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Review of elastomer seal assemblies in oil & gas wells: Performance evaluation, failure mechanisms, and gaps in industry standards

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ABSTRACT

Elastomer seal assemblies are critical components for maintaining well integrity. Evidence suggests that failure of seal can lead to health, safety, and environmental consequences such as blowouts and oil spill. Regulators and the industry have acknowledged the need for improving design and qualification of elastomer seals, particularly for high pressure and high temperature applications.

This paper provides a comprehensive review of literature, research studies, and industry standards relevant to elastomer seal assemblies used in the oil and gas wells. The paper aims to investigate failure modes and various parameters influencing the performance of seal assemblies. The ultimate objective of the review is to discuss gaps in industry standards and propose major areas of research for improving seal reliability.

The industry standards primarily focus on material testing and lack sufficient guidance on equipment level design of elastomer seals. Seal qualification processes are not customized according to design, scale, and function of seal assembly. Research efforts need to be extended beyond material testing to design aspects of seal equipment such as energization method, design of housing and supporting components, functional failures, etc. There is also an imperative need for reliable techniques to extrapolate lab-scale results to field-scale applications spanning years of service.

1. Introduction

Elastomer seals are extensively used in various drilling, completion, and wellhead equipment. Commonly used equipment consisting of elastomer seal components include – wellhead assemblies, packers, subsurface safety valves (SSSV), and blow-out preventers (BOPs). Primary function of these equipment is to isolate fluids within casing, tubing, and/or annuli. A failed seal can eventually permit fluid communication to wellbore, surface, or formation.

Seal assemblies in wellheads or liners are critical barrier elements for maintaining well control. They are typically considered as secondary barriers proceeded by annular cement sheath as the primary barrier against influx of formation fluids (Kiran et al., 2017; Al Ramadan et al., 2019a). The seal assembly and cement sheath act as a dual barrier system. Unfortunately, during well construction, the two barriers can only be pressure tested together as a system rather than independently (BSEE, 2014; Ahmed et al., 2019a). Hence, successful pressure test of the system only indicates that one of the two barriers is competent. In general, cement sheath as a standalone barrier is considered less dependable because of the major concerns such as inherent permeability, potential for gas migration, lack of bonding, presence of microannulus, etc. (Al Ramadan et al., 2019b; Kwatia et al., 2019; Kimanzi et al., 2019; Salehi and Patel, 2019). It is possible that seal assembly masks poor quality cement job during the pressure test and may act as the only effective barrier. This possibility further emphasizes the importance of designing seal assembly with long term reliability.

It has been observed that the failure of seal assembly are often responsible for well control incidents resulting in severe health, safety, and environmental consequences. An informal survey of several Gulf of Mexico operators indicated that about 30%–50% of the pressure seals in liner overlaps failed (Lohoefer et al., 2000). Another report indicates that as many as 18% of offshore wells worldwide are estimated to have some form of weakness or uncertainty in seal assemblies and the record of failures of critical liner-hanger seals in HPHT completions, for example, has become a large concern. (Van Dort, 2009). Concerns with reliability of elastomer seal assemblies has also been acknowledged by the regulatory agency - Bureau of Safety and Environmental Enforcement (BSEE) in form of a technical evaluation report (BSEE, 2014). The agency recommended further investigation into design, reliability, and fitness-for-service assessment of elastomer seal assemblies particularly for liner hanger applications (BSEE, 2014).

This paper provides a comprehensive review of literature, research

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studies, and industry standards relevant to elastomer seal assemblies used in the oil and gas wells. There are four specific objectives of this review paper – (i) identify and discuss potential modes of failure in elastomer seal assemblies, (ii) review relevant experimental, theoretical, and numerical studies, and discuss various parameters influencing the performance of seal assemblies, (iii) perform gap analysis of relevant industry standards and guidelines, and (iv) discover major knowledge gaps for future research on improving design and reliability of elastomer seals.

This review paper serves as a useful reference to all major stake holders - industry professionals, regulators, researchers, and students. Knowledge of potential failure modes will enable engineers and product developers in designing robust seal assemblies. Extensive literature review and proposed knowledge gaps will guide future research studies. Gap analysis of existing standards will help the industry as well as the regulators in strengthening standards, guidelines, and regulations related to qualification process of elastomer seal assemblies.

2. Seal assemblies

The elastomer seal bearing equipment can be ranked in terms of likelihood of presence during different well activity. Elhard et al. (2017) demonstrated that the wellhead followed by BOP are far more likely to be present in a well when a blowout occurs in comparison to the packer and SSSV. In fact, regardless of the well type, wellhead equipment such as casing or liner hangers will always be present. It is a common practice for operators to run a liner string instead of running a full casing string back to the wellhead. The liner is typically hung from the previous casing and cemented in place. Similar to casing hangers, the liner hanger also includes a seal assembly. Typically, these hanger seals are made outside of each individual casing or liner string to seal off the annuli.

The conventional liner hanger equipment consists of cone or compression plate, elastomer element, and slips (Fig. 1a and Fig. 1b). The seal assembly is either integral to the liner running tool (Fig. 1b) or can be installed later requiring second trip (Fig. 1a). The seal assembly is energized by applying hydraulic or mechanical axial force that engages

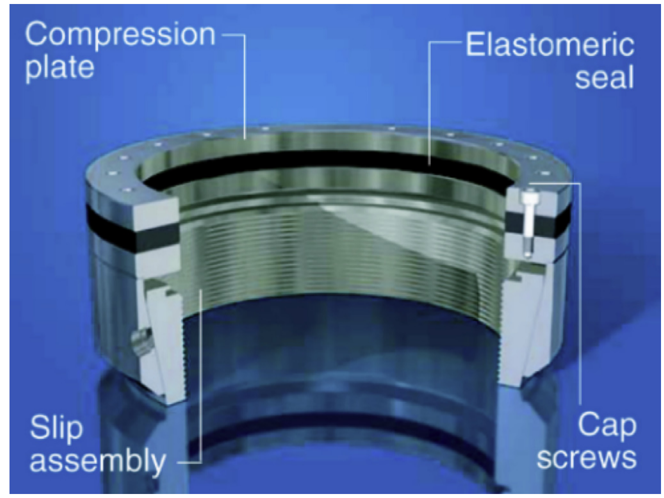


Fig. 2. Mechanical-set slip-and-seal assembly in sub-mudline liner hanger assembly (Speer, 2006).

the slips to the opposite surface. Further increase in axial force compresses the elastomer seal while bottom compression plate is being anchored by the slips.

Expandable liner hanger is a relatively newer technology which consists of a smooth liner body with no moving parts and elastomer elements bonded to its outer profile (Fig. 1c). The idea is to expand the liner either hydraulically by applying internal pressure or mechanically by running a solid mandrel having larger outer dimeter than the internal diameter of hanger. Expansion of hanger body compresses elastomer elements against the casing resulting in seal energization. The seals not only provide hydraulic integrity but also act as anchor for the liner. The advantages and limitations of expandable liner hangers relative to the conventional hangers are readily available in the literature (Mullins, 2016; Mohamed and Al-Zuraigi, 2013; Mccormick et al., 2012; Walvekar and Jackson, 2007; Smith and Williford, 2006; Lohoefer et al., 2000).

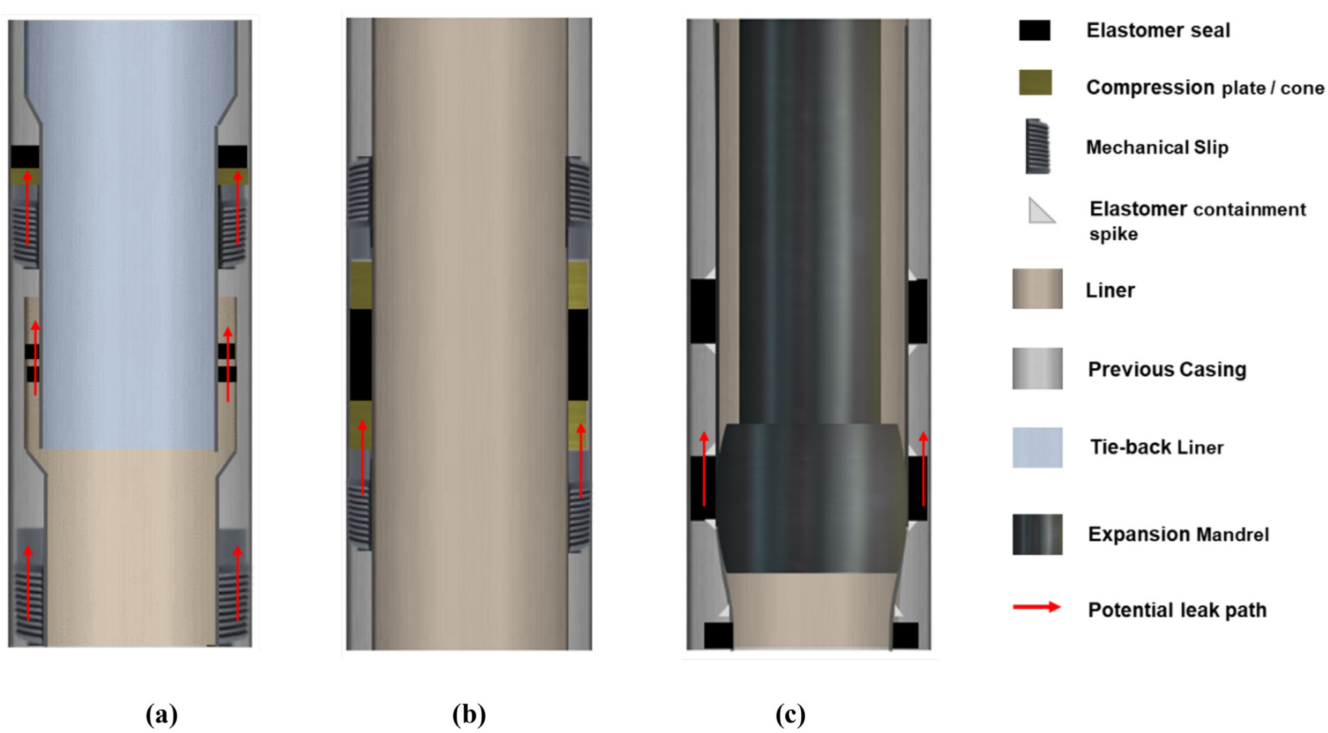


Fig. 1. Comparison among (a) liner top packer assembly, (b) integral liner hanger seal, and (c) expandable liner hanger seal assembly.

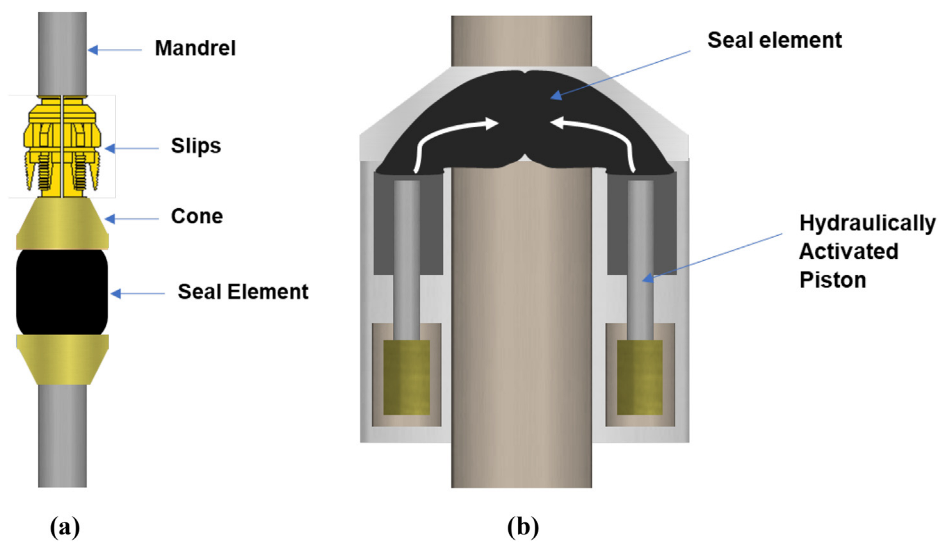


Fig. 3. Elastomer seal components (black color) in (a) packer, and (b) blowout preventer after closure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The wellhead typically uses a slip-and-seal casing-hanger assembly. The slip-and-seal assembly (Fig. 2) is energized similar to conventional liner hanger seal assembly. A load is placed on the elastomer element which expands radially by compression and seals the annulus pressure below the hanger from the wellbore. In the offshore jack up drilling application with mudline, a mechanically set seal assembly is used in which cap screws are made up with a wrench against the compression plate to energize the seal element.

Packer equipment is typically used to isolate production zones or to seal off annular space between production tubing and casing. Similar to casing/liner hangers, packer equipment uses cone and slip assembly to energize the elastomer element by compressing it through mechanical/hydraulic means (Fig. 3a). A newer technology uses elastomer material that swells after contacting oil based fluid. Swelling expands the seal element in radial direction to achieve contact with the opposite surface.

Blowout preventer is a critical wellhead equipment designed to act as a secondary barrier or fail-safe in the event of loss of well control such as a formation kick or blowout. It consists of a solid donut shaped elastomer (Fig. 3b) component. In the event of a potential event of kick, hydraulic pressure is applied to the donut, forcing it to conform tightly around the drill pipe and seal off the well. The elastomer element remains directly exposed to the formation fluid pressure.

3. Failure in seal assembly

Failed seal requires expensive remedial operations which increases the overall well costs, and impacts the business. Furthermore, if a seal failure is not detected early then it can greatly compromise well integrity and results in loss of well control event with greater health, safety, and environmental consequences.

SINTEF maintains a historical database of well blowouts and loss of well control (LOWC) events. It is reported by SINTEF that most blowouts occur during drilling, followed by workover, completion, and production (Elhard et al., 2017). Using the SINTEF data provided in Holand (2017) and Elhard et al. (2017), statistical analysis was performed to calculate frequency of potential seal related causes. Causes of all LOWC events occurred during the period of 1980–1994, and 2000 to 2015 are presented in Fig. 4. In the pie charts, black and gray shades represent causes related to failures in seal and/or seal containing equipment such as - wellhead leak, sub surface safety valve failure, x-mas tree failure, and BOP failure after successful closure. The charts clearly indicate that 46% of the failures in secondary barrier originate in seal containing equipment. The causes of secondary barrier failure were further categorizing based on the well activity - drilling, workover, and production (Fig. 5). It is clear that BOP, x-mas tree, and wellhead leaks are the top three causes of secondary barrier failure.

Failure in seal assembly can be categorized into (i) material failure of the elastomer seal component, and (ii) functional or equipment related failure.

3.1. Material failure

The most common elastomer materials used in the oil and gas industry can be classified into six groups – NBR (Nitrile Butadiene Rubber), EPDM (Ethylene Propylene Diene Monomer), HNBR (Hydrogenated Nitrile Butadiene Rubber), FKM (Fluoroelastomers), FEPM (Perfluoroelastomers), and FFKM (Perfluorocarbon Elastomer). Chemical and mechanical properties of each of these elastomers depend on type of monomer, molecular weight, number, and type of crosslinks. As a general rule, FKM, FEPM, and FFKM are more expensive, demonstrate greater chemical resistance, and have higher operating temperatures (Elhard et al., 2017, James Walker 2017, and Apple Rubber Products Inc, 2009). However, these elastomers typically struggle at lower temperatures compared to NBR, EPDM, and HNBR (James Walker, 2017; and Apple Rubber Products Inc, 2009). Cheaper elastomers such as NBR, exhibit better mechanical properties than fluoroelastomers but they are limited by low resistance to chemicals and heat (James Walker, 2017; and Apple Rubber Products Inc, 2009). HNBR has improved temperature and chemical resistance over NBR and EPDM but it is more expensive (James Walker, 2017; and Apple Rubber Products Inc, 2009).

Some of the major modes of failures in elastomer seal are - rapid gas decompression, temperature and chemical degradation, extrusion and nibbling, compression set, wear, spiral failure, etc. Rapid Gas Decompression (RGD) or explosive decompression is one of the most common modes of seal failure. In downhole high pressure environment, gas may gradually absorb into molecular voids of the elastomer material. If the surrounding pressure suddenly decreases, then the absorbed gas expands and tries to rapidly diffuse out of the material; resulting in development of cracks and eventual 'explosion' (Fig. 6a). Elastomers with less hardness and elastic modulus are more prone to RGD (Marco Rubber and Plastic Inc., 2018). The risk of decompression increases at elevated temperature or very low temperature when elastomer becomes brittle. The term 'explosive' is misleading as decompression damage can occur when pressure decreases gradually over several hours similar to the time associated with tripping out operation (Mackenzie and

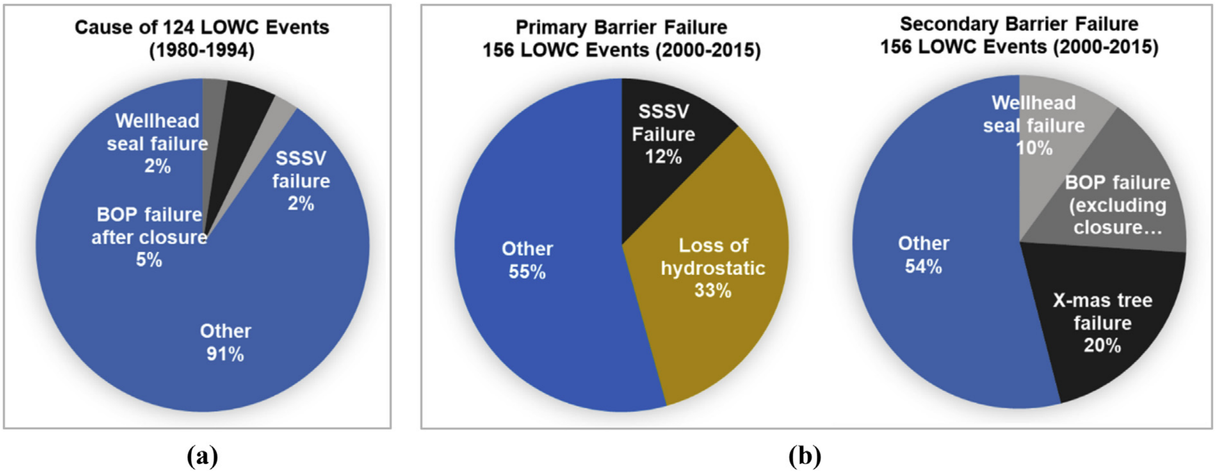


Fig. 4. Causes of LOWC events occurred during (a) 1980–1994, and (b) 2000–2015. Black and gray shades represent causes likely related to seal and/or supporting component failures. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

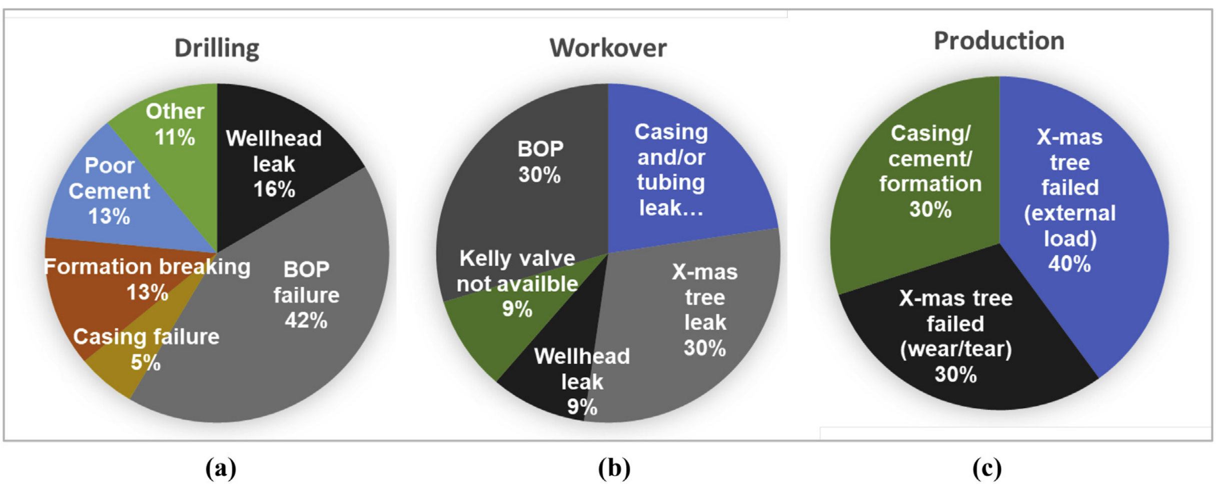


Fig. 5. Causes of secondary barrier failure during (a) drilling, (b) workover, and (c) production in total 156 LWOC events occurred between 2000 and 2015. Black and gray shades represent causes likely related to seal failures. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

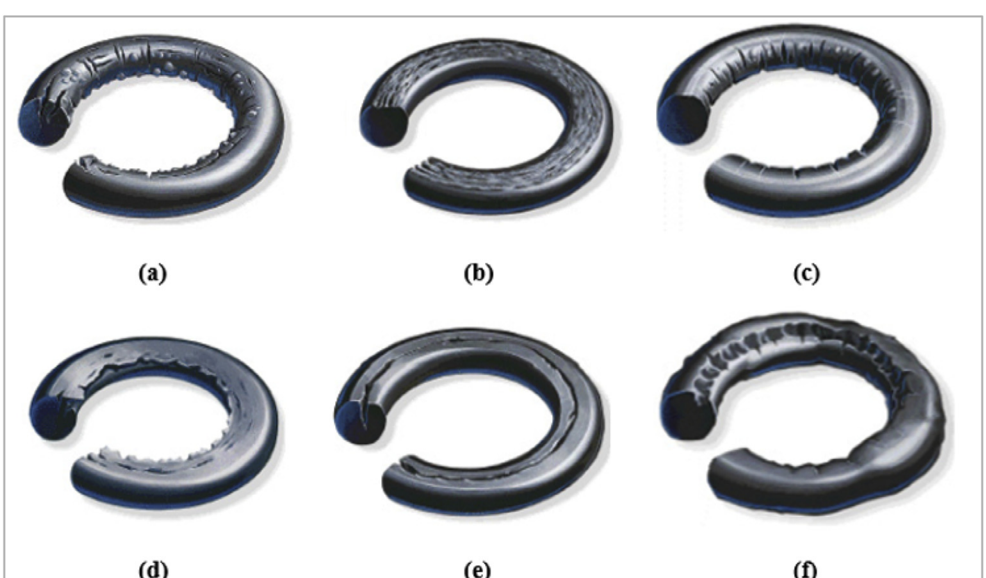


Fig. 6. Failures in elastomer O-ring: (a) explosive decompression, (b) abrasion-friction, (c) thermal degradation, (d) extrusion, (e) compression set, and (f) chemical degradation (image source: Marco Rubber & Plastics Inc.).

Garfield, 2007).

Abrasion or wear type failure (Fig. 6b) can occur during storage, handling, or installation of elastomer seal. Primary causes of this failure are - improper lubrication, uneven contact surfaces, presence of debris/solids at sealing interface etc. Temperature degradation (Fig. 6c) is another common risk associated with elastomers. At high temperature changes, elastomer seal may exhibit radial cracks and/or sign of softening. Typically, it is challenging to seal with elastomer in temperatures beyond 250–300 °F (Mackenzie and Garfield, 2007). Extrusion and nibbling (Fig. 6d) is a type of mechanical failure which can degrade the sealability of elastomer. It occurs when an elastomer seal is sealing against moving surfaces with friction or static interfaces with pulsating or cyclic movements. The seal gets pulled or nibbled resulting in loss of material with time. Failure can also occur due to shearing of seal element across the extrusion gap. The extrusion failure can not only affect sealability but also make the service tool or equipment difficult to retrieve. Compression set failure (Fig. 6e) is permanent deformation of seal. This can typically arise due to improper dimensioning of the seal element (Elhard et al., 2017). This can result in pre-mature extrusion of seals (Daemar Inc, 2015).

Chemical degradation (Fig. 6f) is one of the most common modes of failure in oil and gas applications. During the service, elastomer may come into contact with various chemicals such as drilling fluid, completion fluid, fracturing fluid, formation brine, or production fluid containing various solvents, caustics, acids or corrosive chemicals. Leaching of these chemicals into elastomer can weaken its polymer structure (Campion et al., 2005). The leaching becomes more severe as temperature increases. The absorption of fluid can also lead to volumetric swelling of elastomer which can increase the risk of other type of failure such as abrasion or extrusion (Elhard et al., 2017). Moreover, exposure to oxidation agents such as ozone during storage, transportation, or service can lead to scission reaction within elastomer. The reaction can weaken molecular structure and increase risk of material degradation (Campion et al., 2005). Increase in operating temperature makes chemical degradation faster and worse. Fernández and Castaño (2016) studied effects of crude oil on elastomers at 150 °F and 1000 psi for 168 h. The authors observed reduction in tensile strength and elongation at break of elastomer samples. Aging also deteriorated hardness and compression set, and caused volumetric swelling. Crude oil with high percentage of saturates and aromatic caused more severe degradation.

The three major gases typically encountered in oil and gas wells are Hydrogen Sulfide (H_2S), Carbon Dioxide (CO_2), and Methane (CH_4). CO_2 and H_2S can lead to severe chemical degradation of elastomers. CH_4 typically does not react chemically with elastomer but it can permeate through the material and cause other physical alterations.

3.1.1. Effect of H_2S

H_2S is known to cause notable deterioration in elastomer physical properties. Cong et al. (2013) conducted aging experiments using HNBR samples in aqueous solutions of H_2S at 1000 ± 100 psi pressure and 212 °F temperature. The authors observed reduction in tensile strength, hardness, and elongation capability of the elastomer. Degradation in HNBR sample was attributed to homolysis or heterolysis reactions. In aqueous solution, H_2S dissociates into H^+ and HS^- ions. H^+ causes hydrolysis of the C≡N group in HNBR (Fig. 7) while HS^- attacks C=O. This results in C=S and C–C=S groups. In homolysis, mercapto radicals from H_2S ($H^\bullet$ and $HS^\bullet$) reacts with polymer chain of elastomer and results in macromolecule radical. This radical then react with another mercapto radical. This chain reaction causes dissociation of triple and double bonds in polymer chains and eventually yields saturated C–S–C bonds. These processes notably alter physical properties of elastomer. Fernández and Castaño (2016) studied effect of H_2S concentration on NBR elastomer. The authors observed development of brittle fracture surfaces on NBR with increase in H_2S concentration (Fig. 8). The authors also observed that increase in H_2S concentration reduces tensile strength, elongation break, and resilience of NBR elastomer.

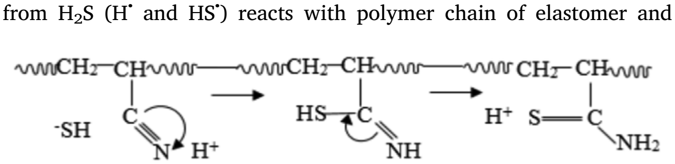


Fig. 7. Nucleophilic reaction mechanism showing breaking of acrylonitrile group in HNBR (Cong et al., 2013).

Tynan (2016) compared reactivity of various elastomers to H_2S and demonstrated that the decreasing order of elastomers in terms of H_2S resistance is FFKM > FKM > FEPM > HNBR > NBR.

3.1.2. Effect of CO_2

Carbon dioxide is stable, inert, and non-toxic under normal conditions. Its carbon-oxygen double bond is very stable with high dissociation energy of 732 kJ/mol (Salehi et al., 2019). Typically, it would not cause chemical reaction with elastomer material (Salehi et al., 2019). However, in presence of aqueous medium such as water or brine, it can form carbonic acid. As discussed by Salehi et al. (2019), in large quantities, this weak acid can become corrosive and cause chemical reaction with elastomers. The acid causes dissociation of weak C≡N bond in NBR and generates amine groups. The C=C double bond in EPDM exhibits relatively higher resistance to dissociation. The C–F bond in Fluorocarbon elastomer is highly stable with very high dissociation energy and hence, FKM exhibits more resistance to CO_2 degradation.

Fernández and Castaño (2016) demonstrated that increase in CO_2 concentration increases volumetric swelling and permanent deformation of NBR elastomer. The increase in permanent deformation plateaus at very high concentration of CO_2. Scanning Electron Microscope (SEM) images show decrease in brittle fracture surface with increase in CO_2 concentration in NBR. Dajiang et al. (2017) studied aging of mechanically compressed NBR and HNBR samples in presence of liquid and gaseous CO_2. The authors observed increase in elastomer weight after aging in comparison to control samples. Reduction in hardness was also observed which was more severe in gaseous CO_2 compared to liquid CO_2. The results indicated that presence of mechanical load makes the CO_2 degradation worse. Based on SEM and energy dispersive spectroscopy, the study concluded that swelling and damage of elastomer increases with increase in compression load (Fig. 9). This damage is more severe in liquid CO_2 environment compared to gaseous.

3.2. Equipment related functional failure

Unlike elastomer material failure, minimal research data is available in public domain that discusses operational, hardware, or other functional failures affecting performance of seal assembly.

Installation of conventional weight-set or mechanical-set seal assembly often requires setting force greater than 100,000 lbf to attain desired seal energization (Williford and Smith, 2007). However, sometimes it is not possible to mechanically exert such force due to variety of reasons such as well deviations, drag forces, insufficient pipe weight etc. Such operational failures can significantly minimize seal performance.

Conventional liner hanger system consists of slip and cone components that provide mechanical anchoring to the liner and also act as support during seal energization. Concentration of excessive radial stress in slips can potentially collapse inner hanger mandrel (Zhong et al., 2017) and affect the energization process. Any compressive or tensile forces applied to the hanger body are permanently trapped in the slips (Fothergill, 2003). The slips also cause damage to casing and potentially increases risk of corrosion and other mechanical failure. Lack of centralization can pose risk of non-uniform seal energization resulting in less than desired contact stress. Failure or deformations in support components such as back-up ring or compression plate can

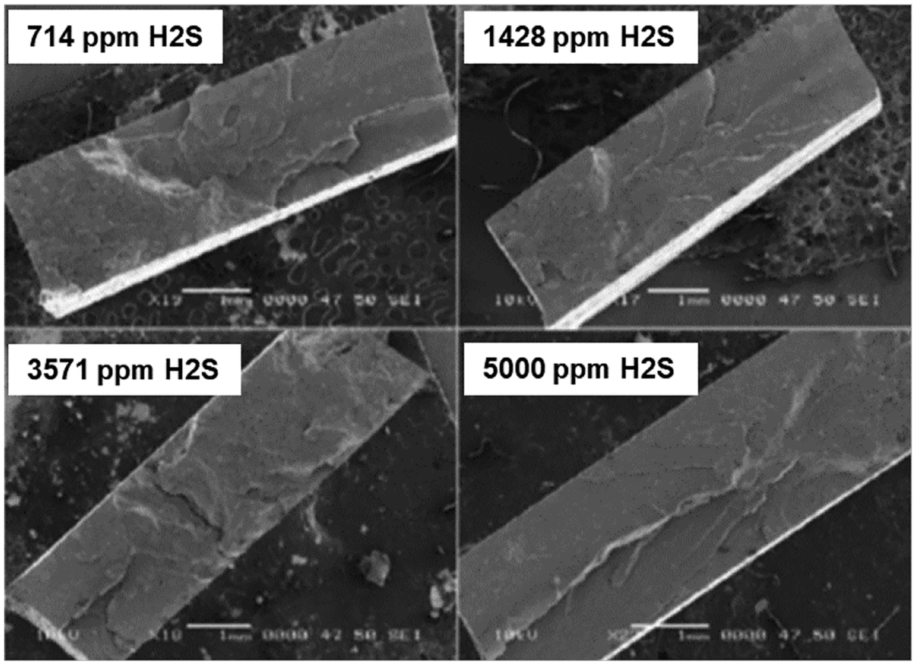


Fig. 8. SEM images of NBR samples aged with different concentration of H_2S for 168 h at 203 °F (Fernández and Castaño, 2016).

result in extrusion of elastomer element (Fig. 10). The back-up system is often designed to expand to the casing ID and fill the extrusion gap between seal and casing ID. Some of the major causes for back-up component failure are - excessive load, bending, shearing, or material strength reduction due to chemical/temperature changes. One such failure in compression packer is shown in Fig. 11a. Upton (2009) investigated 22 incidents of failure in slip joint packing system occurred between 2000 and 2008 and observed that wear of seal element was the primary failure mechanism (Fig. 11b). Some of the failure cases were caused by corrosion pitting of components. Ahmed et al. (2019b) demonstrated that manufacturing defects or irregularities in elastomer component can also deteriorate performance of seal assembly.

Failure of hanger body can also impact performance of seal assembly. The body of hanger assembly can collapse due to excessive stresses generated from above or below the seal element. Payne et al. (2016) presented inadequacy of traditional calculations such as two diameter rule, Barlow equation, Lame equation, API burst equation, etc. for determining capacity of liner hanger body. The authors

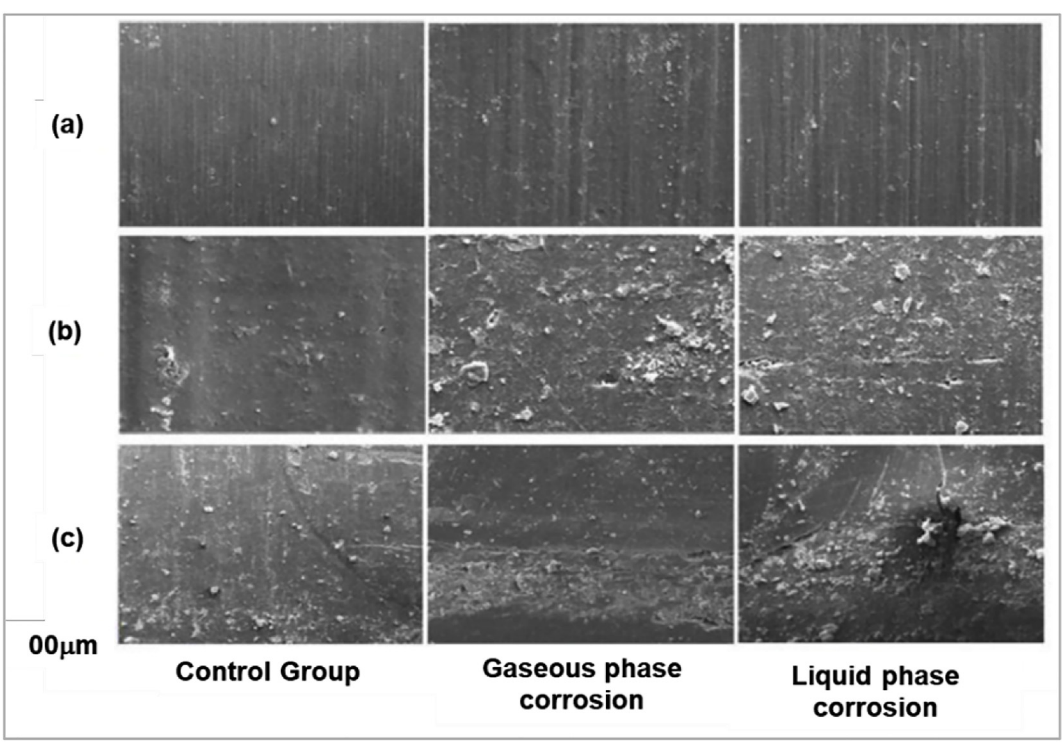


Fig. 9. SEM image of HNBR samples aged in presence of gaseous and liquid CO_2 at different compression loads: 0 lbf (a), 1349 lbf (b), and 2698 lbf (c) (Dajiang et al., 2017).

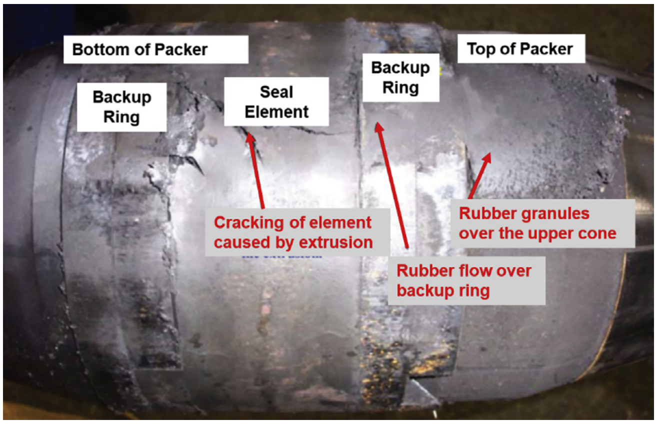


Fig. 10. Extrusion of elastomer element after failure in backup ring of packer equipment (Modified after Humphreys and Ross, 2009).

recommended to use finite element modelling depicting actual complex geometry of hanger assemblies to determine their true structural capacities.

Most of the hanger systems consist of many mechanical moving parts which can act as potential leakage paths. Exposed slips, hydraulic ports, and other moving components act as tortuous path and increase risk of pack-off by solid particles. This can lead to slip hung up or stuck setting tool. The hanger and seal assembly may pre-set while running in the hole if the tripping is too fast or if the element is swabbed off (Walvekar and Jackson, 2007). The cyclic effects of thermal expansion and contraction may lead to relative movements among the components and affect the sealability performance (Brown and Witwer, 2017).

4. Industry standards and limitations

4.1. Relevant standards

Majority of standards from API (American Petroleum Institute), ISO (The International Organization for Standardization), and NORSOK (Norsk Sokkels Konkuranseposisjon - Standards by Norwegian petroleum industry) provide guidelines for elastomer qualification specific to oil and gas applications. Other reviewed standards such as ASTM (American Society for Testing and Materials), and NACE (National Association of Corrosion Engineers) include protocols and guidelines primarily for laboratory based testing of elastomer material properties.

4.1.1. API, ISO, and NORSOK standards

The list of relevant API, ISO, and NORSOK standards is provided in Table 1. Some of the API and ISO standards are similar and cross-reference each other. For example API 17D and ISO 13628 are similar.

API SPEC 6A (or ISO 10423) contains specifications and recommendations for the design, materials testing, inspection, etc. for wellhead and christmas tree equipment. API 17D (ISO 13628–4) specifically deals with the subsea wellhead equipment and often refers back to API 6A. Both these standards use the term “annulus seal assemblies” that encompass hanger seal assemblies. The annexure F of API 6A contains information on elastomer validation testing via pressure and temperature cycles and also covers thermomechanical performance i.e. immersion testing of seals with an option for fixture testing using the actual seal design. API 17D contains three levels of tests for screening elastomer material based on compatibility with various chemicals. However, this section is listed as informative and not mandatory compliance. This standard requires that mechanical stresses exerted on the seal structural components during service follow predetermined limitations as verified by either engineering calculations or finite element analysis. Both of these standard mainly aim to verify functionality of the sealing system rather than the material validation.

ISO 14310:2008E and API Specification 11D1 provide guidelines to both manufacturers and end users in the selection, manufacturing, design, and laboratory testing of many types of commercially available packer equipment. These standards establish a minimum set of parameters with which the manufacturer must comply. There are three grades or levels established for quality control and six grades (plus one special grade) for design verification. The quality standards range from grade Q3 to Q1, with grade Q3 carrying the minimum requirements and Q1 outlining the highest level of inspection and manufacturing verification procedures. Provisions are also established to allow the end user to modify the quality plans to meet the specific application needs. The standard design-validation grades range from V6 to V1. V6 is the lowest grade and V1 represents the highest level of testing. A special grade (V0) was included to meet special acceptance criteria requirements. These validation grades are – (i) V6: supplier/manufacturer-defined, (ii) V5: liquid test, (iii) V4: liquid test + axial loads, (iv) V3: liquid test + axial loads + temperature cycling, (v) V2: gas test + axial loads, (vi) V1: gas test + axial loads + temperature cycling, and (vii) special validation grade V0: gas test + axial loads + temperature cycling + special acceptance criteria (V1 + zero bubble acceptance criterion).

ISO 14310 provides lists of material tests required for elastomer application in packer equipment. These tests include tensile strength, elongation, and tensile modulus tests, as well as compression set and

(a) **(b)**

Fig. 11. (a) Failure of shoulder drop in compression packer (Hu et al., 2017), and (b) internal wear of packer element (Upton, 2009).

Table 1
List of API, ISO, and NORSOK standards relevant to elastomer seal assembly in wellhead and liner hangers.

Standard	Description
API 6A, 2010	Specification for Wellhead and Christmas Tree Equipment
API 11D1, 2015	Packers and Bridge Plugs
API Spec 17D, 2011	Design and Operation of Subsea Production Systems – Subsea Wellhead and Tree Equipment
API 17TR8, 2015	High-pressure High-temperature Design Guidelines
ISO, 2009 (10423)	Specification for Wellhead and Christmas Tree Equipment
ISO, 2001 (13533)	Petroleum and natural gas industries — Drilling and production equipment — Drill through equipment
ISO, 2010 (13628-4)	Design and Operation of Subsea Production Systems – Subsea Wellhead and Tree Equipment
ISO, 2008 (14310)	Petroleum and natural gas industries — Downhole equipment — Packers and bridge plugs
ISO, 2011 (23936-2)	Petroleum, petrochemical and natural gas industries – Non-metallic materials in contact with media related to oil and gas production – Part 2: Elastomers
NORSOK, 2001 (M-710)	Qualification of non-metallic materials and manufacturers - polymers
NORSOK, 2013 (D-010)	Well integrity in drilling and well operations

durometer hardness tests. No minimum elastomer modulus properties are provided to guide elastomer selection in this standard.

API is currently drafting a standard for liner hanger equipment – API 19LH. This specification is expected to specify requirements for conventional and expandable liner systems including liner hangers, liner packers, liner hanger packers, seal assemblies, setting adaptors/sleeves, and running/setting tools etc. It is also anticipated that this standard will include minimum requirements for the functional and technical specifications, including design, design verification, materials, quality control, storage of equipment, etc.

NORSOK M-710 and ISO 23936-2 discuss qualification of elastomeric material. They include guidance for testing chemical compatibility, accelerated aging, resistance to extrusion or creep under high pressures, resistance to change in chemical properties at high temperatures, and RGD. These standards acknowledge that elastomer selection can vary based on the end service environment and selection of appropriate material should be ensured.

4.1.2. ASTM and NACE standards

NACE and ASTM standards discuss protocols and guidelines for laboratory-based tests to evaluate elastomer material properties and failure characteristics after exposure to various fluids, temperatures, and pressures.

In general, NACE standards provide test procedures along with protocols for test conditions, specimen preparation, equipment, and reporting of results. NACE standards focus on measurements of relative resistance of O-rings to the specific test environments. NACE standards offer test methods to measure the ability of elastomeric materials to withstand static exposure to sour gas environment (NACE, 2011), sour liquid environment (NACE, 2014), and carbon dioxide decompression environment (NACE, 2012, NACE, 1997).

ASTM standards provide test procedures to determine chemical and physical properties of elastomers in laboratory environments. The standard test procedures useful for oil and gas applications include – standard testing conditions (ASTM D1349-14, 2008), rubber properties in compression (ASTM D575-91, 2018; ASTM D945-06, 2012), effect of liquid (ASTM D471-12a, 2012), deterioration in air (ASTM D573, 2015), stress relaxation (ASTM D6147-97, 2014), dynamic fatigue (ASTM D430-06, 2018), resilience (ASTM D2632-15, 2015; ASTM D7121-05, 2018), and plasticity and recovery (ASTM D926-08, 2008).

4.2. Limitations

Currently available standards provide valid benchmark and consistent testing methodologies for preliminary testing of elastomer seal assemblies. Although, there is always room for improvement, the standards cannot be made comprehensive to account for all types of applications. Additional layers of qualification testing at the manufacturers, service providers, and operators' side are essential. Following are some of the major limitations in the existing standards where regulators and industry can make improvements.

NORSOK M-710 provides guidance to test a standard O-ring seal with a pre-determined cross-section and squeeze. API 6A uses molded slabs of typically cut in form of bone or dumbbell geometry. Standardized samples are necessary to achieve consistent methodology and provide valid reference for comparisons. However, compliance to standard material samples does not necessarily reflect seal performance in the actual applications involving varying seal geometries (S seals, T-seals, etc.) and cross-sections with varying volume fill, squeeze, etc. For example, increasing volume fill beyond 85% can significantly increase RGD resistance for some applications (Edmond et al., 2001). It has also been demonstrated that increasing the cross-section of seal increases the probability of damage by decompression because of the longer gas diffusion path compared to a smaller seal (Morgan et al., 2008).

The NORSOK M-710 is based on a crack rating system for evaluating RGD failure. The criteria is not only subjective but also has two major limitations. First, a large seal may have cracks developed in localized areas that are not critical from the functional point of view. A seal that passed functional pressure/temperature test can be deemed failed by NORSOK criteria (Tu and Cheng, 2016). Secondly, the cracks are evaluated after removing O-ring from the test fixture. In reality, the seal remains in the housing or fixture during the service. It has been shown that the RGD failure can remain contained under compressed loading state (Morgan et al., 2008).

The acceptance criteria for the aging tests recommended by NORSOK M-710 are not stringent. For example, acceptance of ± 50% change in tensile properties, 20 point loss of hardness, and 25% volume swell may not be stringent enough for applications at high end of performance limits (Slay, 2008). Additionally, use of swelling may not be an appropriate criteria for quantifying or validating seal performance in some conditions. Volume swelling of seal in a closed fixture would result in higher contact stress which may, in fact, lead to better sealability provided that the stress value does not exceed structural stress limits of the fixture (Ahmed et al., 2019b). ISO 14310 doesn't provide minimum elastomer material properties to guide elastomer selection.

One of the major limitations identified is that the ISO, NACE and NORSOK standards do not cover the operating temperature/pressures of field applications. Specifically, it has been shown that these standards do not reflect extreme HPHT conditions increasingly encountered in offshore wells (Elhard et al., 2017). For example, ISO 23936 and NORSOK M-710 specifies 2175 psi and 212 °F as maximum pressure and temperature respectively for the material compatibility tests. These values are significantly less than the API defined HPHT threshold of 15,000 psi and 350 °F. The maximum pressure and temperature required by API 6A to qualify wellhead is 20,000 psi at 121 °C respectively. This is within the range of HPHT pressure conditions, but falls short of qualifying the unit for high temperature service. To supplement this, API published API 17TR8 (HPHT Design Guidelines) to provide design guidelines for service environments with temperatures exceeding 350 °F and pressures exceeding 15,000 psi. These temperature and pressure qualification levels are for the overall unit and not the elastomeric components explicitly. ASTM and NACE provide guidance on qualification of elastomer material properties. The test pressure/temperature conditions specified by these standards are not intended for HPHT oil and gas environments. For example, test procedures discussed in reviewed NACE standards cover temperature up to 446 °F and pressure conditions up to 5500 psi. The pressure condition does not fall within HPHT range. Similarly, standard testing conditions in reviewed ASTM standards also lack coverage of HPHT conditions, particularly the pressures.

Another major gap is absence of guidance on elastomer storage in reviewed standards. No maximum storage timeframes are provided in the standards, and no requalification criteria are defined for elastomers taken from storage prior to being installed in service. None of the API, ISO, and NORSOK standards provide guidelines related to appropriate protection during storage, shipping, handling, and installation (Elhard et al., 2017). No information is available on how logistical and operational conditions can affect elastomer performance or rating. The oil industry can refer to aerospace industry's standard for guidance on storage and shelf life. For example, ISO 27996 (Aerospace fluid systems –Elastomer seals – Storage and shelf life) recommends 112 months for NBR and HNBR, and 160 months for FKN, FFKM, and FEPM as maximum storage timeframes.

All standards discuss chemical compatibility with respect to pure hydrocarbon gases and liquids such as methane, heptane, carbon dioxide etc. No guidance is available on effects of complex downhole chemicals such as drilling or completion fluids, hydrates, scale, corrosion inhibitors and other additives, etc. Additionally, the standards also lack guidance on accelerated laboratory testing of elastomer that is representative of downhole service conditions and can be extrapolated for predicting long term service life (Zhong, 2016).

Within API 6A, casing hangers are categorized into five groups depending on the complexity of their function – (i) absence of seal assembly, (ii) unidirectional and (iii) bidirectional hanging capability, (iv) presence of retention feature to hold hanger in place, and (v) without back pressure valve. However, the standard does not provide different qualification testing requirement for each of these groups. In general, equipment specific qualification requirement are missing. For example, qualification tests used for packers equipment are also used for casing/liner hanger equipment.

The API standards require that the seal element and individual seal structural mechanisms be qualified to claimed ratings. Although structural components can be considered as rigid but small deflections within them can certainly change sealability across various ranges of temperature, pressures, and loads. There is a need to incorporate potential dimensional changes in radial clearance and extrusion gaps in design of seal assemblies (Zhong, 2016). Qualification of material and design of backup components such as anti-extrusion devices and slip components is another area for improvement. The standards can be further improved by incorporating system level validation of elastomer seal assemblies that can test cooperation of both material and functional aspects. As discussed and demonstrated for metallic seals by Brown and Witwer (2017), a system level validation or qualification testing, where hanger and seal assembly react or have relative movement with each other similar to the actual field installation process, is essential to validate performance of seal assembly in its entirety. Similarly, for finite element validation, it becomes important to simulate installation process before pursuing simulations under pressure, temperature, and loading scenarios.

Elhard et al. (2017) presented breakdown of a typical development process of a well component or equipment. The authors examined whether the industry standards provide guidance in all the steps of component design or not. As shown in the results (Table 2), no single family of standards provide complete guidance for elastomer seal selection, qualification of material, functional qualification of seal assembly, packaging, storage, etc. Some of the gaps can be filled by revisiting adjacent industry standards and consolidating them under one family of standards. Nonetheless, additional research is imperative to fill the major gaps particularly HPHT system qualification.

5. Evaluation of seal performance

To evaluate performance of seal, it is important to understand influence of elastomer material properties and assembly design.

5.1. Material properties

Material properties define deformation behavior of the seal under loading and consequently influence sealability. Typically, elastomer seal elements used in oil and gas applications are stiffer and can be assumed to exhibit linear elastic behavior (Bosma et al., 2000). This will require only elastic modulus and poison's ratio to define seal's behavior. Generally, for higher strains, elastomer demonstrates hyperelastic behavior. The loading and unloading curves for hyperelastic material are not same and depend on various factors such as time, frequency, dynamic loading, etc. Modelling such behavior requires use of hyperelastic material models such as Neo-Hookean, Mooney-Rivlin, Ogden, Yeoh, etc. To model hyperelastic behavior, physical tests measuring uniaxial, planer, biaxial stress behaviors, volumetric compression behavior, etc. are required.

There are variety of material tests available that can be used to evaluate the suitability of elastomer seal. Selection of properties varies depending on manufacturer, researcher, and type of application. The major material properties commonly tested are – cure characteristics, hardness, elongation at break, tensile strength, elastic modulus, torsion modulus, compression set, compression stress relaxation, rapid gas decompression, fluid compatibility, permeability, tear resistance, abrasion resistance, extrusion resistance, etc. (James Walker, 2017; and Apple Rubber Products Inc, 2009). Oil and gas literature contains several useful studies on elastomer material properties.

Hogan et al. (1997) employed five different methods to predict change in shear modulus of nitrile based elastomers over thirty years. For more accurate extrapolations, the authors recommended to use a low aging temperature for longer test durations compared to a high temperature for a short period. Edmond et al. (2001) compared decompression test protocols provided in various industry standards and demonstrated their strengths and weaknesses. The authors proposed that end users must incorporate field conditions in testing methodology to achieve reliable prediction of seal's performance. Groves et al. (2001) investigated two common methods used to predict life of elastomer seal components – accelerated testing of O-ring seals and compression set measurements at elevated temperatures. The authors identified limitations of both methods and concluded that long term seal performance predicted from both methods drastically differ and should be used carefully. Slay and Ferrell (2008) presented that traditional measurements such as hardness, tensile strength, tear strength, etc. are sufficient for quality check purposes but do not predict functional performance of seal. The authors advocated use of performance tests such as compression set, stress relaxation, low temperature sealability, high pressure extrusion, and rapid gas decompression as the metric to screen elastomer materials for field applications. Chen et al. (2016) investigated impact of glass transition temperature on performance of various HNBR and FKM elastomers. The authors also examined influence of stress relaxation at high pressure and low temperature on seal performance. The authors recommended that low temperature elastomers should possess RGD resistance and compression fracture resistance at high pressure high temperature to pass API's level 2 performance requirement test. Tu and Cheng (2016) reviewed existing RGD and aging test standards, and proposed use of fixture testing with actual seal cross-section used in field equipment. The authors recommended to use pressure loss or leakage rates as the acceptance

Table 2
Scope of guidance provided by various standard agencies to different steps in component design process (Elhard et al., 2017).

Process	Notes	API	ISO	NORSOK	NACE	ASTM	MIL-SPEC
System Design Guidance	Overall system/tool performance criteria	X	X				
Material Selection Guidance	Selection of most appropriate elastomer			X			X
Laboratory Material Qualification	Lab testing of material properties				X	X	X
HPHT Laboratory Qualification	HPHT laboratory testing of properties						
Chemical Compatibility Qualification	Lab chemical compatibility testing			X	X	X	X
Installed System Qualification	Performance testing of system/tool	X	X				
HPHT System Qualification	HPHT testing of system/tool						
Storage/Shipping Guidance	Packaging and storage considerations	X	X				X
Field Requalification	Evaluation of system components in field						X

criteria for RGD resistance rather than subjective crack ratings. Using case studies, Lehr and Furlan (2017) demonstrated the application of accelerated life testing (ALT) using Arrhenius principle and stress relaxation measurements to predict long term seal performance. The authors also discussed the application of these methods in development of a robust design for reliability (DfR) program for seal systems.

John (1997) investigated compatibility of five common oil field elastomers with different drilling fluids. The author graded the elastomer samples in terms of chemical resistance, quality of bonding to steel, fatigue resistance, and mechanical properties (tensile, tear, and abrasion). Slay and Ray (2003) investigated effect of completion brines on common elastomer materials. The authors concluded that tensile modulus and elongation at break are the most valuable measures of seal's performance as they are not affected by internal or external flaws in the seal. To predict long term performance, the authors advocated the use of exponential relationship like Arrhenius equation to relate changes in mechanical properties to temperature and time. Fernández and Castaño (2016) evaluated NBR aged in different crude, CO_2, and H_2S. The aging had varying impact on different mechanical properties. The study identified NBR to be unsuitable in H_2S environment. Unlike H_2S, which creates brittle fracture surfaces on NBR, CO_2 had softening effect with minor reductions in mechanical properties. Salehi et al. (2019) examined the effect of downhole corrosive environment (H_2S, CO_2, and CH_4) on four common oil field elastomers. Hardness, uniaxial compression, and volumetric swelling measurements before and after aging were presented. The results illustrated CO_2 to be the most damaging gas. FKM and PTFE exhibited higher resistance to the aging conditions compared to NBR and EPDM.

One popular alternative to traditional elastomer compounds is swellable elastomers. After exposure to downhole fluids and conditions, these specialty elastomer exhibits volumetric swelling and establishes contact with opposite surface. These elastomers have been mainly used for packer applications. Swellable packer eliminates the mechanical moving parts required for surface controlled in-situ energization of elastomer seal. While swelling of elastomer in presence of oil is known, recently, water and gas activated swellable elastomers have also been developed (Al-Yami et al., 2008). Various parameters that impact the performance of swelling elastomers are - temperature, pressure, soaking period, and downhole chemical environment such as water salinity, pH, oil composition, gas concentration, etc. (Al-Yami et al. 2008, 2010; Qamar et al., 2009; Pervez et al., 2009; Daou et al., 2014; Wang et al., 2015a). Qamar et al. (2009) compared mechanical properties of water swellable and non-swellable EPDM elastomer samples. The results indicated that unlike non-swelling EPDM, swelling elastomer exhibit linear stress-strain response. The swellable EPDM showed significant increase in thickness and volume with increasing test temperature and decreasing salt concentration. Results also showed that compression set and tensile set increase with increase in test temperature and duration. Al-Yami et al. (2008) demonstrated that presence of acid like HCl and change in fluid pH values can significantly inhibit swelling of elastomer samples. Wang et al. (2015a) presented that heavy brines such as $CaCl_2$ and $CaBr_2$ can inhibit performance of water swelling elastomers.

Researchers have also been experimenting with new elastomers formulated with nanoparticles or nanocomposites to improve material performance (Welch et al., 2012; Wang et al., 2015a; Dolog et al., 2017; Fakoya et al., 2018). Welch et al. (2012) proposed use of nano thin film to commercial rubbers to improve fluid computability, and resistance to swelling. Wang et al. (2015a) recommended the use of nanocomposite microgels in the base polymer of elastomer for improving resistance to heavy brine environment. Dolog et al. (2017) demonstrated application of carbon nanotubes to improve the mechanical properties of HNBR elastomer. Denison et al. (2018) presented application of urethanes in development of wear resistant nitrile elastomers.

Majority of the studies have been focused on laboratory evaluation of elastomer material properties. Only few studies are available in the oil and gas literature that investigate influence of material properties on assembly level performance of seal quantified in terms of contact stress generated at the sealing interface. Hu et al. (2017) studied the effect of elastomer material property on sealing performance of compression packer. The study tested three HNBR elastomers with different carbon black content in chemical formulation. The authors measured uniaxial tension and compression data, and performed a 3-D finite element analysis with non-linear material property models. It was observed that sealing performance increases almost linearly with increase in setting pressure (Fig. 12). No experimental or analytical validation was provided for contact stress. The authors ranked the three elastomer materials in terms of intensity of structural stresses in supporting components and risk of shoulder extrusion.

Wang et al. (2017) investigated extrusion, sliding, and rupture type failure modes of elastomer seals for packer application. The authors fabricated various seals in transparent chambers, and observed the seal for leak and failure. The work presented an analytical model that can predict the pressure-extrusion curves as a function of material parameters (elastic modulus, sliding stress, and fracture energy) and geometric parameters (thickness, length, and pre-compression).

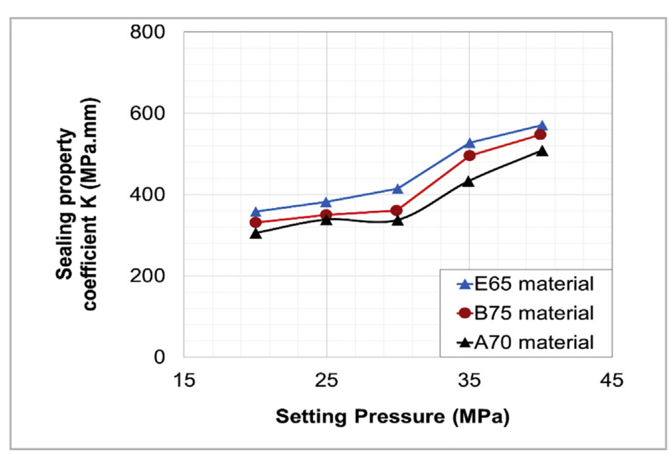


Fig. 12. Sealing performance of elastomer packer element as a function of setting pressure (Hu et al., 2017).

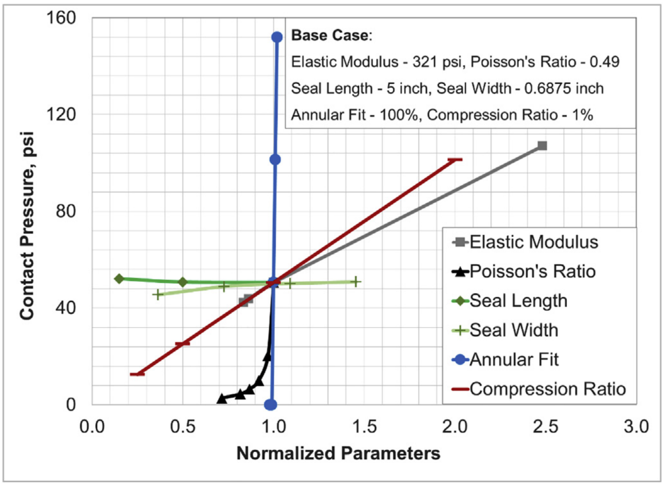


Fig. 13. Sensitivity of contact pressure to various parameters (Recreated after Patel et al., 2019).

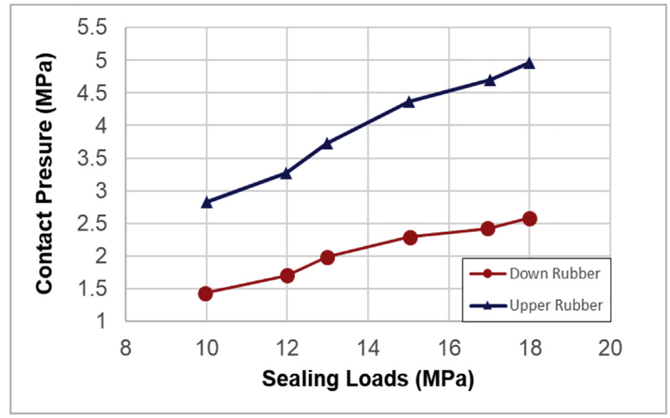


Fig. 14. Contact pressure as a function of setting load (Recreated after Feng et al., 2010).

Experimentally obtained pressure extrusion curves matched well with the model's theoretical predictions (Wang et al., 2017; Liu et al., 2014). Elhard et al. (2017) conducted experimental and FEA study to investigate extrusion of commonly used oil and gas elastomer material. The authors examined extrusion in O-ring samples as a function of differential pressure. For HPHT conditions, crack tear propagation via extrusion-initiated spiral failure was observed to be the dominant failure mechanism. The performance of seal material was observed to depend on critical tear pressure as a function of temperature. The authors emphasized use of FEA to expand testing beyond the O-rings to assembly level seal design. Patel et al. (2019) studied effect of various design parameters on performance of elastomer seal in conventional liner hanger assembly. The authors used analytically validated 3D FEA models to perform parametric analysis. The study indicated significant impact of Poisson's ratio and elastic modulus of seal on contact stress (Fig. 13). The results emphasized the importance of using accurate values of material properties in seal design to avoid significant overestimation or under-estimation of seal's performance. Patel and Salehi (2019) developed three dimensional finite element models of conventional and expandable type liner hanger seal assemblies. In one of the simulation cases, the authors compared contact stress predictions based on linear elastic and hyper-elastic material representation of FKM elastomer. Analytically validated simulation results indicated that the selection of material model does not impact the shape of contact stress profile generated at the seal-pipe interface. For the same amount of volumetric compression, hyper-elastic FKM yielded notably higher contact stress values than linear-elastic representation of FKM. This observation was attributed to the fact that hyper-elastic material model of FKM is able to capture material stiffening at higher strains.

5.2. Seal and assembly design

Various functional aspects of seal assembly such as energization method, seal dimensions, housing dimensions, supporting components, contact characteristics, etc. can also influence the performance of elastomer seal. Majority of the research activity has been focused on elastomer material properties as discussed in the previous section. Comparatively, limited research has been conducted to assess functional aspects of elastomer seal assembly.

Majority of the seals used in an oil and gas well are not self-energized or pressure-energized. As discussed in section 2, seals used in equipment like packers and hanger assemblies are energized post-installation using mechanically or hydraulically transmitted force. Process of seal energization vary depending on manufacturer and type of equipment. The energization process can greatly influence resultant contact stress profile and quality of seal (Patel and Salehi, 2019; Patel et al., 2018; Zhong et al., 2015; Ma et al., 2014a; Feng et al., 2010).

Feng et al. (2010) conducted two-dimensional finite element analysis on packer consisting of two elastomer elements separated by a metal ring. The study examined the contact pressure in both seals for various setting loads and observed a relationship that was practically linear (Fig. 14). The seal on the compression side (top side in this case) had consistently higher contact pressure than the bottom seal. The difference can be attributed to friction between seal and inner pipe surface. Ma et al. (2014a) examined swellable elastomer packer element using two-dimensional finite element model with non-linear elastomer material properties. Elastomer swelling was modelled by means of interference between seal thickness and the annular space between casing and formation. Under the differential pressure of 20 MPa across the packer, the authors studied the contact pressure for different amount of energization i.e. interference thickness. Contact pressure was observed to peak at the middle of the contact length, reduce towards the ends, and then gradual increase at the extreme ends. Zhong et al. (2015) used FEA to investigate performance of large bore expandable liner hanger. The authors simulated seal energization process and presented typical profile of expansions force, cone pull out force, and contact pressure along the hanger assembly. Simulation demonstrated impact of deformation of elastomer containment spikes on contact stress profile. In their simulations, the upstream side spike deformed more than the downstream spike and failed to provide good elastomer containment. The spike at downstream side maintained the contact with casing, prevented elastomer flow, and provided higher contact stress compared to the upstream side. Patel et al. (2019) simulated seal energization in conventional liner hanger assembly using 3D finite element models. The authors simulated contact stress as a function of seal compressions for different commonly used oil field elastomers. Analytically validated results indicated practically linear relationship between contact stress and amount of compression. The results can be used to quantify the loss in seal performance caused by insufficient mechanical load for seal energization. The authors also developed an empirical correlation from simulation data to predict contact stress as a function of various design parameters. Patel and Salehi (2019) used analytically validated 3D FEA models to perform comprehensive comparison of conventional and expandable type seal energization techniques. Simulation results illustrated that in case of conventional type axial energization, contact stress remains uniform along the contact length. In expandable type radial energization, contact stress peaks at the center of the seal length and declines towards either sides of the axial ends (Fig. 15). In expandable assembly, if spikes are used on either side of the seal to contain the elastomer during compression, then the contact stress values increase. The contact stress profile becomes progressively flatter with increase in containment

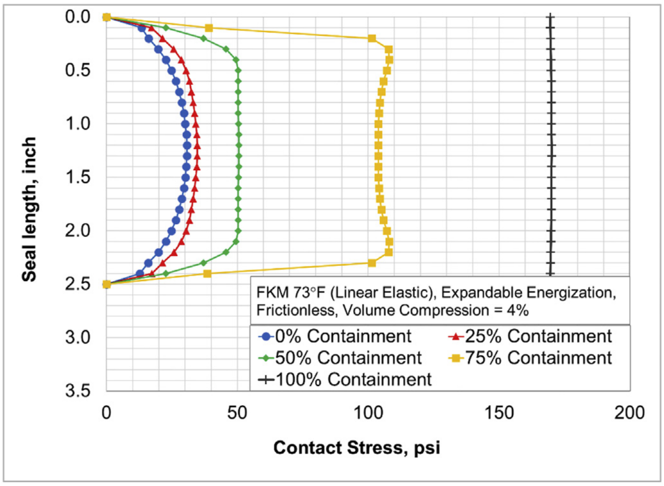


Fig. 15. Contact stress profile along axial length of elastomer element in expandable liner hanger (Recreated after Patel and Salehi, 2019).

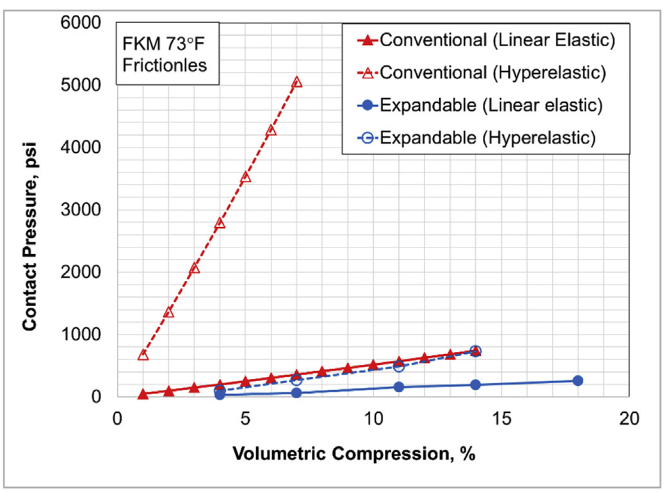


Fig. 16. Contact pressure as a function of volumetric compression of elastomer seal in conventional and expandable liner hanger seal assemblies (Recreated after Patel and Salehi, 2019).

(Fig. 15). The profile becomes similar to conventional seal assembly at 100% containment. In both assemblies, contact pressure was linearly dependent on amount of volumetric compression achieved during compression (Fig. 16).

Seal and housing dimensions are other important parameters that influence seal performance. Dimensions determine the amount of volume fill-in required by seal compression to establish contact and achieve desired contact stress. Effect of seal dimensions on contact stress profile generated sealing itnerface has been studied by few researchers (Patel et al., 2019; Al-Hiddabi et al., 2015; Akhtar et al., 2013; Al-Kharusi et al., 2011; Guo et al., 2011; Alzebdeh et al., 2010).

Alzebdeh et al. (2010) conducted finite element simulation of the elastomeric seals in open hole expandable type liner hanger. The effect of seal length, seal thickness, compression ratio, and shear resistance at seal-formation interface, on the contact pressure were examined. The study indicated that a thicker seal with a larger compression ratio yields higher contact stress (Fig. 17). Furthermore, for higher seal energization (> 50% compression ratio), contact pressure decreased with increase in seal length up to 200 mm beyond which it remained practically constant. For low compression ratios, contact stress was observed to be independent of seal length. The effect of tubular end conditions was also determined to be negligible. Guo et al. (2011) used FEA to study a specific design of packer consisting of rubber tube, cone, central pipe, expansion sleeve, and casing pipe. The authors presented contact pressure variation as a function of applied load at different seal thickness. The results do not indicate significant impact of seal thickness. Al-Kharusi et al. (2011) and Al-Hiddabi et al. (2015) conducted theoretical analysis of elastomer seals in expandable tubular. The authors developed an analytical model for predicting contact stress assuming linear elastic material property. The model is based on elastomer seal that is radially confined between metal tubes with fluid pressures in axial direction. This model can predict contact pressure along the contact length as a function of seal compression ratio, fluid pressures, and material properties. Besides developing the model, Al-Hiddabi et al. (2015) also performed parametric analysis using the model and investigated the effect of seal thickness, seal length, and compression ratio on contact pressure (Fig. 18). The results indicated that seal radial thickness has no effect on contact stress for longer seal (Fig. 18a). For shorter seal, at constant compression ratio, contact stress decreased with increase in seal thickness. Maximum contact stress was observed to increase with increase in seal length up to 50 cm beyond which it plateaus (Fig. 18b). Akhtar et al. (2013) used FEA model of swelling elastomer to investigate effect of seal dimensions on contact stress. Simulation results indicated that contact stress increases with increase in seal length and seal thickness. Ma et al. (2014a) conducted 2D FEA of swellable elastomer packer element. Under a constant differential pressure across the packer, the authors investigated contact pressure at different seal length and thickness. The contact stress increased exponentially with the increase in length and thickness of rubber. Patel et al. (2019) used 3D FEA model of conventional hanger seal assembly to investigate influence of various parameters on the seal's performance. Results from sensitivity analysis indicate that seal's axial length and radial width do not have notable impact on contact pressure (Fig. 13). However, radial thickness of seal relative to available annulus space had the most significant impact. The authors concluded that if the radial gap between seal and opposite casing surface is x% larger than anticipated, then it will reduce effective compression by x% and vice versa.

Operational loads such as wellbore pressure and thermal stresses can also influence the seal's performance. These mechanical loads can cause relative movements or deformations of components in seal housing; resulting in change in contact stress. Operational loads can also cause structural failure in supporting components of seal assembly such as compression plates, cones, slips, etc. and consequently affect seal performance. Very limited studies have been conducted to assess functional failures and resultant change in sealability (Patel et al., 2019; Patel and Salehi, 2019; Wang et al., 2015b; Lin, 2013; Berger, 2004).

Berger (2004) tested various backup systems that provide support during seal energization in a retrievable 7 ¾-in. packer equipment. Different systems such as the carbon steel foldback ring, mesh rings, and garter springs were evaluated at different temperatures and differential pressures. Based on test results, the author recommended foldback ring design with anti-extrusion rings as a promising backup mechanism. Lin (2013) conducted FEA structural analysis of slip element in packers. Simulation results indicated almost linear relationship between maximum stress in slip component and applied setting loads. The work examined stresses in slip components at different teeth spacing. Among the range of spacing investigated, slip tooth spacing of 30 mm was observed to bear wider range of loads. The FEA model was validated by physical test. Wang et al. (2015b) performed structural FEA of inner tube and setting sleeve of a packer equipment to identify zones of high stress concentration for design optimization. Validation of simulation results was not provided. Li et al. (2015) performed two dimensional FEA on rubber sealing ring for rotary liner hanger bearing. The authors studied maximum contact stress as a function of setting pressure at different temperature. Payne et al. (2016) conducted three dimensional FEA and physical tests on liner hanger body without seal assembly. It was demonstrated that liner hanger capacity is sensitive to geometrical features and imperfections such as slots, grooves, ovality,

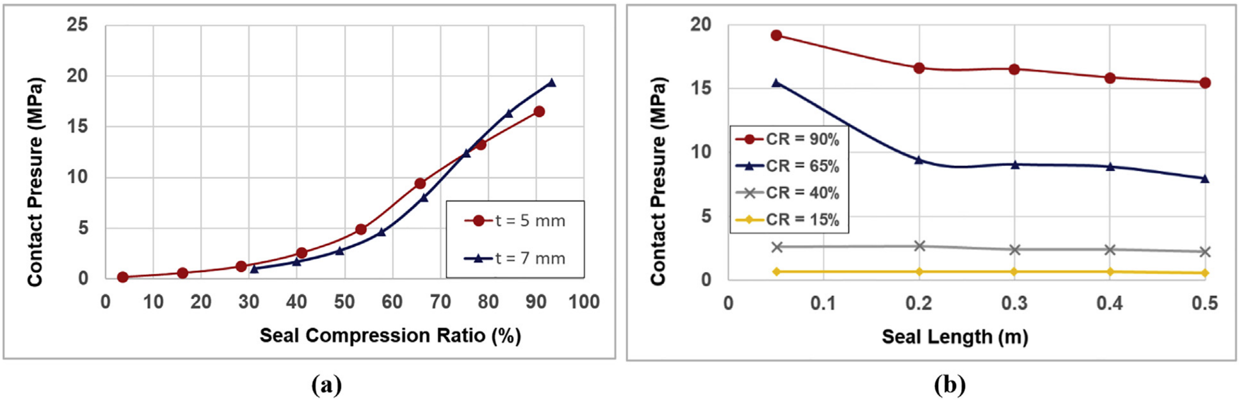


Fig. 17. Effect of seal thickness (a) and seal length (b) on contact pressure at various compression ratio (Recreated after Alzebdeh et al., 2010).

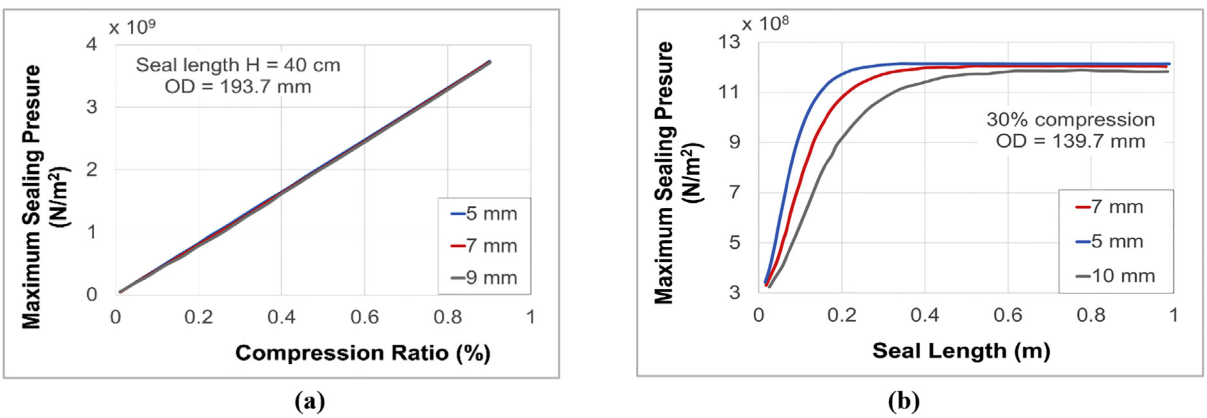


Fig. 18. Maximum contact pressure in expandable tubular as a function of compression ratio (a) and seal length (b) for varying seal thickness (Recreated after Al-Hiddabi et al., 2015).

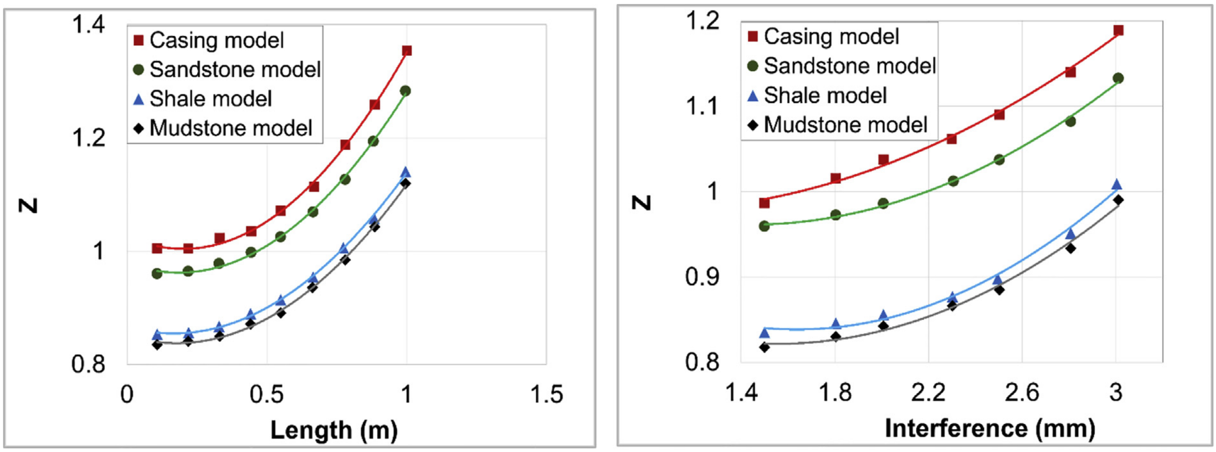
and end effects. The authors highlighted inadequacy of traditional calculations such as two diameter rule, Barlow equation, Lame equation, API burst equation etc. for determining capacity of liner hanger body. Patel and Salehi (2019), based on 3D FEA models of conventional and expandable type linear hanger, concluded that expandable energization is more robust to failure in supporting components than the conventional assembly. Even if both elastomer containment spikes completely fail, the expandable seal assembly would still maintain contact pressure.

Certain seal containing equipment such as open-hole packer provides sealing against subsurface formation. For such equipment, formation type, and geo-mechanical stresses can have notable impact on seal performance. Very limited literature is available on influence of geomechanical parameters on seal performance (Alzebdeh et al., 2010; Akhtar et al., 2013; Ma et al., 2014a).

Alzebdeh et al. (2010) conducted finite element simulation of the elastomeric seals in an open hole expandable type liner hanger. The authors modelled the formation in three different forms - a rigid body, an elastic body, and an elastic-plastic body. It was observed that the rigid formation provides the highest contact pressure among all three formation types investigated. Akhtar et al. (2013) used FEA model of swelling elastomer to compare contact stress values generated against steel pipe and formation. The results indicated higher contact stress values against formation compared to steel tubular. Ma et al. (2014a) examined contact pressure in swellable elastomer packer against different formation types. As shown in Fig. 19, contact pressure obtained against shale and mudstone were less than the operating differential pressure. Using curve-fitting, the authors developed empirical correlation for evaluating contact pressure as a function of seal dimension for different formations. Extrapolating the empirical correlation, authors presented optimum seal dimensions required to seal against each of the formations investigated.

Characteristics of contacting surface such as roughness, presence of lubrication, presence of solid debris etc. are expected to impact sealability. Out of these parameters, impact of only friction coefficient is known to some extent (Patel and Salehi, 2019; Ma et al., 2014b; Guo et al., 2011).

Feng et al. (2010) presented 2D FEA of packer assembly consisting of two axially separated elastomer elements. Simulation results indicate that upper elastomer element always yield higher contact pressure than the bottom elastomer element (Fig. 14). This is because of frictional stresses acting in the same direction as axial compressive force used for seal energization. Ma et al. (2014b) conducted 2D finite element analysis of swellable packer equipment with two elastomer seal element. The authors investigated effect of different friction coefficient and concluded that contact pressure difference between upper and lower seal element of packer equipment can be manipulated by adjusting friction coefficient. Patel and Salehi (2019) studied effect of friction on conventional and expandable type seal energizations. In presence of friction, contact stress profile shape in the expandable type energization remained the same as frictionless condition wherein it peaks at the middle of the contact length and declines towards the end. The contact stress values increased with increase in friction coefficient. In conventional energization, frictional contact stress rapidly peaks near the compression side and declines towards the opposite end (Fig. 20). This significant deviation can be detrimental as low contact pressure at the support end can increase chance of fluid penetration.



(a) (b)

Fig. 19. Sealing safety factor (contact pressure divided by operating fluid pressure) as a function of seal length (a) and interference (b) (Recreated after Ma et al., 2014a).

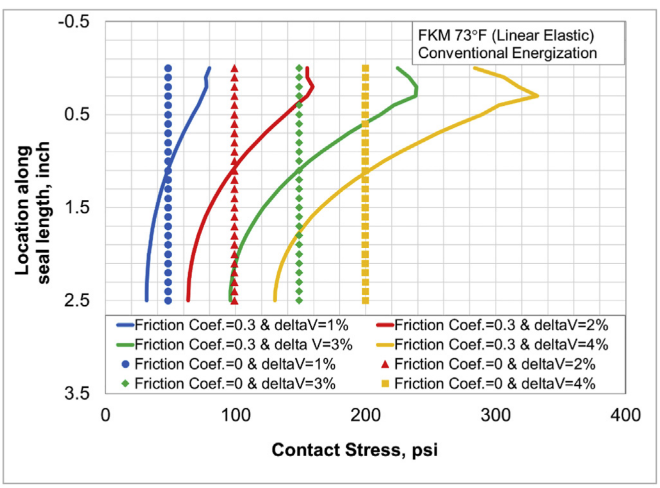


Fig. 20. Effect of friction on contact stress profile in conventional seal assembly (Recreated after Patel and Salehi, 2019).

6. Research gaps and way forward

The industry has been exploring alternatives such as metal-to-metal (M2M) seals (Garfield and Mackenzie, 2007; Dagle et al., 2016; Stautzenberger et al., 2016), particularly for applications in harsh chemical environment, and extreme temperature and pressure conditions. Metal seals offer several benefits such as greater temperature, pressure, and chemical resistance, robust mechanical properties, lack of porosity, and longer shelf life (Krishna and Lefrancois, 2016). However, lack of ductility and elasticity is a major concern with metal seals. To alleviate this concern, researchers are exploring innovative seal designs such as spring energized metal O-rings and lattice seal with thermoplastic matrix and metallic structure (Lamb, 2014; Krishna and Lefrancois, 2016; Yu et al., 2017). However, these newer seal designs are still in research and development stage. Additional challenges with the metal seals are higher costs, and limited selection of material grades.

Moreover, unlike elastomer seals, performance of metallic seal is significantly influenced by surface characteristics of the metal component (Patel et al., 2018). To predict the influence of surface roughness on sealability, Patel et al. (2018) proposed a modelling approach that can be used to model metal-to-metal seal at microscopic level. The model is able to predict contact stress and corresponding leakage rates considering surface characteristics of the metal seal. The authors concluded that leakage rates through M2M seal is primarily a function of surface finishing typically represented in terms of root mean square (RMS) value. The study also concluded that, for the same RMS, seal with randomly rough surface (e.g. manufactured by casting) would require higher contact stress to achieve zero leakage rate than a seal with more uniform distribution of surface asperities (e.g. machined component). Further research is necessary in this area to establish the true leakage criteria for metallic seals. In addition to surface characteristics, dynamic sealing and low effectiveness in presence of debris are other concerns for metallic seals (Krishna and Lefrancois, 2016; Zhong, 2016).

Overall, because of the various challenges discussed above, applications of metal seals are currently limited compared to elastomer seals. Elastomer is still the widely used and preferred seal material primarily because of less cost, resilience, ability to seal against irregular and dynamic surfaces (Tu and Cheng, 2016). With the increasing global energy demand and declining conventional resources, High-Pressure High-Temperature (HPHT) wells (> 350 °F and > 15,000 psi) are becoming increasingly common. An industry survey (Oil and Gas iQ, 2015) indicated that seals are one of the biggest technological challenges associated with HPHT oil & gas exploration (Fig. 21).

Until a more effective and commercially viable alternative is available, it is imperative to improve elastomer materials, seal design, and qualification process. Major knowledge gaps requiring extensive research are as follows:

- There is a lack of comprehensive database of elastomer material

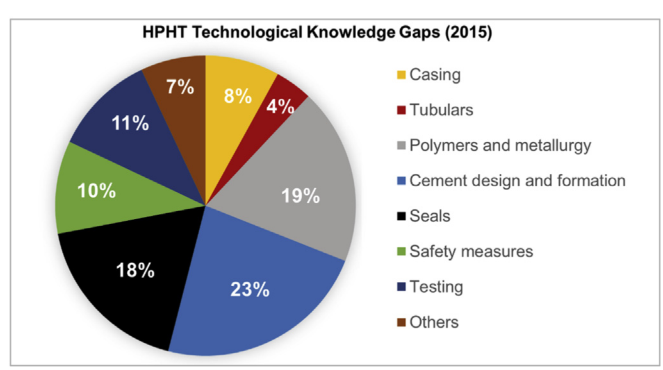


Fig. 21. HPHT technological knowledge gaps (Recreated using data from Oil and Gas iQ, 2015).

properties at HPHT conditions. Since, it is not practically possible to measure all available mechanical properties of elastomer, there is a need to identify critical material properties that are representative of elastomer behavior and must be tested. Development of sophisticated material models is another useful area of research.

- There is no reliable technique to upscale the results obtained with standard elastomer samples and laboratory scale apparatus to larger and complex seal geometries used in field scale equipment.
- Another important research gap is lack of reliable extrapolation technique that can use data from short term aging tests to predict elastomer performance over long term service life spanning several years. There is also a need to identify appropriate test conditions for accelerated laboratory tests that are representative of downhole service conditions.
- Research efforts in the direction of computational modelling tools can minimize the need for expensive and time intensive physical tests, and consequently, shorten research and development time.
- Functional design of elastomer seal assemblies is an important area for further research. Specifically, some of the important questions that need to be answered are - which anti-extrusion mechanism is more resistant to failure? What are the strengths and limitations of various seal energization methods? How does pre-energization shape of seal impact seal energization? How influential is the dimensional tolerance or relative movements of components?
- Majority of the seal assemblies are installed first and then energized in-situ using mechanical or hydraulic forces controlled from the surfaces. In certain conditions such as deviated wells, improper centralization of completion string, pipe buckling, etc., it may not be possible to exert sufficient force necessary to energize the seal. It would be useful to know the expected loss in sealability under such poor quality seal energization conditions.
- Significant research efforts are needed to understand the effects and consequences of functional failure modes of seal assemblies. Examples of such failures include – structural failure in support components like anti-extrusion ring, packer slips, elastomer containment spikes, etc., wear or tear of elastomer element, fluid leakage through the seal, etc.
- Effects of pressure, temperature, chemical exposure, and gas penetration need to be investigated in terms of the influence on assembly level functional performance. For example, effect of high temperature should be discussed not only in terms of variation in material properties but also in terms of anticipated change in contact stress against pipe or formation.
- Additional influential parameters that require further research are - dynamic wellbore loads, thermal stresses, contact characteristics (e.g. presence of debris, fluid film, friction, etc.), and geo-mechanical factors (e.g. formation properties, in-situ stresses, etc.).
- Establishing contact of elastomer seal with opposite surface may not be sufficient to ensure sealability. It would be useful to know range of target contact stress values required to seal in different applications, and operational conditions.

7. Conclusions

This paper presents a comprehensive review of elastomer seal assemblies, their failure modes, and performance evaluation. The ultimate objective of the review was to discover gaps in industry standards and present major areas of research for improving seal reliability. Following are the major conclusions from this review work:

- Review of past loss of well control events indicate that almost half (46%) of the failures in secondary barrier originated in seal equipment. Unlike material failure modes, very limited research has been conducted to investigate functional failures of seal equipment and their impacts.
- Besides material properties of elastomer, performance of a seal assembly is highly dependent on seal geometry, energization process, design of housing and supporting components, operational loads, contact characteristics, and in some cases, geo-mechanical factors.
- Industry standards primarily focus on laboratory-scale material tests performed using standardized samples of seals. There is a lack of guidance and requirements on equipment level design of elastomer seals. The criteria and methods used to qualify seal material, should be customized according to the function, design, and scale of equipment.
- To improve reliability of elastomer seals, research efforts need to be extended beyond material testing to design aspects of seal equipment. There is also an imperative need for reliable techniques that can be used to upscale and extrapolate results from short-term laboratory-scale tests to field-scale applications spanning several years of service life. The industry can also benefit from a comprehensive database of elastomer material properties at HPHT conditions.

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Nomenclature

ALT	Accelerated Life Testing
API	American Petroleum Institute
ASTM	American Society of Testing and Materials
BOP	Blowout Preventer
BSEE	Bureau of Safety and Environmental Enforcement
DfR	Design for Reliability
EPDM	Ethylene Propylene Diene Monomer
FEA	Finite Element Analysis
FEPM	Tetrafluoroethylene Propylene
FFKM	Perfluorocarbon Elastomer
FEA	Finite Element Analysis
FKM	Fluorocarbon Elastomer
HPHT	High Pressure High Temperature
HNBR	Hydrogenated Nitrile Butadiene Rubber
ID	Internal Diameter
ISO	The International Organization for Standardization petroleum industry
LOWC	Loss of Well Control
M2M	Metal-to-Metal
MIL-SPEC	Military Specifications
NACE	National Association of Corrosion Engineers
NBR	Nitrile Butadiene Rubber
NORSOK	Norsk Sokkels Konkuranseposisjon (Standards by Norwegian Petroleum Industry)
PTFE	Polytetrafluoroethylen
RGD	Rapid Gas Decompression
RMS	Root Mean Square
SEM	Scanning Electron Microscope
SSSV	Subsurface Safety Valve

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