Abstract

Historically, cemented plug and perf completions have been used for wells requiring multistage fracturing and stimulation in the North Sea. This is a well-known and trusted process, but also time consuming. Often the turnaround time per stage in the North Sea is 3-7 days. With high rig and frac vessel rates, this excessive operational time can negatively impact project economics and well payback times. Consequently there is a drive to develop new systems to gain efficiencies without compromising the quality of the planned stimulation treatments in these applications. This paper will review two newly developed novel completion systems that significantly reduce time spent performing multistage stimulation in environments where cost and consequence of failure are high.

North America land frac operations rely heavily on ball drop actuated frac sleeve systems now commonly available in the market, however these typically require some over displacement of the previous frac stage and typically are only available for un-cemented liners. Hence, these are not always a good fit for North Sea frac applications. In order to prevent compromising the required stimulation treatment and allow flexibility to run cemented reservoir liners with frac valves, new technologies had to be developed. Both coiled tubing and wireline manipulated sliding sleeve/valve systems and ball-drop actuated systems have been developed and deployed depending on the various completion and stimulation challenges faced. Since the first installation in 2009 these systems have been proven and refined in multiple wells for two large operators. Various well installations will be discussed, illustrating that systems are being tailored for open hole and cemented environments both for proppant and acid frac stimulation treatments. The paper will give the audience insight into the depth of options available with these systems and explain how they are tailored for different types of stimulation and zonal isolation requirements. In addition operational considerations and experience will be shared.

Testing and field data will be presented to verify the development, installation, operation and success of these systems. This data include pressure and temperature data, downhole monitoring during stimulation and sleeve manipulation. An overview of the results and efficiencies achieved in the installations will be presented and compared to conventional methodologies. These completion solutions have a broad application in areas where fracturing and stimulation is required and project cost and risks are significant, both in conventional and unconventional stimulation and fracturing operations.

The installations discussed in the paper include first ever proppant frac done offshore through these systems, and introduction of specially developed intervention tools to aid the operation of the system. It also covers the first ever successful installation of cemented frac valve reservoir liner completions in an offshore environment as well as the use of dissolvable frac balls.
Background

In the North Sea area the stimulation needs of wells are quite diverse. Large carbonate fields are being developed that require everything from matrix acidizing, high rate acid fracs through to crosslinked gel treatments with tip screenouts. There are also tight gas fields that require various designs of proppant fracs in order to yield economical production. In acid stimulation applications overdisplacement is typically not considered an issue. The major concern in a horizontal well completed with transverse fractures is the connectivity between the wellbore and the fractures (van Gijtenbeek et al. 2012). For proppant fracs with tip screenout it is imperative to underdisplace to ensure good connectivity to the conductive hydraulic fracture created. These issues many times will drive the selection of optimal completion and stimulation methodology.

Figure 1: Typical horizontal well with transverse fractures

Infill drilling and development of smaller satellite fields often require subsea wells, or wellhead platforms to be used. Common for all these projects is that drilling, completion and stimulation will typically require offshore rig and frac vessels to be mobilized with very high operating costs. Intervention and workover cost are also high, hence the optimal stimulation design needs to be placed in each zone the first time. Due to the high spread costs involved, excessive operational time and poor production will quickly impact project economics and well payback times. For many of the fields in the North Sea requiring stimulation, cemented plug and perf completions have historically been used. It is a flexible solution in terms of the various types of stimulation designs that can be accommodated. However, due to the large number of perforating runs required, bridge plug setting, retrieving or milling involved and clean outs runs required, it is also very time consuming. The turnaround times per stage have been well documented and often range from 3-7 days (Norris et al SPE-70133). These conditions lead to a continuous drive to optimize efficiencies and create solutions that improve on the overall economics of the projects. This paper will describe the chronological development, qualification and field trialing of two distinct lower completion systems based on the evolving needs of major international oil companies developing fields requiring stimulation in the North Sea.
Prototype development, testing & qualification

Sliding sleeves have been used for flow-control purposes in oil and gas wells for decades. Although simple in design many users have questioned their reliability and they did not see much use for fracturing operations until the mid-2000s when ball drop activated sliding sleeves started entering the market. The method of choice for stimulating a reservoir with a cemented liner stage by stage has been by using plug and perf methods. Plug and perf provides a proven method of initial stimulation, compartment for compartment, but provides no solution for efficient production management over the life of the well.

The entry into the stimulation sleeve market for Trican was triggered by a need in 2008 for a robust sliding sleeve that could be used for multiple applications on a major operator’s field offshore Norway. This initial new product development project materialized into the 5.5" CT activated valve. A high-performance, mechanically operated stimulation/production valve for 8.5" OH. The key parameters in the development of this sleeve were mechanical robustness to be able to cope with the subsiding reservoir, erosion resistance to cope with planned proppant placement, scale tolerant to be able to cope with known scaling issues in the field and sealing integrity for the life of the well to allow future production management and water shutoff. The sleeve would be operated by pipe or coiled tubing and a flow activated shifting tool.

The field the equipment was designed for is a mature chalk field and the reservoir is undergoing considerable subsidence. To cope with the geomechanical forces these wells are typically designed utilizing heavy wall liners. The initial targets for the CT activated sleeve's mechanical ratings were taken from the specifications of a 5.5" Q125 45.5# liner with Hydril WT46 connections. After agreeing on the final design criteria, the project was kicked off in April 2008. The planned activities included final detailed design, a 3rd party design verification by DNV and prototyping followed by erosion testing, function testing with CT tools and testing to ISO 14310 V3.

Figure 2: Valve after erosion testing

Figure 3: Test setup for erosion flow testing
The design and verification was finished in the beginning of June 2008 and the prototype testing started in July. The first test was a 3rd party qualification test program performed by IRIS (International Research Institute of Stavanger) in accordance with ISO 14310 V3 grade. The next test was to simulate a flow rate of 6000 l/min with 4 ppa ceramic proppant through the 16 sleeve ports. To protect the sleeve all the ports had been fitted with tungsten carbide nozzles and the inner surfaces were coated with anti-abrasion coating. The test was performed at the facilities of a major service company in Stavanger, and proppant laden frac fluid was circulated through the sleeve for 8 hrs. The sleeve was then taken back to the Trican facility and opened up for visual inspection. No signs of wear were found. Immediately after the inspection the sleeve was re-assembled and function tested with both 3rd party shifting tools as well as our own shifting tools to verify that the sleeve was functioning and that shifting profiles were working as designed after pumping proppant past them.

After all the testing was concluded and accepted by the client a series of 14 sleeves were manufactured for the first installation in an 8.5" OH. Due to other delays the first installation was however not done until July 2009, and that provided time to do a test on the sleeve in accordance with ISO14310 V0 criteria, thus allowing the 5.5" CT activated valve to be considered as a barrier during the installation. The sleeve was gastight through the entire test program and was V0 qualified at 15,000 psi and 350 F.
First Open Hole Coiled tubing operated MSF sleeved completions in the North Sea

The first CT activated valve lower completion was run in July 2009. The next two wells with 5.5\textit{\textdegree} CT activated valve were installed in September and November the same year. Below is a summary of the completion design for the three wells:

- Well # 1, Horizontal Producer well, 5.5\textit{\textdegree} liner in 8.5\textit{\textdegree} OH, 10 Zones with CT activated valves & metal expandable packers,
- Well # 2, Horizontal Injector well, 5.5\textit{\textdegree} liner in 8.5\textit{\textdegree} OH, 13 Zones with CT activated valves & Swellpackers,
- Well # 3, Horizontal Injector well, 5.5\textit{\textdegree} liner in 8.5\textit{\textdegree} OH, 13 Zones with CT activated valves & Swellpackers,

These three wells were stimulated shortly after installation. Although originally planned to be stimulated with proppant the operator decided to run acid stimulation jobs instead, due to the reservoir thickness encountered in the wells. All of these wells used coil tubing intervention to operate the sleeves. Liner cleanout and conditioning was a key aspect of preparing the wells for trouble free stimulation operations. Specially designed hydraulic shifting tools were used with the coil to operate the valves. Impact hammer for coiled tubing was also available in case additional force was required in the long horizontal wells to operate the valves. The general operational procedure was as follows;

1. Rig up coil equipment.
2. Perform liner clean-out with motor and mill to TD. Pump soap pill as necessary.
3. Perform a clean-out run with venturi junk basket.
4. Open zone #1 sliding sleeve using hydraulic activated shifting tool.
5. Perform reservoir break-down and pump test in zone #1.
6. Stimulate zone
7. Close zone #1 using hydraulic activated shifting tool, and pressure test to verify closed well.
8. Repeat step 4 -6 for all zones, last zone sliding sleeve will not be closed after pump test.
9. After stimulation of last zone RIH to TD, activate shifting tool and open all sliding sleeves while POOH.
10. Hand the well over to production.

![Figure 5: i-Valve CT operated MSF completion with OH packers](image-url)

Following the successful qualification and deployment of the 5.5\textit{\textdegree} CT activated valve, versions were scaled to fit both 3.5\textit{\textdegree}, 4.5\textit{\textdegree} and 7\textit{\textdegree} tubing and successfully ISO 14310 V0 tested and installed for several other clients in both stimulation and regular SSD applications.
Ball drop actuation and multi entry sleeve design

The next step in the evolution of the CT activated valve family was driven by a need from operators in the United States. Since 2008 clients had approached asking for a ball drop activated sleeve system allowing multiple sleeves to be opened by a single ball. A system like this would allow multiple stimulation exit points to be opened within each stimulation stage by one ball; this would eliminate the need to cluster perforate to achieve the same. The initial ball drop sleeve system was designed for use on 4.5” tubing for open hole in the Bakken shale. The initial system design was built around replicating a 4 cluster perf job by running 4 sleeves for each stage. In order to achieve this, a flex-seat had to be developed that would allow the ball to open and pass several sleeves. In addition, a regular fixed seat sleeve to stop the ball in the final sleeve of each stage and isolate below stages had to be developed. All 4 sleeve seats within one stage would have to rely on the same ball size, and this would allow one ball to open each of the flex-sleeves before opening the last fixed sleeve and isolating the previous stage.

A system was designed in Norway and a first prototype proving the functionality of the flex seat sleeve was built in Norway and tested at the IRIS facility in Stavanger. The remaining prototypes were manufactured and assembled in Houston.

The system was first subject to a land trial. This was performed in Bryan, Texas in mid-May 2010 and involved rigging up a single stage with 4 sleeves inside a casing and bringing in 4 frac trucks to pump 4 ppa 40/70 sand through the assembly for 1 hour before dropping a ball to open all sleeves. The max rate pumped during the test was 48 BPM. The ball successfully opened all sleeves in the test setup. All the equipment for the field trial had been manufactured in parallel to the prototypes so with the successful land test, the field trial equipment was ready for installation within one week. The equipment was shipped to North Dakota and 2 sets were installed in stage #15 and #16 in the trial well in the Bakken Shale together with 3rd party open hole isolation packers. 3 sleeves were run in each stage. On both stages the ball landed with a rate of 12-13 BPM and a good pressure signature indicated that all 3 sleeves in the stage were opened by the ball. During this field trial a mix of sands was pumped but the total amount of proppant pumped into the well was 2,573,000 lbs. Since this field trial the ball drop activated valve system has been the backbone of the ball activated frac sleeve solution.

Figure 6: Test setup with frac trucks
Moving to cementable MSF sleeved completions

Until 2011 all installations had been in open hole completions. However, many fields require liners to be cemented for a variety of reasons, hence there was a drive to develop frac sleeves that could be cemented;

- In many areas zonal isolation with cement is a statutory requirement.
- Many fields have successfully used cement to isolate fracs and do not want to change to open hole packers
- Drilling and hole stability issues often mean hole washouts and irregularities prevent deployment of open hole packers in high pressure applications
- A cement filled annulus will typically allow the frac to be initiated at the sleeve, whilst in open hole the frac can initiate anywhere between the open hole packers.
- During a stimulation job the well will see multiple extreme pressure and temperature cycles. Cement will provide isolation and prevent axial movement of the liner during stimulation.

The next step in the stimulation sleeve evolution was adapting the system to enable it to be run in cemented liner applications. The object was to be able to cement directly through the sleeves without the use of inner-strings etc. The sleeves would be wiped clean on the inside by the cement dart. The basis for the cementable ball drop activated valve system was the sleeve for open hole. Only small modifications were made to the sleeves, this included surface treatment to critical parts and incorporating mechanical cement protection features. In addition an upper Otis type profile was added to be able to close the sleeve with shifting tools. This feature would be used in case water had to be isolated from any of the stages stimulated.

The cementable ball drop frac sleeve system was tested and qualified in much the same way as the original open hole ball drop activated sleeve system. First a string of 5 ball seats in decreasing sizes were rigged up in series. A batch of cement was pumped through, followed by a wiper dart, followed by clean water. This test was done to ensure that a "floppy dart" would wipe the ball seats properly clean and to ensure that the pressure needed to pump such a dart through the sleeves is far less than the pressure needed to activate the opening of the sleeve. This test has since been repeated many time to qualify the cementable ball drop activated valve system with various liner hanger/wiper dart combinations and wiper darts have been pumped through as many as 80 sleeves without any problems.

Second, a system test was performed where 2 ea. cementable ball drop activated sleeves were installed inside a 9-5/8" casing. Cement was pumped down on the inside of the sleeves and up through the sleeve-annulus inside the 9-5/8" casing. A cementing dart was pumped down the tubing to wipe clean the ID of the cemented sleeves. Then the ports to the annulus were closed off, and the cement was left for 2 days to set up. A cement sample was taken before attempting to open the sleeves with ball, it confirmed that the compressive strength of the cement had reached 3000psi.

The two cementable ball drop activated sleeves cemented in the casing had 2 different seat sizes so two different size balls were used to activate them individually. Both sleeves opened as expected within the predicted opening shear pressures. All this testing was performed in Lafayette in Louisiana in January 2011. After the cement test the test cell was shipped back to the Houston facility to test the open-close function (OC). This was done by pulling the sleeves closed with a shifting tool on a hydraulic ram multiple times. After this the whole test cell was cut in half right down the centerline in order to inspect that no cement had ingressed into critical areas, the inspection confirmed that the cement protection features had worked as planned. No cement residue was found in critical areas of the cementable ball drop activated sleeve.
First Cemented ball drop MSF sleeved completions in the North Sea

Following the successful land test the first cementable ball drop activated sleeve system was installed in the field offshore Norway in July 2011 when 73 cementable ball drop activated sleeves were run to depth and cemented in place as a part of a 5" reservoir liner in 6.5" hole. The 73 sleeves were split in 4 stimulation stages with the following sleeve distribution:

- Stage # A, 1 ea Fixed seat Frac Sleeve, 16 ea Flex seat Frac sleeves, opened by 2.875" ball
- Stage # B, 1 ea Fixed seat Frac Sleeve, 18 ea Flex seat Frac sleeves, opened by 3.125" ball
- Stage # C, 1 ea Fixed seat Frac Sleeve, 18 ea Flex seat Frac sleeves, opened by 3.375" ball
- Stage # D, 1 ea Fixed seat Frac Sleeve, 17 ea Flex seat Frac sleeves, opened by 3.625" ball

In order to distribute the acid within each stage a limited entry design was incorporated by tailoring the flow area of the sleeves. Each individual sleeve had 3 flow ports with 0.19" diameter. The stimulation was planned as a limited entry high rate acid job so this would ensure proper distribution of acid over the entire stage at high pumping rates.

![Figure 9: 4 stage cemented ball drop actuated MSF completion with 73 sleeves](image)

Equipment was loaded to the rig using tubing cassettes pre-loaded according to the planned running tally. This worked well in ensuring that sleeves were picked up and run in the correct order. The entire liner was made up in just over 11 hours from picking up the shoe. The liner was cemented using foamed cement slurry. The cement was pumped down the well with good indication of the liner wiper plugs landing in the liner shoe at expected volumes. There were no pressure indications as the cement wiper dart passed through the ball drop activated valve seats.

Before stimulation could start it was planned to make a perforating run on tractor to establish injectivity below zone A in order to drop balls to sleeves. Due to heavy barite sagging running tractor to TD was impossible. It was decided to clean out the well to remove the barite, then run Coiled tubing with impact hammer and bullnose to mechanically shift the lower sleeves open to establish injectivity. This was successful and the stimulation vessel was called in to start the pumping operations.

Typical stimulation sequence was as follows;

- Pump preflush through open sleeves, 3-60 bpm, establish max rate.
- Hard shut-down, establish ISIP
- Pump 28% HCL, up to 60 bpm
- Pump overflush
- Drop ball for next stage

All 4 zones were stimulated successfully at rates up to 60 BPM rates with 28% HCL. Balls were pumped and landed at 3-5 bpm rates with good indication of sleeve opening. Rates were then ramped in steps up to 12 bpm to open all sleeves within each stage, again with good indication on the DHPG of sleeves opening.
After opening the first stage with coiled tubing the remaining 3 stages with 56 sleeves in total were successfully opened by actuation balls dropped from surface, over 4000 bbls of 28% HCL acid was pumped per stimulation program. By doing this job with the cementable ball drop activated sleeve system the operator used 1.5 days to perform the same stimulation program that earlier would have taken 40-50 days using the old completion methodology. The cementable ball drop activated sleeve system rapidly established itself as a real alternative to plug and perf and in January 2012 a second well was completed for the Norwegian offshore operator.

One the second job, a 17,000 ft. horizontal oil producer, 39 sleeves were run across two stages. Make up and installation went according to plan. Cement was used for isolation purposes due to high contraction forces during stimulation and for isolation between each stage. Cementing darts were pumped and landed at theoretical displacement volume and a successful pressure test to 5,000 psi was conducted. Based on the learnings from the first well a clean out run was planned. The entire well was cleaned up by using washpipe prior to installing the upper completion. Subsequently a tractor was used for a drift and logging run prior to stimulation. None of the sleeves were opened prematurely. Ten holes were perforated below the first sleeve stage to achieve injectivity. A 3.375" ball was dropped to open the 19 sleeves in the lower stage. The ball landed in the lower seat and provided isolation to the lower perfs during the acid matrix stimulation. Subsequently, a 3.625" ball was dropped to open the 20 sleeves in the upper stage. The ball landed in the lower seat of the upper stage and provided isolation of the previous stage during the acid stimulation and hence each stage was individually stimulated. After opening the sleeves, the cement broke down at low pressures. Each stage was stimulated with high rates close to 60 BPM. Friction calculations proved that the sleeves opened as designed.

A good water hammer effect was seen after the stimulations indicating a good stimulation job. This was supported by high oil production from both stages with very little drawdown. The stimulation results, combined with the operational efficiency and reduced intervention operations, left the operator very pleased with the result.

Figure 90: Treatment plot for Acid Frac through sleeves
More stages, production management features & dissolving balls.

A 2,100 meters multi-stage frac job was planned together with a major operator on the Norwegian Continental Shelf using the cementable ball drop activated sleeves in a 4½” reservoir liner in 6.5” hole. The well is a horizontal producer and the OC (open/close) functionality enables the operator to close sleeves at a later stage with a shifting tool in order to shut off water and/or crossflow. The possibility to adjust the frac port size proved useful for the design engineers when designing the frac for a reservoir with varying layer thickness. The initial option was to run an open-hole completion with swell packers for zonal isolation, with a contingency to run the reservoir completion as a cemented liner if required due to challenging hole-conditions. Drilling proved to be a challenge and decision was made to cement the liner with a reduction from eight to five frac stages with the following setup:

![Diagram of 5 stage cementable ball drop actuated completion with multi entry setup](image)

The liner was cemented and the wiper dart bumped after having passed all sleeves without any problems. Cleanout was done prior to stimulation. The first ball drop activated valve stage was opened by running coiled tubing with a ball nose tool and an impact hammer. This was done to provide an injection point for displacement of frac balls for later stages. During liner run-in TD had to be set high due to collapsing hole, resulting in incorrect space out of the frac sleeved completion. A decision was made not to open stage five as it was too close to previous liner shoe. Stages 1-4 were fracked successfully using a built-for-purpose frac vessel. There were good surface pressure indications of when the new zones were opened and broke down, with good zonal isolation from already stimulated stages below. Stimulation design varied depending on which stage was pumped from lower rates matrix type treatments to higher rates pumping diverters to create wormholing effects. Maximum rates pumped were 25 bpm. The balls used to open the frac sleeves during this operation were made of a material providing initial strength to open the sleeves and perform the stimulation. The balls were also degradable, meaning that they dissolved over time eliminating the need for a dedicated ball mill-out run.

![3.625” OD dissolving ball](image)
Going the full circle

The last step in the evolution was merging all of the knowledge and features now gained with the development of the cementable ball drop activated sleeve and the original coiled tubing activated valve product line. This resulted in 2 new product functionalities;

- The cementable CT activated valve. A mechanical operated sliding sleeve that can be cemented in place as a part of a cemented liner.
- The cementable ball drop activated MOC (Multi-open-close) valve. A ball drop activated sleeve that incorporates shifting profiles in both ends giving production management, re-stimulation and water shut-off capabilities for the life of the well.

Both these sleeves have been designed, qualified and tested in Stavanger. So far the cementable coil tubing actuated sleeve has been run, whilst the ball drop activated MOC sleeve will be run in Q3 2014. The cementable ball drop activated MOC valve has been designed as a full hybrid between the ball drop activated valve and the CT activated valve. Initial opening can be done by ball and one ball can open multiple sleeves if desired by using flex and fixed seats. After the initial ball drop the sleeves can be closed and reopened as many times as needed, either with coiled tubing or wireline tractor. If the ball seat sizes are smaller than the intervention tool string it must be milled out first. All of these features have been tested on land at various testing facilities in Norway through 2013.

Opening the sleeve with ball drop for the initial stimulation has been tested at IRIS in Stavanger. Shifting the sleeves multiple times with a wireline tractor has been tested. This has been done by converting the coil tubing shifting tool to enable it to be activated by the tractor hydraulics. The tractor anchor/stroker tool provides the axial forces needed to shift the sleeves. First the MOC sleeve was shifted closed and opened 5 cycles before milling out the ball seats. Then the ball seats were milled out using the same tractor with a motor. Three seats were milled in one run and the total effective milling time was just over 7 minutes. The MOC sleeve was then again shifted 5 new cycles open/closed with the shifting tools after the milling.

The need for a cementable coiled tubing actuated sleeve came from a North Sea operator. Zonal Isolation in their field in many cases has to be done with conventional cementing, hence open hole frac sleeves are not an option. All of the wells were designed with a cemented 4.5” liner run in 6.5” hole. Rotation of the liner is instrumental in ensuring a good cement job in horizontal wells, hence rotating the liner while cementing was a design requirement for the valve. Anticipated torque during cementing would be 25,000 ft-lbs. This was achieved with the new design. Having a cementable stimulation sleeve that would allow multiple opening and closing sequences to be carried out over the life of the well had many benefits in terms of offering a flexible solution that can cope with various stimulation methodologies, ability to re-stimulate and ability to sequentially flow back fracs. Also, for future production and injection management sleeve could be accessed and operated with coil tubing shifting too. Also, stimulation could be done with coil tubing and shifting tools in the hole to reduce operations time. Since qualification the cementable CT activated valve two wells have been run for stimulation applications;

- Well 1, Horizontal water injector, 4.5” cemented liner in 6.5” hole, 14 sleeves run, acid frac
- Well 2, Horizontal oil producer, 4.5” cemented liner in 6.5” hole, 9 sleeves run, proppant frac

Figure 123: 14 zones cemented CT operated MSF completion
Both wells were left in OBM after cementing, so again two cleanout runs were planned to remove barite and cement residue from the liner ID to ensure trouble free operations. The first cleanout run was with mill and motor and a newly developed flow diversion tool. The motor has rate limitations so in order to achieve rates high enough to lift debris out of the well without stalling the motor the flow diversion tool was set up to open up flow ports above the motor once a certain rate was achieved. This self re-settable feature allowed the entire lateral to be clean in one run without compromising the motor. After the motor run a dedicated venturi junk basket was run according to best practices in the field.

The first well was a horizontal water injector and was stimulated with acid. A smart coiled tubing system was used for the stimulation process. Prior to job execution the impact hammer had to be tested with the coil to evaluate whether the fiber would survive the forces and vibrations generated during hammer operations. Testing confirmed compatibility. A bi-directional flow activated shifting tool was run in the well on 2 3/8" smart coil. Typical sleeve operating & stimulation sequence was as follows;

- RIH with CT to below sleeve to be opened
- Start pumping to activate shifting tool
- POOH and latch shifting dogs into sleeve profile
- POOH to shift sleeve open, confirm with overpull
- Verify sleeve open on surface data & RIH to position BHA below injection point
- Perform pre-acid wash/break down inject into zone, establish max rate
- Shut down and record ISIP
- Stimulate zone by bullheading acid down the annulus
- Perform post wash/break down test into zone
- Activate shifting tool and close sleeve in zone, pressure test liner.
- POOH until next zone and repeat steps to open and stimulate next zones

![Figure 134: CT BHA](image)

All 14 zones were stimulated by operating the sleeves with the coiled tubing tools and stimulation jobs were pumped as planned. After stimulating zone 14 the Shifting tool was run to TD again and all sleeves were opened up and the well was handed over to production. The smart coiled tubing proved an excellent tool to get real time data to verify sleeve opening and allowed operators to compare downhole data to surface coil reel data to prepare for the next well which would be run with standard coiled tubing. The coiled tubing operated sleeves were shifted more than 40 times during the operations, and worked as designed every time.

![Figure 145: Forces during sleeve shifting with CT](image)

The well was stimulated during winter months and there was severe weather that meant the stim vessel had to be disconnected several times. This delayed the job from being carried out as a continuous pumping operation. However, being able to stimulate with coil in the hole saved multiple trips and allowed the operation to be carried out in less time than previous methodologies. Real time temperature and pressure data from the smart coil allowed monitoring of frac fluid and sleeve integrity during stimulation.
The second well was a horizontal producer with 9 sleeves and planned to be stimulated with 10 proppant fracs with crosslinked gel and tip screen out with 14ppa loading. All fracs are under displaced leaving large volumes of proppant in the well that need to be cleaned up before stimulating the next stage. The 10th zone was added in the toe of the well by a dedicated perforating run. Zone 1 was stimulated and screened out to surface. 2 3/8" coiled tubing and a newly developed high flow shifting tool was run in hole.

![Figure 156: High Flow shifting tool BHA setup](image)

The high flow shifting tool allows flow rates up to 4 bpm to be pumped before activating the shifting tool. This allowed a single run to clean out the excess proppant down to below the sleeve in stage 2. Here the remaining proppant was tested as a plug to verify that zone 1 had been isolated. Once this was confirmed the high flow shifting tool was activated and zone 2 sleeve was opened. An overpull and injection test was performed to verify that the sleeve was open, now coiled tubing was POOH and the next zone was stimulated. This process was repeated successfully for zones 3, 4, 5, 6, 7 & 9. This solution allowed 10 coiled tubing trips to be saved during the course of the job and made the operations much more efficient. Placing the planned stimulation treatments through the cemented sleeves proved very successful with most treatments being pumped as per design.
Operational efficiencies, stimulation and production results

Improved operational efficiency is the obvious, proven and easiest to measure benefit of going from the traditional plug and perf methodology to a MSF completion based on sliding sleeves installed as part of the reservoir completion string. The time saved by deploying the means for staged communication between the well and the reservoir as part of the reservoir liner/tubing rather than having to perforate, punch or jet in order to generate communication points provides an immediate great potential for time savings. Taking advantage of the full potential for operational efficiencies requires diligent planning of pumping operations, fluid access and well thought through on-the-job decision-making capabilities.

The use of ball drop sleeve system improved operational efficiency greatly by eliminating the well intervention phase completely during the frac or stimulation operation all together, activation balls are deployed from surface enabling continuous pumping to complete a number of stages. When performing frac operations with more than 20 individually treated stages the eliminated tripping time to deploy perforating gear and isolation plugs can be days and weeks.

The use of ball drop activated sleeves still often required well intervention to remove the activation balls in order to get full access to the reservoir and remove obstacles from the well, complicating future well interventions. The introduction of engineered ball materials which provide high initial strength for MSF sleeve opening and for the frac or stimulation operation and which disintegrates or dissolves over time have eliminated the need for intervention activities to remove activation balls, enabling further time savings.

The operational efficiency improvements allow the rig to complete the well quicker for expedient rig move to the next operation; it also allows the frac or stimulation operation to be completed in significantly shorter time. North Sea pumping operations are typically done with a vessel alongside the rig, which now can complete the pumping sequence in a shorter time. Risk of operational delays as consequence of poor weather is greatly reduced as the dock time alongside rig is reduced. The saved operational time also provides great HSE risk reductions, this includes amongst others reduction in WL rig-up and rig-down operations and the elimination of explosives on deck and under transport.

All changes in well completion and stimulation methodology will first be measured against the traditional methods and achieved results, so also with the use of sleeved MSF operations. The main benchmark has been to ensure that a MSF completion does not compromise well production or injection performance. Throughout the North Sea, MSF installations operator feedback have been consistent on that planned volume of proppants have been placed, planned volumes and rates of acid have been pumped and production results are at least comparable to wells where traditional stimulation methodologies have been used.

Efficiency improvements in the installation and initial stimulation operation are already documented. North Sea wells are very often designed with lifetime horizon of 10 years and more. MSF sleeves provide life of well efficiencies as water producing stages can be easily closed off by manipulating sleeves through a light well intervention operation. The sleeves also provide opportunities for later re-stimulation of stages further providing potential for improving well lifetime.
Conclusion

- By working with the clients and being responsive to their requirements two distinct sleeved MSF systems were developed and successfully trialed.
- Turnaround times to complete stimulation stages were reduced from days and weeks to hours
- Challenges were encountered that required specialized intervention tools to be developed to ensure the success of the MSF completion systems
- The systems have been proven in both land and offshore environments in a variety of applications for acid and proppant stimulations
- Multiple features have been designed into the sleeve systems to provide a robust portfolio with flexible deployment and intervention option available.

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References


Nomenclature

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<td>BBLS</td>
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<td>Bottom hole assembly</td>
</tr>
<tr>
<td>BPM</td>
<td>Barrels per minute</td>
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<td>Coiled tubing</td>
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<tr>
<td>DHPG</td>
<td>Down hole pressure gauge</td>
</tr>
<tr>
<td>DNV</td>
<td>Det Norske Veritas</td>
</tr>
<tr>
<td>FT</td>
<td>Feet</td>
</tr>
<tr>
<td>HCL</td>
<td>Hydrochloric acid</td>
</tr>
<tr>
<td>HSE</td>
<td>Health, safety &amp; environment</td>
</tr>
<tr>
<td>ID</td>
<td>Internal diameter</td>
</tr>
<tr>
<td>IRIS</td>
<td>International Research Institute of Stavanger (Norway)</td>
</tr>
<tr>
<td>ISIP</td>
<td>Injection shut-in pressure</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LBS</td>
<td>Pounds</td>
</tr>
<tr>
<td>MOC</td>
<td>Multi-open-close</td>
</tr>
<tr>
<td>MSF</td>
<td>Multi-stage Fracturing</td>
</tr>
<tr>
<td>OBM</td>
<td>Open hole</td>
</tr>
<tr>
<td>OC</td>
<td>Open-close</td>
</tr>
<tr>
<td>OH</td>
<td>Open hole</td>
</tr>
<tr>
<td>POOH</td>
<td>Pull out of hole</td>
</tr>
<tr>
<td>PPA</td>
<td>Pounds of proppant added (pr gallon)</td>
</tr>
<tr>
<td>RIH</td>
<td>Run in hole</td>
</tr>
<tr>
<td>SPE</td>
<td>Society of Petroleum Engineers</td>
</tr>
<tr>
<td>SSD</td>
<td>Sliding side doors</td>
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<tr>
<td>TD</td>
<td>Total depth</td>
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<tr>
<td>WL</td>
<td>Wireline</td>
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