DRAFT RECOMMENDATIONS

AUTHORS:

Saeed Salehi (PhD), Principal Investigator

Ramadan Ahmed (PhD), Co-Principal Investigator

Catalin Teodoriu (PhD), Co-Principal Investigator

Chinedum Peter Ezeakacha, Graduate Research Assistant

Harshkumar Patel, Graduate Research Assistant

George Kwatia, Graduate Research Assistant

Shawgi Ahmed, Graduate Research Assistant

Mustafa Al-Ramadan, Graduate Research Assistant

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1 EXECUTIVE SUMMARY

This report presents the recommendations and future works based on the accomplishments of the Bureau of Safety and Environmental Enforcement (BSEE) Project #E17PC00005. In this report, the term "barrier(s)" defines the use of cement sheath and the liner hanger seal assembly to prevent uncontrolled influx and migration of formation fluid to a shallow formation or surface facilities. This report is divided into three major sections. The introductory section highlights the important regulatory and industry standards for liner hanger seal assembly and cement system. In this section, some of the gaps in current regulations and standards that are critical to liner hanger seal, cement placement, and tests have been identified. In the second section of this report, recommendations have been made based on the results and conclusions from each of the four sections in which this project was divided. The third section of this report presents the future works that could be embarked on, which are not in the scope of the current project.

2 INTRODUCTION

2.1 LINER HANGER STANDARDS

Liners and liner hangers are commonly used in offshore drilling applications instead of full string casings. They are required to pass certain standards before deploying them in the field. The industry relies on standards developed for packer equipment (*ISO 14310:2008E* or *API Spec 11D1 and 17D*) in evaluating liner hanger seals. Currently, there are no adequate and specific standards and guidelines for assessing seal assembly in a conventional liner hanger or sub-mudline hanger. It is unclear whether the new standard for liner hanger equipment '*API RP 19LH*' - currently being drafted by API, will encompass sufficient guidelines for testing or designing seal assembly. Even though conventional liner-hanger assemblies have had frequent sealability failure issues, no study is available in the public domain that is focused on assessing the sealability of the elastomer element in liner hanger seal assemblies under various conditions.

The reference incident for conducting the studies in this project is documented in the internal QC-FIT report #2014-02 published in December of 2014. The primary cause of this well control incident in the Main Pass Block 295 (MP295) located in the Gulf of Mexico was attributed to gas migration through the sub mudline casing hanger seal and cement sheath into a shallow formation. The sub mudline casing hanger was designed based on the first edition of *API Spec 17D* standard (Design and Operation of Subsea Production Systems – Subsea Wellhead and Tree Equipment), which only requires hydrostatic testing with water. The current (second) edition of *API 17D* was revised in 2011. It requires gas qualification testing of the equipment, addresses the design methodology, as well as verification and validation of wellhead production hangers, sub mudline casing hangers and seals.

ISO 14310/API 11D1 for Packer Equipment established a minimum set of parameters with which the manufacturer must comply. The international standard is structured with the requirements for both quality control and design verification in tiered rankings. 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 that meets the specific application by including additional needs as supplement requirements. 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) is included to meet special acceptance criteria requirements.

API is currently drafting a standard for liner hanger equipment – *API RP 19LH*. This specification will provide requirements for conventional and expandable liner systems including liner hangers, liner packers, liner hanger packers, tieback/polished bore receptacles, seal assemblies, setting adaptors/sleeves, and running/setting tools etc. This specification is also expected to include minimum requirements for the functional specification and technical specification, including design, design verification and validation, materials, quality control etc.

All the standards discuss chemical compatibility with respect to pure hydrocarbon gases and liquids such as methane, heptane, carbon dioxide etc. No guidance is available on the effects of harsh downhole chemicals such as drilling or completion fluids, hydrates, scale, corrosion inhibitors, and other additives, etc. In addition to material testing guidelines, the industry standards may be improved to include - the functional testing of liner hanger seal assemblies, recommended practices for proper seal energization, and performing qualification pre- and post- installation.

2.2 CEMENT STANDARDS

API standard 65 2nd Ed. – Isolating Potential Flow Zones During Well Construction provides best practices for cementing operation. It also contains brief discussions on factors affecting the success of a cement job and post-job evaluation. *API RP 10B-2 or ISO 10426-2* contains guidelines, procedures, and information on equipment for testing cement slurries and related materials in laboratory under simulated well conditions. *API RP 10B – 4, 5, and 6 or ISO 10426-4, 5 and 6* are for testing foamed cement, shrinkage/expansion of cement slurries, and static gel strength respectively. *API SPEC 10A or ISO 10426-1:2009* provides specific chemical and physical properties requirement for all the 8 classes of cement. API technical reports TR 10TR1-4 contains technical information, principles, and results of research on cement sheath evaluation by logging, cement shrinkage and expansion, temperatures in API well simulation test schedule, and selection of centralizers respectively. The current industry standards, recommended practices, and technical reports for cement are primarily focused on cement slurries, their material properties, laboratory testing, consideration during field operation, etc. All the documents have helped in advancing the safety of wells, yet there can still be improvement and expansions in some of the following areas:

The 30 CFR 250.423 (a) regulation recommends 30 minutes duration for pressure tests of conductor and surface casing/liners strings. From the setup II experimental observations, this period is adequate to reveal a leak when the elastomeric sealing element is tested independently. However, the analytical studies from the leakage scenarios (investigated from setup I experiments) suggests that a 30-minute pressure test may not be enough to reveal a significant leak through the cement sheath that is greater or equal to 300 ft in a liner-casing overlap. Based on these observations, the following key questions should be considered and the outcome of their discussions can be incorporated in industry standards: 1) Is the 30 minutes pressure test requirement for cement column sufficient to evaluate its fitness as a primary barrier? 2) Should the duration requirement vary depending on the well design and operating conditions?

Another area that requires attention is the use of gas migration control additives, which is not well addressed in BSEE regulations or industry standards, especially for drilling gas migration prone zones. API RP 65 (Cementing Shallow Water Flow Zones in Deepwater Wells) and API RP 65 – Part 2 (Isolating Potential Flow Zones During Well Construction) have mentioned the need for gas control additives briefly. One major operator stated they always design for the worst-case scenario and add a gas migration control additive into all their cement jobs to reduce the likelihood of gas migration. Further research in this area should be conducted to provide specific guidelines for incorporating gas migration control additives in cement slurry design.

In addition, the current standards can be improved to incorporate sufficient discussions on designing cement systems that are considered "fit for service". Specifically, the guidelines should discuss the selection of appropriate mechanical properties for different conditions, performance curves, or response of set cement under various loading conditions and risk assessment of various failure scenarios.

3 RECOMMENDATIONS

Recommendation have been made based on the results and analyses presented in this project. The recommendations have been subdivided into the sections under which the project goals were accomplished.

3.1 CEMENT TESTS (SETUP I)

- It is recommended to specifically use gas migration additive(s) in formulating a cement recipe for shallow gas formation zones and abnormal pressure intervals. This will prevent the invasion of uncontrolled gas during the transition of cement slurry to the solid phase.
- It is recommended to increase the pressure test duration beyond 30 minutes, depending on the cement column length in the liner-casing overlap. Figure 1 shows how the leakage time will vary with the liner-casing overlap length for various differential pressures at 0.5 mD combined permeability. Referring to the well control incident in the QC-FIT report, the last casing shoe was set at 1000 ft while the liner hanger was set at 700 ft, creating a 300 ft liner-casing overlap. The pressure test was conducted at 900 psi for 30 minutes without any leak indication. Assuming the formation pressure at the casing to be 500 psi, this will create a 400-psi differential pressure on the cement column behind the liner-casing overlap. Assuming a faulty barrier system (cement with 0.5 mD combined permeability and faulty elastomer), it can be observed from Figure 1 that the leakage time will be 87 minutes. This implies that a 30-minute pressure test may not have been sufficient to reveal any significant leak for 300 ft overlap. Therefore, the dashed-red horizontal line (which represents 90 minutes) is the proposed pressure test duration for cement column length ≥ 300 ft in the liner-casing overlap.

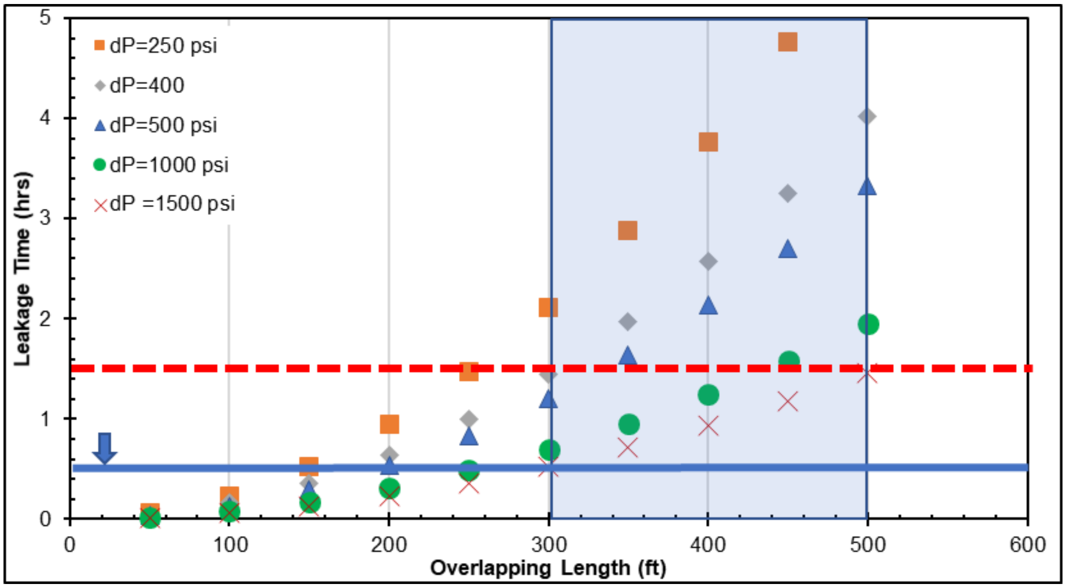

Figure 1: Leakage time versus liner-casing overlapping length for 0.5 mD combined permeability for several differential pressures.

- It is recommended that the cement column in the liner-casing overlap should not be less than 300 ft. The leakage times for all the differential pressure values in Figure 1 are less than 1 hour for 50 ft to 200 ft overlap. Shorter overlaps (50 ft to 200 ft) can be beneficial because pressure tests may quickly identify leaks if the cement and elastomer in the liner hanger are faulty. Cost may also be a contributing factor for using shorter overlaps. However, the leakage scenarios suggest that shorter overlaps have shorter leakage time, which implies shorter time for gas migration through a faulty cement and elastomer in the overlap. To err on the side of caution, particularly in gas zones, the light blue shaded area in Figure 1 represents the proposed cement column length in the liner-casing overlap (300 to 500 ft). This proposed range shows longer leakage times for a gas kick to migrate to the end of the overlap. In practice, the increase in leakage time can translate to longer duration required for detecting and controlling gas influx and migration.

3.2 ELASTOMER AGING TESTS (SETUP III)

- It is recommended to test all sealing systems (elastomeric elements) for the anticipated downhole conditions (gas/liquid, temperature, and pressure), before considering them "fit for service". The elastomers (NBR, EPDM, and Viton) that were aged in this study showed both physical and chemical degradation of their intrinsic properties (hardness, compression, and volumetric swelling). This can compromise their seal integrity.

3.3 SEALING ASSEMBLY TESTS (SETUP II)

- It is recommended not to consider elastomeric elements in liner hanger systems as a primary barrier in a downhole CO_2 environment. Elastomers can lose their seal integrity because of deep CO_2 penetration within the elastomer molecular chains. During the decompression of the

CO_2-aged EPDM samples that was used in setup II, blisters and cracks were created and this compromised their seal integrity.

- In consonance with the first recommendation in 3.1, cement with gas migration additives can be considered as a primary barrier in the case of a faulty elastomer seal.
- It is recommended that elastomer seals be subjected to pressure cycling tests, to assess their reliability during their service life. This is because during the elastomer pressure tests as an independent barrier, some of the pressure cycling tests failed, and this was linked to the elastomer energization.

3.4 LEAKAGE MODELLING AND RISK ASSESSMENT

3.4.1 Seal Assembly Model

- Due to extremely high sensitivity of sealability to annular fit, the tolerance for radial dimension of seal should be stringent. The seal assembly should always be designed to compensate for likely deviations from planned installation configurations such as improper centralization, presence of debris in the annular clearance because of poor hole cleaning, and wear or erosion of seal component during running in. Visual inspection of assembly before installation should be performed if possible.
- Typically, elastomers are known to exhibit a Poisson's ratio of 0.49. However, it is important to ensure that the true value is measured and used while designing the seal component otherwise it could result in significant over-estimation of sealability.
- While qualifying the "fitness for service" of seal assembly, it is important to ensure that elastomers are rated for anticipated operating temperature and chemical/gas environment. The rating should be based on the elastic modulus and Poisson's ratio measurements. The material should either be able to retain the original elastic modulus and Poisson's ratio under operating conditions, or at least be designed to compensate for possible deterioration in both properties. Seal assembly should preferably be designed to minimize exposure of seal element to downhole environment.
- Manufacturer-recommended weight application should be strictly adhered during energization, to attain designed compression ratio and effective contact pressure. Possible restriction on weight application because of friction, well deviation, improper centralization etc. should be anticipated and properly compensated.
- To avoid improper seal energization because of a faulty support, it should be ensured that all the components of the assembly, particularly the slips, are rated for anticipated loading downhole conditions.

3.4.2 Cement Model

- Ensuring 100% annular fit i.e. bonding with pipes on either side should be the first priority in cement design and cementing operation. Anything less than 100% annular fit could significantly impact the sealability of the cement sheath.

- It is possible for the liner to balloon (because of positive wellbore pressure) and close a small micro-annulus in set cement. This means that a positive pressure test has the potential to temporarily mask the failure of annular fit. Further detailed investigation is necessary on this issue. If it is an issue, may be a negative pressure test should be explored?
- Even though radial cracking by hoop stress is often the most likely failure mode, equal consideration should be given to shear failure when designing or selecting cement because it may precede the other in certain conditions.
- Potential events throughout the life of a well that can change wellbore pressure such as pressure test, production, stimulation operation etc. should be carefully considered while designing a cement operation.
- Selection of special pre-stressed or expanding cement system should be based on weighing the positive effect on hoop stress and negative effect on shear stress.
- Cement failure is highly sensitive to Poisson's ratio and Young's modulus of cement. It is important that the design factor is high and calculated based on true material properties under in-situ environment condition.

4 FUTURE WORK

Below are some of the proposed future work that are based on the results and analyses from each task of this project:

4.1 CEMENT TESTS (SETUP I)

- All the tests were conducted at ambient temperature. It is recommended that some tests be conducted at elevated temperature. In this case, between 102°F and 120°F, considering a shallow formation.
- It is recommended to evaluate alternative slurry additives and formulations such as carbon black. This may provide a suitable and cost-effective gas-tight cement slurry.

4.2 ELASTOMER AGING TESTS (SETUP III)

- All the tests conducted in this setup are limited to 180°F based on the proposed project scope. To have a better understanding of elastomer behavior in high temperature conditions, it is recommended to conduct high temperature aging tests on elastomers.
- This study is limited to four types of elastomers (NBR, EPDM, Viton, and PTFE). It is recommended to test other elastomer types in a similar study. Especially because Viton is recognized for its resistance to corrosive medium and aging. However, the Viton used in this study showed blisters and cracks after the elevated temperature (180°F) aging test.

4.3 SEALING ASSEMBLY TESTS (SETUP II)

- Evaluate the performance of additional elastomers such as Viton, Kalrez, and Alfas that are also used in liner hanger sealing assembly. This is in consonance with the last recommendation from the aging test and will assist in establishing the actual corrosive and operating condition limits of the materials.

- Perform additional tests on EPDM samples after exposure to oil/fuel, using similar setup. This will provide an additional evaluation to the performance documented in this study, considering that many manufactures have claimed that it is very susceptible to oil and fuels.
- Conduct further research to investigate the possibility of testing the seal system and the cement sheath independently in field application.

4.4 LEAKAGE MODELLING AND RISK ASSESSMENT

4.4.1 Seal Assembly Model

- Different shapes of unenergized elastomer components of seal assembly should be modelled and compared to understand how shape affects energization and sealability.
- In this project, conventional weight set assembly has been modelled. Further studies can be conducted on different types of seal assembly such as expandable liner hanger, hydraulic set liner packer, etc.
- Multiphysics transient modelling (combination of structural mechanics and fluid dynamics) is challenging but can be explored to understand and simulate more complex modes of fluid penetration and seal failure scenarios.
- The elastomer samples used in this work exhibited linear deformation behavior in the measured stress range. More comprehensive material properties measurements can be conducted to measure accurate Poisson's ratios and capture non-linear elastic behavior of the seals at higher stresses. Incorporating comprehensive material properties in finite element model would yield more accurate prediction of seal behavior.

4.4.2 Cement Model

- Advanced material properties measurements of cement samples including tri-axial tests should be undertaken. Comprehensive knowledge of cement properties would permit the use of more sophisticated material models for finite element modelling; yielding more accurate results.
- Multiphysics transient modelling (combination of structural mechanics and fluid dynamics) is challenging but can be explored to simulate more realistic operational scenarios. Modelling cement as a porous medium may be useful in understanding hydraulic sealability.
- For deeper or high pressure/high temperature wells, it would be useful to model casing-cement-formation system with the appropriate material properties for rock formations. Thermal stresses in the casing may also be significant enough to impact cement performance.

ACKNOWLEDGMENT

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