Review Article

Investigation of Elastomeric Seal Systems in Oil and Gas Well Applications

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Abstract

The article provides a detailed review of literature, research findings, and industrial standards related to elastomer seal assemblies used in oil and gas wells. Elastomer-based seals are essential for maintaining well integrity. Advances in rubber chemistry and sealing technologies were critical in controlling pressure and fluid flow long before the 1901 Spindletop oil eruption in Texas. These materials remain indispensable today, as the cost of constructing a single well can exceed one billion dollars. Almost all modern drilling and completion systems rely on elastomers and other sealing materials to ensure reliable operation throughout their service life. Research shows that seal malfunctions can cause blowouts or oil leaks, creating serious health, safety, and environmental risks. Because of these risks, regulators and industry experts stress the need for improved seal design and qualification, especially for high-pressure, high-temperature (HPHT) applications. This paper evaluates key studies and standards on elastomer sealing systems. It examines the main factors that influence seal performance and the major causes of failure. The review's primary aim is to identify gaps in current standards and propose priority areas for future research to improve seal reliability. The analytical results show how elastomer geometry and material properties influence maximum sealing pressure. The study also analyzes different strain conditions to assess sealing efficiency. Current industry standards focus mainly on material-level testing and offer limited guidance for seal design within complete equipment assemblies. Existing qualification procedures are not well adapted to different seal shapes, sizes, or applications. More comprehensive research is needed on seal assembly design, including energization mechanisms, housing and support structures, and potential functional failures—going beyond basic material evaluation. Furthermore, there is a pressing need for robust methodologies capable of translating laboratory-scale findings into field-level applications that ensure long-term operational reliability.

Keywords: elastomer seal, seal assessment, industry standards, well barriers, well integrity, seal failure

1. Introduction

To ensure effective well control, seal assemblies located in wellheads or liners act as critical barrier elements [1, 2]. These seals typically serve as secondary barriers that prevent formation fluids from entering the wellbore. The primary barrier is the annular cement sheath. Together, the cement sheath and the seal assembly form a dual-barrier system. However, during well construction, it is not possible to pressure-test these two barriers independently. Instead, they must be evaluated as a single integrated system. As a result, a successful pressure test only confirms that at least one barrier is functioning, without identifying which one.

The cement sheath is generally considered less reliable as a standalone barrier because of factors such as inherent permeability, potential gas migration, poor bonding, and the formation of microannuli [3]. In some cases, the seal assembly may compensate for deficiencies in the cement sheath during pressure testing. In such situations, the seal assembly effectively becomes the only dependable pressure-holding element. This outcome highlights the need for seal assemblies with high long-term reliability to ensure overall well integrity.

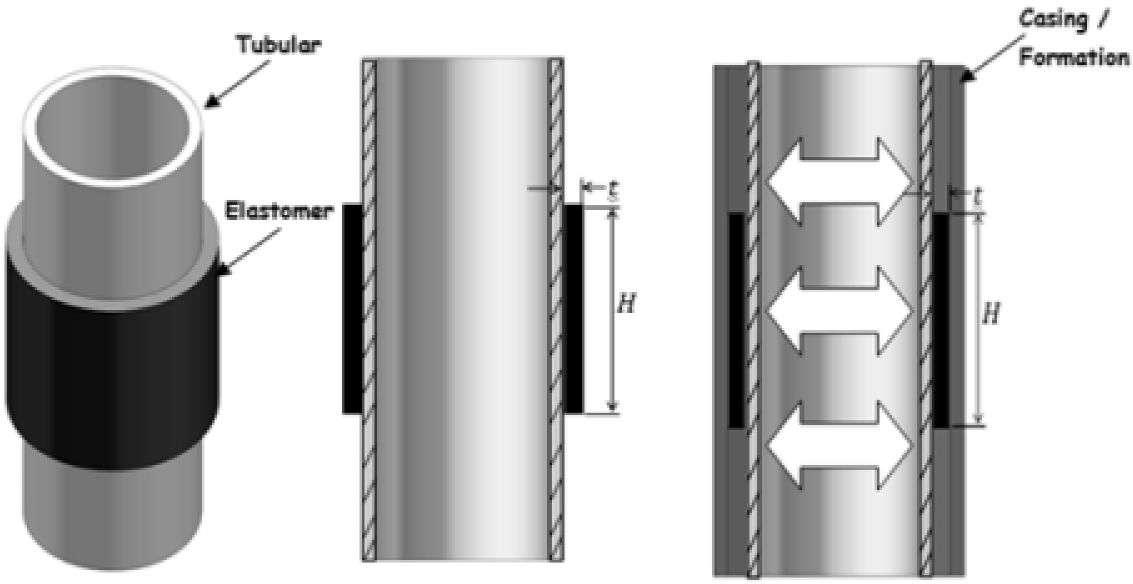


Figure 1. Schematic of a typical swellable packer.

It has been observed that failures in seal assemblies are often a key factor behind well-control incidents that can result in serious consequences for human health, safety, and the environment. An informal evaluation conducted among several operators in the Gulf of Mexico revealed that the failure rate of pressure seals in liner overlaps ranges between 30% and 50%. Another study highlighted growing concerns regarding the reliability of critical liner-hanger seals, particularly in high-pressure, high-temperature (HPHT) completions. Globally, it is estimated that approximately 18% of offshore wells exhibit some degree of uncertainty or weakness related to their seal assemblies [4].

The Bureau of Safety and Environmental Enforcement (BSEE), the primary regulatory authority, has also raised concerns about the reliability of elastomer-based seal assemblies. Through a technical evaluation, the agency emphasized the need for additional research focusing on the design, performance reliability, and service-life assessment of these sealing systems, especially those used in liner-hanger applications.

2. Objective

Elastomer seals are increasingly utilized across multiple sectors, including the oil and gas industry. This review aims to achieve four main objectives [5]: (1) to identify and analyze potential failure mechanisms in elastomer seal assemblies; (2) to review relevant experimental, theoretical, and computational studies; (3) to examine various parameters influencing the performance of sealing systems; and (4) to conduct a gap analysis of current industry standards and practices. Furthermore, the study seeks to pinpoint critical knowledge gaps to guide future research aimed at improving the design and dependability of elastomer seals.

This review serves as a valuable reference for regulators, researchers, engineers, and industry professionals. By understanding possible failure mechanisms, engineers and product developers can design more robust and reliable seal assemblies. A comprehensive analysis of existing literature and identified research gaps will help steer future investigations. Additionally, performing a gap analysis of current standards enables both industry and regulatory bodies to strengthen guidelines, certification procedures, and policies concerning the qualification and use of elastomer seal assemblies.

3. Seal Assemblies

The likelihood of equipment containing elastomer seals being present during different well operations can be evaluated. Studies have shown that, compared to packers and subsurface safety valves (SSSVs), wellhead and blowout preventer (BOP) systems are significantly more likely to be involved when a blowout occurs. In fact, wellhead components such as casing or liner hangers are always part of the well infrastructure, regardless of the well type.

In many cases, operators prefer to deploy a liner string rather than running a full casing string back to the wellhead [6]. The liner is typically suspended from the preceding casing and cemented in place. Similar to casing hangers, liner hangers also contain seal assemblies. These hanger seals are generally installed on the exterior of each casing or liner string to isolate the annular spaces.

A conventional liner hanger assembly typically consists of three main components: a cone or compression plate, an elastomer sealing element, and slips (as shown in Fig. 2a and Fig. 2b). Depending on the design, the seal assembly may either be incorporated into the liner running tool (Fig. 2b) or installed separately, which requires an additional trip into the well (Fig. 2a). The seal assembly is activated by applying either hydraulic or mechanical axial force that sets the slips against the corresponding surface. When axial load is further increased while the lower compression plate is held in position by the slips, the elastomer element becomes compressed, thereby creating the necessary seal.

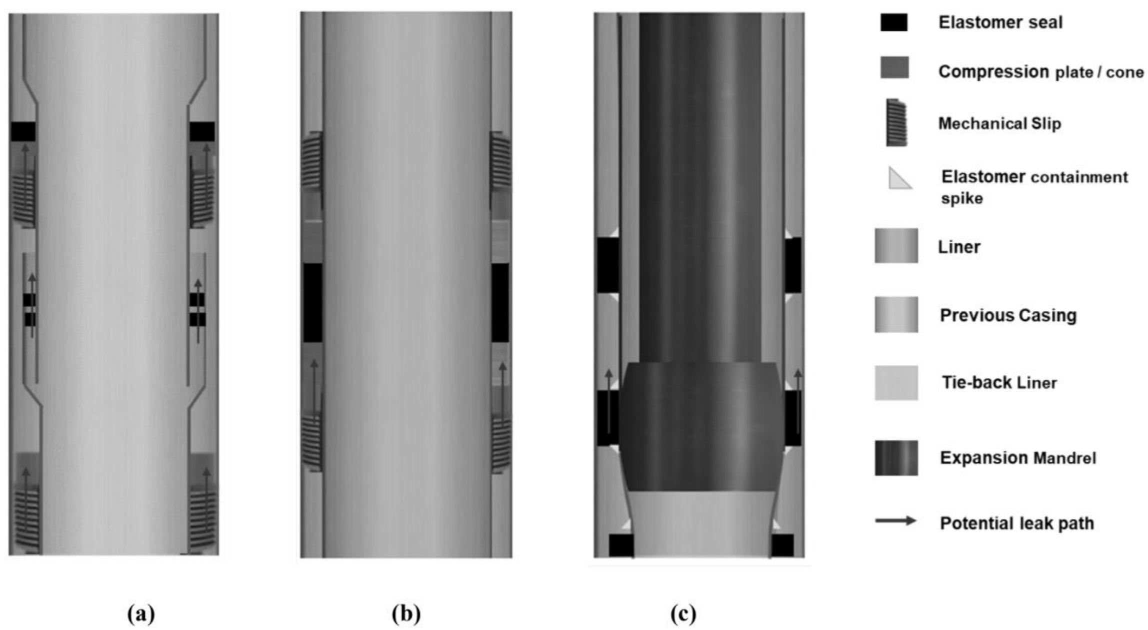


Figure 2. Differences among (a) liner top packer assembly, (b) integral liner hanger seal, (c) expandable liner hanger seal assembly.

An expanded liner hanger represents a relatively recent technological development. It comprises an elastomeric element mounted on the outer surface of a smooth liner body that contains no movable components (Fig. 2c). The operating principle involves running a solid mandrel with an outer diameter larger than the inner diameter of the liner hanger, thereby expanding the liner either mechanically or hydraulically. As the liner body enlarges, the elastomer elements are compressed against the casing wall, activating and energizing the sealing mechanism. These seals not only provide hydraulic isolation but also function as structural anchors for the liner.

At the wellhead, a slip-and-seal type casing-hanger assembly is commonly used [7]. The activation method of a conventional liner hanger seal assembly closely resembles that of the slip-and-seal assembly (Fig. 3). During activation, axial force is transmitted to the elastomer component, causing it to deform radially and create a pressure-tight seal that isolates the annular pressure beneath the hanger from the wellbore.

In offshore jack-up drilling operations with mudline completions, a mechanically set seal assembly is often utilized. In this system, cap screws are manually tightened against the compression plate using a wrench, which in turn compresses the elastomer element and establishes the seal.

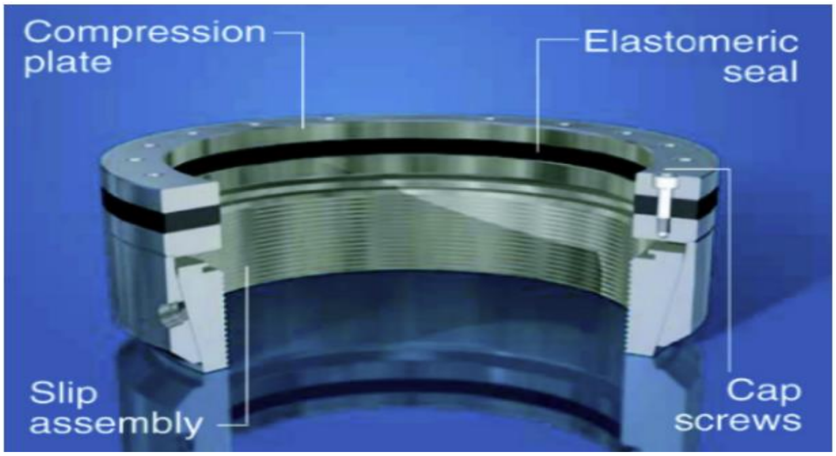
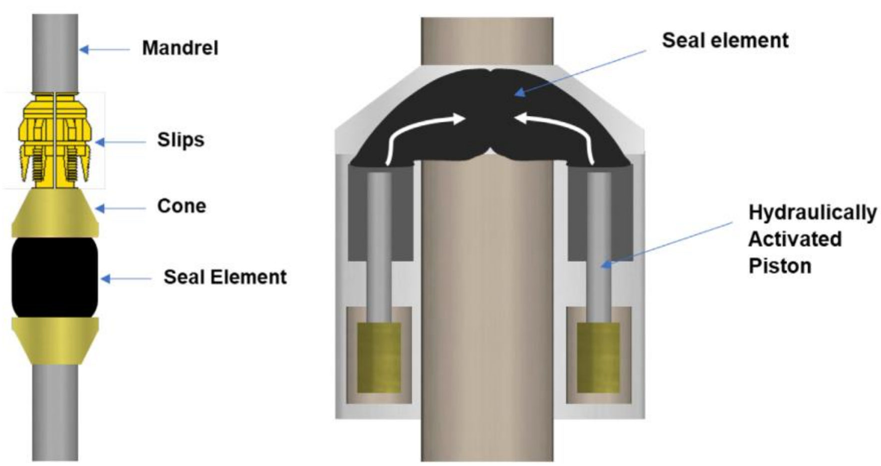


Figure 3. Mechanical set of slip and seal assembly.

Packer equipment is commonly employed to isolate annular spaces between the production tubing and casing or to separate different production zones within a well. Similar to casing and liner hanger systems, packers utilize a cone and slip mechanism to apply either mechanical or hydraulic compression to the elastomer element, thereby activating the seal (Fig. 4a) [8].

Recent advancements in technology have introduced packer systems that use elastomer materials capable of swelling when exposed to oil-based fluids. Upon contact, the elastomer expands radially, allowing the sealing element to press firmly against the opposing surface and establish isolation.

In situations involving loss of well control, such as formation kicks or blowouts, the blowout preventer (BOP) serves as a vital component of wellhead safety equipment. Acting as a secondary barrier or fail-safe mechanism, the BOP typically contains a solid, donut-shaped elastomer element (Fig. 4b). When hydraulic pressure is applied during a potential kick event, the elastomeric donut deforms tightly around the drill pipe, effectively sealing the wellbore. The elastomer remains in sustained contact with the pressure exerted by the formation fluids, maintaining well control and preventing uncontrolled flow.



(a) (b)

Figure 4. Elastomer seal components (black color) in (a) packer, (b) blowout preventor after closure.

4. Failure in Seal Assembly

Seal assembly failures often lead to expensive repair operations, increasing the overall cost of well construction and maintenance while also disrupting company activities. If such failures go undetected for an extended period, they can critically compromise well integrity and potentially cause a loss of well control, posing severe risks to human health, safety, and the environment.

The SINTEF organization maintains a comprehensive historical database documenting incidents of well blowouts and loss of well control (LOWC). According to SINTEF records, most blowouts occur during drilling operations, followed by incidents during workover, completion, and production stages. Several studies have performed statistical analyses of SINTEF's data to estimate how frequently seal-related factors contribute to these incidents.

Figure 5 illustrates the distribution of causes for all LOWC events recorded between 1980-1994 and 2000-2015. The sections of the pie charts shown in black and gray represent incidents associated with failures of subsurface safety valves, leaks in wellhead components, Christmas tree assemblies, or blowout preventers (BOPs) following seal malfunction. The data clearly indicate that approximately 46% of all secondary barrier failures are attributable to equipment containing elastomeric seals.

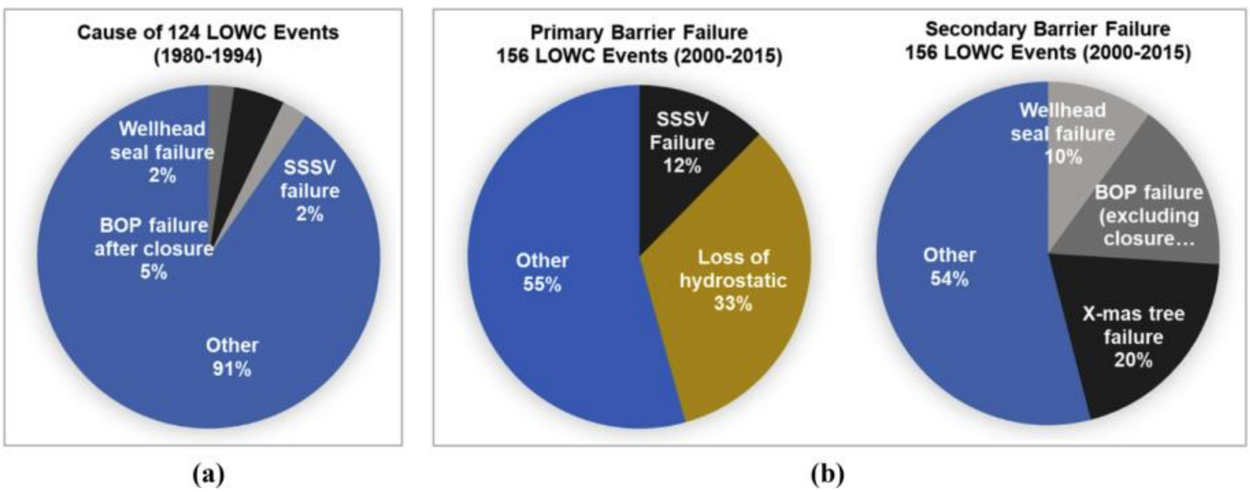


Figure 5. Causes of LOWC events occurred during (a) 1980-1994, and (b) 2000-2015. Black and grey shades represent causes most likely related to sealing.

5. Failure Mechanisms in Elastomer Seals

Elastomer seals are prone to several types of failure mechanisms during their lifecycle, including abrasion and wear (Fig. 6b). Such failures may occur during storage, handling, or installation. The primary causes typically include insufficient lubrication, uneven or rough contact surfaces, and the presence of foreign particles or debris at the sealing interface [9].

Thermal degradation of elastomers at elevated temperatures is another common failure mode. Under extreme temperature variations, elastomer seals may develop radial cracks or display signs of material softening and embrittlement. Generally, elastomeric materials struggle to maintain effective sealing performance at temperatures exceeding 250-300° F.

Mechanical failures such as extrusion and nibbling (Fig. 6d) also significantly reduce sealing efficiency. This issue arises when an elastomer element is exposed to frictional forces on moving surfaces or to cyclic/static loads that induce repeated stress. Over time, the seal material can be pulled, torn, or gradually eroded, leading to material loss. Additionally, shear damage may occur when part of the seal is forced into an extrusion gap. Such extrusion failures not only impair the sealing capability but can also hinder the retrieval of service tools or equipment from the well.

Compression set failure (Fig. 6e) is another degradation mode characterized by permanent deformation of the seal. The most frequent cause is improper seal dimensioning, which can lead to early extrusion or loss of sealing contact pressure.

Among all failure types observed in oil and gas applications, chemical degradation (Fig. 6f) is particularly common. During operation, elastomers are exposed to a variety of chemically aggressive substances, including drilling, completion, and fracturing fluids, as well as formation brines and production fluids containing acids, caustics, solvents, and other corrosive components. These chemicals can diffuse into the elastomer matrix, deteriorating the polymer structure. Elevated temperatures accelerate this process, worsening the chemical attack. Fluid absorption can also cause volumetric swelling of the elastomer, increasing its susceptibility to abrasion and extrusion failures.

Furthermore, contact with oxidizing agents such as ozone during storage, transportation, or service can initiate chain scission reactions within the polymer network. This process weakens the molecular bonds and accelerates material degradation, particularly at higher operating temperatures.
Fernández and Castaño (2016) investigated the effects of crude oil exposure on elastomers over 168 hours at 150° F and 1000 psi. Their results showed that aging led to reduced tensile strength and elongation at break, increased volumetric swelling, and decreased hardness and compression set resistance. The deterioration was more severe when the crude oil contained higher concentrations of saturates and aromatics.

Common gases found in oil and gas wells hydrogen sulfide (H_2S), carbon dioxide (CO_2), and methane (CH_4) can also affect elastomer performance. CO_2 and H_2S are particularly aggressive, causing chemical degradation of elastomeric materials. Although CH_4 does not typically react chemically with elastomers, it can penetrate the polymer structure and induce physical changes such as swelling or blistering, further compromising sealing integrity.

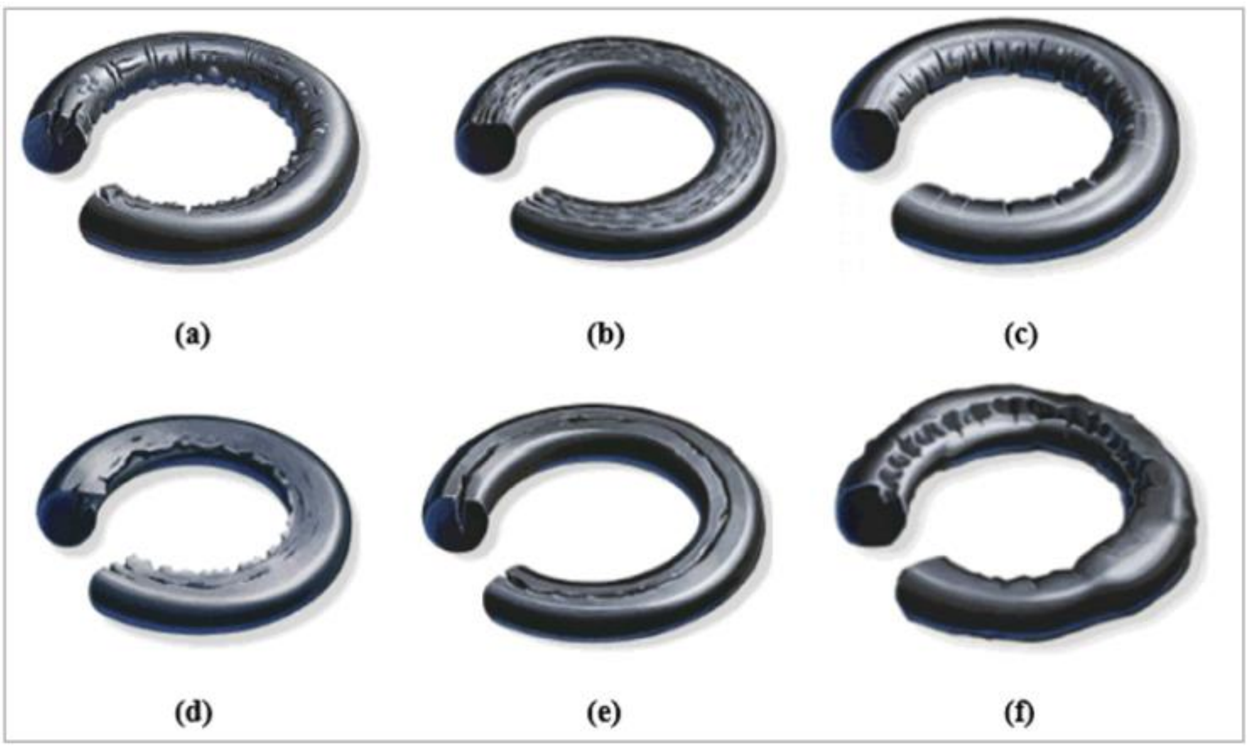


Figure 6. Failures in elastomer O-ring: (a) explosive decompression, (b) abrasion friction, (c) thermal degradation, (d) extrusion, (e) compression set, (f) chemical degradation.

6. Evaluation of Seal Performance

A comprehensive understanding of both elastomer material properties and seal assembly design is essential for accurately assessing sealing performance. The mechanical characteristics of the elastomer determine how the material deforms under load, which in turn influences its ability to maintain an effective seal. In oil and gas applications, elastomer seal components are generally stiffer and often assumed to exhibit linear elastic behavior. Under this assumption, only the elastic modulus and Poisson's ratio are typically required to describe material behavior [10].

However, at higher stress levels, elastomers display hyperelastic characteristics, meaning that their loading and unloading responses differ and depend on factors such as time, frequency, and dynamic load conditions. To model this nonlinear behavior accurately, constitutive models such as Neo-Hookean, Mooney-Rivlin, Ogden, and Yeoh are commonly employed. Experimental testing, such as uniaxial, planar, and biaxial tension tests, as well as volumetric compression tests, is necessary to define the parameters for these hyperelastic models.

To evaluate the suitability of an elastomer seal, a variety of material tests are typically conducted. The selection of test parameters depends on the manufacturer, researcher, and specific application. Commonly measured properties include curing characteristics, hardness, elongation at break, tensile and elastic moduli, torsional modulus, compression set, compression stress relaxation, rapid gas decompression (RGD) resistance, fluid compatibility, permeability, tear and abrasion resistance, and extrusion resistance. Most studies to date have focused on laboratory-scale testing of these fundamental material properties.

However, relatively few investigations have explored how these material properties influence seal assembly performance, particularly in terms of the contact stress generated at the sealing interface. One such study examined the effect of elastomer composition on the sealing behavior of compression packers. Three hydrogenated nitrile butadiene rubber (HNBR) formulations with different carbon black contents were tested. The authors measured uniaxial stress and compression behavior and implemented nonlinear constitutive models in a three-dimensional finite element analysis (FEA). Results indicated that sealing performance increased approximately linearly with applied setting pressure (Fig. 7). Nonetheless, no direct experimental or analytical data on contact stress were reported.

In the same study, the three elastomers were ranked based on structural stress levels in the supporting components and the likelihood of shoulder extrusion. The experimentally obtained extrusion–pressure curves showed strong agreement with theoretical model predictions.

Further research investigated extrusion behavior in commonly used oilfield elastomers through both experimental and FEA approaches. The study examined how differential pressure influenced extrusion in O-ring samples, identifying spiral failure due to extrusion as a primary failure mode under high-pressure, high-temperature (HPHT) conditions. The results demonstrated that the critical tear pressure, which is temperature-dependent, had a significant effect on seal material performance. The authors emphasized the importance of employing FEA not only for O-ring analysis but also for extending testing to full assembly-level seal design.

Additional investigations analyzed the effect of various design parameters on the sealing efficiency of elastomers used in conventional liner hanger assemblies. Parametric studies using validated 3D FEA models revealed that both Poisson's ratio and elastic modulus have a pronounced influence on the resulting contact stress (Fig. 8). The findings highlighted the necessity of using accurate material property data in seal design to avoid significant overestimation or underestimation of sealing performance.

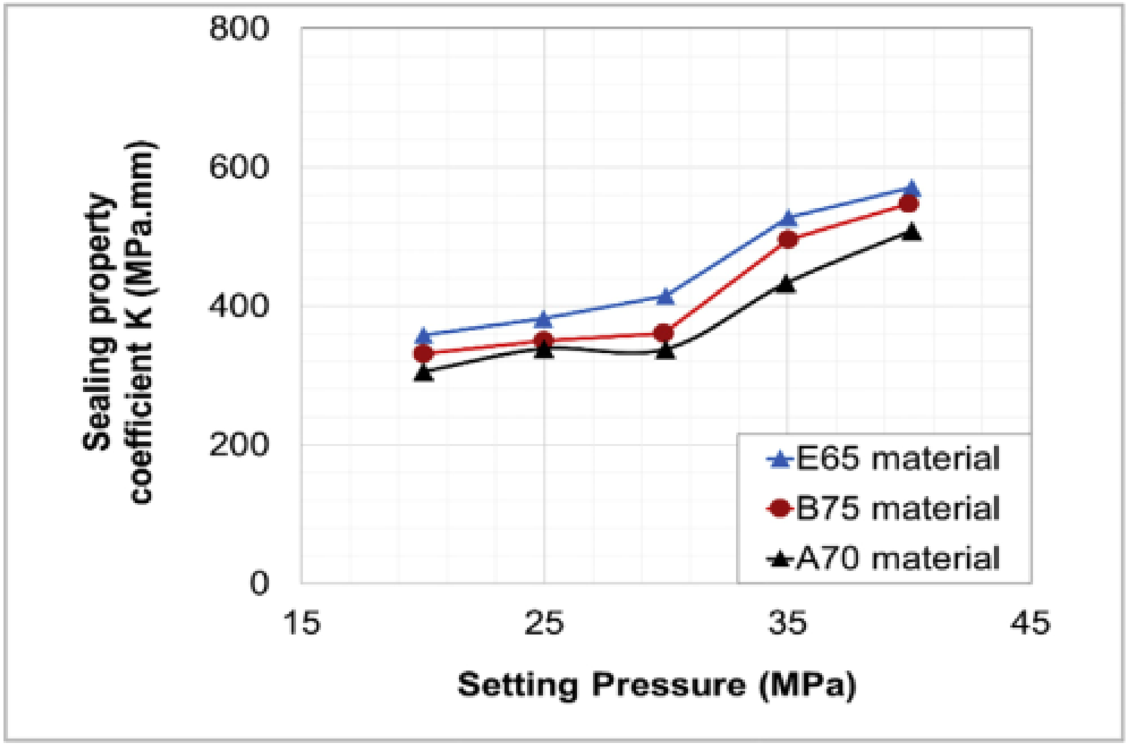


Figure 7. Sealing performance of the elastomer packer element as a function of setting pressure.

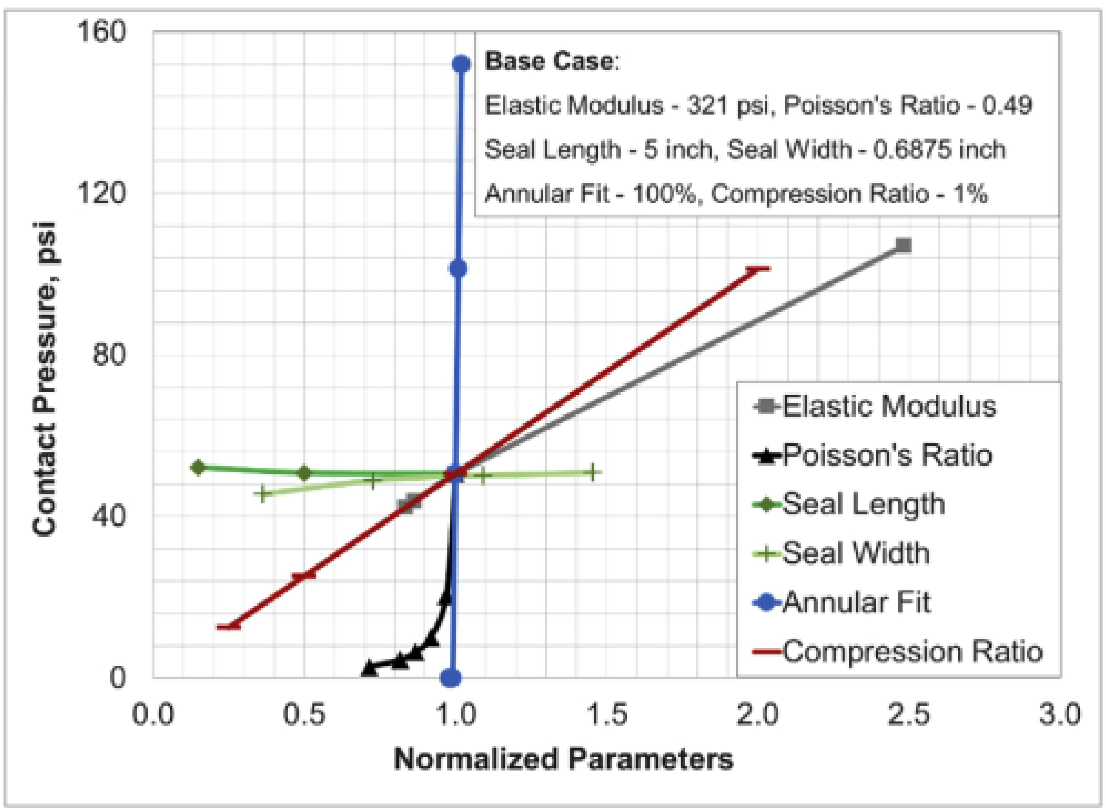


Figure 8. Sensitivity of contact pressure to various parameters.

7. Research Gaps and Future Directions

The industry has explored alternatives such as metal-to-metal (M2M) seals, particularly for applications involving harsh chemical environments, high pressures, and elevated temperatures. Metal seals offer several advantages, including superior resistance to extreme temperatures, pressures, and chemical attack, robust mechanical properties, minimal porosity, and extended shelf life. However, a key limitation of metal seals is their lack of flexibility and elasticity. To address this, researchers are developing innovative designs, such as lattice seals that combine a metallic structure with a thermoplastic matrix. Despite these advancements, these newer seal concepts remain under development.

Other challenges associated with metal seals include higher costs and a limited selection of material grades. Unlike elastomeric seals, the performance of metal seals is highly sensitive to the surface characteristics of the metal components. A microscopic-level modeling approach has been proposed to predict how surface roughness impacts sealability. By accounting for surface properties, the model can estimate contact stresses and corresponding leakage rates. The study concluded that surface finish, typically quantified as a root mean square (RMS) value, is the primary factor controlling leakage in M2M seals. Surfaces with randomly distributed roughness, such as those from casting, require higher contact stresses to achieve zero leakage compared to surfaces with more uniform asperity distributions, like machined components. Further research is needed to determine realistic leakage tolerances for metallic seals.

Additional challenges for metal seals include dynamic sealing performance and reduced effectiveness in the presence of particulate debris. Overall, due to these limitations, metal seals currently have narrower applicability compared to elastomer seals. Elastomers remain the preferred sealing material because of their low cost, durability, and ability to seal against irregular and dynamic surfaces.

8. Results

1. Analysis of historical well control incidents indicates that 46% of secondary barrier failures were attributable to seal equipment. In contrast to studies on material failure mechanisms, there is limited research examining the failure of functional seal assemblies and their impact on well control.
2. The performance of a seal assembly is influenced not only by elastomer material properties but also by factors such as seal geometry, the energization method, design of housing and support components, operational loads, contact interface conditions, and, in some cases, geomechanical considerations.
3. Existing industry standards primarily emphasize laboratory testing of standardized material samples. There are currently no guidelines for the design of elastomer seals at the full equipment level. Standards for material selection should be adapted to the specific application, seal type, and size of the equipment.
4. Future research should focus on seal assembly design, in addition to material characterization, to enhance elastomer reliability. There is a pressing need for robust methodologies that allow scaling laboratory findings to field-scale applications with extended service life. Developing a comprehensive database of elastomer material properties under high-pressure, high-temperature (HPHT) conditions would also provide significant support to the industry.

Author Contributions

The authors collaboratively designed the study, carried out the analysis, and contributed to writing and revising the manuscript. Both authors approved the final version.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

As a review article, this study did not generate any new primary data, code, or experimental results. All findings, conclusions, and data discussed herein are derived exclusively from previously published and publicly available scientific literature, which are fully cited in the References section.

Abbreviations

High-Pressure High-Temperature (HPHT), Bureau of Safety and Environmental Enforcement (BSEE), Subsurface Safety Valves (SSSVs), Blowout Preventer (BOP), Loss of Well Control (LOWC), Selskapet for Industriell og Teknisk Forskning (SINTEF), Hydrogen Sulfide (H_2S), Carbon Dioxide (CO_2), Methane (CH_4), Rapid Gas Decompression (RGD), Hydrogenated Nitrile Butadiene Rubber (HNBR), Finite Element Analysis (FEA), Metal-to-metal (M2M).

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