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Abstract

In well design, intermediate casings are used to isolate sections of the wellbore that are unstable or abnormally pressured and may compromise the well's integrity while drilling further down. Intermediate casings in cavern well design is traditionally run from the setting depth to the surface and cemented to surface. Liners perform the same function as intermediate casings, can be run faster, require less casing and cement.

In this case study two Gulf Coast cavern wells located in the Atchafalaya basin of Louisiana were designed. The intermediate casing section below the surface casing in both wells was long, consisting of unconsolidated sediments and a strong risk of lost circulation in the caprock. Initially, two options were considered for the intermediate section, a single, long intermediate casing to cover the section, or two intermediate casings to divide the long section into two smaller open-hole sections. The single intermediate casing option carried more risk, and the two intermediate casings option was more costly.

A third option was chosen which was composed of a series of large diameter nested liners. The casing design utilizes offshore casing technology and consists of a landing ring welded into the previous cemented casing, a liner hanger with seals and specialized inner string running tools. The inner string running tools provided the ability to pressure test the casing, run the casing to setting depth, cement the casing and wash out any contaminated mud and cement on the way out of the hole.

In total four liners were set in the two wells, with two in each well, leading to the successful completion of the wells. Several issues were encountered during liner setting operations which led to changes in the drilling procedure, running procedure and inner string configuration. Each liner run iteration created a more robust and efficient operation.

Large diameter intermediate liners have shown to be an effective and efficient method to reduce risk associated with wellbore integrity and stability. The success of the large diameter liners has led to the development of the next generation of liner inner strings and running tools. Plans are in place to drill three additional wells in the same field, each incorporating one or more intermediate liners.

Key Words: anhydrite, casing design, domal salt, drilling, drilling and completion, inner string cementing, intermediate casing, large OD casing, liner, lost circulation, Louisiana, mud, regulations, surface casing, underground source of drinking water (USDW), well casing, well cementing, well design

1.0 Introduction

In April of 2023, Texas Brine received an approved budget to drill three cavern wells, Wilbert 7, 8 & 9, on the White Castle dome for salt production. The last well drilled in White Castle, Wilbert 6, experienced severe lost circulation in the caprock zone and drillers had to fight the hole collapsing. Wilbert 7 and 8 in the new drilling program would be drilled in proximity and have caprock and salt tops at roughly the same depth as Wilbert 6. The casing program for Wilbert 6 used a 30in (76.2cm) casing to cover a long section of unconsolidated sands above the caprock. Because of the risks associated with a long open section above a lost circulation zone, the intermediate casing program was revised. The following paper is a methodology and case study of using intermediate liners to reduce risk associated with long intermediate sections and lost circulation.

2.0 Background

The White Castle dome located in the wetlands of the Atchafalaya Basin approximately 22 miles (35.4km) south of Baton Rouge Louisiana. The White Castle dome is a piercement type salt diapir which originated from the Triassic/Jurassic aged Louann salt formation (WSP Project No. 192083F). The dome measures roughly 1.3 miles (2.09km) by 1.6 miles (2.57km) at the -9,000ft (-2,743.2m) contour and is elongated to the northeast. The shallowest expression of the salt is on the western crest of the dome at approximately -2,200ft (-670.6m). The salt then dips gently to the northeast to -4,000ft (-1219.2m) before steeping dramatically. The caprock is composed of anhydrite, gypsum and limestone with varying thickness ranging from 0 ft to 650ft (198.12m). The sediments above the caprock are composed of unconsolidated sands, interspersed with silts and clays.

Texas Brine had drilled nine previous cavern wells on the dome. The first well Wilbert 1 was completed in 2005 and the most recent well completed, Wilbert 6, in 2022. In addition to salt production wells, oil and gas production occurs on and around the dome. Oil and gas production began in 1926 with the completion of Shell Wilbert # 3 and continues to present (Stipe and Stiller, 1960).

The casing program for White Castle wells is like other gulf coast domal salt wells with each casing performing a specific function in the well construction process. The first casing is a drive pipe, driven to refusal which provides stability and allows for circulation of drilling mud. A surface casing is set in the 1st competent formation below the Underground Source of Drinking Water (USDW) and cemented to surface, protecting the USDW from the drilling process. Then a series of intermediate casings are set, one to case off the unconsolidated formations above the caprock, another intermediate casing which cases off the caprock and is the first barrier to the cavern. Room is traditionally left between these two intermediate casings for another contingency intermediate casing if additional downhole issues are encountered. Then the production casing is set in salt and provides the second barrier to mining operations. Additional casings are hung in the well head and used for mining operations.

During Wilbert 6 drilling operations, circulation was lost as the caprock was encountered. The 30in (76.2cm) intermediate casing was set 130ft (39.6m) above the caprock. Below the 30in (76.2cm) shoe and above the caprock the formation consisted of unconsolidated sands and clays. This formation began sloughing into the hole as fluid was lost causing excess torque and drag on the drilling assembly. Lost circulation material was pumped into the hole to maintain fluid levels and stability to the borehole, but the losses and hole stability issues continued through drilling of the caprock and opening the hole. Fortunately, the troublesome section was successfully cased off without loss of the hole.

There are several examples where the hole was lost due to these same circumstances. Examples include Moss Bluff 3, two recent Mont Belvieu wells, and Wilbert 200 on the White Castle dome and others. Lost circulation issues have occurred in 5 of 13 wells drilled at the White Castle dome. The lost circulation can be attributed to fractured or vugular caprock and under pressured/depleted sands from oil and gas production. Two of the wells to be drilled in the 3 well program, Wilbert 7 & 8, were to be drilled in the same area as Wilbert 6 and with similar top of caprock and top of salt depths.

Experience with lost circulation in Wilbert 6 generated concerns regarding the 30in (76.2cm) intermediate casing setting depth. The top of caprock in Wilbert 7 and 8 were predicted to be 2,950ft (899.2m) GL (ground level) and 3,000ft (914.4) GL respectively. If 36in (91.4cm) surface casing was set at 1,300ft (396.2m) and the 1st intermediate casing was set on the top of caprock, then there would be roughly 1,600ft (487.7m) to 1,700ft (518.2m) of open hole exposed as the drilling assembly approached caprock and potential lost circulation. Several casing program options were considered when evaluating this risk (Figure 1). The 1st option was to use the same casing program and run the 30in (72.6cm) casing to the top of caprock. This option carried more risk with the potential for lost circulation and a long open hole. The second option was to set the 30in (72.6cm) intermediate higher in the well and case off 1,000ft (304.8m) of open hole to reduce open hole exposure. Then use another 26in (66cm) intermediate string to case off the unconsolidated sands to the top of caprock. This casing program would reduce open hole risk but significantly increase the cost due to the amount of casing required.

A third casing program option was considered which replaced the 30in (72.6cm) intermediate casing set from caprock to surface with a 30in (72.6cm) intermediate liner and a 26in (66cm) intermediate liner. The 30in 72.6cm) liner would be set at a depth roughly 1,000ft (304.8m) below the 36in (91.4cm) surface casing and would be hung off over 200ft (60.96m) inside the 36in (91.4cm) casing. The 26in (66cm) liner would be set at the top of caprock and hung off 200ft (60.96m) inside the previous 30in (72.6cm) liner. This option reduced the volume of steel in the ground, therefore cost and reduced the length of the open hole sections, therefore the risk.

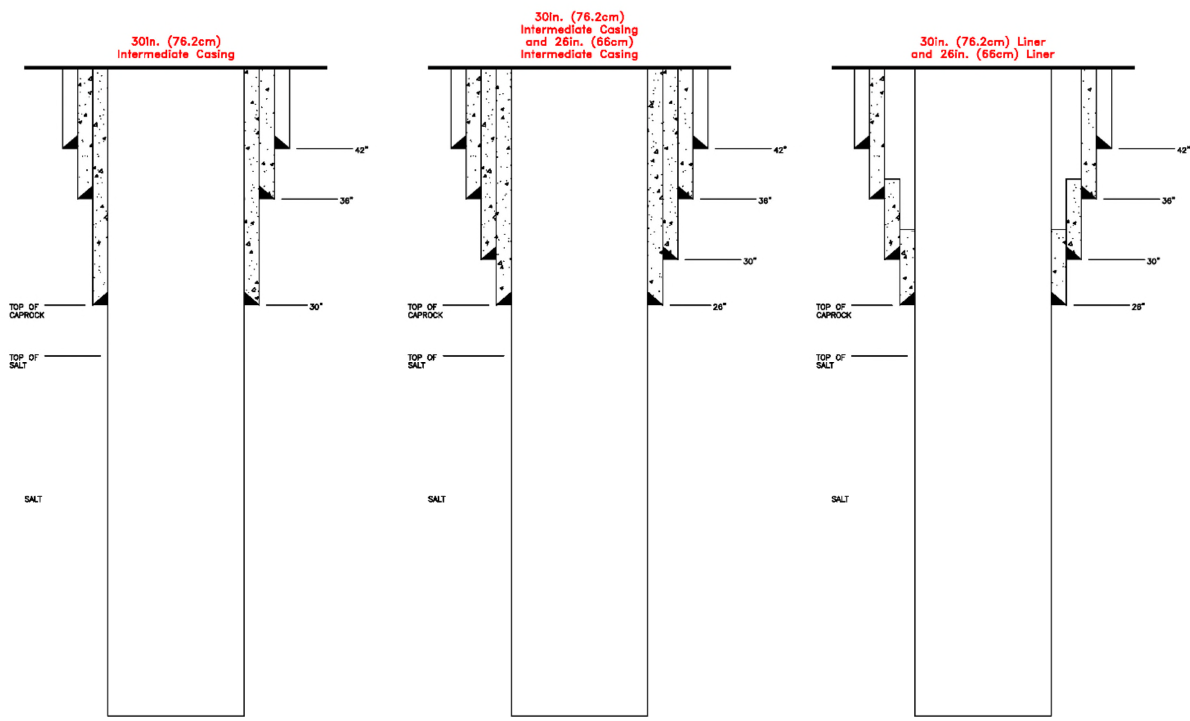

Figure 1 – Intermediate Casing Options

3.0 Engineering

When the concept of running the 30in (72.6cm) string as a nested liner was presented, several options were considered, including conventional liner hangers and subsea wellhead hanger systems. There aren't many conventional liner hanger systems available for this large OD casing and offshore systems would be prohibitively expensive and complicated for the application. Similar liner systems were run many years ago in shallow offshore markets (shelf) but have declined in popularity with the market slowdown in US Shelf operations, so equipment availability and expertise were limited, so the Tubular

Running and Cementing Technologies teams began designing a new casing hanger and running system.

For suspending the liner, an initial design included a custom set of lugs welded into the 36in (91.4cm) host casing that would support the weight of the liner while allowing flow to bypass the hanger during the cementing operation, but relied on bringing cement all the way to the top of the liner to create a “seal” between the two casing sections, which would be difficult to achieve with the large casing and annulus diameters as cement would very likely channel during displacement. A second design was proposed that featured a solid landing ring machined into a sub welded in between casing joints in the 36in (91.4cm) host casing and a mating hanger system that rests on the landing ring inside the 36in (91.4cm) host casing (Figure 2). The hanger features a dual O-ring seal providing a positive seal once the hanger is lowered into the landing ring.

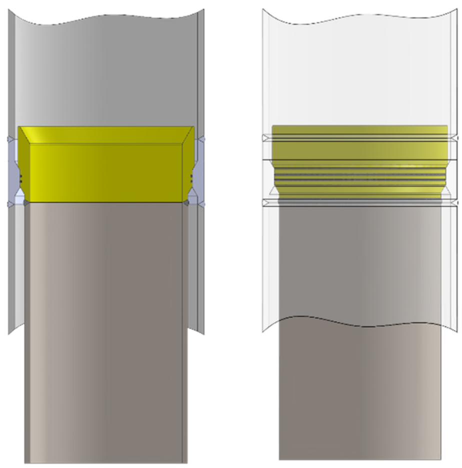

Figure 2 – Liner Landing Ring and Hanger Cross Section

Several options were considered to run and lower the liner into position. Traditionally, large OD casing strings have been landed and cemented using drill pipe run and latched into the float shoe after the casing string was run. The float shoe or collar that the inner string was stung into was designed to support the weight of the casing while lowering into the well, however, these liners were too heavy to utilize this technique. To meet operational timing requirements, a technique used for running contingency liners offshore using a casing fishing spear was chosen, providing the ability to quickly attach the liner to a landing string to lower the liner into position at total depth (TD) and reliably release the casing once landed out. To allow the casing to be washed to bottom and pressure tested, a packer cup design traditionally utilized with Casing Running Tools (CRTs) was adapted to run below the casing spear, sealing on a properly prepared section of the upper ID of the casing just below the casing hanger.

Cementing a liner system is traditionally conducted using Sub-Surface Release (SSR) plugs that are secured inside the casing below the liner hanger and released by drill pipe darts pumped from a surface cement head, however, the large ID and volume of cement to be displaced in large ID casing makes cementing with plugs very challenging, limiting the availability of plug options. As such, large surface casing strings are typically cemented using a stabbed-in inner string that is run as a second trip once the casing has been landed at total depth and supported by slips at the rig floor. This method would be challenging for this application as the liner would have to rest and seal in the landing ring, meaning the cement would have to be bull-headed into the formation, leaving many unknowns as to the weakest zone in the open hole and the depth to which the cement would be pumped. To avoid this issue, a novel inner-string cementing system called SeaCure® was introduced which utilizes a telescoping joint on the inner string to allow a conduit to be spaced out between the casing spear/packer assembly and the float shoe, through the ID of the casing. This conduit from the surface to the shoe allows the liner to be cemented using an inner string while suspended above the landing ring, then lowered into position once appropriate cement displacement has been confirmed, creating a proper "seal" at the liner top and a seal at the shoe using cement pumped from the surface. Once the casing is cemented and landed, a small OD brass ball can be dropped from the surface, landing in a ball seat in the bottom of the inner string SeaCure assembly, and the string pressured up to burst a rupture disk, opening up the inner string to the casing ID so that integrity of the casing string can be tested (against the packer and float shoe). The inner string cementing system and liner running process are illustrated in Figure 3.

One of the concerns with cementing a large diameter casing or liner string is cement channeling, allowing excess cement to reach the surface or top of the liner vs. being placed properly downhole. The risk is compounded in this type of liner application where there is a possibility of having issues releasing the liner hanger running tool after the cement job and having cement harden above the liner hanger. To mitigate risk of the liner hanger running tool being cemented in after the job, a rupture disk sub was placed in the landing string just above the liner hanger running tool (spear) with a ball seat just below the disk, allowing a 2.50in (6.35cm) OD contingency ball to be dropped from surface, isolating the upper portion of the landing string to burst the disk, allowing fluid to be circulated above the liner to flush excess cement away from the liner top.

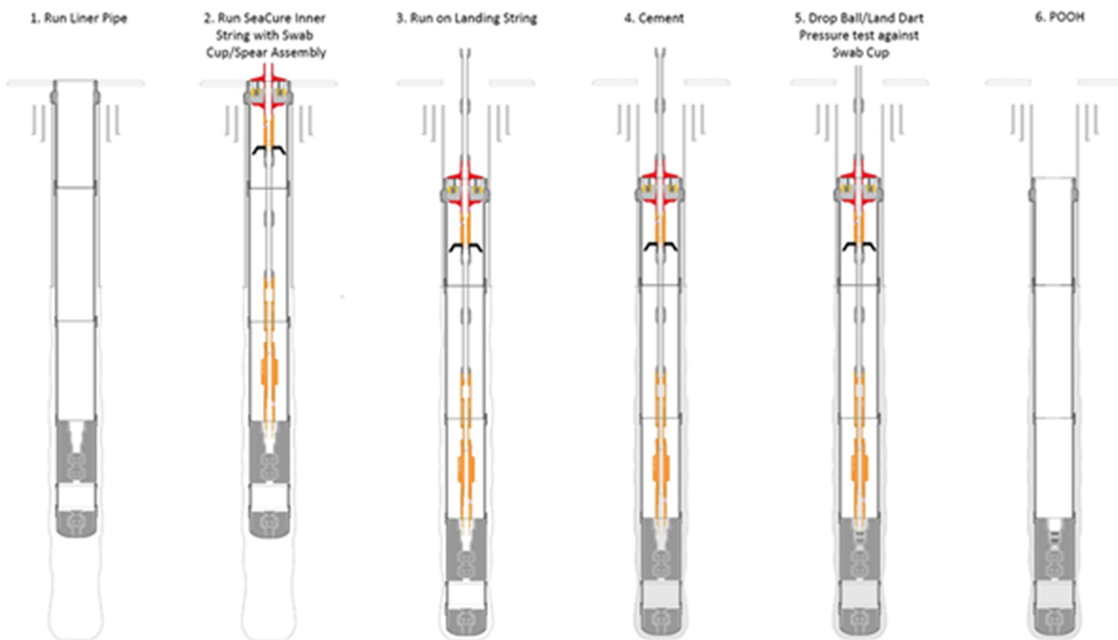

Figure 3 – Liner Running and Cementing Sequence

An estimate was developed to analyze the cost of the liners compared to the cost of a 30in (76.2cm) intermediate casing to surface. The basis of the estimate fell into 4 categories, casing cost, casing running cost, cementing cost and hole opening cost. Rig time was included in both casing running costs and hole opening costs. When comparing a 30in (76.2cm) casing option to the 30in (76.2cm) and 26in (66cm) liner option, the liner option saved significant costs associated with casing as less steel was required. Hole Opening costs were projected to be less as fewer hole opening runs and underreamer runs would be required for the 26in (66cm) liner section. The liner option estimated roughly 30% more casing running costs due to multiple casing crew mobilizations and rig up of casing tools. The estimate indicated cementing costs for the liner option would be substantially more than the 30in (76.2cm) casing option. The cumulative cement volume for the liners would be less than the 30in (76.2cm) casing option as the liner option would have smaller hole volumes through the 26in (66cm) liner section and zero cement excess. The 30in (76.2cm) casing option would have a larger hole volume and required cement volumes with 200% excess to try and get cement to surface. The liner option, however, required specialty inner string cementing tools and a float collar in addition to the float shoe was included on both the liners to provide redundancy during cementing operations. Those two items increased the cost of cementing the liners. Aggregating the costs across the four categories and two options, liners were estimated to be a slightly less expensive option assuming the liners could be run efficiently.

4.0 Regulatory Review and Approval

In Louisiana, The Department of Natural Resources (LDNR) codifies regulations regarding well design and construction in Title 43 Natural Resources, Part XVII Office of Conservation-Injection and Mining Subpart 3. Statewide Order No. 29-3 (Rev. 3) Chapter 3 Hydrocarbon Storage Wells in salt Dome Cavities, Subchapter 317. A review of the regulations found that the casing liners met all the regulatory requirements for Casing Test, Casing Shoe Test, Adequate Cement Isolation, and Cement to Surface. An in-person meeting was set with LDNR to present the liner casing program as this design was new in cavern wells. LDNR wanted to confirm that the USDW would be protected, there would be adequate cement, two barriers to the mining process and regulatory pressure testing of the casing and casing shoe could be completed. The message was communicated to LDNR that the liner design was not new and had been used in continental shelf drilling. The liner design would reduce open hole risk by reducing the length of open hole, time open hole is exposed, and thus making lost circulation more manageable. The liner running process would allow for all regulatory pressure testing and increased the likely hood of a good cement job due to a shorter column of cement, thus reduced hydrostatic pressure on the formation. Following the meeting technical data was provided to LDNR for further review. After reviewing, LDNR approved the liner casing program.

Now with pre-engineering, regulatory approval and cost analyzed, a meeting was set with the client. The discussion began with a review of Wilbert 6 drilling and the issues encountered around the caprock. Risks associated with lost circulation and long open hole sections were discussed as were the casing program options to mitigate the risk. After reviewing the options and costs associated with each, the client approved the intermediate liner option.

5.0 Detailed Design, Engineering and Tool Qualification Testing

The design process began with determining the loads that the liner landing ring must support, including combined effects of tension and pressure of the liner to be supported. The open hole geologic properties were analyzed to determine length of each liner section. Based on the weight of the string (using length and the casing properties (material yield strength and thickness)) and the anticipated maximum internal pressure on the system once positioned in the well, and the max anticipated loading on the system was analyzed to determine the shoulder length of the internal landing ring and interference between the landing ring ID and hanger OD were calculated to ensure the landing ring and hanger could support the anticipated loads, with some safety factor added for any unintended inconsistencies in material yield strength, wellbore loading or other unanticipated conditions of the application. A combination of engineering calculations and finite element analysis (FEA) were used to analyze the system and design the proper components to allow proper function of the system. After detailed drawings were produced, steel forgings were built and machined into functional components for testing.

While landing ring and hanger components were being manufactured, the fishing/running spear was configured to handle the specific weight casing. A packer cup sub designed to adapt a CRT packer cup (Figure 4) to be made up below the casing spear and seal on the ID of the casing, included a contingency rupture disk to allow excess cement to be circulated out of the wellbore in the event that the spear could not be released after the cement job (Figure 5). One concern with the packer cup was sealing on the longitudinal internal weld of the large OD/ID casing string. To eliminate this concern, a layout drawing was made to identify the sealing location of the packer cup inside the top of the liner casing and that area ground smooth to eliminate the weld from protruding in the casing ID, with the weld grind carefully monitored to not reduce the wall thickness of that particular area of the casing that could reduce ratings of the entire liner section. After preparing the ID, the new liner hanger was welded to an 8ft (2.44m) section of casing and a test cap welded onto the bottom to allow a pressure test to be completed once the hanger and packer cup were installed. The entire fixture was housed by a large plate that allowed it to be suspended in a test wellbore, keeping the liner hanger at a safe height for testing, while placing most of the pressure-containing elements safely below ground in the event of a pressure failure.

Figure 4 - 30in (76.2cm) CRT Packer Cup Converted to Spear Packer Cup

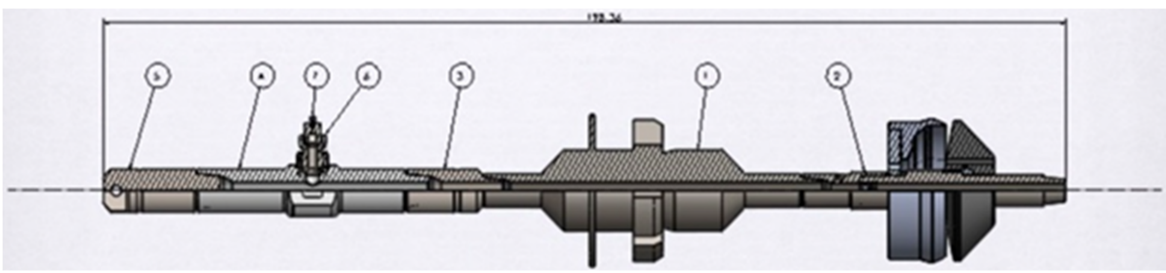

Figure 5 – Spear and Packer Cup Test Assembly

Once the components were completed, the assembly was moved to the test area for function testing (Figure 6). The test casing with hanger was suspended in the test well and partially filled with water. The packer cup/spear assembly was lowered into the casing hanger and the spear manipulated to bite into the ID of the hanger and casing. Confirmation that the spear was engaged was proven by lifting the spear with a tugger line, picking up the entire test casing assembly. Next, the casing was filled with water, venting air in the system through a port in the upper section of the packer cup with a high-pressure hose and ball valve run above the spear, making it easily accessible at the surface. Once the assembly was full of water, the ball valve was closed and pressure applied to the system, pausing at 250psi (1,723.7kPa) increments and ending at 800psi (5,515.8kPa) (Figure 7). This provided a load on the casing spear equivalent to the weight of the casing and inner string with 500psi (3,447.4kPa) of internal pressure at a 1.5x safety factor.

Figure 6 - 30in (76.2cm) Liner Hanger Test Fixture

Figure 7 - 800psi (5515.8kPa) pressure test on 30in (76.2cm) Test Casing, Packer Cup and Spear

With testing completed successfully, production components were manufactured and tool assemblies prepped for execution of the job.

6.0 Wilbert 7 – 30in Liner Installation

Running of the 30in (76.2cm) liner began with the previous 36in (91.4cm) surface casing. The 36in (91.4cm) surface casing was laid out on the pipe rack and the joint with the landing ring for the 30in (76.2cm) liner was identified and marked. The casing was tallied and verification was made that the setting depth of the liner landing ring was greater than 200ft (60.96m) above the float shoe. The 36in (91.4cm) casing was run to 1,365ft (416.1m) RKB (Rig Kelly Bushing) placing the 30in (76.2cm) liner landing ring at 1,159ft (353.3m) RKB. The casing was cemented to surface and regulatory required pressure testing was completed.

The 30in (76.2cm) liner section pilot hole was drilled to a depth of 2,230ft (679.7m) RKB and logged. The hole was then opened to 40in (101.6cm) with a 27.5in (69.85cm) hole opener, a 36in (91.4cm) underreamer and a 40in (101.6cm) underreamer. A 60in (152.4cm) caliper log was run to verify the hole size was large enough to run 30in (76.2cm) casing and try to identify any potential ledges or tight spots. Results from the caliper log showed that the caliper tool preferentially rode one side of the borehole indicating that the borehole was slightly deviated. The caliper arms did show adequate space for 30in (76.2cm) casing to be run to bottom. A “stiff assembly” bore hole assembly was made up which consisted of a 31.25in (79.375cm) center punch and a 27.5in (69.85cm) hole opener spaced 60ft

(18.3m) apart and separated by two 10in (25.4cm) drill collars. The purpose of the “stiff assembly” is to simulate two joints of casing being run to bottom with the ability to use the hole openers to ream any tight spots encountered on the way down. The stiff assembly ran to bottom and found no tight spots or ledges.

Casing crews rigged up the 30in (76.2cm) casing tools, picked up the shoe and second joint, then circulated through the float equipment to verify function. Twenty-six joints of casing were run and set in slips on the rig floor. A spear was picked up and engaged into the liner to take the weight of the 30in (76.2cm) liner. A base plate, bowl and spider were set up underneath the rig floor on top of the 36in (91.4cm) casing. The 30in (76.2cm) liner was then lowered through the rig floor carefully to ensure the ring grooves would not be damaged by the rotary. As the hanger was lowered below the floor, the slips were set on the 30in (76.2cm) liner. The spear was then disengaged and laid down. The rotary bushings were installed, and the casing crew was rigged down.

The inner string equipment was rigged up and the stab in adapter, rigid centralizer and slip joints were run in the hole (Figure 8). When the stab in adapter was close to engaging with the float equipment the packer cup and spear assembly were picked up (Figure 9). The O-rings for the hanger were tied to the spear body and the packer cup was given a coat of grease before being lowered into the hanger. Then the spear was engaged into the 30in (76.2cm) liner and was then lowered until the hanger was just above the 36in (91.4cm) casing and the slips were set again. A pressure testing company rigged up high pressure hoses to the valves and hoses connected to the packer cup. 50psi (344.7kPa) of pressure was applied to the packer cup to verify the packer cup had a good seal (Figure 10). The O-rings were installed on the hanger and a thick coat of grease was applied to the O-rings and the outside of the hanger. The 30in (76.2cm) liner was picked up, then the slips, spider and base plate were removed from the top of the 36in (91.4cm) casing. The 30in (76.2cm) liner was carefully lowered into the 36in (91.4cm) casing to ensure that the O-rings were not damaged by the top edge of the 36in (91.4cm) casing.

The liner landing ring was set at 1,159ft (353.3m) RKB and the liner length was tallied at 1,032ft (314.6m). The plan was to run the liner to a total depth of 2,190ft (667.5m) RKB which would be 1ft (0.3m) above the top of the landing ring. A one-foot gap would allow for circulation of displaced mud during cementing operations. Circulation would be established then the cementing program would commence. The cementing program would consist of a spacer followed by a single slurry of 15.0 ppg (0.065 kPa/m) class A cement. The volume of cement was calculated from the caliper log with zero percent excess. The concern was having cement pile on top of the spear. Then while having cement on top of the spear performing a casing test for 1 hour and having issues with the cement solidifying enough that the spear could not be released.

Figure 8 - Deploying Inner-String Latch-In Stinger with Centralizer and SeaCure Slip-Joint Sub

Figure 9 - Deploying Packer Cup and Spear with Liner

Figure 10 - Pressure Testing Casing Before Running Downhole

As the 30in (76.2cm) liner was being run down hole to the stopping point of 2,190ft (667.5m) RKB, the driller saw that string weight was being lost at 2,014ft (613.9m) RKB. The driller picked up and tried to lower the liner again. The hole was taking the string weight at the same depth so it was believed there may be a ledge or tight spot. Since the liner was being run on a spear, there was concern that if too much string weight was taken by the formation and the spear went into a neutral weight state that the pipe could rotate, and the spear would release the liner. Circulation was established through the float equipment and attempts were made to wash and work the liner past the suspected ledge making sure not to reduce the string weight on the spear to less than 100Klbs (45,359.2Kg). After three hours of working the liner past the ledge and having no success getting the liner deeper, the decision was made to cement the liner in place.

The cementing company was rigged up, lines were tested, then the spacer and cement were pumped. The drill pipe was displaced with mud and the floats were checked. A 1.9in (4.826cm) SeaCure setting ball was placed in the launcher and dropped. Once the ball landed in the circulating sub seat, 2,500psi (17,236.9kPa) of pressure was applied to the ball which burst a rupture disc. This allowed for circulation on the back side of the drill pipe and pressure testing of the casing. However, when circulation commenced, returns were seen in the cellar indicating the packer cup had failed. The decision was made to come out of the hole with the inner string, packer cup and spear assembly. Initial inspection of the packer cup did not show any damage or indications of why a leak occurred. The spear and packer cup were covered in wet cement indicating cement returns through the liner lap (Figure 11).

Figure 11 - Cement Laden Spear and Packer Cup After Run

After 15 hours of waiting on cement a logging truck rigged up wireline to run a temperature log. The temperature tool was run in the hole and sat down at 813ft (247.8m) on contaminated mud and cement. The temperature tool was pulled out of the hole and laid down. Next, the liner lap was to be tested to the regulatory required shoe test pressure with an acceptable test being a 5% or less pressure loss over 1 hour. A pump in swedge was then welded to the 36in (91.4cm) casing to test the liner lap. The swedge was pressured up to 210psi (1,447.9kPa) and the pressure dropped 82psi (565.37kPa) in one hour. The 36in (91.4cm) swedge was cut off the 36in (91.4cm) casing and laid down. A 26in (66cm) center punch and 17.5in (44.45cm) bit were picked up and run in hole to wash out contaminated mud and cement. The hope was that by removing the cement and mud a pressure test of the liner could be achieved using an inflatable packer. The 26in (66cm) center punch washed and reamed contaminated mud and cement from 749ft (228.3m) RKB to 1,315ft (400.8m) RKB, then circulated bottoms up to clear the contaminates.

A logging truck was rigged up and a temperature log was run from the float collar to surface which met LDNR's temperature log requirement. An inflatable packer was then rigged up and run in the hole to 1,023ft (314.6m) RKB, just inside the top of the 30in (76.2cm) liner. The packer element was inflated, and the rig pressured up below the packer to 500psi (3,447.4kPa), but the pressure bled off during multiple attempts. The packer element was deflated and moved up hole to 807ft (246m) and when the element was inflated inside the 36in (91.4cm) casing in an attempt to pressure test the liner lap and casing, the packer element failed. The inflatable packer was pulled out of the hole and it was found that the inflatable packer sleeve was leaking. No other inflatable packers of that size were available. The test cap was welded back on the 36in (91.4cm) casing and pressure test was attempted again, but the leak off rate would not meet the states requirement of 5% leak off over one hour.

LDNR was contacted by phone to discuss the situation regarding the 30in (76.2cm) liner run, cementing, pressure testing and the issues faced during operations. The state regulators were walked through the process, what happened and what contingencies were taken to try and get the regulatory tests, but without success. A few key points were provided to LDNR. The first point was that the 36in (91.4cm) cement job was successful, getting cement to 100ft (30.5m) from surface. A temperature log confirmed the height of the cement and top out job was performed to get cement to surface. In addition to a good cement job on the 36in (91.4cm) casing, the 36in (91.4cm) casing had a good casing test, so the 36in (91.4cm) casing was protecting the United States Drinking Water (USDW). The second point was that since the 30in (76.2cm) liner was set higher, there was now a liner lap of 382ft (116.4m) instead of 206ft (62.8m). Based on the amount of contaminated cement encountered in the casing and the amount of cement seen on the packer cup and spear, cement did come back through the liner lap. In addition, the liner had a shoe track which helped insure good cement around the 30in (76.2cm) liner shoe. The third point was that the 20in (50.8cm) and 16in (40.64cm) casing would be run to surface and cemented provided two barriers to mining operations. The fourth point was a modification to the plan in which after the 26in (66cm) liner was run and cemented, an inflatable packer would be run and set inside the 30in (76.2cm) liner to test the liner lap of the 26in (66cm) liner. After the discussion with LDNR, the same information was transmitted to LDNR with supporting logs and pressure charts. The LDNR approved foregoing the 30in (76.2cm) casing shoe test but emphasized the need for good casing and shoe tests on the 20in (50.8cm) and 16in (40.64cm) casing. With LADNR approval, drilling operations continued.

6.1 Wilbert 7 – 30in Liner Installation Lessons Learned

The team convened a meeting to review the 30in (76.2cm) liner run and discuss how to make the next liner runs more successful. The first issue to be resolved was getting the liners to setting depth. A discussion with the hole opening vendor found that the largest hole opener that could fit through the landing ring in the 36in (91.4cm) casing has arms that extend to 42in (106.68cm). The hole opening program was updated to change the 40in (101.6cm) underreamer to a 42in (106.7cm) underreamer. The stiff assembly for the 30in (76.2cm) liner section would be changed to include three (3) hole openers, a 31in (78.74cm) center punch followed by two 27.5in (69.85cm) hole openers, spaced 30ft (9.1m) apart by drill collars. The 27.5in (69.85cm) hole opener in the middle would stiffen the assembly more and help identify any doglegs or tight spots. While the stiff assembly was in the hole an additional run to wash and ream the lower section where the previous liner sat down would be performed to ensure the liner would run to the setting depth.

Failure of the packer cup and the ability to complete the casing pressure test was the next issue to be resolved. Review of the liner run and inspection of the packer cup did not yield any definitive failure mechanism. It was speculated that when the liner sat down and then was repeatedly worked up and down to get past the ledge, there may have been some deflection in the drill pipe that could have pulled the packer cup to one side of the casing, providing a flow path for circulated mud. Not knowing for sure, the decision was made to pressure test the casing at the surface. The LDNR rules state that the casing must be tested between a 0.7psi/ft (15.8kPa/m) and 0.9psi/ft (20.4kPa/m) gradient. Since there is a column of fluid on the inside of the casing and the outside of the casing, the additional pressure required to meet the gradient creates a differential pressure from the inside of the casing to the outside the casing. Calculating that pressure and testing the casing at the surface would create a greater differential pressure because the original procedure called for the casing test to be completed after cement was pumped. The heavier cement on the outside of the pipe would have reduced the differential pressure across the wall of the pipe. Performing the test at surface would also allow for trouble shooting if the packer cup did not hold pressure.

Setting the packer high and having the packer cup fail created additional issues with pressure testing the liner lap and casing with an inflatable packer. The normal testing procedure calls for the casing test to be completed while the drill string is stabbed into the float equipment, isolating the float equipment from the casing test pressure. With the inner string removed, the float equipment would be exposed and although there are floats and cement, there is not necessarily pressure isolation. Therefore, pressure leaking through the float equipment could affect any pressure testing. The inner string was then redesigned to allow for a 2.00in (5.08cm) OD dart to be dropped, passing through the ball seat for the circulating port and landing in a 2.00in (5.08cm) ID sleeve in the float equipment to lock in place. Pressure could be applied to the dart to verify the float equipment was pressure tight. The procedure to run the liners was changed to land out the liner, then pick up a foot before starting the cementing procedure. This small change ensured that the liner could land out and verified the setting depth so that after cement was pumped, the setting depth would be known when landing out the liner. The vendor supplying the hangers confirmed that when the hangers were landed out, the O-rings would not be damaged and would seal the liner hanger when landed after the cement job.

7.0 Wilbert 7 – 26in (66cm) Liner Installation

A 17.5in (44.45cm) pilot hole was drilled below the 30in (76.2cm) shoe to a depth of 2,962ft RKB and open hole logs were run from TD to the 30in (76.2cm) shoe. The pilot hole was opened from 17.5in (44.45cm) to 32in (81.28cm) using a 26in (66cm) hole opener and a 32in (81.28cm) under reamer. A caliper log was run to verify hole size and showed sufficient hole to run 26in (66cm) casing. Two 26in (66cm) hole openers were configured as a stiff assembly, spaced 60ft (18.29m) apart, run in the hole and washed to bottom. The stiff assembly was laid down and 26in (66cm) casing tools were rigged up.

The hanger on the 26in (66cm) was welded into the previous 30in (76.2cm) liner and was set at 1,803ft (549.6m) RKB, 211ft (64.3m) above the 30in (76.2cm) shoe. The plan was to run the 26in (66cm) liner to the liner hanger, land out the liner then pick up 1ft (0.3m) in preparation for cementing operations. As the 26in (66cm) liner was being run in the hole, the liner sat down hard at 989ft (301.4m). Multiple attempts were made to work the 26in (66cm) liner past the obstruction, but the liner was sitting down hard and no additional footage was made. The depth where the liner was sitting down was very close to the top of the 30in (76.2cm) liner. The decision was made to pull the 26in (66cm) liner out of the hole and lay it down.

When the float equipment was laid down, on one side of the float shoe a chip in the cement and a gouge in the steel were observed. A logging truck was rigged up and a caliper log was run from 2,025ft (617.2m) to 690ft (210.3m). The caliper log showed cement build up on the inside of the 36in (94.4cm) casing above the 30in (76.2cm) liner hanger. When the 26in (66cm) center punch was run inside the 30in (76.2cm) liner to clean out the contaminated mud and cement from the 30in (76.2cm) liner cement job, the 26in (66cm) center punch rode the low side of the pipe leaving a cement sheath on the high side of the pipe. As the 26in (66cm) liner was run in the hole, the cement above the 30in (76.2cm) hanger pushed the 26in (66cm) float shoe to the low side causing the float shoe to set down on the 30in (76.2cm) hanger.

A 33in (83.82cm) center punch was picked up and run in the hole, then washed and reamed cement from 700ft to 983ft, the top of the 30in (76.2cm) liner. A 27.5in (69.85cm) hole opener and a 28in (71.12cm) casing brush were picked up and run in the hole down to the top of the 26in (66in) liner landing ring to ensure any other cement was removed from the 30in (76.2cm) liner. The stiff assembly was picked back up and run to bottom, then the hole was circulated clean.

The 26in (66cm) liner and the inner string were run with the same procedure as the 30in (76.2cm) liner. Once the liner was set in slips on the 36in (91.4cm) casing, the pressure testing crew connecting their high-pressure hoses to the packer cup, pressured up to the casing test pressure and charted the pressure. The casing pressure test passed and the liner was run into the hole. The 26in (66cm) liner was to be set at 2,945ft (897.6m) RKB and land out on the landing ring at 1,803ft (549.6m) RKB. At 2,543ft (775.1m) RKB the 26in (66cm) liner became stuck. Circulation was established and the liner was worked with increasing weights until the liner was unstuck. The liner was then run back in the hole past the tight spot and landed out on the liner hanger. The liner was then picked up one foot in preparation for cementing operations.

The cementing company rigged up and cemented the liner in place with 575bbl (91.4m^3) of 15lb/gal (0.065 kPa/m) cement, which is slightly less than gauge hole volume. Drill pipe was displaced with mud, the floats held and the packer cup and spear assembly were laid down. A logging company was rigged up and a temperature log was run. The temperature tool sat down at 1,315ft (400.8m) RKB and multiple attempts were made to work the tool past this depth without success. A 27.5in (69.85cm) hole opener was picked up spaced 72ft (21.95m) above the bit, run in hole and washed cement from 1,317ft (401.4m) RKB to the top of the 26in (66cm) hanger. The logging truck was rigged up again and another temperature log was run, but the temperature tool sat down at 1,920ft (585.2m) RKB. The logging truck was rigged down and an inflatable packer was rigged up. The inflatable packer was run in the hole to 1,780ft (542.5m) RKB and set. The pressure testing company rigged up to the rig stand pipe and pressure tested the liner lap to 300psi (2,068.4kPa) for one hour for a successful liner lap test. The inflatable packer was laid down and a 23.5in (59.69cm) hole opener was picked up and run in the hole. The float collar, shoe track and float shoe were drilled. The inflatable packer was picked up again and run in to 2,900ft (883.9m) RKB. Attempts to test the 26in (66cm) casing shoe were unsuccessful and were attributed to the formation and not the shoe. The LDNR was notified of the issue and provided approval to continue drilling operations.

7.1 Wilbert 7 – 26in (66cm) Liner Installation Lessons Learned

The team met again to review the previous liner run and several issues were discussed. The first issue was contaminated mud and cement in the casing that prevented temperature logs from being run and required additional runs in the hole with hole openers and casing brushes to clean the casing. Cement volumes as pumped were clearly getting above the liner lap, most likely due to channeling as the volume pumped was slightly less than gauge hole. Further reduction in cement volume was proposed, but the contamination issue inside the pipe would likely not be eliminated.

An idea was then proposed to put a circulating sub with down jets in the bottom section of the inner cementing string. Once cementing operations were complete, a circulating sub with jets could be used to circulate out the cement and wash the green cement out of the casing as the inner string was slowly pulled out of the hole. After discussion with the inner string cementing tool provider, a circulating sub was designed, and the plan was to use the sub on the next liner run (Figure 12). The circulating sub was designed to hold pressure during the cement job, then a ball dropped from the surface landed in a shifting ball seat in the sub, exposing a series of flow ports that were designed to provide as much circumferential wall-jetting velocity as the rig's pumps could provide when pulling the inner string out of the hole. The ball seat inside the circulating sub was designed to allow the 1.90in (4.826cm) setting ball to pass during the previous cementing operation, then catch a 2.25in (5.715cm) ball to shift the sleeve down, forcing the fluid out of the now-exposed circulating ports.

Figure 12 - New Shear Sleeve Circulating Sub

Each liner run encountered issues with ledges/tight spots and getting the liners to setting depth. A number of factors were contributing to this issue. The first being the reduced weight of a liner compared to a full string to surface. A heavier casing string can better push through tight spots as the formation will give way to the weight of the casing. The second issue was the inability to put the full weight of the liner on the formation due to concerns that the spear may release. To manage the issue, it was decided to enlarge the hole for the 26in (66cm) liner by running an additional 36in (91.4cm) underreamer.

8.0 Wilbert 8 - 30in (76.2cm) and 26in (66cm) Liners

The 30in (76.2cm) liner in Wilbert 8 incorporated the lessons learned from Wilbert 7, was successfully run and cemented in place. Key steps to getting the liner to setting depth were opening the hole to 42in (106.7cm) with an underreamer and back reaming each stand with the 42in (106.7cm) underreamer. Additionally, a stiff assembly was run with a third hole opener and the bottom section was rewashed to ensure there were no casing running issues. Once the liner was landed on the hanger ring, the liner was picked up and cementing operations commenced, pumping slightly less than a gauge hole volume of 15lb/gal (0.065 kPa/m) class A cement.

This liner installation would be the first use of the circulating sub to wash contaminated mud and cement out of the casing as the cementing inner string was pulled from the hole. Operations of the circulating sub did not proceed as expected. After cementing, the dart was dropped, landing in the float collar and locking in place. The dart was pressure tested successfully. Then a 2.25in (5.715cm) ball was dropped and landed in a ball seat in the circulating sub. Pressure was applied against the ball to shift the circulating sub, but excessive pressure was required to establish circulation. The inner string was rotated and slowly pulled out of the hole while circulating. Contaminated mud and cement were seen at the surface as returns were taken in the cellar.

When the circulating sub reached the surface, the sleeve had not shifted at all. The contingency circulating port disc ruptured, and circulation was established through that port. While this did establish circulation and clearly helped wash green cement and mud to surface, the process was reviewed. The team found that since the inner string was stabbed into the float collar, when the sleeve tried to shift downward, the sleeve became hydraulically locked as the fluid inside the drill pipe had nowhere to go. The circulating sub procedure was then revised with an additional step to unsting the drill pipe from the float collar prior to shifting the circulating sub sleeve.

Contaminated mud and cement in large volumes continued to be an issue. As a precaution, a 26in (66cm) hole opener was picked up and used to wash the 30in (76.2cm) liner prior to future drilling operations. Additionally, the cementing program was reviewed to reduce contamination in the casing and three changes were proposed for future liner cement jobs. The first change was to circulate the well until all dehydrated mud was circulated out of the mud system prior to pumping cement. The second change was while circulating out dehydrated mud, thin the drilling mud with fresh water to reduce viscosity. A reduced mud viscosity should reduce the channeling of the cement. The third change was to reduce the pumping rate of the cement from 8bbl/min (1.27m^3/min) to 4bbl/min (0.64m^3/min) to further reduce cement channeling. The cementing company was consulted regarding the pump times required to halve the pump rate and the cement blend was updated to accommodate the increased pump time.

The 26in (66cm) liner incorporated previous lessons learned and was successfully installed. The revised cementing and circulating sub procedures were successfully implemented. No contaminated mud or cement was seen at the surface, therefore a cleaning run with a hole opener was not required inside the 26in (66cm) liner. The temperature log was successfully run and showed adequate cement. All regulatory pressure testing of the casing, liner lap and casing shoe were successfully completed.

9.0 Current Tool Design Limitations

For the liner running and testing, several limitations were discovered during job execution. First, the transition between running casing and landing the casing was challenging. The hanger joint did not have a box casing connection, so picking up the last joint of casing with the traditional casing running equipment was not possible. A custom handling assembly was required that added 4 hours of handling time to the operation.

Once the hanger joint was made up to the casing string, the entire liner needed to be lowered through the rig floor and hung in the cellar to allow the inner string to be safely and efficiently run from the rig floor vs. rigging up a false rotary and having the rig crew run the inner string from a platform. Traditional

CRT could not be lowered below the rotary and due to limited contingency spear/packer availability, a second spear was required, which added additional cost to the operation. Because of slight rig misalignment, it was also difficult to make up the spear into the casing at the rig floor. Once the casing was suspended with the spear, the casing handling spiders were repositioned in the cellar, the liner was lowered below the rig floor and liner suspended in the repositioned spider. When the liner weight was transferred to the spiders, the spear became unlatched from the casing. Due to the rig misalignment and location of the top of the casing, it was difficult to relatch the spear to lower down to the cellar to swap out the running tool, adding additional rig time. Once the casing was lowered to the cellar, the rig misalignment made it difficult to set the spear/packer running tool and for the packer cup to seal. Several attempts to center the spear into the casing were made before finally centering the spear/packer cup into the casing hanger and allowing a proper pick up and sealing of the packer cup.

10.0 Future Design and Implementation

After completion of two wells and several lessons learned over the four liner runs, there was a pause in drilling activity that allowed time for consideration of the operational activities to improve future performance. The first improvement to be recognized was the deployment method utilizing the casing spear and packer cup to run the liner and test the casing. There were always concerns about premature release of the hanger once casing weight went to neutral and the ability of the spear to transmit rotating torque to the liner string. The packer cup assembly worked under surface conditions where casing and inner string alignment could be controlled, but downhole, the packer was not as reliable as desired.

An examination of previous offshore shelf designs and collaboration between operations, engineering and sales teams led to the design concept of a new liner hanger and running tool design (Figure 13). The new design would replace the packer cup with a proper O-ring seal between the running tool and casing hanger, to maintain alignment and pressure integrity throughout the running and cementing operation. The new running tool features a retractable dog system to support the liner string weight while running in the hole, providing positive tensile and compression loading capability to run the liner to total depth. The dogs are locked in position by a sliding sleeve that is held in position until hydraulic pressure is applied to a mating sleeve to shift the locking sleeve down, removing support for the dogs and allowing them to retract once the liner weight is removed from the system, i.e. landed in the liner hanger landing profile. The new running tool also features torque lugs to transmit right hand rotational torque through the drill pipe and into the liner string to roll the pipe off of any ledges or restrictions encountered in the open hole section of the well. The design of the running tool also provides a mechanical secondary release should the dogs fail to retract properly. One-quarter turn to the left once the running tool is placed into compression moves the dogs into a relief groove, allowing them to be pulled vertically out of the liner hanger. The new running tool also features a contingency ball seat, allowing an additional circulation port to pump channeled cement off of the top of the running tool should both primary and contingency liner releases not function properly.

The design of this new running tool will also allow the liner hanger system to be pre-assembled, picked up and lowered below the rotary to the cellar without any special handling equipment, saving rig time and reducing risk of damage to personnel or equipment.

At the time of this report, the new 30in (76.2cm) running tool internal components have been successfully tested by pumping a 2.00in (5.08cm) OD dart through the new running tool, then dropping a 2.25in (5.715cm) OD ball into the hanger ball seat to shear the screws and shift the dog sleeve down, exposing the dogs and allowing them to retract successfully. The remaining components have been received, and full-scale testing will occur mid-April 2025.

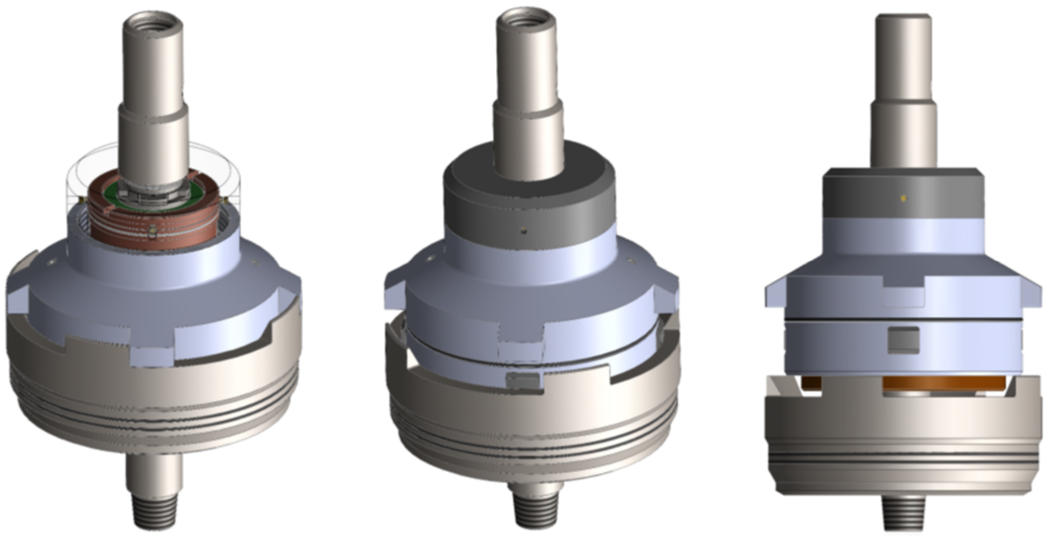

Figure 13 - New Liner Running Tool and Hanger

The liner design is another area identified for cost and drilling optimization. When the liner concept was being developed, the casings used in the design were either already purchased or the only casing available at that time. Future casing designs will look to reduce casing wall thickness for several reasons. The first reason is simply cost. The less steel required, the less expensive the casing. This assumes that a thinner wall casing will meet collapse and burst rating requirements. The second reason is thinner wall casing allows for larger hole openers or underreamers to pass through. Using larger tools to open the hole for future hole sections could reduce the number of hole opening runs required, reducing tool and rig time costs.

With four successful cement jobs completed, no float collar failure, plus adding the latching dart which holds pressure from below as a redundancy to the float valves, the decision has been made to move to only running a double valve float shoe. This will reduce the cost of the float collar, welding costs, eliminates the shoe track, which will also reduce drill out time and should improve bit performance while drilling the next open hole interval.

11.0 Large Diameter Liner Cost

Costs associated with intermediate casing liners were projected to be a slight savings versus an intermediate casing run to surface and a significant savings versus two intermediate casings run to surface. In implementing the liners, various issues were encountered which incurred additional cost. This was not unexpected as the four liners run were proof of concept. The result of which is a design and procedure to successfully and efficiently run large diameter liners.

There are a few other insights regarding costs from the proof of concept. The cost of a single liner run versus a single intermediate casing to surface is significantly less. The drivers of the savings are reduced casing cost and time to run the liner. The cost of running two liners in place of a single intermediate casing to surface while calculated to be a slight savings is realistically comparable in costs, maybe slightly more. The driver of those costs are multiple mobilizations of contractors, additional logging runs, additional trips for hole opening and associated rig time for each. The purpose of the liner however is to mitigate down hole risk, therefore these costs are really a savings monetarily or in risk reduction when compared to other casing design options.

12.0 Future Applications of the Liner Design

The need for intermediate casings in cavern well casing design will continue as trouble zones are encountered and wells are completed in deeper salt. Intermediate liners can be used in lieu of any intermediate casing set below the surface casing and above caprock assuming the liner and previous casing(s) meet design spec for downhole conditions. It is not recommended to use liners as a secondary barrier to the cavern. If there is room in a casing program for a contingency casing, a liner landing ring could be run in the previous casing as cheap insurance if the contingency casing is needed, as the contingency casing would not need to be run to surface. The goal for these liners is to be able to run them efficiently, keep the inside of the casing clean, meet regulatory requirements with a cost-effective solution to manage downhole risk.

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