Chapter

Introductory Chapter: Swelling Elastomers in Petroleum Drilling and Development

Sayyad Zahid Qamar, Maaz Akhtar and Tasneem Pervez

> *A man ceases to be a beginner in any given science and becomes a master in that science when he has learned that he is going to be a beginner all his life.*
>
> *Robin George Collingwood*

1. Introduction

A major goal of the petroleum industry is to maximize oil production while reducing developmental and operational costs. Maintaining the profitability of old wells and exploiting economically inaccessible new reservoirs are some of the main challenges of petroleum industry [1]. Also, zonal isolation and optimization of the hole size with economic production for both conventional and deep water wells are ongoing problems. A few critical issues such as failure of equipment or application strategy, lack of reliability, complexity of deployment, operational issues, and higher energy requirement for initialization, become hurdles in achieving this target [2]. The relatively new swelling elastomer technology offers innovative and economically viable solutions. It has been successfully tried out in a variety of applications due to its simplicity of design, relatively inexpensive production, and ease of installation and initialization [3]. Petroleum exploration and development industry is witnessing a rapid growth in the use of swelling elastomers. These new applications are aimed at improved oil recovery (IOR) and enhanced oil recovery (and EOR) through slimming of well design, reliable zonal isolation, successful water shutoff, etc. [4]. Initially developed as a mitigation strategy for repair of damaged wells, swelling elastomers are now targeting major savings in cost and time through reduction in borehole diameter, reduced casing clearance, and cementless completions. Swelling elastomers are being used as sealing materials in many applications that target continued profitability of old wells, restarting of production from closed wells, and economic production from inaccessible new reservoirs [5].

Study of swelling elastomers is essential in resolving both application and design problems. Design issues involve seal material, seal geometry, seal performance, rate of swelling, and field conditions. Proper choice of material is of great significance in seal design, as it should possess characteristics that will allow sealing for a long period of time without failure. Material should also be strong enough to bear all types of loads, resist thermal conditions, and have good wear resistance against rock formation. Seal material should also be fast-swelling so that the well can go into production as early as possible. Rate of swelling is very important as it directly affects production, quality, and cost [6]. Proper seal geometry should be used so that seal integrity and reliability can be efficiently maintained. Seal geometry includes thickness and length of sealing elements, number of seals in a series, and gap between sealing elements. Environmental conditions such as temperature, pressure, swelling medium (water, oil, or acid), and formation properties are also very important for seal design. **Figure 1** illustrates the various issues that need to be addressed regarding the use of swelling elastomers and swell packers in the oil and gas industry.

Swell packers, also known as swellable element packers or reactive element packers, are constructed of base pipe similar to the completion tubing in oil and gas wells [7]. Schematic of a typical swell packer is shown in **Figure 2**. Manufacturing of these packers is on a custom-build basis to suit a certain well completion strategy. Application-specific elastomer is molded, thermally cured, and glued (vulcanized) to the base pipe. Back-up (anti-extrusion) rings are integrated into the design in certain cases to keep the elastomer element in place [8].

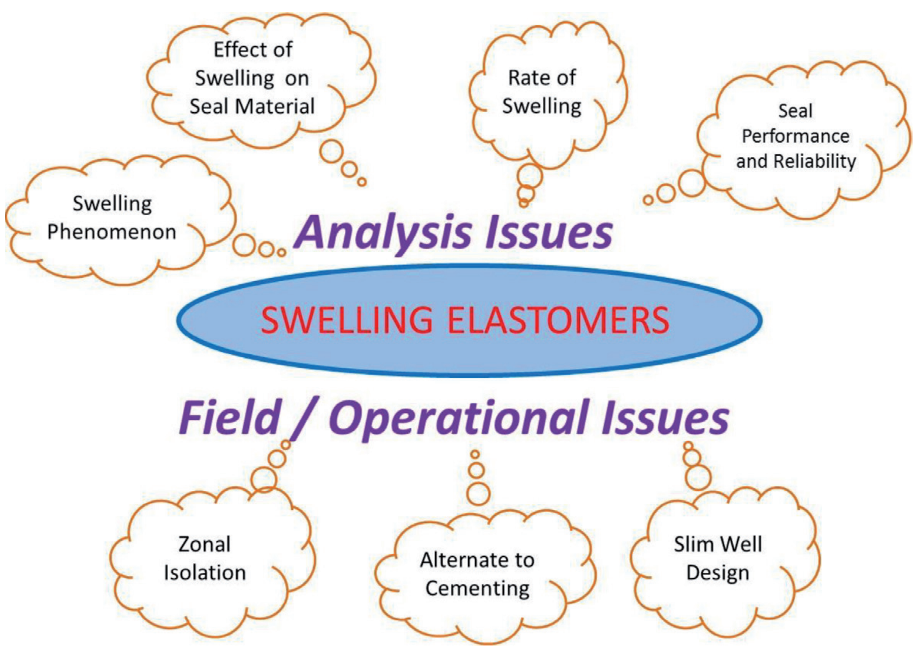

Figure 1.
Various issues related to the use of swelling elastomers and swell packers in the oil and gas industry.

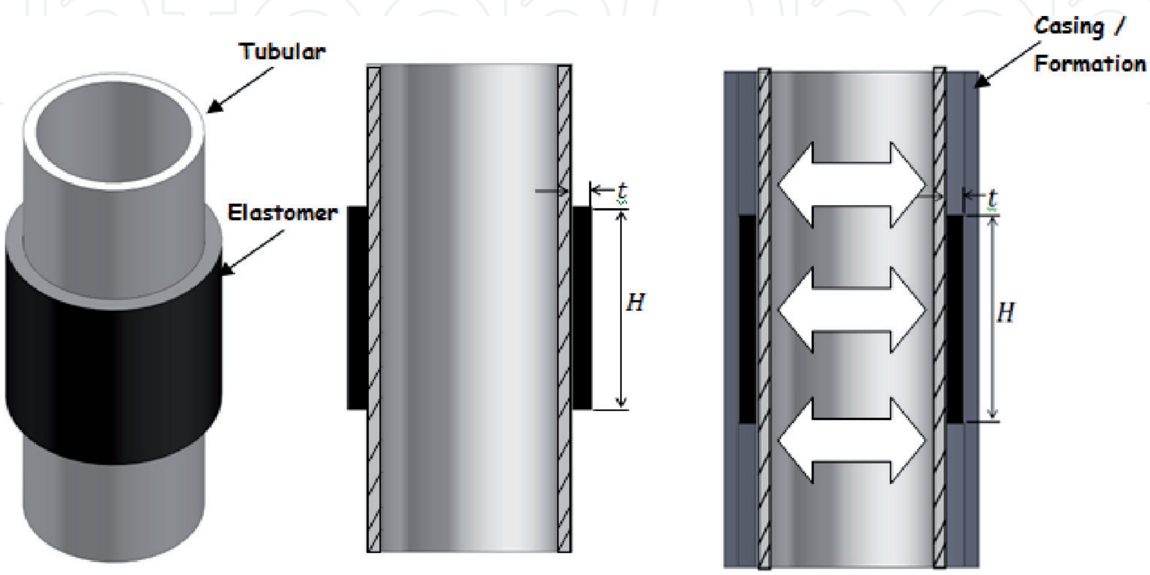

Figure 2.
Schematic of a typical swellable packer.

2. Swelling elastomers

Manufacturing, transportation, communication, mega-structures, virtually each segment of our everyday life is influenced by materials. The development of many technologies that make complex challenging tasks easier has been intimately associated with the accessibility of suitable materials. Advancement in the understanding of a material type is often the predecessor to the stepwise progression of a technology. Metals, ceramics, and naturally occurring polymers have been used as engineering materials for centuries. However, since World War II, the field of materials has been virtually revolutionized by the advent of synthetic polymers.

At room temperature, raw rubbers are amorphous and have linking of only physical nature (entanglements). An agent is required to create a network by producing cross-links. Elastomers are commonly cross-linked by the use of sulfur or peroxide. An elastomer is a type of polymer that has long and flexible molecular structure which has the ability to stretch to several times its original length. It is an ideal material for many applications because it can withstand very large strains. Besides elastic recovery, elastomers have special physical properties (such as flexibility, extensibility, resilience, and durability), which are unmatched by other types of materials.

Swelling elastomer is a new breed of advanced polymer which swells when it interacts with fluids like water, oil, or acid. It is also sometimes referred to as a 'gel' which is an aggregate form of elastomer swollen by immersion into a solvent. Addition of hydrophilic fillers (usually sodium polyacrylate and polyethylene glycol) is needed to make inert elastomers swellable. Examples of some swelling elastomers used in the field are ehtylene propylene rubbers (EPDM), flouroelastomers (AFLAS), hydrogenated nitrile rubbers (HNBR), etc. Karmanova et al. [9] discussed the technology of producing water-swellable elastomers to be used in packer seals for the oil production industry. They used mathematical modeling techniques to predict the effect of hydrophilic additives on the degree of swelling of ethylene-propylene based elastomers.

Swelling results in change in volume, thickness, density, hardness, and other material properties [10–15]. Water-swelling elastomers swell through absorption of saline water through the mechanism of osmosis [16]. To induce swelling in water-based elastomers, large chemical potential gradient is required. Osmotic pressure rises when two solutions of different concentrations are separated by a semi-permeable membrane. When salt dissolved in water becomes mobilized, solute particles collide with the elastomer and transfer momentum, thus generating pressure. This osmotic pressure causes water to flow into the elastomer. Solvent molecules in dilute phase have higher chemical potential than those in concentrated phase; hence this

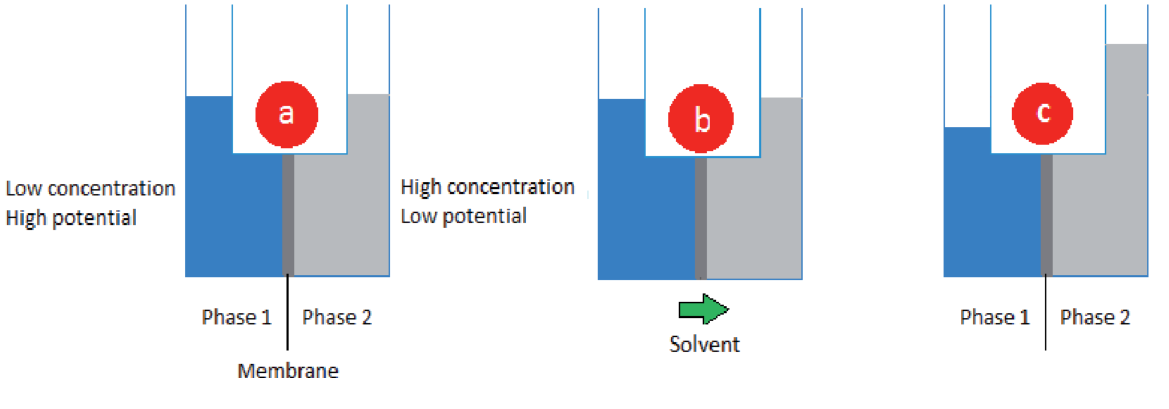

Figure 3.
Fluid influx into the elastomer causes swelling.

concentration gradient (difference in chemical potential) causes solvent flow from solution to elastomer; **Figure 3**.

Swelling in oil-based elastomers takes place by absorption of hydrocarbons through the process of diffusion [16]. Molecules intermingle due to their kinetic energy of random motion. In general, oil-swelling elastomers swell more at higher temperatures and in lighter hydrocarbons. Increase in temperature raises the kinetic energy and decreases the viscosity, resulting in higher swelling rates. For both water-swellable and oil-swellable elastomers, swelling rate depends on temperature, pressure, type of elastomer, and composition of liquid.

3. Brief discussion of applications

Due to the capability of changing properties while interacting with different fluids, swelling elastomers (or gels) are used in a variety of applications in bio-engineering, micro fluidics, and petroleum industry. Biocompatible materials or biosensors that respond to particular molecules (glucose or antigens) are used in drug delivery [17–19]. **Figure 4** schematically shows drug delivery in a bio-responsive gel. Lenses and diapers are other examples of gels [20–22]. Lenses are made of polymers that are hard when dry but readily absorb water and become soft when hydrated. Diapers are superabsorbent materials, absorbing large amounts of liquid but remaining almost dry.

Some researchers and practitioners mathematically and chemically describe a swelling elastomer as a *gel*, because of the rubber consistency after it has absorbed a significant amount of water or other liquid. There are many applications of gels in which volume change takes place. Disposable diapers, human tissues, microfluidic actuators or valves, seals used in different petroleum applications, are some examples. Different biomaterials such as articular cartilage, meniscus, tendons and ligaments, etc. have solid collagen fibrillar network, a fluid phase composed of water, and an ionic phase similar to gels [23]. Soft hydrated tissues swell due to the flow of water and charged ions. Spine consists of intervertebral disc having cartilaginous tissue that connects the vertebral body and allows spine movement. Mechanism of back pain can be understood by studying the mechanics of load transfer in the spine (intervertebral disc), which is affected by swelling of the cartilaginous tissues [24]. One such application, microfluidic valves with fluid–structure interaction, has been described by Zhang et al. [25]. Solid polymeric gel is placed in the fluid flow; volume of the gel starts to increase due to swelling, resulting in closure of the area. **Figure 4** gives a schematic representation of a valve in microfluidics.

Swelling elastomer seals are used in different petroleum applications such as zonal isolation, enhanced oil recovery, water production management, sand

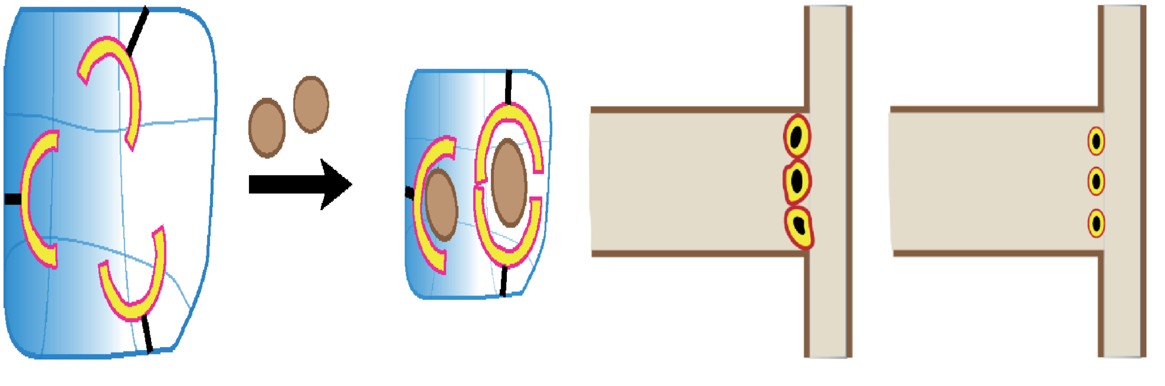

Figure 4.
Drug delivery of bio-responsive gel (left); a microfluidics valve (right).

control, reservoir compartmentalization, production separation, inflow profile control, condensate banking, well completion, slim well technology, intelligent wells, open-hole completions, cased-hole completions, horizontal wells, alternate to cementing, well stimulation, multistage fracturing, etc. More detailed account of the use of swelling elastomers in different petroleum applications is given in Chapter 2.

4. Motivation and significance

Before using a swelling elastomer for any application, its response under different fluids and with different geometries should be taken into account. Erroneous estimation of the elastomer's behavior can result in huge loss of resources and time. Major topic of the current book is performance analysis of swelling elastomer seals and packers for the petroleum drilling and development industry. This assessment can be done through experimental work, numerical simulation, and analytical modeling. All three types of investigations are described in different chapters.

One segment of the current book describes different sets of experiments that will help field engineers choose the correct type and geometry of elastomer seal to be used before deployment in an actual well. Various water-swelling and oil-swelling elastomers are allowed to swell for long periods in salt-water solutions of different salinities and crude oils of different viscosities. Periodic measurements are made for the amount of swelling, density, hardness, tensile properties, compression and bulk properties, etc. Tests are carried out on laboratory scale elastomer samples, and on actual swell packers.

It is sometimes very difficult to test all the parameters experimentally, especially under varying sets of field conditions. On the other hand, a hit-and-trial approach is neither reliable nor efficient, since making a well ready for production needs highly complex, time consuming, and expensive processes. Numerical techniques can be then used to predict the behavior. Appropriate simulations allow us to recreate the physical reality on a computer, and to virtually work out the solutions to these problems. Another section of the book illustrates the use of the finite element method (FEM) to simulate different experiments and seal behavior. This can also help engineers and developers in designing and optimizing the seal geometry for different applications.

Numerical simulation, especially with the proper choice of a material model, can be a powerful tool for performance analysis of swelling elastomers in oil and gas wells. However, a new simulation has to be carried out for every change of rubber or formation material, well type and conditions, etc. This can lead to very high computational costs and time delays. A closed-form solution that predicts the amount of swelling and changes in elastomer properties can be a far more efficient tool for design and development of swelling elastomer applications. One chapter of the book discusses the development of an analytical model for assessment of seal integrity by predicting the seal contact pressure under different conditions and for different seal parameters.

Finite element (FE) analysis requires a suitable material model, a geometrical model of the seal, and proper boundary conditions and applied loads depicting the actual field conditions. Some hyperelastic material models are available for rubber-like materials, and FE simulations using these material models give reasonably accurate results. However, no material model is currently available that mimics the actual behavior of swelling elastomers. FE analysis of higher accuracy is not possible without a more accurate material model. The last chapter of the book takes us through the development of a new material model that can capture the behavior of swelling elastomers more closely, and can be used in future FE simulations.

5. Synopsis of the book

As the title suggests, this book describes applications, performance analysis, and material modeling for swelling elastomers used in petroleum drilling and development. Different sections of the book are dedicated to experimental, numerical, and analytical investigation of swelling elastomer applications in oil and gas wells. Some of the salient features of this research monograph are listed below.

- A thorough literature review has been conducted covering different areas such as applications of inert and swelling elastomer seals and associated technologies, experimental and numerical studies related to swelling elastomers and their applications, material models for hyperelastic and other rubber-like materials, etc.

- Experimental facilities have been designed and constructed, and a variety of experiments have been conducted to understand the effect of various parameters on material properties and behavior of swelling elastomers.

- Three sets of experiments are conducted to determine swelling behavior (change in volume, thickness, hardness, and density), compression properties (stress–strain patterns, elastic modulus, etc), and bulk properties (bulk modulus, Poisson's ratio, etc). These material characterization tests are carried out before swelling and at various stages of swelling. Test parameters (from actual oilfields) include swelling media (water, oil, acid), elastomer materials, water salinities, test temperatures, swelling periods, etc.

- Some of the experimental results are used to determine different structural properties of elastomers such as chain density, and number-average chain molecular weight. Experiments are also conducted to determine the viscosity and density of saline water at particular temperatures. These properties, along with structural properties and specific volume of elastomer, molar volume of liquid, etc. are used to determine the polymer interaction parameter. This is later used in the newly developed material model for parameterization of free swelling.

- Lab tests are conducted on small elastomer samples. No one knows what really happens to sealing elements and swell packers in actual wells. A testing-cum-demonstration unit has been designed and constructed for visualization of the swelling phenomenon, and its effect on swell packers in cased and open holes. Different packers of inert and swelling elastomers are placed in actual petroleum tubulars, and against a concrete wall having sections of different roughnesses, replicating an actual rock formation.

- All tests on swelling elastomers reported in published literature are conducted for a maximum period of a few weeks. However, over long periods of time, even very good elastomers may experience serious material degradation and loss of properties. Durability, integrity, and effectiveness of elastomer seals and packers over long periods is an uncharted area. To address these never-tacked issues, a full-scale longevity test setup has been designed and conducted for actual swell packers of different water-swelling and oil-swelling elastomers, different diametral sizes, maintained at different temperatures over a five-year test period.

- Existing material models that describe the behavior of rubbers and elastomers (hyperelastic materials) are investigated and compared. Compression and bulk experiments are simulated using existing material models and results are compared against empirical data from actual swelling elastomers, before and after different stages of swelling. Material model that gives the closest predictions is selected for further work.

- Numerical modeling and simulation of swelling elastomer seals has been conducted using the best existing material model available in the commercial (nonlinear) finite element package ABAQUS. A large number of simulations are carried out to investigate sealing behavior against different types of elastomer material, field conditions, water salinity, swelling time, seal length, seal thickness, compression ratio, and wall type (rock formation or steel casing). Recommendations are made about the suitability of certain seals for field conditions and parameters in actual oilfields.

- Though numerical simulations can do reasonably accurate performance evaluation, computational time and cost can be large. Mathematical modeling of the behavior of swell packers can be really challenging. However, an analytical model, if developed, can be very time-wise efficient. A closed-form solution has been developed for performance assessment of elastomer packers, especially in terms of the seal contact pressure under different conditions and for different seal parameters.

- A new material model has been developed to closely capture the swelling phenomenon in elastomers, including parameters that were not considered in any of the existing models. This new model is based on the mechanics of swelling,

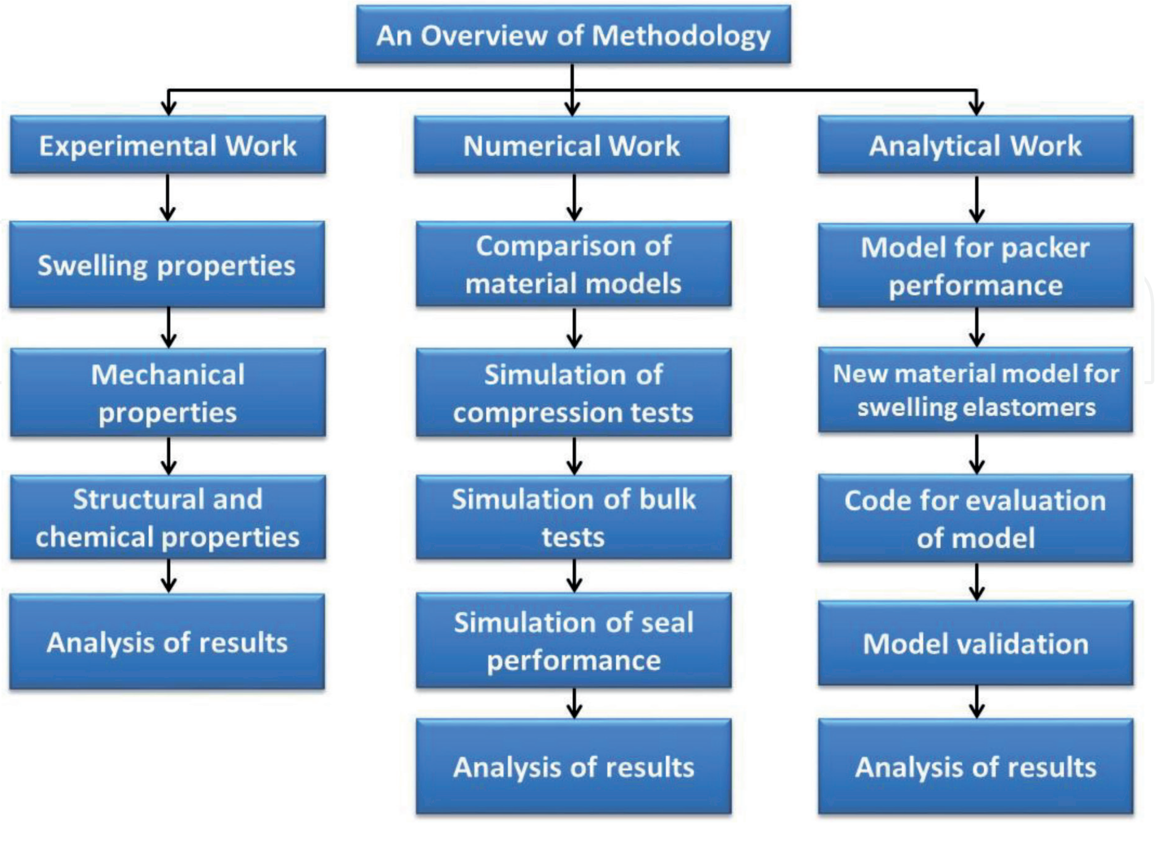

Figure 5.
An overview of methodology for the various studies (experimental, numerical, and analytical) presented in the book.

and it can be used to determine the volume, thickness, etc. after swelling. This model can take actual field conditions as inputs (such as water salinity, operating temperature, mechanical properties, swelling time, etc). Model validation is done using different experimental results.

An overview of methodology for the various modules and studies presented in the book is shown in **Figure 5**.

6. Chapter-wise summary

Chapter-1 introduces the book, and its various sections and chapters. Chapter-2 reviews swelling elastomers and their uses in different petroleum applications. Chapter-3 describes experimental work conducted to investigate the swelling behavior of different elastomers under water, oil, and acid. Chapter-4 describes the design and construction of a demonstration-cum-experimental setup for swell packers in cased and open holes. Chapter-5 discusses longevity testing of water-swelling and oil-swelling packers at different temperatures and pressures, over a five-year period. Chapter-6 presents a comparison of different existing material models (for hyperelastic materials) that can be used to simulate the behavior of swelling elastomers. Chapter-7 explains the determination of different mechanical and structural properties of swelling elastomers under compression, needed for extraction of parameters for numerical simulations. Chapter-8 covers performance evaluation of elastomer seals used in petroleum applications, using FE simulations. Chapter-9 discusses numerical investigation (FEA) of swelling elastomer seals used in conjunction with solid expandable tubulars (SETs). Chapter-10 presents an analytical model for performance evaluation of swell packers in terms of the seal contact pressure. Chapter-11 describes the development of a new material model for swelling elastomers, incorporating mechanics of swelling, thermodynamics of mixing, Gaussian statistics, and other concepts.

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