, safety, and operational efficiency by providing enhanced strength, durability, corrosion resistance, and extended well lifespan, thus reducing maintenance costs, risk of catastrophic failures, and environmental impact. These materials are suitable for harsh environments, enhancing compliance with EOR techniques and integrating with emerging technologies like smart well systems. They also enhance performance and dependability;
- Impact of Ageing Wells on Sustained Casing Pressure: Given the increasing number of ageing wells worldwide, research is essential to comprehend the long-term degradation processes that affect the integrity of the wellbore and their role in causing sustained casing pressure. The study of the impact of ageing wells can lead to improved safety, cost-effectiveness, streamlined manufacturing processes, adherence to regulations, environmental protection mitigation, asset management, operational efficiency, and improved corporate reputation. Preventive measures can detect potential risks, minimise emergency interventions and extend the well's lifespan. Knowledge gained through this study can also improve asset management and resource utilisation;
- Integration of Data Analytics and Monitoring: Create integrated data systems that combine real-time monitoring data with sophisticated analytics to offer early indicators of well integrity concerns and possible threats of sustained casing pressure. Data analytics improves operators' operational efficiency, reduces waste, enhances decision-making, and reduces operating costs. It allows for predictive maintenance, real-time safety monitoring, and regulatory compliance. It also promotes innovation and market leadership by optimising operations and minimising environmental impact. Data analytics also fosters interdepartmental cooperation, enabling efficient knowledge retention and sharing. Scalable solutions derived through data analysis and monitoring would enable companies to adapt to changing circumstances, ensuring resilience and continuity of operations;
- Life Cycle Cost Analysis of Different Mitigation Strategies: Perform thorough life cycle cost evaluations to assess the economic feasibility and long-term efficiency of several techniques for mitigating sustained casing pressure. Oil and gas operators will make informed decisions about mitigation techniques, investment prioritisation, asset management, regulatory compliance, strategic planning, operational efficiency, and

market differentiation. It will also aid in identifying cost-effective risk mitigation solutions, align with regulatory mandates, and reduce environmental impact. Successful implementation can lead to a competitive advantage, improved stakeholder image, and continuous cost reduction, safety, and sustainability improvement.

Exploring these research options will greatly assist the oil and gas sector in guaranteeing the integrity of mature wells, mitigating environmental concerns, and enhancing the sustainability of oil and gas operations.

4. Conclusions

A comprehensive review of well life cycle integrity challenges and their implications on SCP in the oil and gas industry has been undertaken. Ultimately, the magnitude of integrity problems stems from inadequately designed wells. The casing's quality, stability, pressure control, geological properties, operational parameters, maintenance, human error, environmental conditions, and compliance with regulations are crucial factors. Conducting routine inspections, using error prevention measures, and adhering to industry standards help reduce the severity of failures and ensure the integrity of oil and gas wells. It was revealed that there is insufficient evidence about any potential issues associated with SCP in relation to the 16-inch surface casing, 8 $^{5}/_{8}$-inch intermediate casing, and 7 $^{5}/_{8}$-inch and 6 $^{5}/_{8}$-inch production casings. Ensuring the successful transition to a net zero economy by 2050 requires addressing the challenges associated with SCP concerns. A compromised reservoir integrity might result in the leakage of stored CO_2 or hydrogen. Future SCP management should focus on integrated risk management systems that consider geological, operational, and regulatory issues. Operators should use data analytics and AI for informed decision-making, minimise ecological footprint, and optimise supply chain disruptions. Digital twin models, IoT sensors, and cloud-based platforms can help simulate scenarios. Prioritising knowledge dissemination and technology transfer is crucial.

In summary, the examination of the problems related to the integrity of the life cycle and their impact on SCP emphasises the need for a thorough and forward-thinking approach to well management. By using cutting-edge drilling methods, revolutionary material solutions, and making decisions based on risk assessment, the industry may work towards preserving the structural soundness of wells over their entire operational lifetime, thereby guaranteeing the safety and sustainability of oil and gas activities as well as its transformation in the utilisation for carbon dioxide and hydrogen storage.

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