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A fitness for purpose assessment of the use of a modified expandable casing patch as a barrier against H_2S exposure

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Abstract

The Mars water flood project is expected to increase lifetime recovery by about 100 million barrels of oil. But the project economics depend on employing existing wells not designed for sour conditions, for water flood zones. A review of the production casing designs found that the emergency back out sub and the mud line tieback sub were not fit for purpose for the mildly sour conditions expected from the water flood. The well remediation team selected a modified expandable corrugated patch made to cover these two components. The patch is a longitudinally corrugated mild steel patch that is expanded to a circular cross section down hole. The gap between the thin metal patch and the casing is filled with a cured-in-place fiberglass-reinforced epoxy that forms a gasket between the patch and casing. The patch had to be modified and tested before it was fit for purpose. Pass through clearance and epoxy durability were the primary issues that drove the modifications and subsequent proof testing. The modified design features a thin wall corrugated patch that is constructed in a continuous 20' section, a durable epoxy resin for the casing-patch gap, and a modified expansion tool. To meet the clearance objectives, the redesigned patch was combined with a modified completion design. A program of laboratory and full scale testing showed that together the modified completion and patch were fit for service.

Introduction

The Mars water flood project will increase the lifetime recovery from the basin by more than 100 million barrels of oil. In addition it will reduce compaction and the potential for compaction related well failures. Even with these benefits, the project economics depend on employing existing wells to produce the water flood zones.

One of the risks of water flooding is souring of the production. While the project includes stringent controls on the injection water quality, sulfide-reducing bacteria (SRBs) are expected to sour the production after water breakthrough. [1,2] Because water flooding was not considered in the original design and material selection for the wells, the safety case review of the project identified sulfide stress corrosion cracking (SSC) as risk.

Remediation selection

A detailed metallurgical review and fitness for purpose testing showed that three components in the production casing could not be qualified as fit for service under the water flood conditions. These components were the surface casing hanger, the mud line tieback sub (TBS), which supports the production casing below the mud line, and the emergency back out sub (EBO). On the Mars wells, the TBS is located at the mud line at a depth of 3,100 ft and the EBO is located at a depth between 8,000 and 10,000 ft.

It was concluded that the EBO and TBS would need to be repaired or replaced. The water flood team determined that, based on the project economics, replacement would be too expensive and too impractical and a repair strategy was adopted for the TBS and EBO. The plan was to leave the casing intact and use some method to isolate the inside surface of these components from exposure to H_2S contaminated fluid in the annulus. A number of options were considered, including corrosion inhibitors, a solid expandable, an isolation packer, and an expandable corrugated patch.

Work was done to evaluate each of the alternatives, including setting and callipering a corrugated patch inside a TBS, some design engineering for an isolation packer assembly, and some evaluation of a solid expandable.

A corrosion inhibitor solution could not be implemented after gas lift, while both the solid expandable and isolation packer solutions would be both expensive and time consuming to develop for the Mars application.

The most significant advantages for using the corrugated patch to cover the EBO and TBS included long experience with the corrugated patch tool, a lower engineering cost and a shorter development time. With more than 10,000 such patches deployed since their introduction in the 1960's, the installation of these patches is well established. Compared to the alternatives, the costs for engineering a specially engineered patch were expected to be low and the needed engineering modifications would be relatively easy to implement. Finally, it was seen that the compliant expansion process that places the patch as close to the casing ID as the fiberglass mat allows, had the best chance of resulting in the best clearance.

Description of the patch

Corrugated casing patches were first introduced in the early 1960's. [3,4] The basic concept of the corrugated casing patch is simple. A thin, mild steel, longitudinally corrugated patch is expanded against the inner diameter (ID) of the casing with specially designed tool. The longitudinal corrugations (or flutes) reduce the running outer diameter (OD) of the tool. The patch is run down hole in a tool string that includes a hold down device for keeping the patch in position during the initial setting stroke, a hydraulic piston that drives the expander through the patch, and the expander, consisting of cone followed by a segmented collet. Figure 1 shows a conceptual diagram of the tool. The collet section of the expander is compliant; the individual segments (or fingers) in the collet can flex so that it can follow minor irregularities in the casing. The tool flattens the corrugations, and presses the patch against casing ID. It is held in place by the radial interference between the patch OD and the casing ID. A layer of epoxy impregnated fiberglass mat on the patch exterior seals the patch by filling the gap between casing ID and the patch OD. The fiberglass is glued to the exterior of the patch during fabrication. Immediately prior to running the patch in the hole, the uncured epoxy formulation is applied to the mat. The expansion process extrudes the unset epoxy between the casing and patch, filling irregularities in the casing. This increases the likelihood of a satisfactory seal even when the condition of the casing ID is uncertain. The standard patch is constructed of 11-gauge mild sheet steel (0.12" thick). With the epoxy-fiberglass layer, the standard patch reduces the casing ID by approximately 0.3". [5]

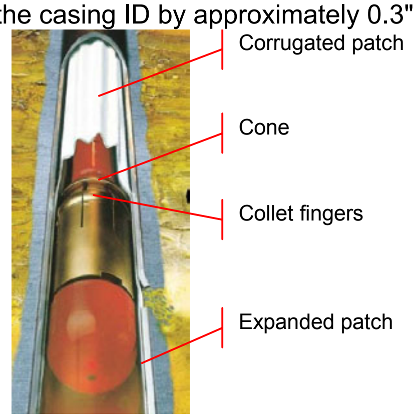

Figure 1. Schematic of patch expander

Modifications for the Mars Application

There were two major modifications that were necessary to make the corrugated patch suitable for the Mars application. These were:

- Reduce the patch wall thickness to provide enough clearance to allow 4 ½" production tubing and accessories to pass through the installed patch without sticking or snagging. One of the critical difficulties in cladding the EBO and TBS is that these components have machined IDs that are slightly less than the nominal casing diameter.
- Reformulate the epoxy used to impregnate a fiberglass mat on the patch OD to extend the long-term durability of the casing-patch seal and to ensure that the epoxy would cure at cool mud line conditions.

In order to develop and show that the modified patch was fit for purpose the following tasks were undertaken:

- Build and test at the surface a thin wall patch and a tool designed to deploy a thin wall patch.
- Modify or redesign the large diameter completion equipment such as cross coupling control-line protectors (CCP), the production packer, SCSSV, and gas lift side pocket mandrels.
- Design and test an epoxy formulation with an increased resistance to post-curing damage, thermal cycling and aging, while still being able to cure at 40°F.
- Do "dress rehearsal" in a test well that demonstrates that the completion system can be run through a patch installed in a well without snagging or sticking on the patch, or damaging or wearing the patch itself.
- Extract the patch and tieback assembly installed in the test well, and perform a full-scale integrity testing.

Engineering modifications

Clearance: During the initial screening of solutions, a trial installation of a standard thickness patch showed that there was too little through patch clearance. In order to increase clearance, the manufacturer suggested reducing the thickness of the patch from 11-gauge to 13-gauge material. Since small diameter patches are fabricated from 13-gauge material, the manufacturer did not consider this as a significant change in their standard manufacturing processes.

The caliper measurements of the initial test showed that the patch ID surface took on the shape of the segmented collet section of the expander. In order make the ID surface more circular, the manufacturer's engineering staff developed a tandem expander, shown in Figure 2, consisting of one cone and two segmented collets. The collets have a radial offset so that the gap between trailing collet segments correspond to the centers of the leading collet segments.

Figure 2. Two stage expander

Standard patches are constructed in ten-foot sections butt-welded together. The first thin wall patch set at surface was constructed from one ten-foot and two five-foot sections, assembled such that the butt welds would be located in the larger i.d. casing rather than in the TBS. This patch was set inside a simulated tie back. Caliper measurements showed that the smallest clearances through the patch were at circumferential welds between the patch segments and that these prominent welds could potentially snag or damage equipment. To eliminate this risk, the tooling needed to fabricate and weld one-piece 20-foot sections of patch was developed.

For the thin wall patch set at the surface, the caliper measured the minimum ID in the patch inside a simulated tieback as 5.820". The same patched component easily passed a 42×5.705" drift.

Epoxy: Conventional applications use a standard general-purpose epoxy on the exterior of the patch. For most applications this formulation will perform satisfactorily; however, the operating conditions for the Mars application require that the epoxy forms a seal to isolate the TBS and EBO for 15-year lifetime, have good resistance to thermal aging and cycling while being able to cure at the mud line temperature (40°F).

Because it was uncertain that the standard all-purpose epoxy formulation could satisfactorily meet the above criteria, the team initiated a resin study to select a formulation that could meet the above requirements.

Shell investigated several different sealing strategies, however the final design concentrated on the same cast in place application method used for standard patches. A number of resins, resin modifiers and curing agents were evaluated. In addition, Shell designed several testing protocols and equipment to evaluate the effect of thermal aging and cycling on the interfacial seal created by the epoxy-fiberglass composite. Comparing the alternative formulations to the formulation used by the patch manufacturer for their standard application patches, the relative improvement in thermal cycling performance for the new formulations was demonstrated. Temperature acceleration was used to evaluate and compare thermal aging performance. These acceleration protocols were based on standard methods for interpreting the time dependence of physical properties using temperature acceleration. [6]

The final epoxy formulation was a multi-component blend. The base resin was a bisphenol-A diglycidyl ether liquid epoxy resin blended with a polyhydroxyether thermoplastic modifier. The base resin was too viscous for application so a multi-functional reactive diluent was used to reduce viscosity and adjust material properties for the application. Polyamide curing agents were blended to provide required low temperature curing. The curing agent blend also produced a low glass transition temperature in the cured resin.

The thermoplastic polyhydroxyether and multi-functional reactive diluent modifiers increase thermal cycling resistance of the interfacial seal by decreasing the elastic modulus, increasing adhesion, and reducing post-cure shrinkage. The small scale testing of this formulation concluded that the formulation's seal lifetime is between 18 and 50 years – significantly longer than the expected life for the conventional formulation.

Completion equipment: Table 1 shows the diameters of the largest diameter components in the production tubing string. The production packer is the largest component in the string. When this is turned down it has a maximum outside diameter of 5.675" and a critical length of 10'. In this configuration, the packer element is also more prone to damage from the irregular surface of the patch as it is run past.

Table 1. Completion component sizes

Component	Max OD	Comment
Sub-mud line tubing hanger	5.695"	Max OD over 1' interval only
Chemical injection valve	5.515"	
Subsurface safety valve	5.680"	With control lines and special protector
Downhole pressure gauge	5.317"	
Packer (gas lift option 1)	5.680"×10'	Permanent packer, trimmed gauge rings
Over collar protectors	5.540"	No encapsulation on PDPG line and modified over collar protector.
Hydraulic gas lift valve	5.650" to 5.700"	To be developed
Gas lift mandrels	5.550"	

Since many over collar protectors must be run pass the patch, protectors snagging, and hanging up on the patch and protectors damaging or wearing the patch were of concern. In order to reduce the risk, SEPCo's protector supplier, Cannon was engaged to design a minimum clearance protector. The number and size of the control lines was reviewed to optimize the design.

Fitness for service testing

Table 2 summarizes the tests performed as part of the program to demonstrate that the corrugated casing patch is fit for purpose. These tests included:

- two patches set inside tiebacks and callipered at the patch supplier's manufacturing facility,
- a battery of tests to evaluate the epoxy interfacial seal and epoxy mechanical and curing properties,
- a full scale demonstration of the proposed repair in a test well, and
- a full scale integrity test.

Table 2 summarizes each test with their major observations and conclusions.

Conclusions

The Mars water flood casing upgrade program resulted in a fit for purpose design that met the water flood's technical and economic requirements. While the design selected was based on the established casing patch tool, several modifications both to the tool and the completion string were needed to implement the patch as a suitable method of isolating the EBO and TBS from the fluids in the production casing annulus. The design modifications to the corrugated patch system resulted in:

- single unit fabrication: 20' long patch without any circumferential welds,
- 13-gauge thin wall patch,
- a modified expansion tool to result in a more uniform ID surface, and
- an optimized epoxy formulation selection, with good low temperature curing and long term seal durability.

The modifications made to the completion string were:

- a different configuration of the control lines,
- a slimmer design for the over collar protectors, and
- a turned down production packer.

The program of design, testing and analysis shows that the modifications made to the corrugated casing patch and the completion equipment are fit-for-service. The testing program demonstrated:

- that clearances through the patch are sufficient to pass a modified Mars completion with a minimum OD of 5.675" without sticking, snagging or damaging the patch,
- that the recommended epoxy formulation results in a durable fiberglass-epoxy seal, and
- that a patch set in a well under realistic conditions prevents gas migration behind it through the epoxy-fiberglass seal.

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Nomenclature

CCP = Cross coupling control line protector
EBO = Emergency back out sub
ID = Inside diameter
OD = Outside diameter
PDPG = Permanent down hole pressure gauge
SCSSV = Surface controlled subsurface safety valve
SRB = Sulfate reducing bacteria
TBS = Tieback sub

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Table 2. Testing program

Test description	Result
Ten-foot standard patch expanded at the patch manufacturer's facility in scrap TBS. Patched assembly was callipered.	Clearance for standard patch too small for Mars application but large enough to pursue redesign to meet through patch ID requirements.
Ten-foot standard patch milled out of TBS on a horizontal test bed at the patch supplier's research and development center using a power swivel driving a taper mill followed by a watermelon mill. The torque required to back off the TBS was measured.	Mill removed the entire patch from the ID bore; some debris was still left in recesses. Milling did not significantly increase the back-off torque of TBS. This showed that patch could be removed from mud line hanger so that tieback and riser could be pulled as designed.
Twenty foot thin wall patch constructed of 1~10' section and 2~5' sections butt-welded together was set inside a simulated tieback at the patch supplier's manufacturing facility using tandem collet expander at surface. Resulting assembly was drifted and callipered.	Results: Minimum measured through tieback diameter was 5.820". Easily passed 5.705"×42" drift. Min ID (≈5.800") was at the butt welds joining the patch sections. Tandem expander raised pressures needed to set patch but still within the limits of the tool. Concluded that welds could hang up or damage completion components and therefore a single piece 20' patch should be developed.
Interfacial seal endurance to thermal cycling for the candidate epoxy formulations was estimated using annular specimen cycled in a water bath from 40° to 150°F.	Result showed that modified formulations with flexiblizers and adhesion promoters had significantly longer cycling lifetimes than standard formulation. The recommended modified formulation had an estimated lifetime more than 20 years.
Epoxy pot life and curing time tests.	Results showed that recommended curing agent could cure epoxy at 40°F while having a pot life of between 2 and 3 hours at surface temperatures.
Epoxy thermal interfacial seal aging endurance was estimated using solid epoxy specimens in a 0.12"(ID)×12"(L) tube and in an expanded inner specimen resulting in an annular fiberglass-epoxy specimen. Specimens were cured at 40°F then placed in furnaces with temperatures ranging from 158°F to 305°F for a maximum of 90 days for solid specimens and 45 for the expanded specimens.	Results were evaluated using the ASTM recommended methods. Using Arrhenius' method, the thermal aging endurance of the modified formulations was shown to be significantly better than the standard formulation. The estimated thermal aging lifetime for the recommended formulation ranged from 18 years (un-reinforced) to more than 50 years (fiberglass composite in an expanded specimen).

Table 2 (continued). Testing program

Test description	Result
Epoxy cured and uncured material properties, including uncured viscosity, elastic modulus, Poisson's ratio, and glass transition temperature.	Tests on uncured samples showed that the viscosity of the recommended formulation could be matched to the standard formulation, so that formulation is consistent with the standard application and running procedures. The modifiers added to the recommended formulation resulted in low elastic modulus and an increased glass transition temperature; the combination improves seal flexibility and durability.
Dress rehearsal was performed at a test well in Lafayette, LA. A single piece 20'-long, thin wall patch was set inside a simulated tieback sub placed at approximately 800' TVD). Patch was located using RA tags in tieback sub. After setting, a clean out gauge mill (ø 5.75") was run through patch. A packer drift sub (ø 5.675") was run through the patch. A trial completion string was cycled through the patch to simulate the number of protectors passing the patch if the production tubing was run to 20,000'. The equipment run (packer, collar protectors, etc) was examined for damage. Patched simulated tieback sub assembly was extracted from well and also examined for damage and saved for later testing.	This test demonstrated that a modified Mars completion could be run successfully through a patch, without damaging either the patch or the completion. Patch was set approximately 4' deep; otherwise procedure went exactly as planned. Pot life should be extended to ease the time pressure in locating and setting the patch. The trial completion was run without hanging up or sticking. Minor scratches were observed on the tubing and protectors, probably caused by irregular patch. A small gouge approximately ¼" long and nearly through wall was found on the patch ID. Debris caught between the expander and the patch while it was set probably caused the gouge. The completion itself caused no damage to the patch.
Differential gas pressure integrity test was performed on the recovered patched assembly from test well. Test used a specially designed fixture that applied a 100-psi gas pressure to the end of the patch to determine whether gas would migrate through epoxy-fiberglass filled gap. Ten test/monitoring ports drilled through casing down stream of the pressure application point were observed for gas migration.	No gas migration was observed when 100 psi was applied to the patch.