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The Evolution of a TAML L-4 Multilateral System To Meet the Challenges of a BP Deepwater Subsea Well

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Abstract

The Schiehallion field lies in water depths of 1,150 to 1 475 ft and is situated west of the Shetland Islands. The reservoir was discovered in 1993 and first brought on stream in 1998. It is the largest field operated by BP in the region and is one of the largest producing fields in the UK sector. Currently there are 19 production and 19 water-injection wells in the field, which have yielded more than 250 million BOE to date.

At the outset, the North West Area Development (NWAD) of the Schiehallion field was planned to have four penetrations, consisting of two producers, each with its accompanying injector; however, design and economic reviews indicated that development with a multilateral well and matching injectors was more viable. The selected multilateral system consisted of a hollow whipstock through which perforations would be made after the completion was installed. While the perforating gun and low-side weight bias orientation system are not new technologies, they still required substantial qualification because of the unique construction of the well, driven primarily by well control policies and the requirement for an intelligent completion to facilitate independent flow control of both laterals. The resultant integration of technologies supplied by several service companies demanded rigorous testing and qualification of the various components. Several tests were performed to validate the viability of the completion design, such as perforating gun suitability; confirmation that minimal tubing deformation would occur; perforation hole sizes; the likelihood and containment of perforation debris; and testing of a straddle system required to bridge off the tubing perforations to isolate and control the mother bore production. The test program culminated in a full-scale stackup of the intelligent completion within a test well, followed by perforating and subsequent quantification of the debris generated and captured.

This paper details the development trials carried out on the perforation system required for this multilateral system to meet the needs of drilling and completing a subsea multilateral producer with an intelligent completion. In addition to discussing the physical testing, this paper summarizes the results obtained from erosion modeling and productivity evaluation, which also influenced the final well design.

Introduction

The Schiehallion field is located, along with the Foinaven and Loyal fields, approximately 103 nautical miles west of the Shetlands Islands, offshore UKCS. The development of these fields has been based upon two floating production storage and offtake (FPSO) vessels receiving oil from clusters of subsea wells via both rigid flowlines and flexible risers. Shuttle tankers offload oil from Foinaven to the Flotta terminal and to the Sullom Voe terminal for Schiehallion and Loyal fields. All these fields inject seawater, and either re-inject produced gas or export it to the Magnus field system for use in an enhanced oil recovery (EOR) scheme.

The NWAD development of Schiehallion field was originally conceived as a four-penetration project consisting of two producing wells, each with its own dedicated water-injection well; however, it was decided early in the planning of the project that the producer penetrations should be in the form of a multilateral well design incorporating a hollow whipstock. The original well design allowed the lateral legs to produce and commingle through a single completion string to surface; however, during the detailed planning of the well, this design philosophy was challenged and adapted to facilitate remote downhole flow control (DHFC) of the production of each lateral.

Consequently, “Phase 1a” of the Schiehallion NWAD was planned to access reserves in the Segment 2 and 3 T35 Sands, using one multilateral producer and two water injectors. The multilateral producer, FP02, would have one leg in the Segment 2 fault block and one leg in the Segment 3 fault block, with each leg being supported by a water injector **(Fig. 1).** Well FP02 was drilled in the summer of 2006, using the Paul B. Lloyd Junior semi-submersible rig, and subsequently completed with DHFC equipment to optimize well operability and reserves recovery.

Well Design

The basis of the TAML L-4 multilateral well was to be a hollow whipstock through which perforations would be made to access the production from the mother bore; however, the change in design and the inclusion of intelligent completion control had a substantial effect on the perforation strategy to be used at the junction and on the completion design itself.As can be seen in **Figs. 2, 3, and 4,** the completion tubing spans the junction area, is perforated at the junction, and includes a straddle packoff, run to isolate the perforations through the tubing. This design was chosen to allow remote DHFC of each leg of the multilateral. The completion design allows the lateral to flow conventionally up the tubing string, with on/off control by the remote downhole ball valve. The mother bore flows up through the hollow whipstock and 7 5/8-in. liner once perforated, and between the OD of the 4 1/2-in. tubing and the ID of the 7 5/8-in. liner; its access to the 5 1/2-in. tubing is controlled by the upper variable DHFC valve. This design and its resulting operational requirements posed many questions and generated a series of tests to verify their viability.

The 9 5/8-in. hollow whipstock system selected had been used by BP on several previous occasions.[1] Typically, a junction of this type is perforated through the liner, the cement, and the whipstock face, but in this case the 4 1/2-in. tubing would also have to be perforated. This requirement posed several problems:

- Would the 3 3/8-in. guns planned for use provide sufficient depth of penetration and hole size?
- Would the 4 1/2-in. tubing be adversely affected by the perforation process, compromising completion integrity and straddle deployment?
- Would the resultant gun debris cause access problems during the straddle deployment?

The design team had decided that they would only consider running the intelligent completion into the well if they had a tested mechanical barrier for each leg of the well. This decision meant that, for the main bore, the hollow whipstock junction would not be perforated and a mechanical ball isolation valve device would be run into the lateral leg. During the deployment of the upper completion, which included a five-cable flat pack clamped along its length, both laterals had these tested mechanical barriers in place.

Over a period of several months, a series of tests were devised, including contingencies such as blowout preventer (BOP) shear ram tests and annular BOP sealing tests on the completion tubing with this flat pack to prove up the well design and safe deployment of the upper completion.

Quarry Testing

The chosen well design entailed perforating the target area of the junction with the 3 3/8-in. perforating gun and shooting through the 4 1/2-in. tubing, 7 5/8-in. liner, and cement as well as the whipstock face plate to allow the mother bore to flow.

This method of construction had never been carried out before, and the result of shooting through unsupported 4 1/2-in., 12.6-lb/ft tubing with this particular 3 3/8-in. gun was unknown. As part one of the proposed perforating trials, the design team planned to shoot two perforating guns within the 4 1/2-in. tubing over the same interval and in the same orientation. The base-case completion was to shoot twice to maximize the flow area and therefore reduce the potential for erosion of the straddle. In addition, this proposed completion construction method required that a retrievable straddle be run through the perforated 4 1/2-in. tubing and effect a seal above and below the newly shot perforations. Consequently, the final internal shape and condition of the perforated tubing were of particular interest.

During September 2005 testing was carried out to determine what would happen to a joint of unsupported 4 1/2-in., 12.6-lb/ft tubing when two 3 3/8-in., 4-spf zero-phased perforating guns were fired over the same area and in the same phasing. These tests were conducted using a specially designed test fixture at a remote quarry loch, the scope of work being:

- Measure the ovality of the joint of 4 1/2-in., 12.6-lb/ft tubing over a 20-ft length where the two guns will be fired.
- Drift the ID of the joint with the appropriate 3.833-in. API drift.
- Fire the first gun in the middle of the 20-ft controlled/measured section of tubing.
- Measure the OD of the tubing to compare with the measurements taken before shooting.
- Position and fire the second gun across the same area and orientation as the first.
- Measure and compare the tubing OD against previous data.

Two joints of 4 1/2-in., 12.6-lb/ft 13% cr tubing were prepared for the test, and lugs were welded in place to make the tubing suitable for handling and to restrain the tubing safely during the firing of the perforating gun. The OD was measured at every 90° and every 4 in. over the 20-ft length of the tubing; and a line was marked in the middle of the tubing joint, which was aligned with the middle shot of the perforating gun, thus providing for controlled measurement of the joint 6 ft past each end perforation. One end of the tubing joint was bolted into a cradle fixed to the key side of the loch, and the other end was suspended from a crane and lowered 10 ft into the loch.

The first gun was fired and the tubing joint retrieved for ovality checks. The measurements taken indicated a slight change in OD but nothing significant, and all shots fired successfully, resulting in a zero-phased 33-shot pattern on the low side of the tubing, as shown in **Fig. 5.** The test fixture was rebuilt, and a second gun was installed inside the same tubing joint, with the charges aligned to shoot between the first set of shots. All shots of the second gun fired and resulted in splitting the low side of the tubing, as shown in **Fig. 6.** The split was not confined to the area of the perforations; rather, it propagated past the last perforation hole, in two directions, in the form of a fracture. As the base plan for this well was to perforate the tubing on the low side of the hole and subsequently run an electric-line tool string to correlate on depth and set a straddle, these results raised concerns that the wireline would drop out of the split tubing and result in a stuck or lost tool string.

The second perforation test consisted of shooting only one gun inside a joint of 4 1/2-in., 12.6-lb/ft 13% cr tubing; and, as in the first test, illustrated in **Fig. 5**, the joint of tubing did not split after firing. Attempts were made to drift the tubing with a 3.833-in. OD × 42-in. long Teflon® drift, but it held up, apparently on small particles of debris; however, the tools and/or pressure washers needed to clean the tubing ID were not available on site, so the test was concluded. A substantial amount of debris was generated during these perforation runs, leading to the conclusion that, to reduce the debris to a minimum, further studies during the perforating gun qualification tests were required.

With these test results in mind, the design team also decided to remodel the expected production rates of the well to confirm whether the well could be produced effectively with only one gun run and thus one set of perforations.

Straddle Testing

A suitable straddle packoff had to be identified because the completion design required that the 4 1/2-in. tubing string be perforated and the resultant perforations isolated to allow production of the mother bore by way of the 4 1/2-in. tubing by 7 5/8-in. liner annulus. The joint of 4 1/2-in. tubing perforated with one gun during the quarry trials was used to test several straddle systems from two vendors.

To ensure fair and unbiased selection of a straddle, the following test procedure was drafted and all of the straddles were tested using the same parameters according to this procedure:

1. Drift the 4 1/2-in. tubing joint with a 3.833–in. API drift, with the perforations low side.
2. Install running tool into straddle.
3. Ensure that the perforations are on the low side of the tubing.
4. Insert straddle into 4 1/2-in. perforated joint.
5. Pass straddle through the perforations three times in each direction.
6. Inspect elastomeric elements, gauge rings, and slips.
7. Pull straddle back to midpoint across the perforations.
8. Set straddle, using hydraulic setting tool.
9. Install test cap on bottom end of joint, and place assembly into test pit.
10. Fill tubing joint with test fluid, and install upper test cap.
11. Pressure-test straddle to 4,000 psi for 60 minutes.
12. Bleed off pressure, but do not drain fluid, and remove from test pit.
13. Install control line from 4 1/2-in. test cap, and coil.
14. Install 4 1/2-in. joint inside 7-in. test casing so that control line tail protrudes from the 7-in. casing.
15. Install test plug so that tail of control line exits through the 7-in. test cap.
16. Ensure that both inside and outside of straddle are full of fluid.
17. Pressure-test 7-in. casing to 4,000 psi for 60 minutes while monitoring pressure from the 4 1/2-in. casing.
18. Bleed off pressure, and remove test caps.
19. Remove test casing from pit.
20. Remove 4 1/2-in. perforated joint from 7-in. test casing.
21. Remove straddle from joint, and inspect.

The first set of trials with one particular brand of straddle proved difficult; and, although the tests were attempted several times, a successful test was never achieved. Another vendor's straddle system was subsequently tested, and the results were successful, resulting in its selection for the project.

The dimensional data from the test of the selected straddle were then used to perform some computational flow dynamic simulations to show how the straddle might be affected by the flow from the well directly at the straddle through the perforations. The simulations assumed that the 4 1/2-in. tubing would be rigidly centralized inside the 7 5/8-in. liner.

Erosion Modeling

As part of the straddle evaluation, erosion modeling was conducted to assess the effects of the mother-bore flow through the perforated junction. Modeling specifically focused on flow erosion of the "retrievable straddle" set within the 4 1/2-in. tubing tailpipe, as failure of the retrievable straddle would result in loss of DHFC functionality. Two erosion studies were conducted and are summarized below:

- In-house erosion modeling estimated the erosion generated by a jet of fluid with solids impacting a flat plate with no standoff. This model was considered conservative and represented the worst case.
- Computational fluid dynamics (CFD)[2] modeling took account of geometry and fluid flow paths. This model was considered an optimistic or best-case outcome.

For both these studies, erosion rates were estimated at various levels of water cut and particle sizes based on the following assumptions:

- Produced sand concentration of 5 pptb was assumed as realistic.
- Assuming sand control integrity was maintained, the D50 produced particle size was estimated to be around 50 microns. This assumption was based on a review of sand retention testing conducted for FP02 and an analysis of the produced solids samples taken from various West of Shetland producers.
- A 20,000-bpd liquid rate with 1,000 scf/stb gas/oil ratio (GOR) from the mother bore via the perforated whipstock was assumed. This assumption covered a scenario in which the mother-bore target had to be flowed at higher rates than planned because of poor flow efficiency from the lateral target.

The "in-house" modeling indicated that one perforating run would suggest that a straddle with wall thickness of around 0.28 in. would remain intact over the lifetime of FP02 (See **Fig. 7**). This was based on 20,000 bpd of liquid, with an increasing water-cut profile and an impacting fluid stream with 50-micron particle size. In this case total wastage would be around 60 to 70% of the straddle thickness over a 15-yr lifetime.

The results from the CFD modeling are shown in **Fig. 8.** As can be seen, erosional wastage is less and is thought to be a consequence of the “cushioning layer” between the 4 1/2-in. tubing tailpipe and the straddle (See **Fig. 9**).

The results of both the in-house model and the CFD model indicated an acceptable life expectancy, allowing the project to proceed as planned. The conclusions from the erosion modeling are summarized below and assume successful deployment of the main-bore target sandface completion and adequate sand control across the main-bore target during the life of the well.

- The “retrievable straddle” design was within acceptable erosion limits. The in-house erosion model results were used as the definitive output, given that it was conservative and modeled a worst-case scenario.
- Based on the in-house modeling, one perforating run was considered acceptable with regard to straddle erosion, assuming that the flow area was maximized at the junction by aiming for 100% charge penetration through the whipstock.
- Standoff had to be maximized at the junction by using a 7 5/8-in. liner across the whipstock and centralized 4 1/2-in. tubing tailpipe.

Productivity Modeling

Productivity modeling was also performed for the proposed completion to assess the effect of using only one perforating run with 33 shots. Whipstock, liner, and production tubing perforation coupon testing indicated that, assuming 100% success for 33 shots, a total flow area of 2.57 sq in. would be achieved, which equates to an equivalent diameter of 1.81 in. A 30% reduction was applied to the 1.81-in. equivalent diameter to account for increased friction through the perforated whipstock, giving a revised equivalent diameter of 1.27 in., which was used for the modeling.

The following table summarizes the productivity modeling output based on:

- One perforating run across the 4 1/2-in. tubing tailpipe, 7 5/8-in. liner, and whipstock, using the assumptions described above
- 7-in. production tubing
- 10 3/4-in. casing deployed across the DHFC valves and gauge mandrel setting depths
- 5 1/2-in. production tubing from main-bore reservoir target to whipstock
- 4 1/2-in. production tubing from lateral-leg reservoir target to whipstock

Productivity Modeling Output

	Rate (BOPD)
Total multilateral rate	28,000
P3A split (Main bore)	13,000
P2A split (Lateral bore)	15,000

Based on the above productivity modeling, one perforating run across the 4 1/2-in tubing tailpipe, 7 5/8-in. liner, and whipstock was deemed acceptable with regard to planned production forecasts. Although two perforating runs would produce a greater flow area and reduce the associated whipstock pressure drop, the risk to operational success and completion integrity outweighed the productivity benefits.

Perforating Gun Qualification

Successful perforating of the hollow whipstock was of primary concern. Not only did the perforating charges have to penetrate the extra layer of the 4 1/2-in. tubing, but also the shape of the tubing inside which the gun was to be fired had to remain useable for the subsequent placement of a straddle packer. A test procedure was generated to determine whether the selected 3 3/8-in. perforating gun would fulfill these extra requirements. The key concerns were:

- Perforating hole size in the whipstock faceplate and tubular members
- Quantity and size of debris generated from the perforating inside both the gun and the tubular members
- Ovality of the 4 1/2-in. tubing after perforating
- Type and size of the flashing around the perforated holes in the 4 1/2-in. tubing

A full gun test was planned to provide data on all of these concerns, and the test fixture was designed to facilitate the collection of as much undisturbed data as possible. The fixture was constructed from four tubular elements, as illustrated in **Fig. 10**: 4 1/2-in. 13% chrome tubing; 7 5/8-in., 29.7-lb/ft 13% chrome casing; 12 3/4-in. casing to simulate the whipstock face; and 26-in. steel casing to house the fixture. The perforating gun and the 4 1/2-in. tubing were designed for easy removal from the fixture for measurements and collection of debris. The testing was performed at the perforating gun manufacturer’s facility. Safety meetings were held before the test and at various times during the test, as warranted, and there were no incidents or near misses for the duration of the ballistic tests. The 4 1/2-in. tubing was first removed, measured for ovality, and drifted with a 3.833–in. OD drift, with no indications of binding. The fixture was then loaded with the perforating gun and lowered into the test trench, which was then filled with water. The fixture was designed to allow this water to flow between the tubes, except for the 7 5/8- × 12 3/4-in. annulus, which was filled with cement. The gun was then fired, the fixture removed from the trench, and the water allowed to drain. The fixture was rotated on its side to complete the draining and to turn the perforation holes away from the low side for removal and collection of the debris.

The perforating gun was carefully removed and wrapped in plastic to preserve the debris, which was later removed and weighed according to API RP 19B[3]. The perforating gun was then measured for swell, the maximum on this occasion being 3.523 in., which was similar to results of the previous testing. Debris was next removed and collected from inside the 4 1/2-in. tubing; and, finally, the debris that was in the annulus between the 4 1/2-in. tubing and the 7 5/8-in. liner was recovered. The 4 1/2-in. tubing was measured at 4-in.

intervals—both perpendicular and parallel to the line of perforations—for ovality. The tubing OD increased an average of 0.035 in., from 4.529 to 4.564 in., with the greatest OD changes being 0.077 in. for a perpendicular reading and 0.172 in. for a parallel reading. Some of the measurement locations were across the perforation holes, which explained some of the high readings.

The 3.833-in. OD drift was passed through the 4 1/2-in. tubing with no indication of binding, and the tubing was cut open lengthwise to enable examination of the perforation holes (See **Fig. 11**). The areas around the perforation holes were recessed by the perforating process, and a small metal birm protruded into the ID. Because of the recess the birm did not enter into the effective ID of the tubing and did not interfere with the drift bar.

The average exit hole diameter for the 12 3/4-in. tube (0.34 in.) was the same as seen in the original gun development. There was 0.6 lb (150-cc volume, or 4.5% of the total) of debris inside the 4 1/2-in. tubing, while the perforating gun had 12.2 lb (1,944-cc volume), which was 89% of the total.

The shapes of the perforation holes in the 4 1/2-in. tube in this test and in the previous coupon tests were compared. In this test the holes were recessed as a consequence of the blast, and the flashing was smaller than in the coupon tests. The differences were effects of the test being conducted in water, using a complete tube rather than just a section, as in the coupon tests.

The results of the test confirmed that the perforating gun would produce sufficient-size holes through all the members without adversely deforming the 4 1/2-in. tubing. The 4 1/2-in. tubing had slight swelling from the test, but the ID was easily drifted with a 3.833-in. OD drift; and so it was concluded that access should not pose a problem in the field operations when a straddle-packer system is run past this area.

Some 89% of the debris generated by this test remained inside the gun, and it was concluded that adding length to the gun as a sump would reduce the amount that could fall out during tripping out of the hole. The total debris generated equated to 26.5 in. of additional gun length; therefore, to contain most of the debris inside the perforating gun, a 12-ft gun length was recommended, providing a 3-ft sump for its collection.

Test Well Deployment

A stackup test was conducted at a facility in Aberdeen to ensure that the completion components interfaced and that the proposed intervention operations could be carried out as planned. The objectives of this test were as follows:

- Confirm access for tools through completion geometry.
- Confirm suitability of flat-pack clamps and installation techniques.
- Confirm ability to orient and fire the perforating gun on the low side at the multilateral junction.
- Quantify perforating gun debris.
- Confirm straddle deployment, integrity, and its retrievability on wireline.
- Collate lessons learned, and incorporate them into the operational programme.

The condensed completion was run in to the test well to a point where the well deviation was 58°, as it would be in the actual well, with the joint of 4 1/2-in. tubing to be perforated at 1,645 ft MD. At this point the test well had a dogleg severity of 11.95º/100 ft, which exceeded the planned dogleg for the actual well. During the running of the completion, valuable experience was gained and lessons learned with regards to the installation of the five-core flat pack and the clamps, placement of the flat pack spooler reel and sheave, and trial-testing equipment to help tension and protect the flat pack from damage running through the rotary table and slip system.

The decision made during the quarry and perforating gun testing to run only one gun made both the correlation of depth and the orientation of the gun critical. It was decided to experiment with some electronic equipment designed for confirming the orientation of perforation guns for sand-control perforating. It was thought that, if these tools could give a surface real-time orientation of the gun when on depth, it would provide additional confidence that the gun would be fired in exactly the right orientation. This involved using a gyro for the initial correlation and then relying on a wireline-oriented perforating tool (WOPT) for the shooting run as shots through the gyro tool, as designed, were not possible.

Accordingly a drift run was performed with the following components (BHA No. 1):

- Dummy 12-ft × 3 3/8-in. perforating gun, complete with eccentric weight bars, for orienting the shots to the low side. Bow-spring centralisers were attached to the weight bars.
- Gyro tool for reading the orientation of the gun at depth.
- WOPT for correlating to the gyro reading, as the gyro could not be run on the gun firing run.
- Orientation confirmation device (OCD), modified to be housed within a special 3 3/8-in. housing.
- Casing collar locator (CCL) for locating the gun depth, using the tubing couplings correlated with the pipe tally.

BHA No. 1 (See **Fig. 12**) was run into the well, unhindered to the shooting depth; although, when attempting to run past the shooting depth to allow wireline correlation on the upstroke, the tool string started to lose momentum at approximately 1,640 ft and stopped moving at 1,722 ft. Several attempts were made to run farther into the well, but without success. It was suspected that the bow springs on BHA No. 1 might be adding too much drag to the tool string; so the BHA was pulled and modified with a single eccentric weight bar and no bow-spring centralizers (BHA No. 2, **Fig. 13**). This BHA was run in the hole and behaved in exactly the same manner. As the inclination of the test increased to 70º at 1,706 ft, it was decided that this was the best that could be done with fresh water in the tubing and no friction- reducing components on the tool string.

Running the tool strings BHAs No. 1 and 2 fulfilled several functions: 1) It proved that the tool string could actually reach shooting depth through the completion jewelry. 2) It correlated the wireline depths to the completion, using a CCL. 3) It calibrated the gyro to the WOPT, as a live gun could not be fired with the gyro in the BHA. During the running of BHAs No. 1 and 2 the calibration between the gyro and the WOPT was carried out at seven separate stations within the well. These stations confirmed the functionality of the tools and proved the repeatability of the WOPT readings even though the tool was working outside its normal operational limits.

The next step was to run the live gun with 8 ft of 4-spf, zero-phased charges, and a 3-ft sump for debris collection. The gun was weighed before it was run in the test well, and, after the fired gun was pulled from the well, it was weighed again. It was found that the gun now weighed 0.46 lb less, which was extrapolated to be the amount of debris lost downhole, although some of that weight would have been lost as a result of some internal components vaporising. The sump section of the gun was cut off and the debris captured and weighed in at 10.3 lb, which indicated that only 4.3% of the debris was lost downhole.

In the next phase of the test, a drift was run in the hole to replicate running the straddle. This phase was conducted without problems, and the straddle was subsequently run and set across the perforations. It was tested successfully to 4,000 psi and then retrieved on wireline, all without operational problems.

This test deployment provided very useful experience in several critical areas:

- The proposed completion procedure worked well and provided excellent training for personnel for the actual well completion.
- The running of the flat pack provided several improvements in the final procedure to be used.
- Verification of the orientation and firing of the guns was achieved.
- Verification of both the amount of debris that would be lost downhole and the suitability of the sump design was successful.
- Preparation and practice running, testing, and the retrieval of the straddle pack-off.

Actual Operational Deployment

The completion equipment was run into well FP-02, with all procedures and equipment performance identical to those in the test deployment. Having run two different tool string configurations (BHAs No. 1 and 2) during the test rig trials and witnessing very similar results, it was decided to run BHA No. 4 (See **Fig. 14**) for the perforating part of the operation, as the connections and crossovers would be supplied by one vendor helping with logistics and tool interfaces. When the first tool string was run into the well, it was found that, after six passes over the perforation area, the tool string was rotating consistently clockwise between 27º and 44º.

The fact that the tool string could actually be seen to be rotating in real time validated the decision to have a system that could show where the zero-phased gun was facing before it was fired. Had this functionality not been available, a simple log would have been performed across the target area, using the gamma ray/casing collar location (GR/CCL) tool on depth, and the assumption made that gravity had rotated the gun to the low side. This would certainly have resulted in the perforations missing the target area, with consequent disastrous effects on the completion and its flow control functions.

The decision was taken to add more eccentric weight and one bow spring to the tool string in an attempt to keep the gun facing the low side with the added eccentric weight and to reduce the rotation by having a bow spring act as a rotational brake, as in BHA No. 3 (See **Fig. 15**).

This assembly was run into the well; and, although it performed better, it was still rotating clock wise on average 20º at the shooting depth. After 24 passes were completed over the target area, sufficient repeatability was shown; therefore, the BHA was pulled, the armed gun installed, and the gyro removed from the string. This run would be with the same BHA No. 3 but, having no gyro, reliance was now fully placed on the WOPT to confirm the orientation of the gun. The armed 3 3/8-in., 4-spf gun was installed, and the 20º tool string rotation was accommodated by misaligning the gun to the weight bars at surface. On depth the tool string behaved as expected; the gun was fired with good indications, both electrical and by well pressure response, to indicate that the gun had fired successfully.

The tool string was pulled out of the hole and firing of all 33 shots confirmed. When the OCD portion of the tool string was stripped down, the indentation of the marker within the tool indicated that the gun fired within the tolerable error band of 16.5º either right or left of low side (See **Fig. 16**).

The gun was shrink-wrapped to retain any debris within it and shipped back to shore, where it was cut open for examination of the debris captured within the sump. After the perforation run was completed, a small injection test was carried out to correlate against one that had been performed earlier in the operations. To pressure up the well, extra fluid was required in an amount significant enough to confirm that the hollow whipstock had been perforated successfully.

A wireline drift run was carried out, which replicated as close as possible the length and ODs of the straddle yet to be run to patch the holes now in the 4 1/2-in. tubing. Also incorporated into this drift run, in an attempt to recover any loose steel debris from the wellbore, was a magnet at the bottom. The drift BHA ran past the perforation depth without problem, and, upon recovery, there was very little steel debris attached to the magnet.

The straddle was then run to depth, correlated across the perforations, and set. The depth control of the straddle used a GR/CCL tool to correlate to the radioactive tags within the hollow whipstock, as had the perforation gun. The straddle was tested successfully and the well completed.

Conclusions and Recommendations

FP-02 was an extremely challenging well for many reasons. The fact that only one perforation-gun run could be made without losing the intelligent functionality of the well focused efforts on ensuring that the one gun could be run and fired at the correct depth and orientation. Without this focus, it is likely that no electronics would have been run to confirm gun orientation before firing. Although weight-bias-oriented gun systems work in most cases, there are circumstances in which friction, geometry, dogleg severity, and inclination can create surprises.

Reliance on gravity alone to orient a perforating gun on the low side for this type of operation, as was originally planned, would certainly have resulted in the gun shots missing the target. The gun BHA was not expected to rotate while correlating over the target area. Deployment of a gyro and WOPT to provide gun orientation data at depth was deemed more of a confirmation measure rather than a control measure; however, their inclusion turned out to be crucial and invaluable to the operation.

There was significantly more time spent correlating the wireline BHAs over the perforation area than was anticipated. Most of this time was spent correlating the gyro to the WOPT, as it was necessary to remove the gyro for the actual shooting BHA and rely on the WOPT. For future similar operations, the ability to run a "disposable" or "shoot-through" gyro tool to reduce the amount of correlation time and trips required is currently an ongoing discussion topic with the vendors.

The use of the WOPT, OCD, and gyro package to confirm the orientation of the 3 3/8-in. gun was a success. Although the actual correlation between the WOPT and the gyro took longer than anticipated, the end result was that the team could see in real time how the tool string was reacting at the shooting depth and could therefore compensate for it and shoot the gun in the desired orientation. Without the inclusion of this technology, the downhole flow control for this well may well have been compromised and the added value of flow management never realized.

Debris control and management are of the utmost importance during the construction of a multilateral well. Specific operations during the construction and commissioning phases will generate more debris, and they should be addressed accordingly.

An area of particular concern to this operation was the amount of debris generated during the perforation of the hollow whipstock. A considerable amount of time and money had been spent on the well at this stage, and the last two operations were to perforate and set the straddle pack-off across these perforations; failure could have compromised the overall well objectives. The debris generated by this 3 3/8-in. gun was quantified during the quarry and perforating-gun qualification trials and was deemed to be a substantial risk if lost in to the wellbore during recovery of the spent gun. Taking into account the substantial amount of debris generated, the gun body was elongated by 3 ft, allowing the gun to capture and recover its own debris. Had the team not taken the extra time and made the extra effort to understand and manage the debris generated by this perforating gun, it may not have been possible for the straddle pack-off system to reach depth as it had successfully on the first attempt ; however the inclusion of an integral sump to the 3 3/8-in. gun was such an easy modification to carry out that its added value can only be estimated. This strategy proved to be a "low-cost" yet "high-value" modification and will certainly be recommended for further operations of this type.

Low-cost computer modeling studies should be used where possible. The erosion and productivity modeling conducted for FP-02 provided valuable insight into the range of potential outcomes and associated effects on completion integrity and well construction.

Pre-completion evaluation in a test well for such a critical and demanding completion was a key contributor to the success of FP-02 and should be considered whenever a "first-time" deployment is planned. This test well stack-up allowed the team to evaluate the operations in a lower-cost environment while both the onshore support team and offshore operations team viewed, learned, and commented on the trial deployment. During these trials a substantial amount of learnings were taken away by the team and incorporated into the actual program. In addition, by having the majority of the service companies on site during these trials, an appreciation of each other's roles, responsibilities, and interfaces was gained.

Use of the WOPT, the OCD, and the gyro package to confirm the orientation of the 3 3/8-in. gun was a success. Without the inclusion of this technology, the downhole flow control for this well may well have been compromised, and the added value of flow management never realized.

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A number of people have recorded completion installation and performance data across the West of Shetlands fields since 1997, and the case study presented here would not be possible without these data.

The authors also thank other members of the BP West of Shetland Team, the BP Technology Group, and the respective vendors for their contributions and review.

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Acronyms

API	American Petroleum Institute
BHA	bottomhole assembly
BOE	barrels of oil equivalent
BOP	blowout preventer
BOPD	barrels of oil per day
CCL	casing collar locator
CFD	computational fluid dynamics
DHFC	downhole flow control
EOR	enhanced oil recovery
ft	feet
FPSO	floating production storage offtake
GOR	gas/oil ratio
GR/CCL	gamma ray/casing collar locator
ID	inside diameter
in.	inch
lb	pounds
lb/ft	pounds per foot
MD	measured depth
NWAD	North West Area Development
OCD	orientation confirmation device
OD	outside diameter
pptb	pounds per thousand barrels
psi	pounds per square inch
scf	standard cubic feet
spf	shots per foot
stb	stock tank barrel
TAML	Technology Advancement of Multilaterals
UKCS	United Kingdom Continental Shelf
WOPT	wireline-oriented perforating tool

Figures

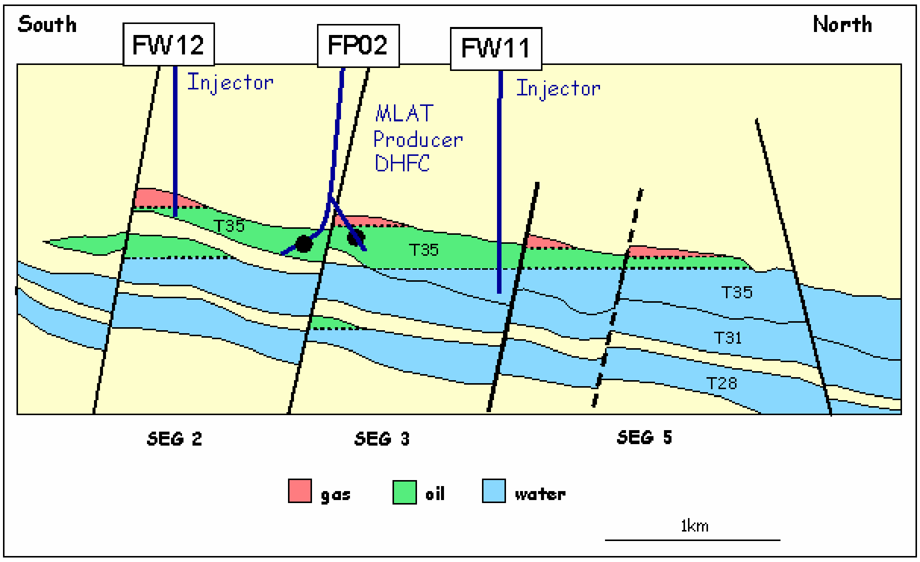

Fig. 1. North West Area Development Cross Section

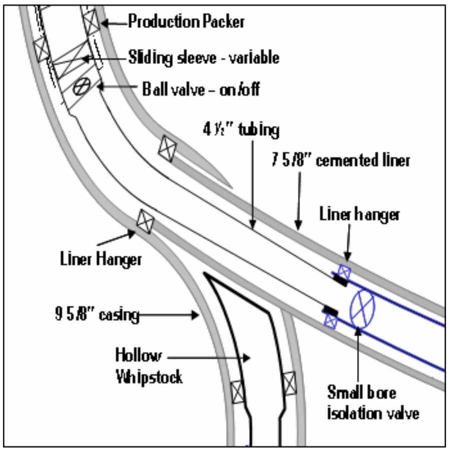

Fig. 2. Junction Configuration before Perforating

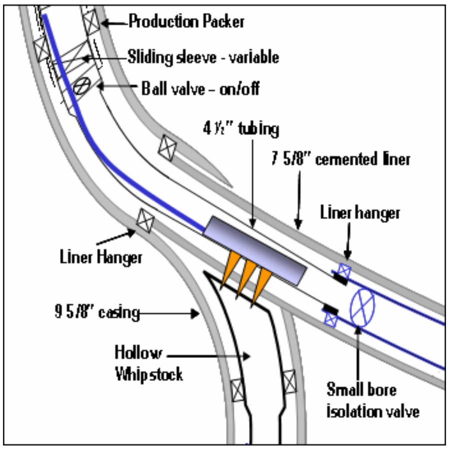

Fig. 3. Perforating the Tubing, Liner and Hollow Whipstock

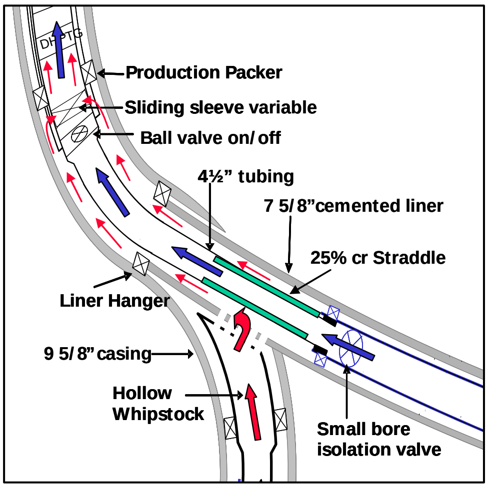

Fig. 4. Straddle in Place Showing Flow Paths

Fig. 5. Joint of 4 1/2-in. Tubing Shot with One Gun

Fig. 6. Joint of 4 1/2-in. Tubing Shot with Two Guns

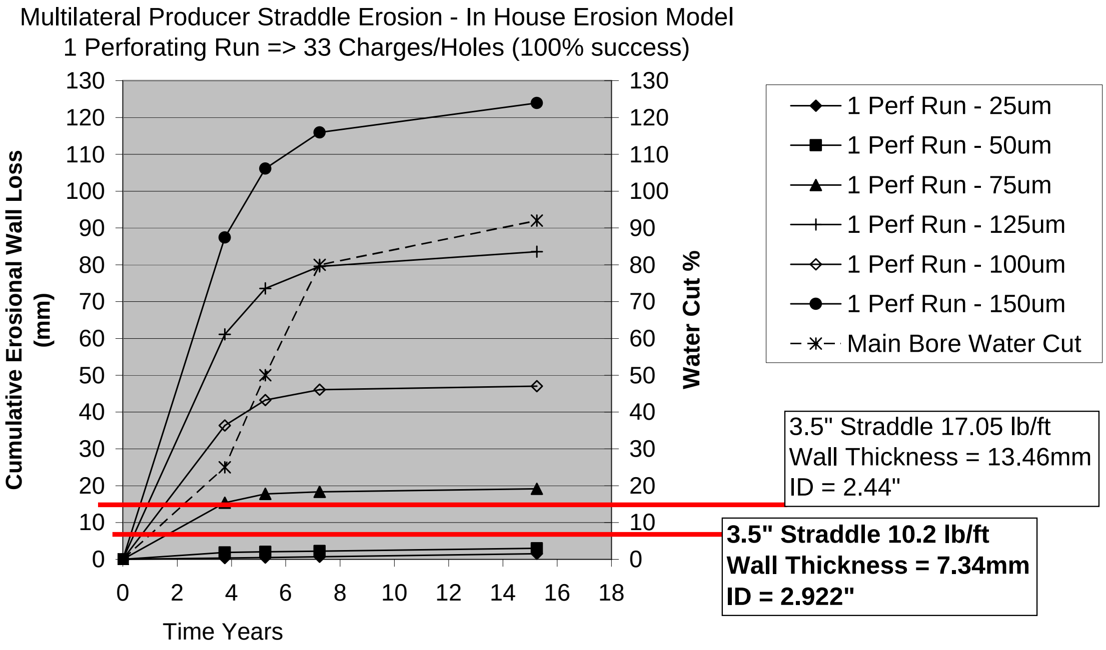

Fig. 7. In-house Erosion Model Output, One Perforating Run

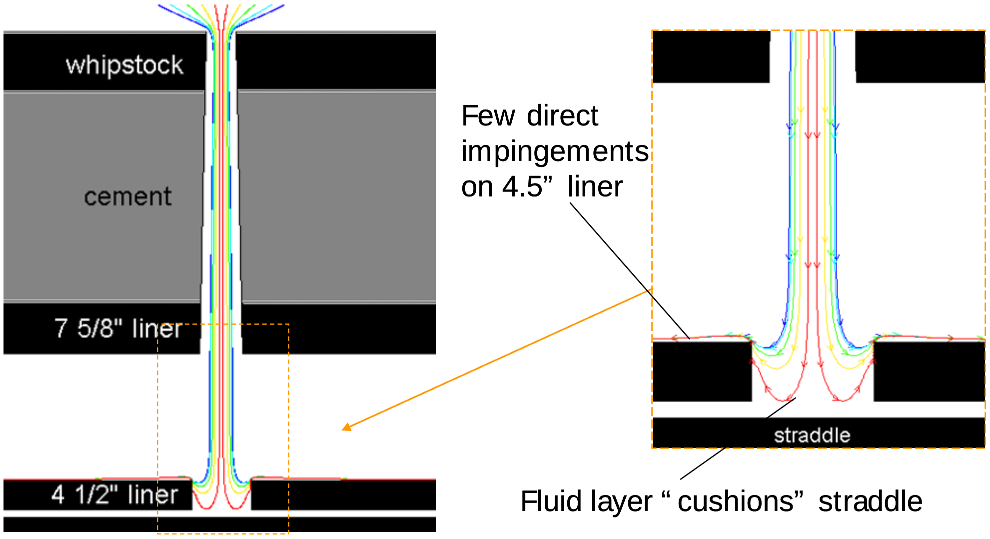

Fig. 8. CFD Erosion Model, Predicted Mean Particle Trajectories

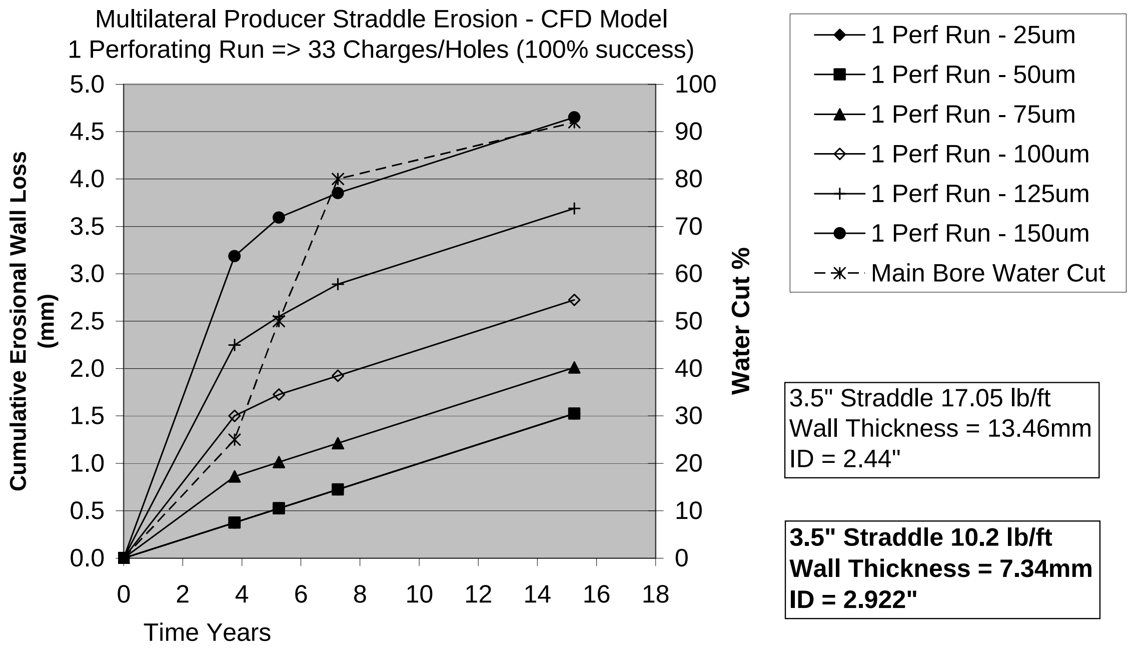

Fig. 9. Straddle Erosional Wastage Chart

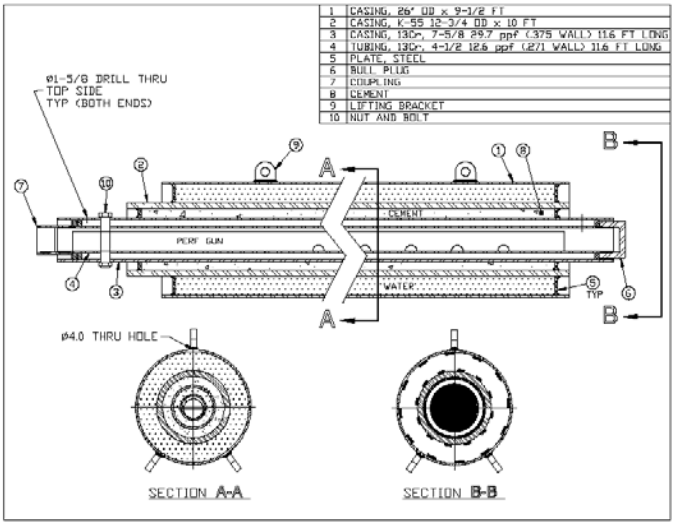

Fig. 10. Perforating Gun Qualification Test Fixture

Fig. 11. Cutaway Section of 4 1/2-in., 12.6-lb/ft Tubing Showing the 33 Perforations

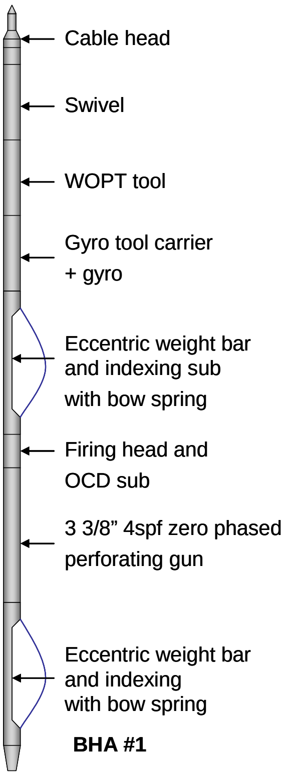

Fig. 12. First Correlation Tool String Run in the Test Well, BHA No. 1

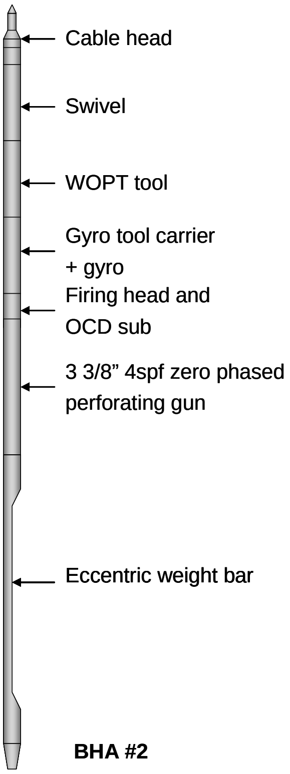

Fig. 13. Perforation Tool String Run in the Test Well, BHA No. 2

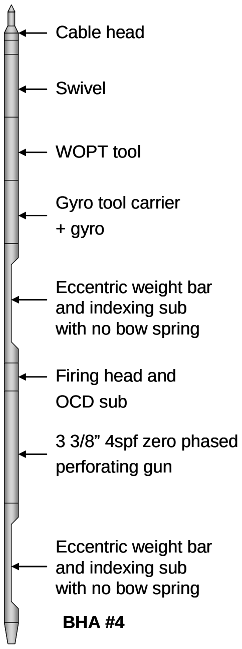

Fig. 14. First Correlation Tool String Run in the Actual Well, BHA No. 4

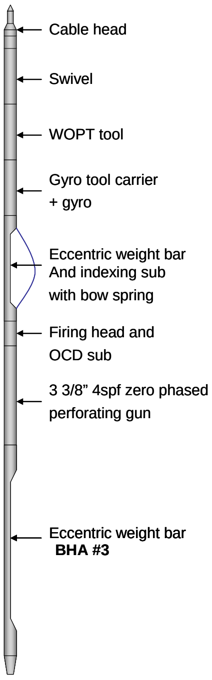

Fig. 15. Perforation Tool String Run in the Actual Well, BHA No. 3

Fig. 16. Orientation Confirmation Device Showing Actual Orientation of the Gun Downhole When Fired