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Casing structural integrity and failure modes in a range of well types: a review.

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Casing Structural Integrity and Failure Modes in a Range of Well Types - A Review

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Abstract:

This paper focus on factors attributing to casing failure, their failure mechanism and the resulting failure mode. The casing is a critical component in a well and the main mechanical structural barrier element that provide conduits and avenue for oil and gas production over the well lifecycle and beyond. The casings are normally subjected to material degradation, varying local loads, induced stresses during stimulation, natural fractures, slip and shear during their installation and operation leading to different kinds of casing failure modes. The review paper also covers recent developments in casing integrity assessment techniques and their respective limitations.

The taxonomy of the major causes and cases of casing failure in different well types is covered. In addition, an overview of casing trend utilisation and failure mix by grades is provided. The trend of casing utilisation in different wells examined show deep-water and shale gas horizontal wells employing higher tensile grades (P110 & Q125) due to their characteristics. Additionally, this review presents casing failure mixed by grades, with P110 recording the highest failure cases owing to its stiffness, high application in injection wells, shale gas, deep-water and high temperature and high temperature (HPHT) wells with high failure probability. A summary of existing tools used for the assessment of well integrity issues and their respective limitations is provided and conclusions drawn.

Key words: Casing, Failure modes, Well Integrity, Logs

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1. Introduction

The category of unconventional wells (horizontal wells) pose unique sets of challenges during drilling, completion, production and abandonment. This is primarily due to increasing global oil and gas demand that has been pushing exploration and production boundaries to more difficult frontier petroleum provinces.

Recent wells' statistics from around the world, on both conventional and unconventional wells, from countries that includes: Canada, China, Netherlands, Norway, United Kingdom, and United States show that approximately 26, 600 wells out of 380,000 wells have at least one form of integrity failure (Davies et al. 2014). In addition, Noshi et al. (2018) examined casing failure cases from historical data and found out that 20 production casing failed out of 80 examined in the Western Anadarko Basin of the North Texas and Oklahoma Panhandles that comprises Cleveland Sandstone, Granite Wash and Marmaton formations. In addition, 85% of these occurred during or after hydraulic fracturing. The study further revealed that 75% of the failed casings inspected suffered from high hoop stress.

King and King (2013) reported 45% tubular failures out of 14,297 wells in the US Gulf of Mexico during the 1980s. The study covered offshore wells with at least a leak incident on tubulars. Casing leaks can range from poor make-up in connections to corrosion due to acidic fluids and age during production operations. However, recent advances in artificial intelligence has enable development automated power tongs that minimises human interference error and ensure accuracy and consistency in casing connections. This development has dramatically reduces casing integrity issues (connection leaks) and ensure proper connection makeup and long-term wellbore integrity. Kiran et al. (2017) pointed out the main causes of leaks in oil and gas wells are thread breakage, casing corrosion, micro-annuli in cement, mud channels and gas migration through damaged cap rock.

In Asmari formation in Iran, forty-eight casing collapses due to reservoir compaction, geo-mechanical effects and corrosion were reported (Salehi et al. 2009). Although production commenced in the early 1950s, casing collapse was only recorded 24 years afterwards and the reported incidents continue to increase over years. This is attributed to the geological anomaly of a major fault that traverse across the carbonate oil-field (Asmari 'M') and casing age.

In China, 15-30% casing failure in thermal recovery wells were due to substandard casing design according to Han et al. (2018). The cyclic steam stimulation (CCS) process in this field adopt three different processes; which are steam injection, soaking and oil production. In particular, during injection thermal stresses causes casing to expand meanwhile, axial compressive load from both cement and formation restrained this expansion. At an approximate temperature differential of 180°C casing material yield beyond its elastic limit. However, in the production stage, significant decrease in temperature may lead to alternating loads from compression during injection to tension during production because of external restrains making casing failure likely in such an operation. Furthermore, Xi et al. (2018) study reported a casing failure rate of 34% out of 101 wells drilled in Weiyuan shale play. Investigation on 25 wells in this field suggested that lithological influence and combined effect of internal and external stresses acting on the casing during fracturing contributed to the high failure rate. However, apart from these suggestions; poor cementing practice and activation of weak structural interfaces during stimulation were to blame for the casing failures reported (Yin et al., 2018; Yan et al., 2017).

In particular, specific casing integrity differ with well type, function and operations even in the same well, field and location. Classic example of this challenge is casing lateral buckling or deformation (Yan et al., 2017; Yin et al., 2018; Xi et al., 2018). However, this phenomenon of casing deformation has several negative impact on the production capacity of the well, both short and long term integrity of the production casing, other barriers of the well and ultimately environment. Moreover, this challenge (casing deformation) has been attributed to so many factors leading to downhole complexities (Liang et al., 2017), and as such not well understood at present.

As noted above, numerous reports exist on casing failures, however, there are scarce detailed studies in the open literature on solutions to curtail these failures. Excellent literature review studies are available by King and King (2013) on environmental impact of well-construction failure, on oil and gas wells integrity by Davies et al. (2014) and study by Kiran et al. (2017) on well integrity barriers. Interested readers are referred to these works. The numerous casing failures are partly due to the sophisticated factors attributing to casing failure phenomena, hence still remain an engineering challenge in the process of developing shale gas horizontal wells. On the other hand, cost of alternative high performance materials and current industrial compliance practice restricts material choice that can cope with the casing functional requirements.

In order to completely understand current state of the art, the underpinning causes and the resulting failure modes and mechanism under different operating conditions, we have conducted a review surrounding all aspect of the casing string in both conventional and unconventional wells is required. This aims to improve our current understanding of sophisticated factors causing casing failure and enable us to take steps to reduce casing failure and their effects. Least to say, there is an urgent need to identify solutions, the root cause for the casing failures and perhaps paradigm change in future wells construction practices and process. This study therefore covers classification by well types, their failure modes and assessment techniques and sets light on future solutions.

The casing integrity challenge in different well types. The section looks at casing integrity challenges in high pressure and high temperature (HPHT) wells, geothermal wells, injection, shale gas horizontal wells, steam injection wells, under specific well operation to present state of the art on casing integrity issues. The specific casing failure modes are covered in Chapter 3. The sub-chapters provides itemised key sources of stresses before and after well drilling oil and gas wells and also present the severity of stress variation between vertical and horizontal well as well as the effect of material non-linearity on casing collapse resistance. Chapter 4 covers both existing and emerging casing integrity assessment techniques and also explores an overview of techniques currently employed in the industry to access casing health status together with their respective limitations. The opportunities and challenges related to casing integrity are covered in Chapter 5 and conclusions drawn

2. Casing integrity challenge in different well types

Exploration and production is venturing into difficult environment and frontier basins. Examples of frontier petroleum provinces are; deep-water, high pressure and high temperature fields and shale gas. HPHT wells refer to wells that have undisturbed bottom hole temperature of at least 300 °F (149°C) and requiring surface control pressure equipment (BOP) in excess of 10,000psi (69MPa). These fields have long been established to pose numerous challenges to drilling, completions, production and integrity of barrier elements (Kiran et al., 2017). Numerous factors can cause casing failure, which can lead to accident, negative financial implications, loss of asset and damage to the environment. However, the major aim of well construction is to produce oil and gas with no fluid leakage, barrier longevity and reliable well integrity through the well lifecycle and beyond. The wells can be classified into conventional and unconventional wells. According to Ma (2016) unconventional resources or wells are reservoirs or wells that are not conventionally developed. Classic characteristics of unconventional wells include, extreme depth, high stresses, elevated bottom hole temperature, and may contain greenhouse gases to mention a few. Specifically, shale gas and tight oil reservoirs exhibit very low permeability justifying the need for excessive stimulation stages to aid commercial oil and gas production through hydraulic fracturing. The hydraulic fractures, natural fractures, fault activation, slips, excessive stimulation stages and formation shear displacement lead to casing failures. Apart from casing integrity, issues encountered in unconventional wells, conventional wells also develop well integrity problems during production operations such as stimulation, thermal recovery and enhanced oil and gas recoveries.

2.1 HPHT & Geothermal wells

The high-pressure nature of a HPHT well is a key factor that aids in commercial oil and gas production. Conversely, it poses many challenges to drilling, completion, production and well integrity. On the other hand, geothermal wells exhibit elevated bottom hole temperature ranging from 450 to 750 °F (232 to 399°C). Wells of this type are often found in location with high geothermal gradient greater than 1.4°F/100ft (world's average) according to (Smithson 2016).

During HPHT well drilling, changes in pore pressure, temperature and associated stresses that results; create borehole stability issues and jeopardise casing integrity in the long term (Yuan et al., 2013). In addition, high temperature differentials in both HPHT and geothermal wells can lead to wellbore collapse, which can negatively affect both casing and cement behind it. Furthermore, because of high temperature in these wells, cement could set in hours even after administering appropriate quantities of retarders at temperatures above 450 °F. This results in poor cement with micro voids, poor bond and inappropriate compressive strength. The cumulative effect is well integrity failure. Voids in cement have much more negative impact on casing integrity than eccentricity as noted by (Wilcox et al., 2016).

Both abnormal and subnormal pressure zones develop during diagenesis leading to alternating sequence of high- and low-pressure zones from the normal formation pressure in an area. This alternating pressure sequence in gas wells pose severe threat to well mechanical barriers such as casing and cement (Joule Thomson effect). Also, accelerated casing damage is experience due to change between production and injection which lead to cyclic loading (Kaldal et al., 2014). This, however, leads to greater risk of casing collapse and deformation. Moreover, after long production history in thermal wells, the combine influence of sand production and reservoir compaction could be the main cause of failures in casings - such as collapse and burst. For instance, sand production offset initial casing equilibrium state while reservoir compaction adds compressive loads on casing. These two load events exert an additional load on the casing leading to high probability of buckling in thermal wells.

Again, the high temperature in HPHT and geothermal wells can accelerate corrosion rates leading to rapid casing degradation and resulting casing integrity concerns (Klapper and Stevens, 2013). Also, according to Kiran et al. (2017), presence of voids between casing and cement increase the chances of casing collapse during well heat up as fluid behind the casing cannot expand. Under this situation, high pressure is generated that usually exceeds the casing collapse resistance.

In addition, for geothermal wells that have low permeability, hydraulic fractures are created to increase productivity. Temperature difference between the injected water and reservoir induce significant structural damage of both casing and cement (Okech et al., 2015.) Also, Shadravan et al. (2015) indicated that the main corrosion agent in almost every geothermal well is CO_2 – which when it encounters water or steam, forms carbonic acid that leads to metal corrosion. This can be divided into two principal forms of CO_2 corrosion: mesa attack (localised CO_2 corrosion) and pitting.

2.2 Shale gas horizontal wells

Shale gas and tight oil reservoirs exhibit very low permeability justifying the need for excessive stimulation stages to aid commercial oil and gas production through hydraulic fracturing. Another key feature of shale gas horizontal well is the very long horizontal lateral section. In the process of hydraulic fracturing, with high-flow-rate, fluid retention in cement voids contract due to sudden temperature decrease inside the casing. Consequently, pressure drops inside the cement sheath voids causing uneven load distribution on the casing paving way for potential casing deformation (Yan et al., 2017).

The study by Chen and Xiang (2017) identified fracture and bedding as the main internal factors responsible for casing deformation during hydraulic fracturing. In addition, when casing is placed in a poor lateral support with high pumping pressure requirement to fracture the formation, this creates high internal pressure inside the casing which is the basis of casing failure. Yan et al. (2017) pointed to the fact that under the combined effect of high internal pressure in a high tortuous wellbore, external stress becomes critical and casing deformation risk is higher in such a situation. However, owing to long lateral sections, casing standoff is a challenge especially in the horizontal section due to gravity. Lack of good standoff (70% and above), could lead to potential points for lateral buckling in a horizontal well. Casing standoff is a measure of the ratio of how the casing is centrally placed relative to the well diameter (concentricity). Furthermore, Gorokhova et al. (2014) compared soft string and stiff string models for casing centralisation and established that both approaches yield similar standoff ratio during planning phase. However, they concluded that the stiff string model gives more accurate prediction in the presences of well tortuosity and open hole enlargements. Operational efficiency, models predictions and optimum number of centralisers and type (spring-bow or rigid) play crucial role in establishing good standoff and potentials buckle points along the lateral section of the well. Figure 2 (A & B) shows the effects of centraliser on casing deformations, while (C & D) presents buckling due to fracture and lead mould impression justifying casing deformation respectively.

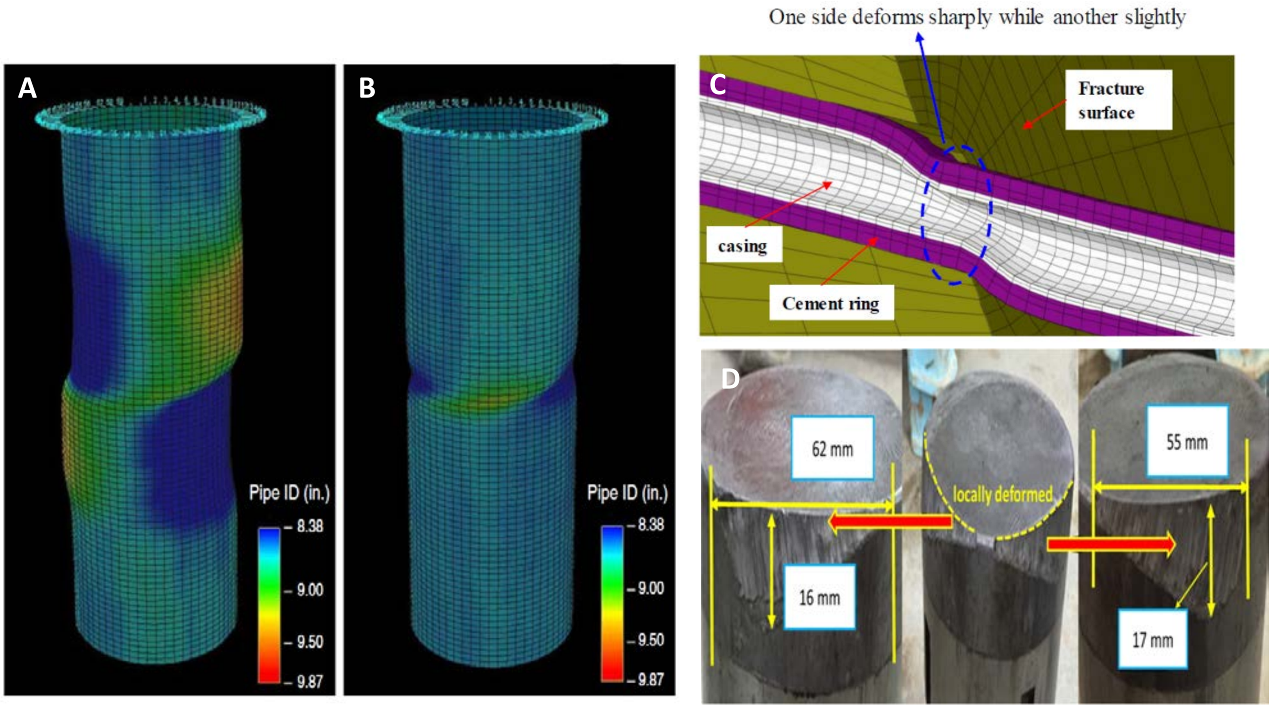

Fig. 2. 3D view of deformed casing from well F1 showing the effect of centralisation. (A) non-centralised (B) Centralised (After Mainguy and Innes, 2018). (C) Sectional view of simulation result of casing deformation caused by natural fracture (NF) or fault slip (After Li et al., 2017). (D) Lead mould wash-out from a deform casing. (After Yan et al., 2017).

The key factors attributed to casing failure are unequal external and internal loads acting on the casing during fracturing operation. For example, Yin et al. (2018), showed that shear deformation of casing was due to slip of shear fractures in shale gas reservoirs, based on curvature screening criteria. The study further revealed that slip displacement led to large transverse displacement and stress concentration points on casing. Furui et al. (2012) established that simultaneous fracking and acidising can lead to compaction, wellbore integrity issues and casing failure. In a different study, Yu et al. (2016) examined the effect of hydraulic fracturing on reservoir deformation and concluded that fractures caused casing and subsurface deformations. Yang et al. (2018) examined the high failure cases of casing in Changning Weiyuan shale and reported that 34% of the 101 wells that underwent hydraulic fracturing had casing deformation.

In summary, hydraulic fracturing cause structural stresses that lead to wellbore integrity decline (Yin et al., 2018; Furui et al., 2017; Yuan et al., 2016; Li et al.,

2012 and Abou-Sayed et al., 2005). Similarly, both Xi et al. (2017) and Wang et al. (2018) indicated that when weak plane is activated in shale reservoirs, such activation and bedding caused casing shear deformation. Another reason for casing deformation was proposed by Hagshenas et al. (2017) and Liu et al. (2017) who noted that additional load is exerted on casing by fracture slip through the wellbore. Again, Yin et al. (2018) pointed that fracture slip during hydraulic fracturing can cause casing shear failure. During this process; fracture slips through the wellbore, which induce a shear load on the casing resulting in -casing damage under the action of formation shear slip.
The study of Xi et al. (2018) identified key factors such as fracturing pressure, formation anisotropy, lithologic interface, temperature and cement to increase casing stress. Consequently, casing deform under combined stresses. Figure 3 provides statistical analysis showing deformation points of 12 wells out of 25 horizontal wells during hydraulic fracturing. It could be seen three different categories of casing deformations were encountered i.e. during fracturing, tripping bridge plug and those related to drilling out the bridge plug.

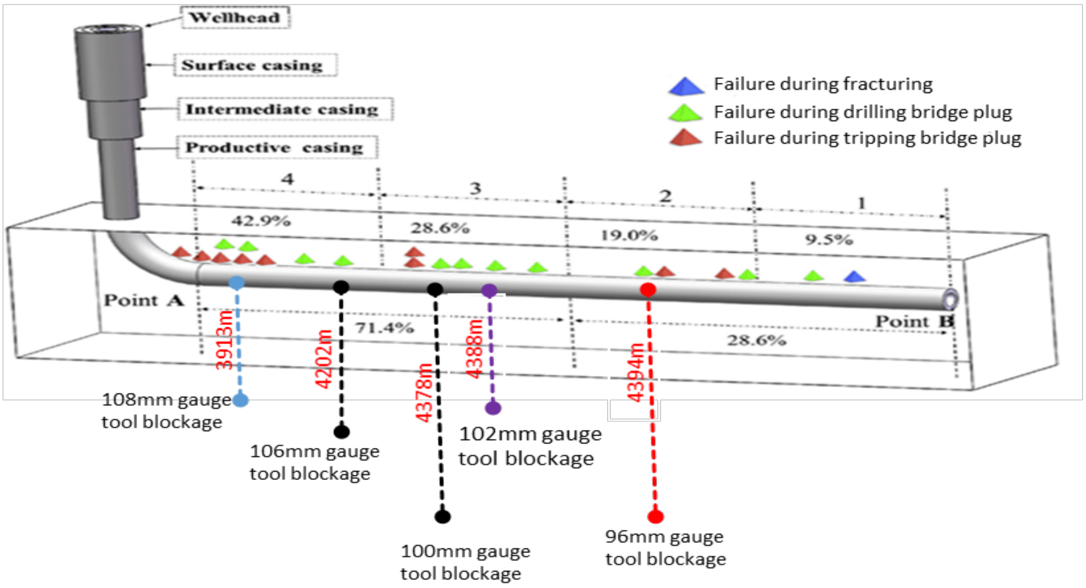

Fig. 3 Statistics on casing deformation points of 12 horizontal wells (After Xi et al., 2018). And specific example of Wei-204H7-3 with 5 deformation points as shown (After Yan et al., 2017)

However, based on the formation characteristics and the cementing process in Sichuan Basin and Annular Pressure Build-up (APB) noticed in conventional wells, physical models and finite element models were established to study this phenomenon. Many factors, like void, bedding plane angles, temperature change, magnitude of the internal pressure and in-situ stress were examined. Results obtained show that cement void contract due to high fracturing flow rate and sudden temperature reduction inside the casing. As a result; pressure inside the cement sheath voids dropped significantly within a short time; thereby imposing varying load on the casing. Hence, the buckling failure results under such a situation.

In almost all fracturing projects, high pumping pressure is needed to overcome rock compressive stress particularly in a high geo-stress shale block. This high pumping pressure is necessary to fracture the formation, which in turn induce a higher internal pressure inside the casing (Yan et al., 2017). Under this opposing load events occurring downhole on the casing, deformation and buckling failure become imminent. This study adjudged factors responsible for casing deformation to be high internal pressure and non-uniform external loading on the casing during fracturing. Furthermore, cement sheath defects and shale characteristics are amongst the features responsible to casing deformity.

Also, Yan et al. (2017) claimed that for deformations around ‘heel’ region (end of build section in horizontal well) shearing force is exerted on casing, as a result causing such deformations. However, the curved section casing experienced significant shear force during fracturing. Some field specialists recognised that casing deformation in shale gas might be also caused by formation/fault slip induced by hydraulic energy. It could be an acceptable explanation for deformation around build section. Evidence of casing buckling beyond the build section is presented by lead mould printing (refer to Figure 2 D).

It is however a non-trivial task to explain these deformations that occurred far away from the build section in horizontal part especially deformation near the toe (tail end of horizontal section). Taking the Wei-204H7-3 well as an example, this well is expected to be fractured in 21 stages. Before the first stage fracturing; milling shoe (108 mm) was driven through the casing to the bottom at 5205 m without any resistance. However, after the first stage fracture, the gauge cutter (108 mm diameter) was blocked at 3913.4 m, and even the 96 mm diameter gauge cutter could not pass through the casing (block at 4394 m). After several attempts, five casing deformation points were determined, and these deformation points distributed along the entire horizontal well as shown on Figure 3 (Yan et al., 2017). Li et al. (2017) examined casing failure mechanism using finite element model (FEM) during volume fracturing technique in low permeability gas reservoirs. The study established casing deformation based on field data including completions, reservoir rock and micro seismic surveillance data. Tight horizontal gas well was investigated for casing deformation and result obtained showed that the natural fracture slip is accompanied by extreme local casing shrinkage with slight deformation one side and severe at other, as shown on Figure 2 (C).

Lian et al. (2015) indicated that stress deficit and clustering perforations make horizontal well deformed radially and s-shaped deformation axially. Excessive stimulated segments and big pumping delivery rate during volume fracturing process , complicate casing’s mechanical behaviour which results in shear failure, leap and slip, around the horizontal section and change in in-situ stress field (Chipperfield et al., 2007; Hossain et al., 2010). All these factors mentioned frequently lead to in-accessible well caused by casing deformational failure. Consequently, usual completion and stimulation cannot be performed as planned during drilling operations (Tang et al., 20013; Yu et al., 2016, Brantley et al., 2014). To address this challenge, Furui et al. (2010) suggest an advanced comprehensive model that can analyse wellbore stability and casing linear deformation during hydraulic fracturing and acidising. But, this model is limited to highly compacting chalk formation and cannot be employed to analysed shale gas well stability.

2.3 Deepwater wells

In the context of oil and gas exploration and production (E&P) industry, deep-water is defined as water depth greater than 1,000 feet and ultra-deep water is defined as greater than 5,000 feet (Somarin, 2014). During exploration, huge accumulation of hydrocarbon are found in deep-water typically below salt formations (Wang and Samuel, 2016). Well drilling, completion and production form this environment is risky and expensive due to well traverse salt formations; salt formations flow plastically under creep to close the wellbore (Zhao et al., 2011). The result is creep deformational failure of the casing. Casing design for salt beds is a major engineering challenge during oil exploration and exploitation. In China for example, casing failure problems due to the uneven external salt loading are often encountered and cause significant economic losses (Zhao et al., 2011).

In a related study, Furui et al. (2012) reported casing and screen failures are numerous in deep-water oil fields, especially in Gulf of Mexico and other locations around the world. However, they based these failures on; fault slip beside the reservoir if the fault had sealing potentials and could maintain a large pressure differential across the fault plane. Additionally, they reported lithological anomalies and stress changes due to overburden on casing as potential reason/ causes of casing failure.

In addition, salt domes are highly dynamic and often encountered during well construction, which can cause adverse wellbore stability problems (Figure 4). Furthermore, salt dome is known for water absorption and move to cause wellbore anomalies leading to casing and cement deformity (Kiran et al., 2017). Apart from well drilling, salt formation progressively moves over geologic time scales to deform surrounding formations thereby exerting various forms of loads that eventually cause casing failure whenever a well is drilled. According to Wang and Samuel (2016), and Wang et al. (2019) creep and casing eccentricity effect in salts formation can lead to potential wellbore failure and severe stresses on the casing.

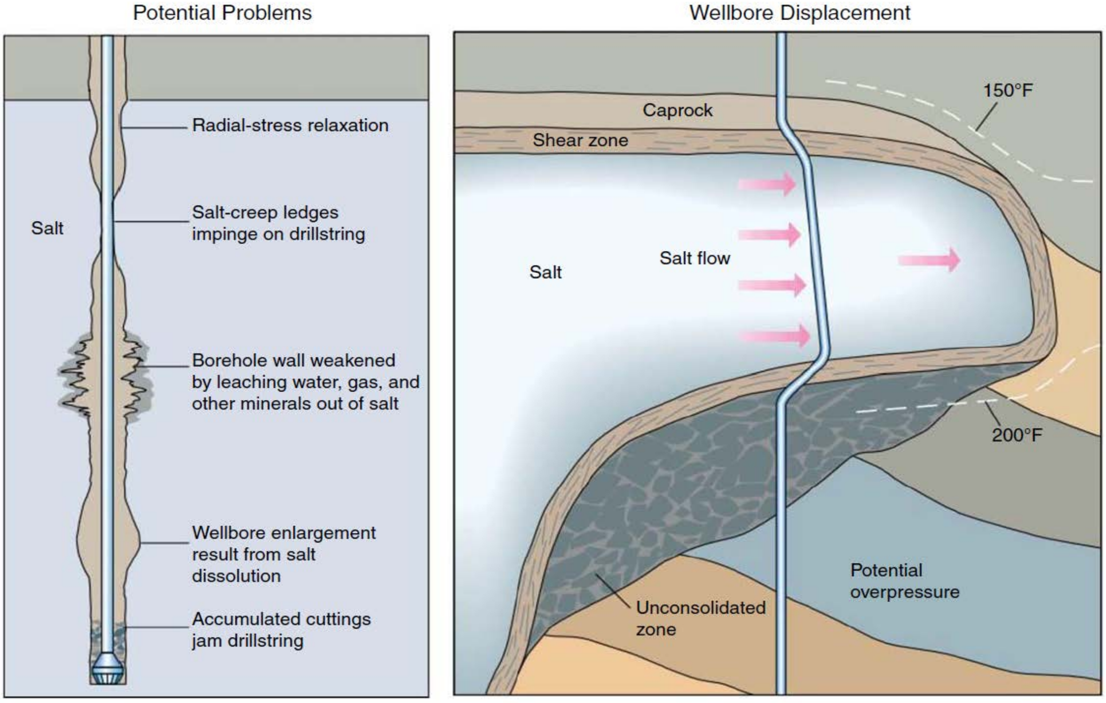

Fig. 4 Challenges of drilling and completion in a salt formation (After Fammer et al., 1996).

Another reason for accelerated casing deformation in presalt formations is tortuosity and eccentricity. Due to well tortuosity; salt creep could be much more serious than expected. However, this challenge is normally mitigated using optimum centralisers to ensure good casing standoff (concentricity). Casing non-alignment could bring about fast salt creep behavior which result in uneven load distributions on the casing. This situation deformed casing faster than the usual (Wang and Samuel, 2016; Matsuzawa et al., 2006; Cheatham and McEver, 1964).

A study reported by Wang and Samuel (2016) related casing deformation to salt creep rate and casing temperature conditions; and presented a Gulf of Mexico case study to justify the effect of temperature on a particular well. The well had a top salt temperature of 118 °F or (48°C) and the bottom (base salt) at 200 °F or (93°C). Keeping differential stress between wellbore and the salt internal pressure constant within the salt section, then the creep rate at the bottom would have been 100 times faster because of temperature difference. In addition, Fan et al. (2018) and Dusseault et al. (2004) showed that temperature increase lead to decrease in tangential stress of the cement sheath resulting in corresponding increase in compressive stress on the casing, thereby increasing casing buckling probability.

2.4 Injection wells

When reservoir drive mechanism declines, oil extraction is often accomplished with water injection for pressure maintenance to enhance oil and gas production. Using this technique injection wells are drilled or producing well may be converted to injector depending on the injection pattern and optimum sweep efficiency needed in the project. This enhanced oil recovery (EOR) method is called water flooding. Yin et al. (2018) studied the mechanical behaviour of casing during water flooding in an oilfield. Based on log data interpretation and statistical analysis, formation slippage was identified as the dominant cause of casing failure. This failure mode reduces the longevity of wells and economic benefit of oilfields. For example, 72% of production wells and 63% of injection wells presented casing failure in block VI of Casabe oilfield (Figure 5).

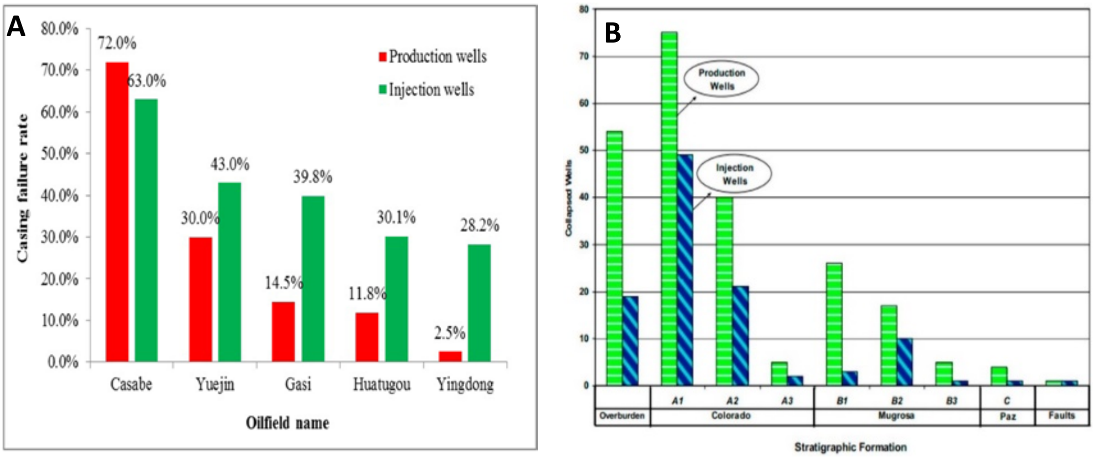

Figure 5(A) Casing failure rate in some selected water flooding oilfields (B) Casing failure distribution by stratigraphic formation (After Olarte et al., 2009).

More data of casing failure rate in water flooding oilfields can be seen on Figure 5 (B) including the casing failure distribution relative to stratigraphic formation. The A1, A2, B1 and B2 are the injection formations. Casing failure particularly occurred at the injection formations and overburden formation. Moreover, casing failure rate was higher in the years with high injection volume. It indicated that injection induces the formation deformation and additional load on the casing Yin et al. (2017).

2.5 Steam injection for heavy oil recovery

In countries such as Venezuela and Canada that have abundant heavy oil and tar sands resources; enhanced oil recovery in these types of resources are mostly achieved by some variation of cyclic steam stimulation (CSS), steam flood or steam assisted gravity drainage - SAGD (Guo, et al., 2016). These methods are called thermal recovery. The steam injected reduces the crude oil viscosity to facilitate oil production but induces additional thermal stress to production casing during the process. Casing-cement de-bonding is the common cement failure in this kind of enhanced oil recovery (EOR). Thermal cyclic loads induce casing buckling and formation shear movements (Wu et al., 2006). Also, during these processes enormous amount of volumetric changes occur, owing to high temperature, convective heat transfer and contraction. The net effect is entire structural deformity of both, cement casing and the surrounding formation. In addition, these thermal recovery wells have experienced numerous well casing failures around the world, often resulting in loss of wellbore integrity, lost production and added costs as noted by Xie and Liu (2008). Typical operating temperatures during thermal recovery could range from 430 to 660 °F (221 to 349°C). The casing failures in this case are mainly due to combined influence of high internal pressure due to injection and high steam temperatures; stresses often exceed elastic limit of typical thermal well casing materials. Also, Ichim and Teodoriu (2016) study noted that cyclic stresses during heavy oil recovery negatively affect the well mechanical response leading to well integrity issues. Kaldal et al. (2015) indicated that large and rapid wellbore temperature changes in high temperature and or geothermal wells during production and stimulation, produce large thermal stresses in the production casing which can cause casing failures. Casing buckling and shear could manifest in thermal wells. Furthermore, connection leakage and/or parting due to excessive casing strain during intervention in thermal recovery wells are experienced. Chang et al. (2009) pointed out that for the cyclic stress-due to temperature response, several field observations have suggested that casings can be subjected to curvature loads, resulting in casing buckling due to thermal compressive stress.

In addition, Medeiros de Souza et al. (2018) investigated the thermomechanical effects on cement integrity during steam injection. The results obtained show that issues of cement sheath integrity under steam injection are usually confined in the region near the formation, and that they are mainly related to the heating phase of the well. It also established that combining the use of a more flexible and expansive cement slurry formulation with the gentle increase of temperature gradient generally improves cement sheath integrity during steam injection. Also, Wu et al. (2008) examined casing failure in cyclic steam injection, which attributed the high failure rate to elevated temperature to steam injection. Results from this study shows that high thermal axial compressive stress/strain caused the casing to hot-yield leading lack of access and buckling failure of the casing. Furthermore, Garside et al. (2009) pointed out that during steam injection project- casing experience inelastic loading such as static and cyclic fatigue due to temperature which affect material strength negatively.

Table 1 provide taxonomy of the major causes and reasons of casing failure in different well types under specific operating scenarios. For example row 2 looks at vertical well under waterflooding. It presents study approach as simulation and references that study the phenomena. It also indicate formation slippage as the main reason for casing failure during waterflooding.

Table 1: A summary of selected casing failure based on well type and operation as well as the main cause of failure.

Well/Operation	Major Cause of Failure/Reasons	Study approach	References
Vertical/ Water flooding	Formation slippage	Simulation	Yin et al., 2017; Han, Dussealt and Xu (2006)
Producers and injectors/ water flooding	Water flooding effect and pressure differentials, high value of injection pressure, asymmetric distribution fractures, both natural fracture and induced fractures and Poor quality cementing ring.	Statistics and simulation	Olarte et al., 2009
Deviated/ drilling and completion	Violent string contact / Wear and corrosion. Dog-leg and large pressure fluctuations during fracturing	Simulation and Experiment	Lin et al., 2016; Yu et al., 2018
Vertical/ steam flooding	Large thermal stresses, in situ combustion, fatigue, steam leak leading to formation slip and thermo-chemical mechanical loads.	Simulation and experiment	Kaldal et al., 2015; Yang et al., 2018; Han et al., 2018; Ichim and Teodiriu, (2016)
Vetical / SAGD and CSS	Thermally induced strain based cyclic axial loading and net internal & external pressure differentials.	Simulation	Dall' Acqua et al., 2012
Horizontal well/ Hydraulic Fracturing	Fault slip, unequal in-situ stress field, degree and stress deficit areas - increased the shear effect to increase, and the radial ellipse deformation and axial S-shaped deformation of casing to increase at the same time. Fatigue coupled thermal-mechanical effect, shear, leap, and slip around the casing String. Natural fractures and faults increase failure probability. Shear deformation induced by the slip of shear fractures.	Simulation	Chen et al., 2018; Lian et al., 2015; Liu et al., 2018; Xi et al., 2018; Lin et al., 2017; Zhao et al., 2018; Yin et al., 2018; Zhang et al., 2016
Vertical /Drilling, completion and production	Collapse pressure from salt rock creep, annulus pressure build-up owing to fluid thermal expansion in sealed annuli.	Experiment and simulations	Zhao, Chen and Wang (2011) Wang and Samuel (2016) Zhu and Liu (2017) Hu et al., 2018
Deviated / perforations	High perforations density and reservoir compaction	Simulations	Guo, Blanford and Candella (2015).
Deviated/cyclic steam stimulation	Extra plastic deformation under tension and compression loads during thermal stimulation.	Experiments and Simulations	Han et al., 2018; Teodiriu et al., 2008
Vertical/Production and depletion	Inclination and reservoir compaction/depletion.	Simulation	Yamada and Furui 2018; Furiu, Fuh and Morita (2012).
Others	Unequal in situ stress, non-uniform external pressure, fatigue crack nucleation, Wear, well closure and instability due to creep, drawdown /compaction and corrosion.	Experiment and Simulation	Kuanhai et al., 2016 Huang and Gao (2016); Cirimello et al., 2016; Xie and Tao (1999); Liang et al., 2013; Li and Samuel (2016) Matsumoto et al., 2018; Dai et al., 2018; Mao Cai and Wang (2018); Zhang et al., 2018

3. Overview of Failure Modes

Existing and induced downhole stresses in conventional and unconventional wells pose several challenges to casing integrity over well life cycle. Existing downhole stresses however, are attributed to in-situ stress variations specific to well location, diagenesis, reservoir characteristics and regional geo-stress distribution. On the other hand; induced stress caused from drilling and completion characteristics, well configurations, production related stresses and well stimulation processes pose additional sets of stresses which undermine the robustness of casing integrity.

In-situ stresses, regional tectonic as well as micro earthquakes are key sources of potential wellbore failures. In-situ stress in an area can change before and after drilling owing to rock removal and well configuration. Depending on stress variation and degree of rock consolidation and strength - wellbore instability issues could occur during and after drilling and can initiate downhole integrity challenges. Radial and tangential stresses are critical to borehole stability. Also, tangential (hoop) stress variation in horizontal wells is even much more severe which can lead to casing plastic deformation. In addition, Kiran et al. (2017) indicated that due to material non-linearity between casing and the cement, differences in moduli can cause significant variation in stresses along the radial and tangential directions. As a result, at cement-casing interface, moduli variation can affect casing collapse resistance by up to 10%.

3.1 Buckling failure or deformation

This section is specific to factors causing casing lateral buckling and the failure mechanism. Wang et al. (2014) described local buckling as a failure mode along the wall of a casing that does not extend to its centre. While, in column buckling (deformation) the casing is completely deformed with the centre of the casing bending leading lack of access through the casing. In addition, Chen et al. (1989) classified two types of buckling for casing in horizontal well; which are sinusoidal and helical. Axial compression load gives rise to sinusoidal buckling configuration but, depend on casing stiffness, weight, and hole size. In contrast, with increased axial compression sinusoidal buckling changes to helical buckling. Njuguna (2007) pointed out that buckling and flutter are two major types of instability of column structures. Flutter is associated with self-excitation of structures which undermine its durability, safety and efficiency. In addition, flutter is more of a phenomenon where amplitude of vibration due to initial applied load grows without limit. On the other hand, column buckling refers to the change of equilibrium state of the column from one to another in response to a compressive load. However, subsurface structures (oil well casing) in the horizontal section of the well operate under compressive load throughout the well life cycle. As such, casing lateral buckling especially in shale gas horizontal wells is a major area of concern in the oil and gas industry.

Dusseault et al. (1998), and Liu et al. (2017) pointed out that local stresses and shear of weak formation are the main causes of casing deformation mechanism. These local stresses are typically tangential, axial and radial resulting from in situ stresses. Depending on the degree of rock consolidation and the formation characteristics wellbore stability issues can develop. Daneshy (2005) and Han et al. (2006) indicated that effect of tensile, compressive, shear stresses and huge formation deformation are the factors responsible for casing failure in this mode. In a separate study, Furui et al. (2010) attributed primary factors of casing/ liner buckling to increased axial loading, caused by combined effect of perforation and huge volume of acid treatments. These lead to big vertical cavities and poor radial constraint of the casing.

In addition, Yin et al. (2018) and He et al. (2014), established through finite element analysis (FEA) that fracture slip during fracturing causes casing lateral buckling in shale gas wells. Additionally, with increase in pumping rates, a critical value is reached which cause natural fracture to shear rock mass, leading to casing lateral deformation. Moreover, Zhaowei, et al. (2017) indicated that at some critical pressure, natural fracture is activated which move and induce casing failure. According to Guo et al. (2019); sudden temperature change between reservoir and fracturing fluids increase casing failure probability. Similarly, Yu et al. (2016) show casing failure to be caused by formation alternation, in situ stress variation, irregular fracturing zones. Under this situation in situ stress increases and become very severe downhole to deform the casing radially. Moreover, Zeng et al. (2018) attributed casing deformation to change in in-situ stress because of large scale fracturing which lead to sliding of strata of rocks. However, the study added that well trajectory, cement quality and temperature may influence casing deformation under this situation. In situ vertical stress (overburden) is a function of depth, and rock densities and always vary due to different rock mineralogy, porosity and volume of open fractures within the rock. On the other hand, in situ horizontal stresses vary because of topography of the formation, tectonic activity and proximity to faults. When oil and gas wells are drilled, the rock removal create an imbalance between the overburden and horizontal stress. Consequently, wellbore stability issues manifest leading to buckled casing.

Furthermore, Guo et al. (2015) and Xi et al. (2018) both pointed out that casing deformation results due to slip of bedding planes and natural fracture caused by uneven loads during fracturing. Also, dip angle of various strata and resulting displacement that occur during fracturing, could give rise to normal fault, reverse or thrust fault etc. Each of these faults will develop unique casing buckling failure in the well. However, Yan et al. (2017) and Ke et al. (2015) hold different view, which attributed casing failure to presence of voids in cement- that causes pressure deviations on the casing as the main factor of casing deformation. Cement voids and micro annulus are potential areas for well integrity issues due to different stress regime associated with it leading to casing buckling. Kui et al. (2016) discussed the dependency of stress between cement and casing and found that the cement is more vulnerable to yield than casing as a result of casing internal pressure during fracturing. Xing et al. (2017) established that; shale gas horizontal wells suffered casing deformation because of complex stresses downhole during fracturing. Chen et al. (2018) attributed casing deformational failure to inter well interference, poor cementing and local stresses. Interestingly, Wilcox et al. (2016) demonstrated that casing eccentricity causes uneven load distribution behind the casing which impede fluid flow and results in poor cementing and well integrity issues.

Yu et al. (2016), compare 3D finite element model (FEM) and multi arm caliper log to examine casing deformation and failure during multi layered fracking in vertical well. Figure 6 presents well logs signatures of a section in the well where the casing has buckled (highlighted in red ellipse as shown). Teodoriu et al. (2016) established that casing eccentricity could increase the local stress distribution in the well and makes the cement most likely to fail and causes subsequent casing failure in the process. In addition, McDaniel et al. (2014) in a study on cement sheath durability in Marcellus shale show that sustained casing pressure is the main reason behind cement damage. The casing whipping exerts additional stress on the cement, which resulted in cracks and fluids pathways that eventually undermine the well integrity.

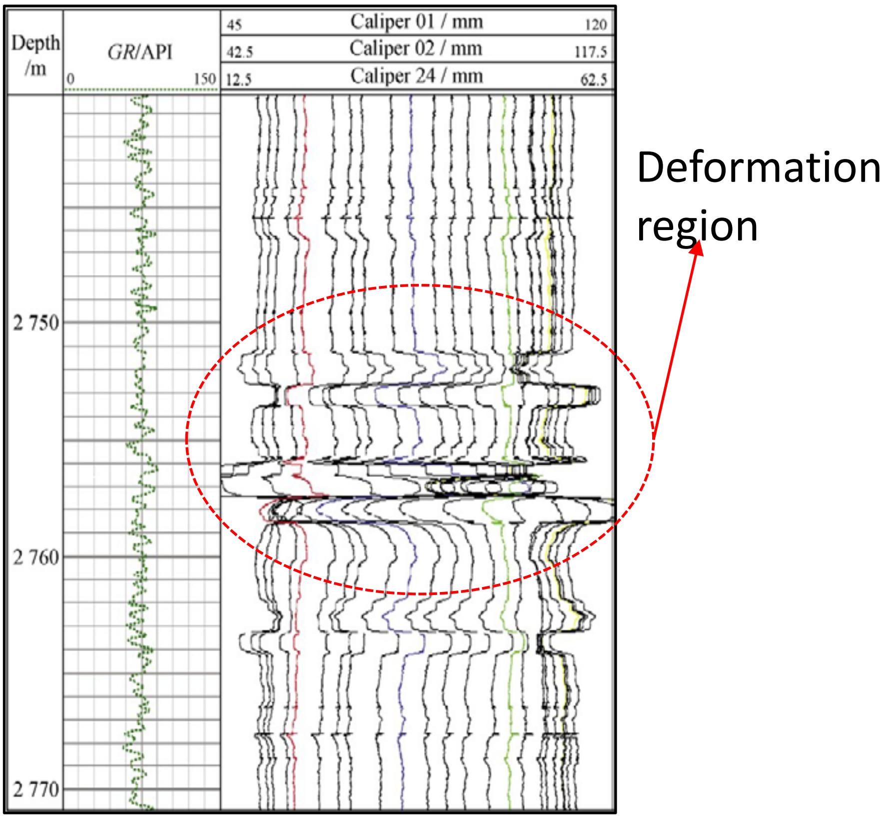

Figure 6 Typical well log signature showing casing deformation (After Yin et al., 2018).

However, Yu et al. (2016) and Lian et al. (2015) resolved that some casing failures were as a result of the connection and rock property change, asymmetric treatment zones and stress field redistribution. Using finite element modelling; the study found out that with heterogeneity, severity of stress field increases significantly.

Kuanhai et al. (2016) studied failure mechanism of P110 casing under opposed line load experimentally. They established that under nonlinear opposed line load radial displacement and plastic deformation determined to be 46.5mm and 36.1mm at maximum external load of 102 tones. Sone (2012) reported that shales show extensive variety of mechanical properties owing to various material compositions and fabric anisotropy. This anisotropy may occasionally result fluctuating stress distribution downhole making casing buckling failure imminent.

Beside, tensional and compressional casing failure could manifest during steel casing installation. Steel casing is the main structural barrier that isolate reservoir and provide avenue for oil and gas production (Standard, 2004). It also protects shallow water zones and help seal off troublesome zones that may be encountered before reaching the target reservoir. In performing these functions, casing mechanical properties (geometry, burst, and collapse, tensile and compressive loads rating) changed. Over time and considering geological characteristics downhole; casing structural integrity deteriorate due to corrosive reaction, static and dynamic loads (stresses) leading to potential casing failures.

Bending load may result when a casing is being rotated and forced through a curve well section during installation. Mostly top surface compress and the bottom in tension. If on the other hand, the rotated casing is constrained torsional failure may occur. Quigley et al. (1994), stated that designing a casing string requires detailed knowledge of its tension forces during installation. Some casing design criteria recommend a large safety factor (typically 1.8) in tension to cover effects of unknown installation loads. This may result in over-designing casing for tension loads and thereby increasing cost unnecessarily. Accurate and precise knowledge of tension forces on casing during its installation is desirable for accurate and cheaper casing designs in the future. However, significant elongation may occur leading casing failure in tension or compression if design do not integrate local loads Yamada et al. (2018). Han et al. (2018) examined strain-based casing design for cyclic steam stimulation in an oil filed in China and reported 15-30% failure rate. The study concluded that the failure is mainly as a result of extra plastic deformation under tension and compression during thermal cycles.

3.2 Shear failure

Dusseault et al. (2004) described casing shear because of formation shear that happen due to changes in stress and pressure caused by the type of exploiting condition- depletion, injection and heating. Wang et al. (2011) described shear failure mechanism due to displacement of the rock strata along bedding plane or steeply inclined fault planes. Yin et al. (2018) reported that fracture slip during hydraulic fracturing can cause casing shear failure as shown on Figure 7. Fracture slips through the wellbore during hydraulic fracturing induce shear load on the casing subsequently resulting into casing damage under the action of formation shear slip. It can be seen on Figure 7 (A) that one side of casing dips inward and the opposite side bulges outward reflecting shear deformation and hence support the notion of formation slippage during water flooding i.e. the slippage of weak structural interfaces.

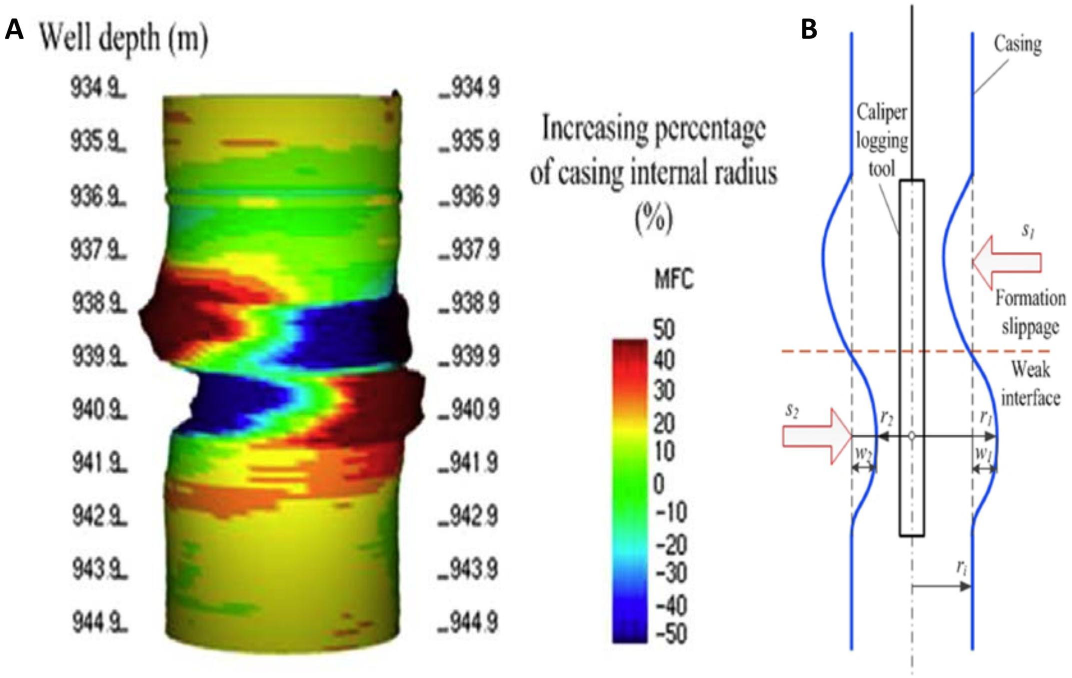

Figure 7(A) Casing imaging logging of an injection well (B) Illustration of shear formation slip inducing casing failure (After Yin et al., 2018).

Hu et al. (2016) calculated the critical displacement that can induce casing shear within a weak structural interface using numerical simulation. However, this study suggested that lower casing grade could be utilised around the weak structural interface if it meets all downhole requirements. And the study concluded that if casing elongation could be improved by 60%, then critical casing failure slip displacement can be increased by 21.4%. Daqing Oilfield in China has been known for casing shear failure and/or deformation. Han et al. (2006) established that existence of a thick fragile shale formation and the high vertical heterogeneity are the intrinsic causes of casing shear failure. In addition, Han et al. (2006) used both experiment and numerical modelling to calculate the pressure limits for individual wells in Daqing oilfield and the differential pressures for the entire oilfield causing casing shear failure. The study concluded that the main factors are decreased in effective stress and internal friction within the formation in Daqing oil fields. As a result, invaded mudstone and shales in this field lost their strength and consequently, creep deformation was induced leading to casing shear.

Another reason for casing failure is water injection into the subsurface formation for pressure maintenance. At high differential pressure, casing shear occurs. In addition, reservoirs in Daqing oilfields are not homogeneous (Li.et al., 2012). This inhomogeneity in strength and stiffness resulted in the formation of a shear band along a lithological interface (high stiffness contrast, therefore a high shear stress contrast) with the weak shale (low strength). In general, rather than general shear straining, one would expect shear distortion in such media to coalesce on a single interface, an observation confirmed in fields in Alberta, California, the North Sea among others. Plaxton et al. (2018) established that strain localisation is the main root cause of casing failure in Firebag oilfield and concluded that the lack of stress uniformity between the formation, cement and the casing as one of the causes to this failure.

3.3 Collapse / Burst Failure

Vudovich et al. (1988) reported that casing failure modes are inter related with casing failing in one or more of the failure modes - collapse or burst; which is attributed to radial stress. Tensile failure due to axial tension and connection jump out as the result of compression or tension. However, one factor may reduce the occurrence of a failure mode but promote another kind of failure. According to Wang et al. (2014) collapse failure are a result of different mechanical loading from sand, cement and casing itself. Kiran et al. (2017) also suggested that presence of voids and cement channels at casing-cement interface could induce up to 60% reduction on casing collapse resistance. Meanwhile, when compared to eccentricity, the presence of voids and channels is by far more troublesome than eccentricity. Conversely; eccentricity has its own attendant effect on the casing structural integrity. Additionally, during production, stress consistently change due to variable flow rates and dynamic loading; this stress variation has also been established to cause casing collapse.

The mechanism is mainly attributed to unequal external load exceeding casing yield strength which change the circular orientation to oval (Huang and Gao, 2015). Collapse of the casing are mainly classified into yield, transitional, elastic and plastic. The industry standard approach to differentiating these collapses are based on slenderness ratio which is a ratio (casing diameter to its thickness). However, Abdideh and Khah (2018) presents casing collapse phenomena as abnormal displacements of rock formations on the casing leading to collapse. Bastola et al. (2014) examined the factors influencing pipe's collapse resistance and concluded that effects are small for 3D models with length to diameter (d/t) ratios above 10, and that an increase in initial ovality would lead to a decrease in the pipe's resistance to collapse.
Salehi et al. (2009) showed that reservoir compaction results in 4 different casing collapse mechanism; buckling, bending, traction and shear. The creep phenomenon is important in relation to the salt layers with significant uplift potentials. Shear due to compaction will occur due to differential loading across lithology interfaces, especially if it is an interface between hard and soft formation sequence. The reservoir depletion directly affect the horizontal stresses due to poro-elastic response of the reservoir rock. This phenomenon result in a reduction of the horizontal stresses in the reservoir rock and these stresses must be taken by the surrounding rocks above and below the reservoir.

On the other hand, burst failure of the casing is imminent when the internal pressure exceeds the casing material yield strength. However, this failure type hugely depends on the external load resisting the internal pressure that give rise to burst failure. Li and Samuel (2016) developed a model to determine the threshold burst pressure of degraded casing that has undergone crescent wear. The study presents a method of calculating varying hoop strength of casing-based on casing wall thickness. They claimed that crescent shape model provides more realistic estimation of casing burst resistance than the API and Nadal models. Nawathe et al. (2016) examined residual stress variability on C110 casing grades using numerical simulation. However, they concluded that cracks are leading force for either burst or collapse failure of the casing under such circumstances especially in deep-water well applications.

Fleckenstein et al. (2001) studied burst induce stress in cemented wellbores using FEA under different operational scenarios. Result show that casing constrained within the cemented wellbore has much lower stresses of approximately 40,000 psi (von Mises Stress) represents a decrease of 58.4%. This reduction in stress would allow the casing to be design with a lower-yield pipe, such as K55 (55,000 psi yield strength) or 379MPa, or a lower-weight casing with less wall thickness. The unconstrained casing studied in unconstrained case would require a higher grade of casing such as N80 (80,000 psi yield strength) or 552MPa. Therefore, this suggest burst failure is much likely in un-cemented casing than in cemented especially in open hole completions.

Furthermore, Dall'Acqua et al. (2013) claimed that API design equation for burst and collapse do not address body response when axial stress exceeds the material yield strength. However, during thermal recovery in places like Canada where SAGD and CSS with typical operating temperatures of 390 °F (199°C) and above casing yielding is a common phenomenon. As a result, both active and passive loading evolved on the casing, which exacerbate thermally induced strain based cyclic axial loading occurring in conjunction with net internal or external pressure differentials. Kalil and McSpadden (2012) study on casing burst stress in particulate annuli concluded that depending on the casing grade bonded annulus fill material provides more than 5% added support to the cemented casing's nominal burst rating.

3.4 Fatigue Failure

Fatigue is the progressive and localised structural damage that occurs when a material is subjected to cyclic loading Bai and Bai (2014). Fatigue is also described as simply a mechanism associated with cyclic loading and is an irreversible and cumulative damage that occurs when a material is subjected to cyclic stress (Gao and Hsu, 1998). The cyclic loading or stresses could either be fully reversed, repeated or fluctuating loads. Moreover, these loadings are either low cycle or high cycles (Liu et al., 2015; Cirimello et al., 2018 and Chen et al., 2018). Casing fatigue failure could occur when the well exhibit alternating temperatures during production. Also, during stimulation fatigue loading is induced due to temperature difference between stimulation fluids and the reservoir fluids. Casing gains high temperatures during steam injection, while in soak periods its temperature reduces significantly.

During steam injection the casing is under thermal axial compression and undergo axial tensile stress in soak periods. This alternation in tension-compression result in casing fatigue failure (Wu et al., 2017). In addition, Lim et al. (2012) pointed that during drilling in stormy weather; wave and currents action and heave motions of the sea are transferred down the riser to the wellhead, conductor and casing system and can cause fatigue failures at critical casing connectors (joints) and welds as shown on Figure 8. Also, Teodoriu et al. (2008) established that changes in temperature and internal pressure in geothermal wells operations can subject the casing to variable loads capable of causing fatigue failure. However, thermal loads have the potential to alter hoop and increase mechanical stresses considerably during injection.

On the other hand, cooling cycles promote de-bonding and tensile failure because of contraction (Kiran et al., 2017). Cirimello et al. (2017) explained the concept of drilling with casing (DwC) as an innovative method particularly widespread in deep shale plays, that reduces the time and cost of drilling stages. However, casings are not designed for this purpose, and both the connections and body are required to remain sealed in the well after sustaining a large amount of drilling cycles and possible damage.

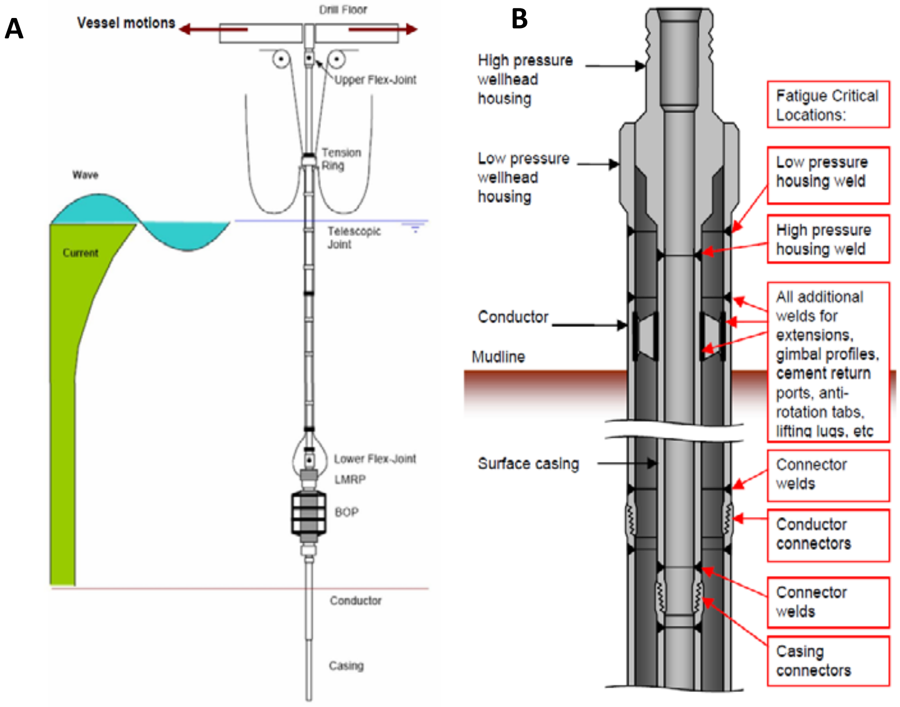

Figure 8(A) Riser pipe stack-up and sources of motion (B) Fatigue critical locations (After Lim et al., 2012).

The study examined the failure of a 9 5/8″ diameter K55 seamless casing during drilling an oil well. Fractographic analyses identified fatigue crack nucleation and growth in the tube/coupling (T/C) transition zone (Cirimello et al., 2017). The failure analysis included physical and chemical material tests and numerical stress analyses at the T/C threaded joints when subjected to the loads logged during drilling. Fatigue cracks were found in other casings but did not lead to fast fracture. However, this may cause leaking during subsequent well completion and production. The most relevant conclusion is that future integrity of casings used for drilling could not be assured. Reducing cyclic drilling stresses below the actual fatigue strength of casing and connections is not easy task due to the continued rotation of the casing string. The industry tendency to go to slim-hole DwC, with ever increasing operating loads is not a foreseeable future. Also, according to Liu et al. (2018) recent literature have reported casing fatigue during multistage hydraulic fracturing particularly at casing joints. The study attributed cause of casing fatigue loading to cyclic hydraulic fracturing with varying temperature between stages. Series of plugs and perforation and the subsequent fracturing lead to varying loads on the casing which usher in fatigue loading in the process. Furthermore, production casing is subjected to cyclic loading of both pressure and temperature during multistage hydraulic fracturing. The net result is casing fatigue failure.

3.5 Wear / erosion / corrosion failure

Mao et al. (2018) described casing wear failure; as failure resulting from frictional contact of the drill string with casing thereby shelving or removing part of the surface of the casing. Consequently, this friction point wear (thickness reduces) which depends on the contact force magnitude, contact area, angle, fluids and material strength. In addition, corrosion is one example of metal loss in casing that can leads to potential leaks, (Wilson 2018).

According to Zhang et al. (2016) wear is a kind of material loss by removal of solid surface under mechanical action (friction). Wear can also be described as a fundamental type of material loss that is characterised as the removal of material from solid surfaces by mechanical action (Fischer and Bobzin, 2009). It can be classified into adhesive wear, abrasive wear, surface fatigue wear and corrosive wear in terms of the fundamental mechanisms and characteristics of wear surface (Andersson, 2011). Casing wear caused by drill string rotation may be classed as typical adhesive wear and abrasive wear. Adhesive wear is the transfer of material between solid surfaces during relative friction motion and adhesive interactions between rubbing surfaces (Best, 1986). Abrasive wear is the material loss caused by hard tool joint protuberances (two body abrasion) or by hard particles (three-body abrasion). It is characterised as a series of grooves on softer surface caused by hard surface or hard particles. Adhesive and abrasive wear may coexist in downhole casing wear. The adhesive wear takes a leading mechanism under high contact pressure between tool joint and casing. The abrasive wear is dominant when drilling mud contains high content of hard weighting agent or cutting.

The research by Gao et al. (2010) and Shen and Beck (2014) observed that the casing wear is often encountered as a result of contact between rotating drillstring and the stationary casing during extended reach drilling. Under this circumstance, a major wear of the casing can cause delays, costly repairs and huge economic loss. In addition, casing wear lead to reduced well life and facilitate early well integrity issues. Wear can cause casing failure, add nonproductive time (during drilling and expensive remedial operations (Dai et al., 2018), Zhang et al. (2016). Casing wear resulting from the friction between tool joint and casing (Figure 9) in high dog-leg section has a significant impact on the residual strength and integrity of casing string. Assessing properly the strength of the worn pipe can be the key to achieving a feasible technical and economical well design (Junior et al., 2015).

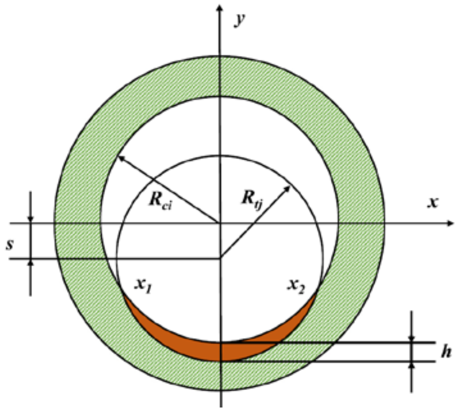

Figure 9 Schematic of casing wear (After Zhang et al., 2016).

Zhang et al. (2016) showed that casing wear during directional well drilling remains a prominent problem because it can cause casing strength degradation, casing deformation and even well abandonment. Mao et al. (2018) showed that wear rate varied with increasing rotational speed of drilling pipe, but not in a linear manner. The reasons for the nonlinear behaviour was explained in terms of a combination of abrasive wear, erosive wear, and corrosive wear. The activity of the Cl-ions in the drilling fluid could influence the formation and properties of the protective film on the casing surface further attest to the nonlinear wear rate.

Bai and Bai (2018) pointed out that particulate erosion due to sand (sand erosion) is the most common source of erosion problems in hydrocarbon systems. This is because small amounts of sand entrained in the produced fluid can result in significant erosion and erosion-corrosion damage. Erosion has been long recognised as a potential source of problems in hydrocarbon production systems. Many dangerous elbow failures due to erosion have occurred on production platforms, drilling units, and other subsea equipment in the past decades (Barton, 2003). Ogunsesan et al. (2019) observed that pipe erosion is more prevalent at 45° angle in elbows using CFD simulations. Feng and Gary (2017) present a finite element analysis for simulating the realistic sanding process, considering coupling between mechanical failure and hydrodynamic erosion of the rock. This study concluded that for perforated-casing completion, sand erosion mainly occurs in the region near the tip of the perforation due to strong stress concentration. This however, pave way for potential casing integrity issues around perforations. Furthermore, when the perforation is parallel to minimum horizontal stress (S_h), sand erosion may only arise near the tip area; whereas, erosion also inclines to occur near the perforation inlet for perforation parallel to maximum horizontal stress (S_H).

The research work of Yuan et al. (2012) examined casing operation of 5-8 years using FEA. They recommended higher strength casing like P110 and T-95 for production casing. Lin et al. (2016) state that when casing is exposed to corrosive environments, corrosion develops pits and cavities at both the inner and outer walls of the casing. The burst and collapse loads acted on the corroded casing will cause stress concentration and degrade casing strength. Strength degradation can significantly shorten casing life, and even cause failure of the well. Corrosion logging provides average measurement of casing integrity and can be used as a predictive measure as well. A casing leak is expected whenever an average-metal-loss value is between 30 and 70%. Also, the probability of a casing failure can be inferred to be unity when average metal loss is above 70% and zero when it is below 30%.

3.6 Well barriers

Well barriers are critical components of the well. Barrier elements are classified into primary and secondary (Standard, 2004). The primary being hydrostatic pressure of the mud column, (barrier during drilling) the secondary come into action when the primary barrier element failed. Secondary barrier element consists of cement, casing, blow out prevent (BOP), riser pipe and wellhead/Christmas tree. Figure 1(A) present well barrier envelope and (B) barrier elements around a well, while (C & D) present exhaustive concepts and/or arrangements of primary and secondary barrier elements in a typical well.

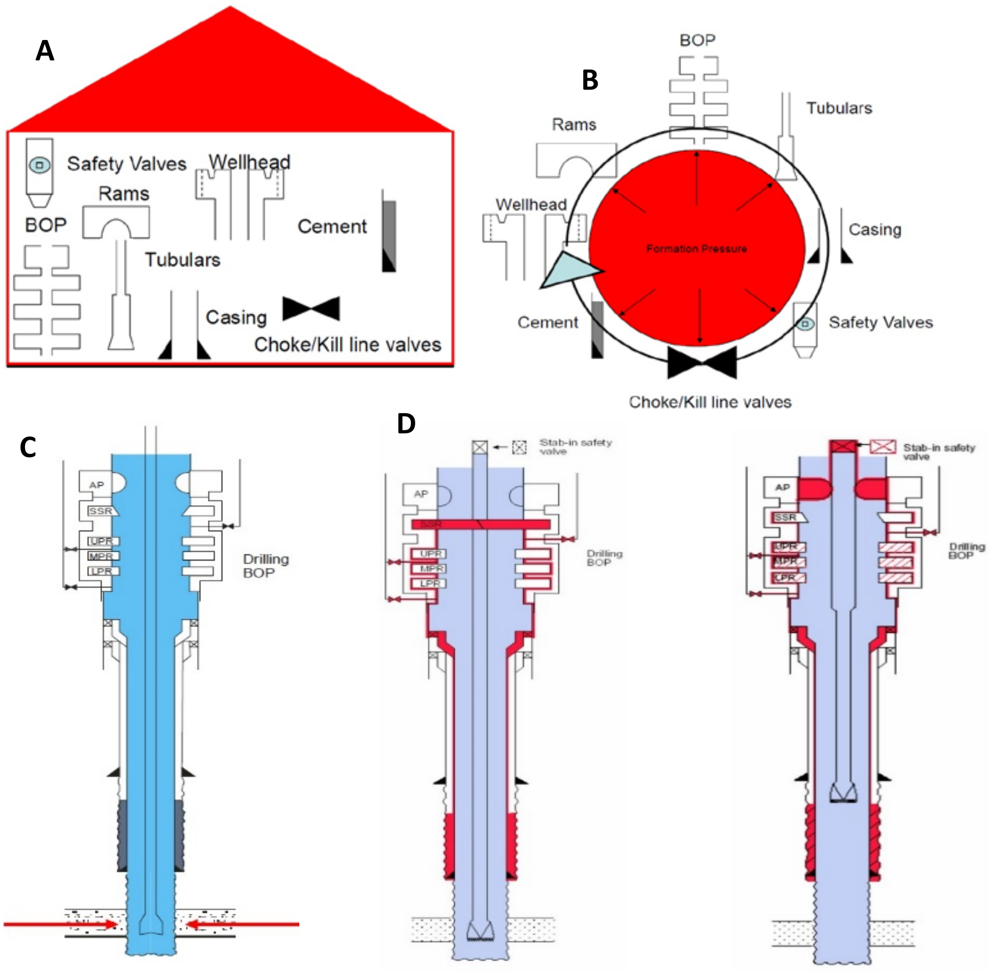

Fig. 1(A) Well barrier envelop (B) Barrier elements around a well (C) Concept of primary barrier- mud column and (D) Concept of secondary barriers. (After Know Energy Solution, 2019).

Overall, the casing failure rate and well integrity issues in unconventional wells is significantly higher compared to conventional well types. It must be stated; that wellbore integrity varies depending on the type of well, reservoir, and the barrier elements. Kiran et al. (2017) pointed out that well integrity issues are basically related to primary and secondary barrier elements. The primary barrier being hydrostatic pressure of the mud column, the secondary come into effect when the primary barrier fails. Secondary barriers comprise of cement, casing, riser pipes, and blowout preventers (BOP). In addition, according to NORSOK D -010 hydrostatics pressure of the mud is the main line of defence; which ensure overbalance, there by excluding influx of reservoir or formation fluids into the well during drilling. On the other hand, mechanical barriers are usually manufactured from steel to provide additional line of safety. However, from the nature of these mechanical barriers, and the downhole environment in which they are utilised as well as time; all play a significant role in determining their service life and well integrity as whole. Ceccarelli et al. (2009) indicated that; mechanical barriers enable the transition from completion to production by providing additional wellbore integrity during the process. But, the situation downhole make tubulars (casing and liners) vulnerable to failure of different kinds; because of ‘triobocorrosion’ (Das and Samuel, 2018).

Hausler et al. (2017) pointed out that the performance of tubular hardware (tubing and casing) depends on tubes properties, existing and applied stresses and the environment in which the tube is operating. High level standard specifications for casing, tubing and line pipes applicable to oil and gas wells are documented by the API under API specification 5CT. Selecting safe and economical materials for unconventional wells is challenging. Materials that could withstand the harsh downhole condition are generally of higher strength capacity and thicker geometries; but expensive compared to inexpensive lower strength capacity materials (grades). Besides, Kaldal et al. (2015) indicated that large temperature changes pose many design challenges in a diverse range of structures. This applies to high pressure and high temperature (HPHT), geothermal wells that exhibit large wellbore temperature and pressure changes; leading to thermal loads in the casing and in general resulting in casing deformity and buckled failure.

Furthermore, Yin et al. (2018) pointed out that during volume fracturing, formation deformation and subsequent rock slippage induce casing failure. This is particularly true for shale rock that are known for wellbore stability problems even during drilling. In addition, during fracturing, both natural fracture and hydraulic fracture slips to buckle the casing in the lateral section of shale gas horizontal wells. Similarly, in water flooded wells, high injection pressure caused casing to buckle because of lithological differences (shale/sand sequence), overburden and shear loads that result during injection (Maxwell et al., 2009; Ozan et al., 2011; Yin et al., 2018). Moreover; excessive stimulation stages, coupled with huge volume displacement and pumping pressure intensify complex stress field and resulting shear, leap and deformation of the casing (Chipperfield et al., 2007; Zeng and Yao, 2015; Hou et al., 2016).

3.7 Connection Failure

The API has specified three types of threading connections which are rounded thread couplings (short & long), buttress connection with asymmetrical trapezoidal thread couplings and extreme-line connection thread without couplings. However, enormous challenges of well integrity surrounding casing connection/seals especially for unconventional wells like HPHT, deep-water and shale gas horizontal well remains. Fundamentally, ensuring accurate, consistent and air tight connections on the entire casing string is complicated and difficult to achieve through manual means. However, recent advances in artificial intelligence has enable the development of automated hydraulic and power tongs that provide accurate and consistent make-up connections on entire casing (Thiemann, 2018). This has drastically reduce/ eliminate potential leaks around tool joint and casing connections resulting due to inappropriate make-up connections. In addition, introduction of brazing technology has remarkably increase integrity of casing connection especially metal-to-metal seals. Brazing technology allows the joining of two different materials using a filler material to compensate for expansion of casing connections (Ernens et al., 2018; 2019).

Furthermore, during cementing in horizontal wells, rotation of the casing in the lateral section is a common practice to reduce/eliminate voids present in the cement slurry. However, this rotation subject the casing connection to high rotating-bending loads leading to connection failures (Hamilton et al., 2019). Under this situation, casing connections in long lateral section of horizontal well suffer significant cyclic loads which affect the connection sealing efficiency and the structural integrity of the entire casing string. In addition, poor casing stand-up in the wellbore create channels which ended in forming voids resulting in poor concentricity of the casing. The study of Yan et al. (2017) established that such a cement voids can cause casing failure at low fracturing pressure when the avoid angle reach 90°. It is crucial therefore, to establish a balance between cement voids and rotation which supress voids in cement during cementing operations.
In-appropriate connection make-up can lead to dangerous connection failure such as shown in figure 10 (A & B). Moreover, poor connection make-up can cause severe thread worn-out as shown in 10 (C & D).

Other failures that could manifest are either that of casing connections and/or auxiliary equipment such as wellhead etc during the producing life of the well. Each of these has specific effect on the well integrity as a whole. Sathuvalli and Suryanarayana (2016) and Aasen et al. (2003) both examined the relationship between structural casing and formation effects on wellhead motion due to temperature loads and resulting casing deformation. The studies established that casing deformation cause noticeable movement of the wellhead. As such, they developed a semi- analytical model that can be applicable to study various wellhead loading situations that can potentially cause motion in the upward direction. In contrast, Awe et al. (2015) and Jellison and Brock (1998) identified connection failure, local buckling and shear failure as the main types of failures on casing strings.

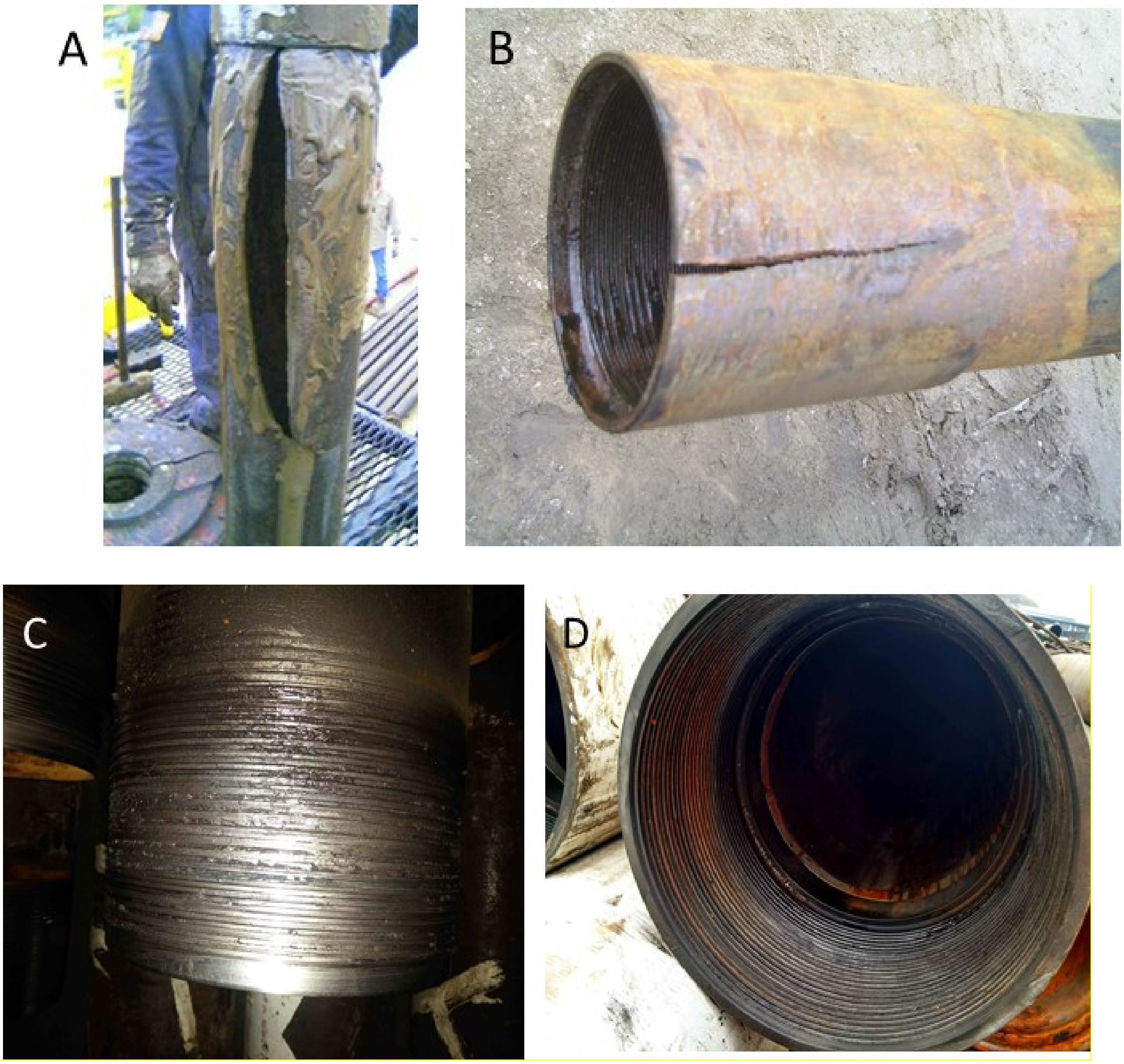

Figure 10 (A&B) typical example of casing connection failure (After Magill, 2013). 10 (C&D) presents pin and box thread damage (After Derphynoy, 2019).

Even though both API and ISO have issued recommended practice for connection evaluation procedure (API RP 5C5 and ISO/PAS 12835) left much to be desired for hydraulically fractured wells (Hamilton 2019). In addition, with the development of well projects pushing the current limits of connection and tubular performance, operators and connection manufacturers realised that there were some limitations to ISO 13679, as such, industry experts worked to update ISO 13679 to reflect the well design requirements and load conditions of modern wells, specifically offshore HPHT wells, where the consequences of connection failure can be extremely high.

3.7 Joint Seal Failure

Packer systems and elastomers are used to provide seals necessary to restrict fluids leakage at strategic points within the well. Traditionally, elastomers are the most common chosen materials for downhole seals during well construction and production operations. However, this organic based elastomers are not reliable at temperature of 316°C (158°C), HPHT and steam injection wells (Xu et al., 2017). A new promising composite material called elastic carbon composite

(ECC) is developed recently to overcome the challenge of high temperature differentials which occur in HPHT and steam injection wells. ECC have good thermal stability with resistant to corrosion at temperatures up-to 538°C or 281°C (Zhao et al., 2017; Xu et al., 2017). This new sealing element have demonstrated capacity in terms of both sealing and chemical resistance to downhole fluids than commercial graphite seal. Metal-to-metal seals can provide high temperature tolerance but lack elasticity requirements to provide reliable seal at downhole condition (Dall'Acqua et al., 2018).
Swell packers are now being widely used for increased recovery from difficult oil and gas reservoirs and for remediation of various well problems (Akhtar et al., 2018). Swellable packers are made by blending swellable nanocomposite microgels with nitrile butadiene rubber (NBR). This swell packers are used to seal the open hole-production casing annulus (Sadana et al., 2017). It is important to know how the swell packer actually swells in a particular well, how much time is required to achieve sealing and sealing pressure generated is a challenge in a typical well. However, Patel et al. (2018) work presents finite element showing approach to assess performance and fitness-for-service of conventional elastomer hanger seal assembly. Three-dimensional computer models consisting of liner, casing, and seal assembly elements were used for this purpose. Sealability was evaluated in terms of the contact stress generated at the seal-pipe interface. An analytical model was used to validate and confirm accuracy of FEA results.

However, the two categories of wellhead system are surface and subsea wellhead. In surface wellhead system it is relatively easy to monitor annulus A, B, and C, by extension to know the integrity around the wellhead. In subsea wells, there is limitation we can only monitor annulus A. Hence, this limitation lead to lack of understanding of what is happening behind casing (annuli B &C) annular pressure can build-up without notice (Grimstad, 2018). This can become critical to buckle the casing. According to (Brown and Witwer, 2017), the subsea wellhead system work in a dynamic and complex environment- associated with thermal growth, annulus pressure build-up, and other factors that will push the wellhead systems and seals beyond their operating limit. Under this circumstance; the cumulative effect of pressure and temperature on subsea seals/ casing hanger system may fail resulting leakages at the mudline. However, Brown and Witwer (2017) suggested that the their test and validation on metal-to-metal seals that do not utilise elastomer and thermoplastic elements show that; metal-to metal seals can withstand complex dynamic loads in subsea wellhead system. Based on this suggestion metal-to metal seals may meet the need of upstream oil and gas equipment requirement for deeper and harsher subsea wellhead system applications.

3.8 Casing –Cement-Formation Failure.

Looking at casing, cement and formation as an integrated system, various well integrity issues, could manifest. However, mechanical failures of the steel casing and the cement sheath are two primary failure in such a system. Liu et al. (2017) pointed out that; casing-cement failure is caused by induced stresses and downhole stress changes due to hydraulic fracturing, steam injection, well test during well operations. In addition, casing and cement failure could be accelerated if chemical reaction degrade casing and cement barriers as a result of corrosive substances present in the well. Besides, failure of cement could endanger the health state of casing and its connection. Similarly failure of casing undermine cement integrity- i.e. the integrity of casing- cement system is mutually inclusive.

In addition, Ferla et al. (2009) simulated the effect of injecting surface fluids (sea water, CO_2 steam) in oil and gas reservoirs to ascertain the stresses in the composite system near the wellbore region. The result show that the casing is in compression due to the thermal stresses during injection but the rock formation has an excessive impact on the stresses in the casing. Furthermore, analysis of the radial stresses on (hard-soft-hard rock sequence – under steady state) has shown that tensile radial stresses developed at the interface between the casing and the cement in the neighbourhood of the boundaries between the rock layers. These radial stresses are found in the simulations runs with and without casing pre-tensioning. Moreover, analysis of the shear stress produced at the interfaces of casing/cement and cement/rock indicates that increased shear stresses are produced near the central layer. However, this study concluded that; a complex stress environments form along the well that may include high axial stresses, shear stresses along the boundaries casing/cement and cement/rock, or even tensile radial stresses between the casing and the cement. These stress conditions may result in the material failure which can jeopardize the well integrity during steam injection.

Zhang et al. (2012) study the cement- formation interface adhesion in a horizontal well using elastic mechanics and composite structure model. This study found that at the interface (cement-formation) cement strength increase with a second interface adhesion. However, when the bottom hole temperature become severe casing-cement de-bonding may be the result (Li, 2008). In a separate research, Peng et al. (2017) examined a case study of casing failure in unconsolidated formation in Shengli oilfield of China. The study simulated the interactions between the casing and surrounding formation rock, and effects of sanding-induced cavities on the casing determined. The simulation results show that the cavities in the formation due to sanding cause the formation more probable to fail and the casing to suffer much higher deformations. Further analysis on the results show that casing failures primarily occurred in unconsolidated sandstones, were caused by sanding-induced cavities. The results also revealed that most failures were caused by the casing buckling and fracturing due to the cavities and varying stress distribution in the unconsolidated formation. In addition, Lavrov, et al. (2015) investigated tensile thermal stresses in casing-cement formation system with rock heterogeneities. The influence of thermal conductivity and material properties on tensile stresses and tensile damage development during heating and cooling of a downscaled casing-cement-rock assembly was examined. Tensile failure was predicted during thermal cycling of the casing/cement/rock assembly at both heating and cooling stages. The failure occurred mostly in damaged cement and damaged rock. The simulation results suggested that cement immediately adjacent to the casing pipe is most prone to tensile cracking during both heating and cooling. Heating the casing to a higher temperature activates tensile cracks located in cement increasingly farther away from the hole.

Modelling of casing-cement and formation system in steam injection wells show that expansion and stresses lead to cement failure behind the casing by cracking under high hoop stress. Additionally, due thermal expansion of the casing, cement and formation system caused casing to fail in form of excessive deformation, buckling and collapse. In particular, when injection parameters are greater than 700psi and 500° F (4.8MPa and 260°C) production casing often fail

(Wu et al., 2006). Although, when casing is cemented in the well, we assumed that it is totally restricted in axial direction, but it expand/contract radially and tangentially owing to temperature change. However, in steam injection projects, both casing, cement and formation are heated and all expand/contract based on their coefficients of thermal expansion. This results in different radial stresses developed at the casing-cement interface and cement-formation boundary respectively (Fang et al., 2015; Wu et al., 2006).

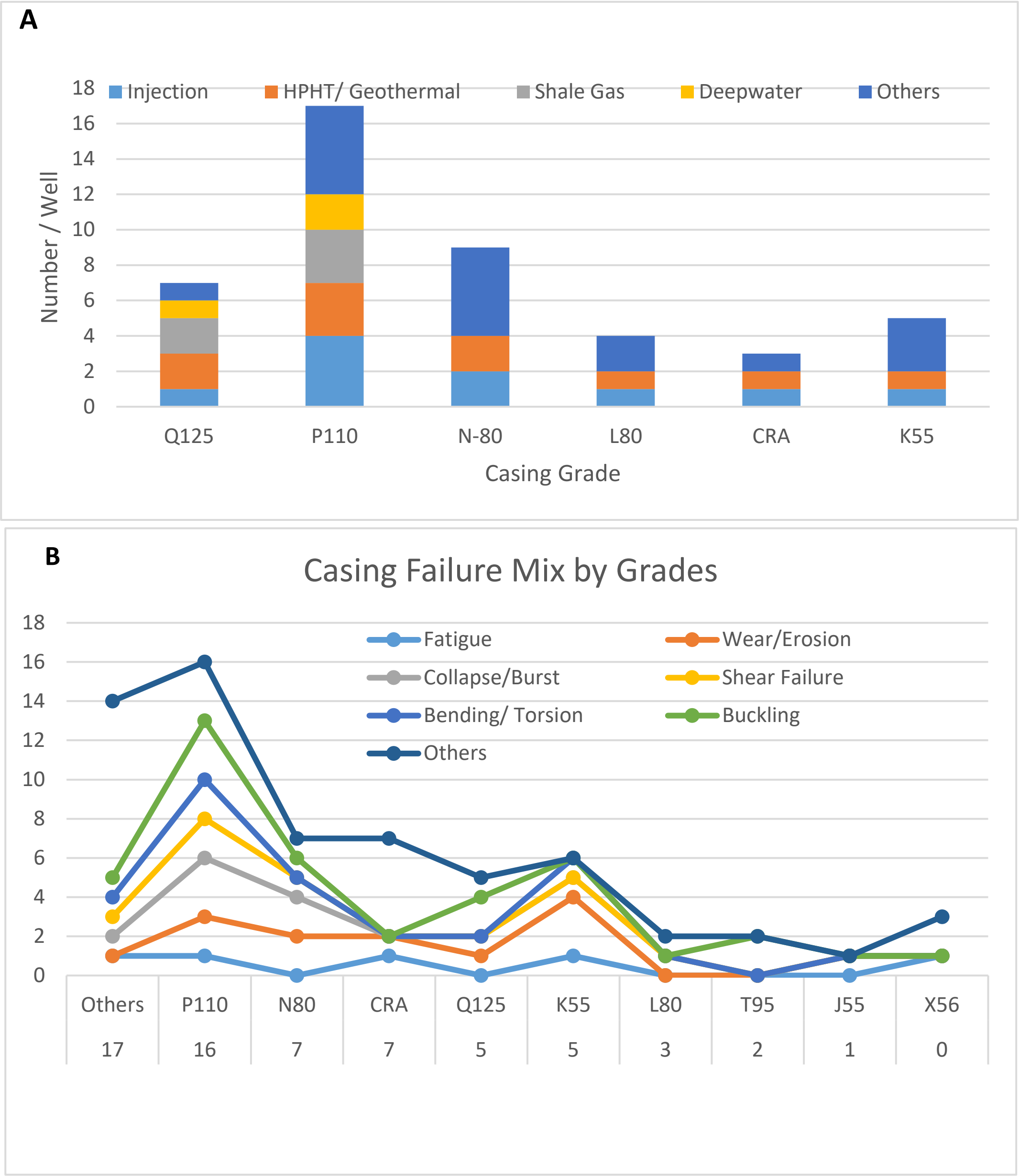

Figure 11 (A) presents a concise summary of casing utilisation by well type (B) Casing failure mix by grades based on the articles reviewed.

Figure 11 (A) shows utilisation of casing grades in range of well types based on the articles reviewed. Shale gas and deep-water wells utilised higher strength casing grades. Additionally, P110 and N-80 grades are more applied in injection wells than other grades owing to their stiffness and may be cost. Figure 11 (B) gives a summary of casing failure mixed by grades. It can be seen that; P110 casing grade have higher failure rate of buckling than other grades - probably due to its higher utilisation in shale gas, deep-water and injection wells.

3.9 Predictive Mechanical Models

The research work of Li and Samuel (2016) developed an analytical model that can be used to predict a threshold pressure for a degraded casing with a crescent wear. API standard method account for 12.5% wall thickness tolerance is still in used for design purposes; this study argue that the API model is overly conservative. When compared to the crescent wear model, the crescent wear model gives higher burst capacity prediction than the API uniform wear model. Like the API model, the crescent wear model can be applied to estimate residual strength of the worn casing, tubing and riser pipes. Furthermore, Shen and Beck (2012) developed an analytical mode that calculates stress profiles in a worn casing with consideration of downhole temperature effect and confining formation effects. Results from the analytical show that the wear impacts hoop stress more than the radial stress around the worn casing. Additionally, the worn part of the casing is likely to fail in compression when thermal load in increased. In a similar study on casing wear, Yu et al. (2016) developed analytical model for the prediction of casing wear in a deviated well. This study utilised both experiment and simulation to establish the model. This model can calculate both von Mises stress and displacement at the wear point in the casing. In addition, Tan, Gao and Zhou (2018) developed a circumferential casing wear depth (CCWD) model. The basis for the development is based on energy principle and geometry. This new model assumes buckled drillsting to cause the wear, and on this basis the model provides practical method of accurately predicting casing wear in extended reach wells and horizontal wells.

Additionally, Yin and Gao (2015) developed and analytical model for the estimation of sustain casing pressure in shale gas horizontal well. The model based on temperature change during fracturing that cause the pressure differential in the casing causing failure. The model incorporate temperature change and annular volume change to reliably predict casing behavior under hydraulic fracturing. Sustain casing pressure displays a polynomial increase with well temperature. Using this model sustain casing pressure can be computed and used in design of production casing for shale gas horizontal well undergoing fracturing. In addition, Brechan et al. (2018) build upon Klever and Tamano model to developed ultimate limit strength (ULS) for the prediction of tubular collapse failure following a joint API/1SO work group (WG2b) guidelines and recommendation. Results obtained from this model (ULS) is in good agreement with actual collapse test conducted on 113 samples by drilling engineering associations (DEA).

Besides, Rodriguez-Prada (1990) developed a predictive simulator that calculates casing strains and stresses due to steam injection and /or hot fluid production. The simulator enabled the determination of radial and hoop stresses and displacements resulting from thermal induce stresses and pressure changes in the system. Results obtained from this study can take care of casing with slenderness ratio of less than 20 as the API model is only valid for slenderness ratio greater than 20. This model is built upon the energy distortion theory was used in the analysis of the combined stresses. All of these calculations can be carried out at any point along the casing and with any boundary conditions.

Conversely, Liu et al. (2017) developed a new method for detection and localisation leaks in gas wells' tubing. The study experimented with tubing/casing annulus and acoustic method to established leak and its location in the tubing. However, the localisation of leak using this method need further research as the result obtained do not corresponds with leaks below liquid surface. Add something on leaks

Buckling is a type of failure resulting from a compressive force applied leading to sideways deflection of a tubular in oil and gas wells. Casing and tubing buckling could occur during installation in the well, completion, stimulation and production operations. However, recent literature indicated rising cases of casing buckling/ deformation particularly during shale gas development process (Lian et al., 2015). Historically, the underlying theory for buckling was first introduced by Euler in 1757. This model is specifically meant to determine critical buckling limit of a weightless rod in vertical column members (Hearn, 1997). However, Lubunski (1950) were the first to developed pipe buckling in oil and gas wells accounting for weight of the pipe. Lubunski model was developed to predict both sinusoidal and helical buckling. Other models developed are that of Mitchell for helical buckling and Dawson and Paslay (1984) model for sinusoidal buckling of pipes in inclined wells (Kyllingstad, 1995).

Menand et al. (2011) developed analytical model and compares the model results with a full-scale buckling tests. The new buckling model takes into account the actual tortuosity of the wellbore. Menand et al. (2011) argue that field observation reveal that the existing model do not predict buckling phenomena like lockup and assume the wellbore to be idealistically perfect devoid of any deviations.

Mitchell and Miska (2006) developed a three-dimensional buckling of pipes with connectors with an applied torque. The formulation of the model build upon Lubinski buckling theory; the wellbore is vertical and straight. The beam-column equations considered in the plane buckling analysis are used, but now there are deflections out of the plane in this model. A solution for helical buckling is developed that produces pipe sag, maximum dogleg angle, contact force, and bending stress magnification as a function of pipe effective axial force and torque. Moreover Mitchell et al. (2011) developed a semi-empirical model for the prediction of drillstring buckling in horizontal and extended reach wells. The semi-empirical model predicts contact forces in the string and result from this model matches very well with drill-drag software. Furthermore, Mitchell et al. (2019) developed a predictive dynamic model than could estimate tubular stresses in horizontal wells. In particular, this model provides an ideal means of prediction critical cyclic stresses that result due to excessive stimulation stages in shale gas horizontal well development. In addition, Sathuvalli et al. (2019) presented an analytical model for the determination of mechanical response of concentric cemented casing from a farfield geomechanical stress. Results obtained from this model show that it can effectively quantify the effect of the loads on the concentric casings and the intervening cement sheaths, and to assess the effect of the formation.

Heathman and Beck (2006) used DIANA software to modelled casing, cement and formation system to re-evaluate the design basis of casing due to significant failure experience in East Texas HPHT wells. Their analysis show that when all critical aspect of the well are include in the design; previous failures encountered in this field will be avoided and ensure cost effective well being drilled and stimulated effectively in future development. However, casing buckling/deformation recently encountered in horizontal well during shale gas development take various forms and modes. Hence, casing buckling can be closely related to some of this models mention above. Table 2 presents a comparisons of selected cases of casing/deformation to the models.

Table 2 Summary of widely used casing buckling and related buckling mode .

Buckling Model	Assumptions	Operation	Reference
Euler	Beyond critical load casing deflect/buckled in vertical wells	Injection of water leads to slippage of weak structural interfaces which cause buckling of casing	Yin et al., (2018); Lin et al., (2017); Xi et al., (2018); Lin et al., (2017)
Lubunski	Buckling occur when effective axial force is applied	Volume fracturing lead to casing axial deflection	Lian et al., (2015); Liang et al., (2013); Li and Samuel, (2016)
Dawson & Paslay	Beyond critical load casing deflect/buckled in deviated wells	Volume fracturing activate faults and fractures which cause several deform section in horizontal wells	Guo et al., (2019); Yin et al., (2018); Chen et al.; (2018); Xi et al. (2018)
Mitchell	Sinusoidal buckling occur when critical force is less than effective axial force and effective force less than $2.8F_{cr}$. Helical buckling occur before reaching $2.8F_{cr}$.	Horizontal well stimulation lead to complex stresses on the casing which lead sinusoidal buckling of casing	Zhao et al., (2018); Yin et al., (2018); Zhang et al., (2016)

4. Assessment Techniques

The previous section investigated the attributing factors responsible for casing failure and the resulting failure modes in a range of wells and circumstances. This section covers methods and techniques commonly employed to assess and/ or monitor casing integrity. Historically, casing and cement inspection has involved running evaluation tools on separate strings in multiple trips downhole, a limitation that adds cost and time to the operation Randeberg et al. (2012). However, recent advances have enable the combination of several casing and cement evaluation tools on one string; to minimise non-productive time (NPT) and rig time and enhances data quality by delivering a complementary and independent set of measurements (Dawson et al., 2018). Each tool generates a distinct set of curves or signatures that complement each other, facilitating better log-quality control, data confidence and comprehensive analysis.

It is worthy to mention that casing is the major subsurface structural components of oil and gas wells. Structural casing is selected, design based on anticipated subsurface loads, with impeccable aim of assuring intact well integrity over the well's producing life to abandonment and beyond. However, casing structural health hardly remain intact over this period; due to existing and induced stresses as well as earth movement and resulting fractures and tectonic activity. Several casing integrity assessment techniques that included caliper, ultrasonic, real time compaction imager (RTCI) etc are applied to periodically examine casing structural health.

While structural health monitoring (SHM) techniques has been advanced and applied in aeronautics, civil structures and nuclear industries, SHM in oil and gas industry is relatively new and not widely applied. SHM is a technology to automate inspection process to assess and evaluate the health status of a structure in real time or over a specified time interval (Njuguna, 2007). In doing so; structures are embedded with sensors and actuators to enable the structures to response to external disturbances. A response consists of deforming or deflecting the structure and communicating the information to a control centre. Smart structures sense external stimuli process; the sensed information respond with active control to the stimuli in real time or near real time. Furthermore, intelligent, self-healing structures that have self-inspecting gadgets detect and responds with autonomous adjustment and repair (Njuguna, 2007). Hence, the two families of SHM are active and passive method of control. The active control employs the use of sensors and actuators to detect and locate the problem. While passive; the active elements are only sensor which 'listen' to structure and no energy is embedded into the structure to 'report' problem of the structure.

In the context of petroleum industry, logging is the typical operation usually conducted to assess well integrity Kiran et al. (2017). Logging involves the deployment and running downhole measuring devices to record data against well depth. The acquired data is analysed to determine downhole condition of the well. There are several ways to measure casing deformation in either real-time during fracture treatment or post treatment. These include mechanical caliper technologies, electromagnetic detection technology, ultrasonic detection in a process called logging (Sun et al., 2014) as shown on Table 3. Developments in ultrasonic scanning tools have resulted in more effective casing thickness measurements, and advances in magnetic flux leakage tools deliver greater reliability in identifying otherwise undetectable holes, cracks and other anomalies in the casing (Tello et al., 2014). New 3-D visualization capabilities with high-resolution data delivered in real time enable operators to detect cement and casing imperfections with greater accuracy and certainty. Other methods for measuring casing deformation are combined multi-finger imaging and magnetic thickness tools, cross multipole array acoustic technology, borehole ultrasonic casing imaging (UCI), and fibre optic sensors (Morikawa et al., 2010; Zhou et al., 2010).

Table 3 Summary of casing assessment tools and/or techniques

Assessment Techniques	Uses	Limitations	Remarks
Caliper log	measure diameter at a specific chord across the well	No insights to outer diameter	Proven
Electromagnetic Induction Tool	Measure corrosion and thickness	No information on casing deformation	Proven
Acoustic Tool	Used to detect casing leaks	No information on casing deformation	Proven
CBL	Measure bond between casing and cement	No information on casing deformation	Proven
Electric potential tool	used to detect the occurrence of cathodic corrosion	No information on casing deformation	Proven
RTCI system	measure reservoir compaction	No information on casing deformation	Under qualification and Testing
FEA+Analytics	Measure casing deformation	No prediction of casing leaks & corrosion	Emerging concept

4.1 Fibre optic sensors

Monitoring very small strain deformations require higher accuracy, resolution, and sensitivity that can be obtained using electronic and fibre-optic type sensors. The primary advantages of fibre optic sensors include high-speed data transmission, smaller cable to carry the same information, no issues related to electrical noise and high bandwidth capacity (Jinke et al., 2005). Fibre optic sensors can be embedded in composite materials in a nonobtrusive manner that does not degrade casing structural integrity. In general, the embedded fibre optic sensors can monitor the health of the structures in service condition. These can be installed as a continuous distributed sensor, quasi-distributed or at a point sensing (Pearce et al., 2009). Note that distributed monitoring systems are those in which the whole length of a cable is used as a monitoring system, and data can be acquired anywhere along its length, limited only by spatial resolution. Quasi-distributed monitoring systems consist of a dense array of sensors typically more than 10, Pearce et al. (2009) that will monitor only the points where the sensors are located (Figure 11).

One of the first fibre optic technologies for casing strain monitoring is the fibre-bragg grating (FBG) sensor that was originally developed for compaction monitoring (Bruno 2017). Udo et al. (2014) analysed FBG and propose possible methods of designing high performance FBG sensors for oil and gas applications through simulations. The small size of the FBG sensor allows embedding them in composite structures, while the real-time compaction imager (RTCI) is a powerful new tool that applies advanced fibre-sensing technology to monitor well integrity in real time without well intervention. It essentially replaces logging with radioactive tags (RAT) and multi-finger or acoustic calipers (Earles, 2011). A special fibre optic cable containing many closely spaced (~ 1 cm) fibre bragg grating strain gauges is wrapped around a well tubular, and the strains at each discrete gauge along the fibre are simultaneously recorded.

In addition, according to Pearce et al. (2009) real time compaction imager (RTCI) provides real-time monitoring of the well tubular shape by attaching thousands of fibre-optic strain sensors on the casing. The system is an early detection system allowing the operator enough time to properly plan and execute remedial actions aimed at preventing completion damages. For example, controlling production rates either in conventional wells or via intelligent well components, or by conducting planned stimulations or other remediation interventions. This study further revealed that by applying an inversion algorithm to the data, the RTCI renders three dimensional images of the well deformation with axial spatial resolutions on the order of a few centimetres. In addition, continuous monitoring of casing deformations in real time improves the understanding of compaction and other strain related conditions of the reservoir, which in turn, is essential for optimising production and reservoir recovery. As shown in Figure 12, the most common deformation encountered in the well are axial strain, bending and ovalisation as reported by (Pearce et al., 2009).

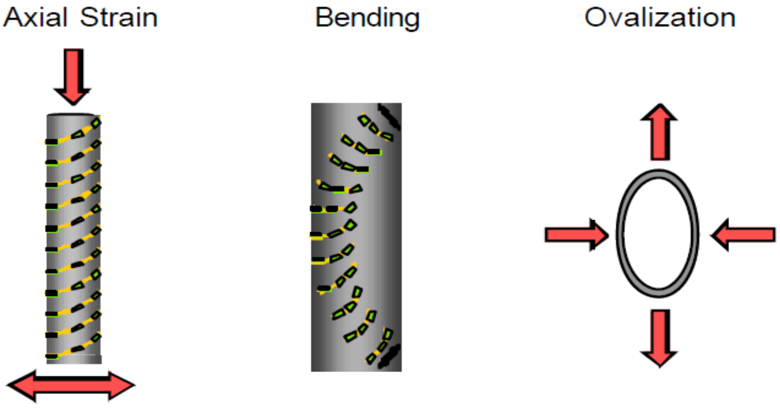

Figure 12 Modes of well tubular deformation (After Pearce et al., 2009).

4.2 Caliper logs

A mechanical multi-finger tool that uses multiple high-resolution calipers to measure changes in the internal diameter of tubing and casing strings is called caliper log. The tool deploys an array of hard- surfaced fingers that monitors the inner pipe wall. Each finger is associated with sensor that generates an independent signal that is recorded against depth (Lavery and Imrie, 2017). After the data is acquired during logging operations, it is processed and interpreted to reveal the casing integrity status. Wilson (2018) presented high level discussion on casing leaks based on three types of non-invasive electromagnetic measurements to characterise well casings, using low-, medium-, and high-frequency induction currents. These are related to the casing-wall thickness, inside diameter, and conductivity respectively. This study pointed that; lower frequency gives deeper penetration up to the outer casings. Each parameter is averaged around the pipe circumference. The tool has multiple transmitters and receivers to send and receive electromagnetic signals. It detects average metal loss and changes in casing geometry irrespective of fluid type.

In addition, the study pointed out that sound well-integrity-management strategy in mature fields, where wells can sustain economic production for 30 to 50 years, is vitally important. Failing to implement this strategy can lead to a catastrophic loss of both assets and human life (Wilson, 2018).

4.3 Casing imaging log

Electromagnetic casing inspection logs (EMIT) are commonly used in the industry to survey the condition of casing. Logs may be used to estimate the amount of pitting, degree of corrosion, wall thinning, changes in diameter, and other casing features. Occasionally, casing inspection logs are used to investigate a casing failure in a well (Wooley and Hatcher 1989; Martin et al. 2017).

Interpretations of casing inspection logs may be used to determine the type of remedial work on a well where a casing failure has occurred. Understanding of the capabilities and limitations of casing inspection logs to detect and define a casing failure has been qualitative. An electromagnetic signal is transmitted from one coil to the other through the casing, and the transmitted and received signals are compared. The shift in signal phase between the transmitter and receiver is proportional to the casing wall thickness, frequency, electrical permeability and resistivity of the casing (Al-Ajmi et al., 2017). However, available wall thickness tools include NL McCullough casing inspection tool, Dresser Atlas Magnelog™, and the Schlumberger Electronic Thickness Tool.

Conversely, there are two logs available that measure disturbances in magnetic flux lines caused by defects in pipe. Dresser Atlas offers the Vertilog™ and Schlumberger has the Pipe Analysis Log (PAL). This tool contains two rows of magnetic sensors, each row consisting of six sensors. Each sensor inspects approximately 60° of the casing circumferences. Four curves recorded are (1) the sum of Row 1 signals, (2) the maximum of Row 1 signals, (3) the maximum of Row 2 signals, and (4) the maximum eddy current readings from all 12 sensors (Wooley and Hatcher, 1989).

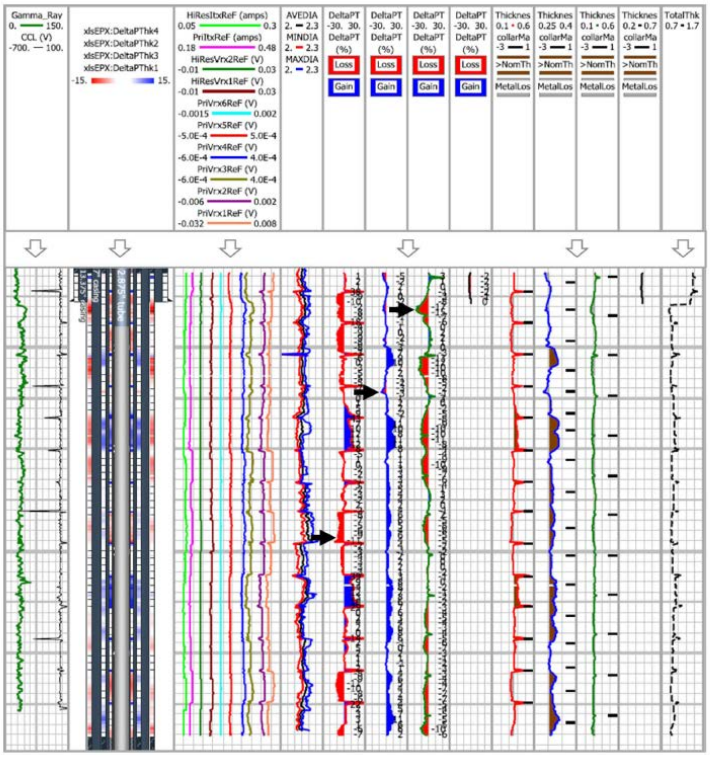

Figure 13 Typical casing imaging log (After Haliburton, 2017)

Electric potential tool is a casing inspection tool that does not use electromagnetic signals, but instead measures electric potential or resistance between two points in the casing. Casing potential tools are available from Schlumberger, Dresser Atlas, and NL McCullough. This tool is used to detect the occurrence of cathodic corrosion in casing and to provide a measurement of rate of corrosion. For purposes of interpreting casing failures, this device would be useful for distinguishing between split pipe and a part, such as a connection jump-out. The electrical resistance is discontinuous for parted casing, but not for split pipe. Figure 13 above presents sample casing imaging logs of a typical well.

Regardless of log type employed to access the casing integrity; safety, of both personnel and the environment is of paramount importance. Well integrity is a mandatory requirement for well through drilling, completion production and abandonment. Meeting up with this requirement is challenging. However, sustaining, robust integrity management system will provide near ideal well integrity that could preclude any chance of casing failure during this time. A study on well integrity using load resistant monitoring and predictive analytic on P110 casing grade in HPHT well; point that if the right data is monitored, right features extracted predictive analytics can identify integrity issues in advance Das and Samuel (2017). In addition, real time monitoring plays crucial role in identifying leading stimulants and retarding indicators to casing failure. Figure 14 presents and overview of damage evolution and how real time monitoring (RTM) could assist to monitor failure processes.

4.4 Emerging techniques

Besides, well integrity issues and localise deformation could occur for casing length as short as 3 feet (Pearce et al., 2009). Fundamentally; fibre optic distributed strain sensing (DSS) has significantly advanced casing integrity assessment in recent times. The use of real time compaction imager (RTCI) is a classic example. Moreover, one can utilise RTCI data (sensor data) to calibrate and validate numerical models to aid in monitoring casing deformation and present realistic prediction of the well deformation using data mining and analytics. Other methods such as pressure metres, gyros, inclinometers, and radar indirectly measure subsidence but not casing deformation. Figure 14(A) presents RTCI system while 14 (B) is a layout of optical fibre sensors for reservoir compaction monitoring in an open-hole completion.

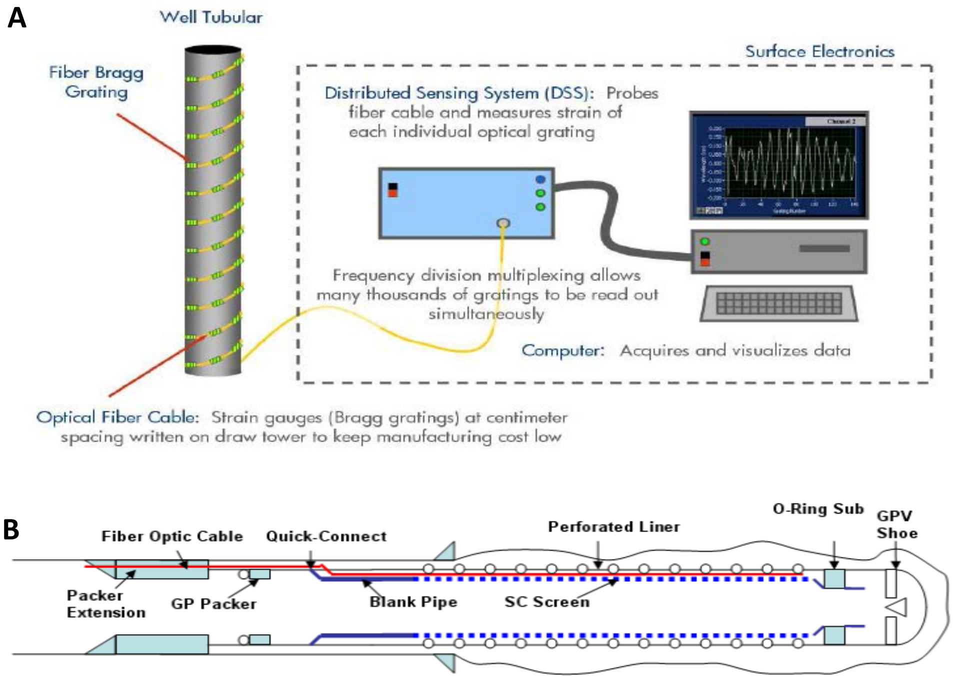

Figure 14: (A) Overview of Real time compaction system (B) Perforated liner in open hole completion with RTCM for compaction monitoring (Earles, 2011).

4.5 Machine Learning

According to Mitchell (2006) machine learning is defined as a well- modelled learning problem - where a computer programme learn from experience *(E)* with respect to some task *(T)* and some performance measure *(P)*, if its performance on *(T)* as measured by *(P)* increase with experience *(E)*. Despite, the tremendous impact data mining techniques have had in other industries, its potentials has not been fully tap in oil and gas business (Noshi et al., 2018). Data driven modelling provides the procedure for evaluating and establishing the relationships between the state of a system characteristics and highly independent variables within a system under investigation. There are four types of machine learning algorithms, these are:

- Supervised learning
- Unsupervised learning
- Semi-supervised learning
- Reinforcement learning

In supervised learning a training data set is required where each sample contains a predictor feature with a class of complementary target. The supervised learning algorithm then acquire patterns in the data provided and learns it for proper application on input variables. Conversely, in the unsupervised learning, no target training dataset are provided, the algorithm distinguishes the similarity between input features and organises observations based on these comparisons like in clustering. A training dataset consisting of both labelled and unlabelled datasets characterised semi-supervised machine learning. In reinforcement learning, the algorithm repeat procedure of trial and error to induce training with response being provided to the algorithm on the causes of error but no instruction for error refinement is provided.

In this section we present a few selected examples of machine learning application and data mining in oil and gas activities. Pollock et al. (2018) used machine learning techniques to improve directional drilling and noted that controlling tool face orientation and maintaining good rate of penetration is challenging. Using historical data from different rigs to develop the artificial intelligent model to optimise ROP, improve wellbore geometry and reduce number of personnel on board. The collected data was filtered and used to structure and train artificial neural network (ANN) and the appropriate parameters selected. Further modification of the model was accomplished with reinforcement learning with the initial historical data. Then using a computational model for drill string physics was employed to simulate the mechanics of directional drilling. The end result was a model that minimise both deviation from the planned well trajectory and wellbore tortuosity and maximise ROP.

In a different study, Hoeink and Zambrano (2017) used logistic linear regression to classify lithology and automate shale picking in a vertical well. The lithological interpretation is one of the most important tasks at the commencement of geomechanical workflows; which is the classification of lithological units based on well log data. In particular, differentiation between shale rocks and non-shale layers significantly influences the quality of pore pressure prediction and wellbore stability analyses.

Shales are naturally associated with high densities, relatively high gamma ray count and low resistivity, with comparatively good uniformities within a formation. However, relationships obtained from one well can frequently be employed in nearby wells (well-to well-correlation). Yet, precise relations do not typically apply to wells in other formations. Local calibrations are therefore required. When done by humans, the careful and considerate picking of shale intervals is often very time consuming, inconsistent and different practitioners frequently produce different interpretations (Hoeink and Zambrano, 2017). Hence, lithological column classification is based on sandy – shale formations through the reservoir and was understood by analysing the characteristics of density, gamma ray, resistivity, compressional and shear slowness logs. Using machine learning the predicted results with training and test data from a single well and cross-well predictions on new unseen data demonstrate remarkable performance. Results indicate that machine learning methods with adequately trained classifiers have the potential to automate shale picking.

Cao et al. (2016) used machine learning techniques to forecast production in existing wells and new wells to be drilled in an unconventional reservoir. In this study, geological data, fluid production history data, pressure and operational data are utilised to build the artificial neural network model (ANN). This involves using the historical data to train and optimise the ANN and then the model is used to predict both existing wells' production and new wells to be drilled. The model can forecast production from nearby wells with similar characteristics.

The work of Noshi, et al. (2018) and Noshi et al. (2019) made an excellent attempt using machine learning and data analytics to identify possible factors that may have been responsible for casing failure. They employ artificial neural network (ANN) and python coding, descriptive and predictive analytic to process casing failure in Granite Wash Play of Western Anadarko basin. Results from this study identified all the factors and their respective contribution to casing failure.

5. Concluding Remarks, Opportunities and Challenges

Data available from the literature have shown that there is an increasing cases of casing failure during shale gas development process. However, well integrity as whole is comparatively new in relation to drilling, completion, production and health safety and environment (HSE). It is anticipated that well integrity will therefore see both quantitative and qualitative step changes in technology and procedure in short and long term (Brechan et al., 2018). For example step changes in equipment recently lead to development of elastic carbon composite (ECC) in connection seals is replacing organic elastomers in HPHT wells and steam injection wells. In terms of well integrity, barriers, and well integrity management system (WIMS), new concepts are being promulgated through joint industry project with API and ISO to cope with ever demanding need of recommended practice, guidelines, manufacturing, testing and qualification of equipment and procedures to be able meet today's unconventional well requirement.

However, opportunities around manufacturing new materials and designs as well as the used of big data and analytics can lead to rapid transformation in many aspect of well construction and operation in future. For example development in artificial intelligence (AI) has led to development of automated hydraulic tongs for make-up and break-up casing and drill pipe connections, and automated surveillance of offshore platforms. Recent advances in technology has led to the designs and development of subsea field support with autonomous under water vehicles (AUV) to reduce maintenance cost. In addition, Brechan et al. (2018) pointed out that modern oilfield will most likely utilise wireless technology where signal will be transmitted to a central control room and action taken in real time. Another area where data and wireless communication will see future applications is digital twins. Digital twining is a technique in which oil & gas companies can precisely build an exact digital replica of their physical assets in the cloud from design, development, to the end of the product or asset life cycle.

In summary, the opportunities are huge particularly around digitalisation strategy the industry is yearning for. Digitalisation has the potential to transform operations by leveraging advanced digital technology to drive efficiencies and to open new opportunities. Doing so might involve so-called digital twins (virtual simulations of assets) that can improve the efficiency of predictive maintenance. It might also take the form of using drones to inspect offshore platforms, which reduces workers' exposure to hazardous tasks; data analytics to optimise production and reserves; or other new processes and practices.

On the other hand, every new technology and advancement or modernisation there are challenges associated with it. First, the challenge of adoption. People and organisations are naturally reluctant to change from traditional and/or habitual way of doing things. Another aspect is that regulation and reliability of the new systems and processes as well as the technology. In addition, the challenge of monitoring well integrity especially in annulus ‘B’ & ‘C’ for subsea wells as shown on figure 15 is still a technological challenge. Much of the well integrity monitoring techniques are still manual in nature. It involves collecting, retrieving, processing, interpretation and reporting lots of data. This challenge of repetitive activities for well integrity assessment can be modelled and automated to reduce human interaction over the life cycle (Gouda and Alsam, 2018). However, one key factor /challenge that determine the overall development of this new approaches (technologies and models) is sufficient and reliable data. Table 4 provide summary of some selected cases of well integrity indicating current practice and potential future solutions and opportunities.

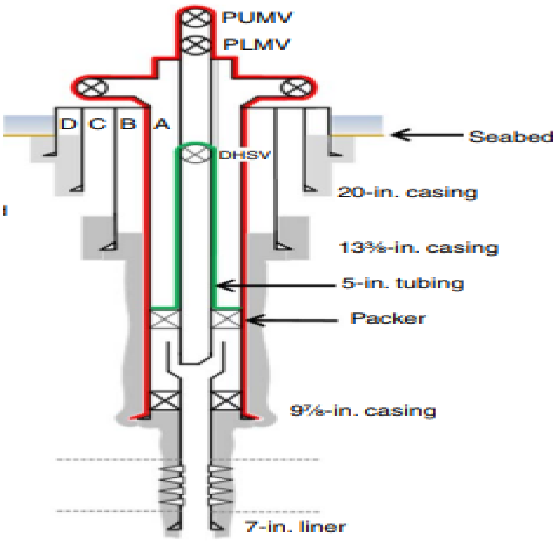

Figure 15 schematic of subsea wellhead system showing annulus A, B, C and D (After Mainguy and Innes, 2018)

Table 4 brief summary of selected integrity challenges showing current practice and potential future solutions/opportunities.

Well integrity Problem / Challenge	**Current solutions / practices**	**Potential future solutions / opportunities**
Buckling failure or deformation	Decreasing the well trajectory to ensure crossing angle has minimum impact and employing the cement with a low Young's modulus or even no cementing can be the effective measures to prevent buckling	Development of predictive tool at the design stage to investigate impending casing buckling/deformation. Future opportunities for instrumentation of the casing with sensors for twining and monitoring of asset.
Shear failure	Slow water injection rate at low pressure	Re-evaluate casing design for waterflooding project using predictive models
Collapse / Burst Failure	Design based on API specifications 5C3 and apply safety factors typically 1.0- 1.25.	Modification of existing API models and development of new models for prediction of burst / collapse failure of tubulars
Fatigue Failure	Materials (well tubulars and equipment) selected, design and installed based on specific well type and purpose	Future opportunities for instrumentation of wells and equipment with sensors for twining and monitoring of asset in real time.
Wear / erosion / corrosion failure	Avoid contact of the joint and casing at high wear-stress areas. Also numerical models are developed to determine the critical erosion and corrosion rates	Development of antifriction between tool joint and casing and/or software tool that can predict contact at low wear-stress arears. New erosion and corrosion resistant materials and / or smart coatings for real time notification equipment status.
Connection Failure	Proper connection makeup, good practice and application of suitable dope.	Currently, artificial intelligence has enable the development of automated power tongs for consistent & accurate connection makeup torque
Joint Seal Failure	Used packer and elastomers that can provide good for significant well life.	New material are now developed to cope with high temperature challenge. E.g. Elastic carbon composite (ECC)
Casing –Cement-Formation Failure	Materials (casing and cement) selected and design based on anticipated downhole condition.	Potential application of FEA and machine learning to develop a predictive tool for use at the design stage to investigate failure mechanics of a combined system based on initial material section. Also, future opportunities for instrumentation of the casing with sensors for twining and monitoring of asset.

The casing integrity is reviewed for a range of well types and operating conditions. Factors that undermine casing robustness and their effect on well integrity failure are presented. It is noted that these factors can cause casing failure and lead to accident, negative financial implications, loss of asset and damage to environment. In particular, the severity and magnitude of casing failure depend hugely on wellbore environment (pressure, temperature, fluid content, time) and the type of well. The induced stresses due to stimulation tend to promote casing failure more than in-situ geo-mechanical stresses. This study found that Q125 and P110 casing grade are mainly employed in HPTHT shale gas, injection wells and deep-water. This is due to the characteristic of these wells requiring higher strength materials. Additionally, the review has examined both sources and causes of casings and connection failures currently faced in the industry from drilling, completion production to abandonment. Recent advances in materials, equipment designs and future trend of casing integrity assessment have been explored and documented in this study.

Casing failure is highly likely particularly in both conventional and unconventional wells experiencing any kind of induce stresses. Different well types operating scenarios, failure modes and failure mechanism of various case studies from around the world are studied. Therefore, meticulous and pragmatic design, installation, operation and evaluation of the casing structural integrity is a must in increasing and sustaining casing integrity over the well life and beyond. However, based on the few new advances looked in this review, there is room for further optimisation of both casings, connections and design methodology of casing string in these challenging wells. In addition, specific example on data mining and machine learning have shown their potentials in other aspect of oil and gas business including casing failure assessment.

The casing structural integrity assessment is required over the entire lifecycle of the well. The present conventional approach of wireline logs is limited in accuracy and long-term continuous health monitoring capability. The casing integrity assessment is mostly performed with wireline logs such as caliper, ultrasonic imaging log and electromagnetic induction tools; which delay production, significantly increase well operational cost and only measure large scale casing deformation. Future opportunities that exist around twinning, numerical modelling and machine learning algorithms can assist to predict quantitative effect of geometry and material selection for casing structural integrity at the design phase as well as development of accurate predictive models that will predict casing failure based on historical data will be a useful tool.

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