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The technical analysis and study of decommissioning and abandonment of offshore oil field surface facilities and subsea system

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Abstract. With more than 100 years exploration and development of offshore oil, more and more offshore oil fields will gradually lose the economic profit to operate. In this article, to take the target oil field for example, the procedure of decommissioning for FPSO, TCMS, subsea system and well abandonment have been analyzed. Meanwhile, the environment impact and mitigation measure have been proposed. The successful project experience will provide a guide line for the offshore facilities decommissioning and abandonment.

Keywords: FPSO; TCMS; decommissioning; well abandonment; economic limit

1. Introduction

The total area of global ocean accounts for 71% of Earth surface, and it is estimated that there is about 135 billion oil which is stored in the reservoir under ocean bed, which is about 2/3 of total world oil reservoir. Nowadays more and more countries are focusing on the exploration and development of the offshore oil and gas (Gao *et al*. 2010). The first offshore oil and gas field was developed in 1897 in the world and in China the first offshore oilfield was installed in 1966. With oil development of 50 years, some offshore oil field may lose the value of development. In order to evaluate when to abandon a production well the "economic limit" should be defined. The "economic limit" of a well is defined as the production rate below which the net revenue from the production will not meet the expenses, including taxes. In general, the economic limit for oil wells can be expressed using the following formula (Richard *et al.* 2012)

$$EL_{oil} = \frac{\mathrm{WI} \times \mathrm{LOE}}{\mathrm{NRI}\left\{\mathrm{P_o} + \frac{\mathrm{P_g} + \mathrm{GOR}}{1000}\right\} \times (1-\mathrm{T})} \quad) \tag{1}$$

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Where:
EL_{oil}= economic limit for oil well, in oil barrels per month (bbls/month)
P_o, P_g= current oil and gas prices, in $/bbls and $/mscf respectively
LOE= lease operating expenses, $/well/month
WI= working interest, as a fraction
GOR= gas/oil ratio, scf/bbl
T= production and severance taxes, as a fraction.

At the economic limit there often is still a significant amount of unrecoverable oil left in the reservoir. It might be tempting to defer physical abandonment for a extended period of time that the oil price will go up or that new supplemental recovery techniques will be perfected. However, lease provisions and governmental regulations usually require quick abandonment; liability and taxes concerns also may favor abandonment.

The target oil field is located offshore approximately 80 km north east of Mediterranean with a water depth of approximately 300 m. The vertical oil producer (W-1) and water injector (W-2) development wells were drilled in 2006. Production from the oil field has been routed through a flow line via a TCMS (Tripod Catenary Mooring System) linked to the FPSO (Floating Production, Storage and Offloading Unit), a tanker of 130,000 tons for the treatment, storage and offloading of crude oil. The oil field is a typical offshore marginal field with reserves about 9 million barrels of oil. The shortness of the field life, three to six years, was predicted in field development plan. Due to the uncertainty of oilfield shut down, it is necessary to analyze and study the technical requirement of decommissioning and abandonment of oil field. There are only a few national and industrial regulations on the oil field abandonment in China. The local and international codes, regulations and standards are to be referred. (Temporary regulation on abandonment management of offshore production facilities 2010, Wells Abandonment regulations in Offshore, UKOOA 2005, NORSOK, Environmental Guidance Document: Well Abandonment and Inactive Well Practices for U.S. Exploration and Production operations)

2. Overview of oil field

2.1 Description of offshore oil field facilities

The oil producer is completed with a subsea wellhead linked to FPSO via a 6 inch production flowlin a 4 inch flow line for power fluid to activate the jet pump to assist well production and a flexible umbilical for wellhead hydraulic control. The water injector is also completed with a subsea wellhead and is linked to the FPSO via a 4 inch flowline to inject treated water from the surface installation and a flexible umbilical for well head hydraulic control.

The FPSO is moored in place with a TCMS composed of three legs attached to a node representing the center of the TCMS; and the FPSO is attached to the node through a chafe chain constituting the primary link and two polypropylene ropes for redundancy in case of chain failure.

Each mooring leg is composed commencing from node down with a small portion of chain, a polypropylene mooring line for the suspended portion of the leg, a chain portion of approximately 400 m, a 50 tons anchor, and approximately 800 m of chain to act as dead weight required to compensate the lacking portion of required tension.

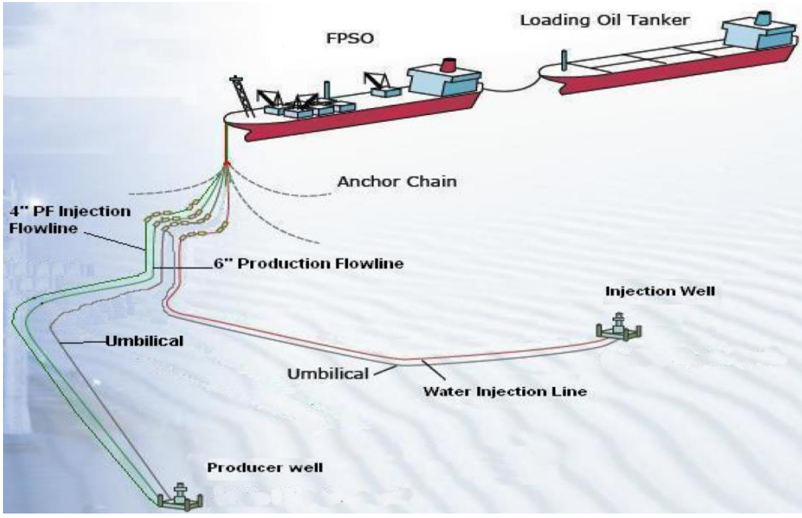

Fig. 1 The Layout of Oil Field Facilities and Subsea system

The chafe chain supports 10 guide frames equipped each with five guide cans to route the risers and umbilicals, and with dead weights to cover the balance for guide cans of possible additional risers and umbilicals. On the vessel the chafe chain is connected to a surge connector, an intermediary piece, which allows the passage through the chute and hence avoid potential weakness of a chain link through exposure to extensive wear. Beyond the surge connector the chain is secured on a wren hook integrated into a specially reinforced area of the vessel structure to sustain all the mooring tension.

The two wells are equipped with subsea well heads which are controlled hydraulically from the FPSO with a wellhead control panel and an umbilical, one umbilical per well, with five cores containing the hydraulic fluid. For the oil producer, well effluent is evacuated to the FPSO via a 6 inch flowline riser; and power fluid is routed to the well in a 4 inch riser flowline connected to the Xmas tree annulus ports. Treated sea water for injection in the reservoir is routed to the injector well, via a 4 inch riser flow line.

On the FPSO the well effluent is routed from the gantry arrival point to a manifold through 3 hard pipe lines and then processed into the production installation located on the deck structure consisting in production and test separators, associated gas venting system, produced water treatment installation. The treated oil is routed to storage tanks of the FPSO. Total storage capacity is 590,000bbls. The treated produced water is assessed complying with the quality requirement of 40ppm before it is discharged to sea. Possibility to rout the produced water to slop tanks is maintained for contingency measures. The FPSO is equipped with segregated ballast system to enable ballast fluctuation as required without environmental constraints.

2.1.1 The FPSO

The FPSO is a floating barge used at the same time for the production and the storage of crude oil. It has been modified to include mainly new equipments such as production pumps and water injection pumps driven by diesel engines. The FPSO has a segregate ballast system. Tank capacity allows the storage of about 81,000 tons of stabilized oil. Treatment installations are located on the deck structure of the FPSO. They consist in a production separator, test separator, a 2^{nd} stage separator for three phase separations, a knock out vessel for oil & gas separation before gas goes to flare.

The water is then processed to a "degasser" for initial gas and oil separation and then processed overboard through a centrifugal system, where the last droplets of oil are taken away, so the water will meet the required specifications before to go to sea. If the specs aren't met then the water is automatically diverted to slop tanks.

Main characteristics of the FPSO are tabulated in the Table 2.

2.1.2 Mooring system

The TCMS is the means of both mooring the FPSO vessel and guiding the flowlines and umbilicals through the 5 riser guide cans connected to the guide frames supported by the guide frames. The TCMS mooring part has at its lower end three legs, each 120° apart, each anchored with a Stevshark anchor. The ground chains are 127 mm standard studless chain, each is of 245 m long. These three legs come together at a "node", This node has three pad eyes at 120° apart, and also a padeye at the top into which is shackled a chafe chain.

The chafe chain insuring the connection of the mooring system to the FPSO is passing into the guide frame arrangement consisting of a series of the following components: Nine Guide frame plates, each of 1,162 kg with 2x130 mm D shackles and joined together by short lengths of 142 mm chain. All but one of the chain sections is identical, being 6 common links.

The lowest section between the guide frame (GF) 9 and the Node consist of 5 links (three common links, one enlarged and one end link). The upper chafe chain is 130 mm studless chain and comes on board the ship via a surge connector positioned over the fabricated bow cantilever in a 2 m radiused ramp, and then parallel to the deck to a releasable bow stopper. The FPSO can rotate freely around the TCMS for one & half rotation along a radius not exceeding 60 meters of offset from the central position.

These are the legs described by the general direction they head away from the Node.

- N = North leg (compass direction is 340°T)
- SE = South East leg (compass direction is 100°T)
- SW = South West leg (compass direction is 220°T)

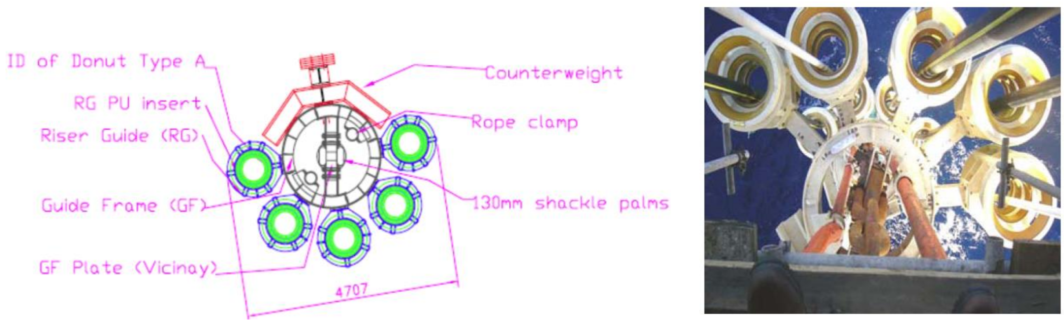

Fig. 2-1 Typical Schematic Diagram of Guide Frame

Table 2 Main Parameters of FPSO

Item	Main Parameters	Unit	Description
1	Extreme length	m	292
2	Breadth moulde	m	41.15
3	Depth moulde to main deck	m	21.95
4	Summer draft	m	16.6
5	Displacement	t	25705
6	Summer deadweight	t	133560

Each leg consists of:

- Upper chain – attached to the Node. This is 20 m long and is 142 mm chain but with an extra wide link; this chain is sometimes referred to as "poly chain" because it connects the polyester rope;
- Polyester rope – approx 400 m (originally manufactured as 389 m but it will have stretched) of 242 mm diameter braided cover rope. The same has an eye at each end around a steel thimble, and these are connected to the chains at each end by H shackles;
- Lower chain – the length is different on different legs, but the links are all extra long 135 mm chain. The ROV Chain Measuring Equipment (CME) is made to fit these links. This chain is continuous to the anchors;
- However from the touchdown outwards this chain is between 0.5 m and 1.0 m below the visible seabed.
- Extension chain – on the N and SE legs, about 100m from the anchor a special ROV operable shackle joins some 120 mm standard stud-link chain that acts as an additional friction leg to supplement the holding power of the drag anchors.

On the SW leg the extension chain is shackled to the end of the lower chain. The full extent of the Extension chains are expected to be below the seabed and not visible.

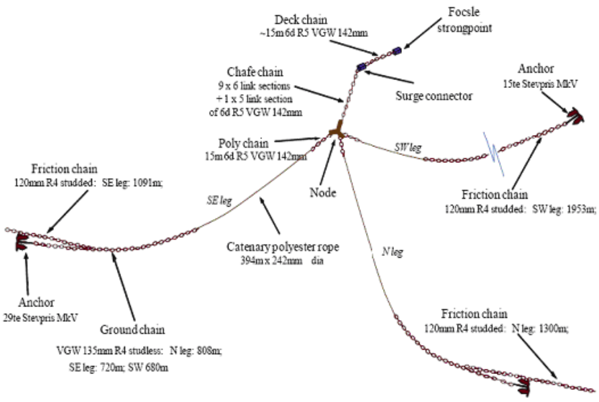

Fig. 2-2 The Layout of FPSO Mooring System

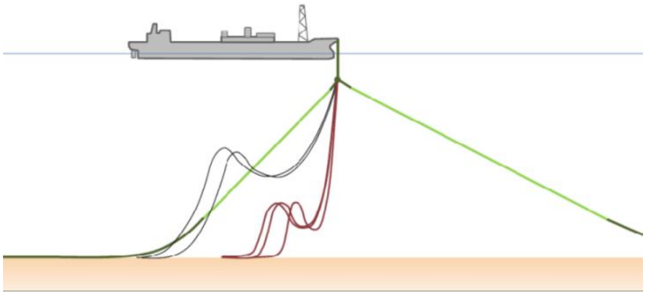

Fig. 2-3 Schematic of Subsea structures

2.1.3 Subsea Flowlines & Umbilicals

The flowlines channeling the production effluent, injection water, power fluids and control Hydraulic fluids between the FPSO and the well heads are composed of:

(1) Three separate risers

- Two risers are serving oil producer: 0ne riser of 6 inch moves produced effluent from the tree to the production installation on FPSO and one 4 inch riser connected to the Christmas tree annulus ports routs the power fluid injection to activate the jet pump assisting the well production.
- The third one is providing water to injector tree. All risers are of the same specs and are “Wellstream product”.

(2) Two Umbilicals

It provides hydraulic control fluids from the power control station on the FPSO to each of producer and injector wellheads. All production flowlines and umbilicals are 1363 m for producer and 1857 m for injector. Throughout the project these have been labeled as follows, from SW going counterclockwise:

- Towards W-1 to the southeast of the node:
  - UP = Production Umbilical
  - PF = Power Fluid riser
  - P = Production riser
- Towards W-2 to the east of the node:
  - UW= Water Injection umbilical
  - W = Water Injection riser

The two umbilicals have a touchdown much further out from the TCMS centre than the risers; 290 m vs 115 m. However the jewellery on all five risers, and their touchdowns, are very similar.

3. Technical analysis of decommissioning and abandonment

The field decommissioning works will be planned for execution in several stages starting with works enabling release of the FPSO to achieve costs optimization. A thorough analysis of the various options of dismantling and removing of the installations from the oil field is carried out to enable defining the most appropriate solutions to this case while paying special attention to effects on the environment, observing safe practices, and taking into account technical and technological constraints. (Wells Abandonment regulations in Offshore, UKOOA, NORSOK). The decommissioning and abandonment of the oil field will be performed in two separate phases:

- Phase I: Well Killing & FPSO disconnection
- Phase II: Full and safe abandonment of wells.

The permanent well abandonment includes isolation of zones in uncased hole, isolation of open hole, plugging of annular space, surface plug, testing of plugs, and clearance of location. The procedure and criterion of well abandonment should be followed with related the previous designed parameters of the wells, international codes and local regulations. (Wells Abandonment regulations in Offshore, Environmental Guidance Document: Well Abandonment and Inactive Well Practices for U.S. Exploration and Production operations). The detailed operations of each phase are presented as follows:

3.1 Phase I: Well killing & FPSO disconnection

This phase consists of clearing all production facilities, killing the producing well with seawater, disconnecting and laying down the two umbilicals and the three flowline risers, and clearing off the FPSO from the TCMS.

3.1.1 Step 1: Killing of wells

(1) Deplete the reservoir by stopping water injection 2 to 3 weeks before producer well shut off.

(2) Change power fluid system liquid supply from 2nd stage crude to water from produced water station. This will ensure adequate flushing of the power fluid system, riser, and well annular section down to the jet pump.

When production will be shut in, back wash production riser with water, from water injection facility, back into the well. This can be achieved by connecting water injection system at the receiving manifold level to production header via a suitable hose; while injecting water in the annular part at 5,000 bpd.

(3) Kill the wells with quality controlled sea water pumped through the production flowline, while injecting same water in the annular section at 5,000 bpd. Then observe well head pressure for 24 hours.

(4) Close well head valves and make sure that they are locked in closed position.

The wells are then in safe conditions at three levels:

- Wells filled with water and hence non eruptive
- Two serial valves of the well head closed.

3.1.2 Step 2: Cleaning of tanks

- Off loading of the cargo into an export tanker.
- Wash all cargo tanks with crude oil.
- Flushing the production piping to the slop tanks.
- Treatment of oily water in slop tanks.
- Gas freeing, Digging out remaining sludge, transport to shore and clean tanks in order to meet dry dock requirements.

3.1.3 Step 3: Flowlines disconnection

Before commencing this operation, the vessel should be on a heading between 135°T and 225°T and that there is a sufficient duration of weather window to complete the operation consisting of:

- Disconnect risers and umbilicals from the FPSO side. All production and control lines of the FPSO will be filled with water and laid down onto the sea bed.

Disconnection equipment (Lifting appliances & tools) should have been inspected and delivered to oil field in view of preparing the disconnection of the FPSO from the TCMS.

- Risers and umbilicals disconnection

The flowline risers buoyancy is to be increased through installation of additional buoys with aid of ROV. This is required to preserve risers from kinking when lowered below guide frames.

The flowlines (risers & umbilicals) disconnection will be carried out using, divers, wires and links capable of holding relevant strains and tensions. Once arrived below guide frame 10, the flowline link will be connected by the diver to a supply vessel wire in order to achieve the lay down of the flowline on the sea bed.

3.1.4 Step 4: Mooring system disconnection

- Start disconnecting the 10 guide frames, from top to bottom by use of divers and welders from a working platform to be installed outboard FPSO at the guide frame #2 level.
- Install air bags of 70 tons (total of 4) to alleviate the TCMS tension to less than 400 tons. Install and secure a buoyancy fender of 70 m^3.
- Connect linear winch cable to deck chafe chain and conduct pull test (expect 340 tons). Release tension from linear winch.
- Ballast FPSO in such a way that maximum allowable trim is achieved.
- Connect tug vessel wire loose to chafe chain link close to surge connector.
- Take weight with linear winch, disconnect from Wren Hook and lower chafe chain slowly by some 30 m. This would have released all TCMS tension.
- Tug vessel to pick up TCMS weight. Release linear winch wire.
- FPSO is free to sail away.
- Second vessel to pick up and cut 1st mooring rope at junction with mooring chain.
- Tug vessel to recover chafe chain and node on deck.
- Cut 1st mooring rope and pass on to Second vessel to recover.
- Cut 2nd mooring rope at node level and pass on to second vessel to recover and cut at the other end; then lay down mooring chain.
- Repeat exercise with 3rd mooring rope.

At this stage all disconnection operations are completed. An ROV survey will be undertaken as an intermediate subsea site survey. A suitable signpost is to be installed in the area in order to indicate the position of the producer and injector well heads. Regular visits to the site are to be carried out, while preparing for the final well abandonment. Three chains of 400 m each and the relevant three anchors and chain adjuster and one length of chain will be left in situ; they are imbedded into sea floor due to the very soft nature of sediments in the area.

3.2 Phase 2: Well abandonment analysis

In order to assess the abandonment requirements for the producer and injector wells, it covers the abandonment requirements for both wellbores from the Xmas tree to the reservoir.

3.3.1 Well killing

The oil field production has declined as from water breakthrough in the producer well and will continue to do so. The production of oil field will be ceased when production rates become insufficient for economic viability and decommissioning works of the installations will be conducted according to the following processes.

- Cease water injection and continue production for some 15 days to deplete the reservoir and achieve dead wells, unable to produce on natural flow.
- Flush clean the flowlines with sea water from the FPSO.
- Kill the producer well with treated sea water from the FPSO.
- Close the wellhead valves.

3.3.2 Wellbore descriptions

The W-1 well was completed as an oil producer utilizing a jet pump for artificial lift. The W-2 well was completed as a water injector with an integral injection valve.

An initial review of the production casing cement reports for both wells show that:

- There were no Condition of Production Casing Cement

As can be seen above, the production casing in both producer and injector have been well cemented in place and losses observed in either well during cementing.

- The wiper plugs bumped as per plan in both wells.
- There was no backflow indicating the float collars were holding in both wells.
- There was no cement seen in returns in either well (i.e. cement did not string out to surface).

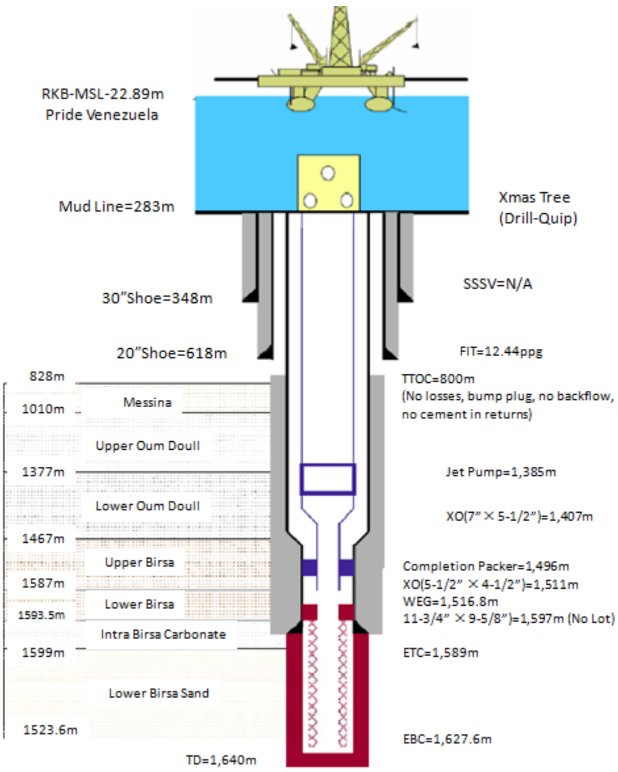

Fig. 3-2 Scheme of Producer Well (W-1)

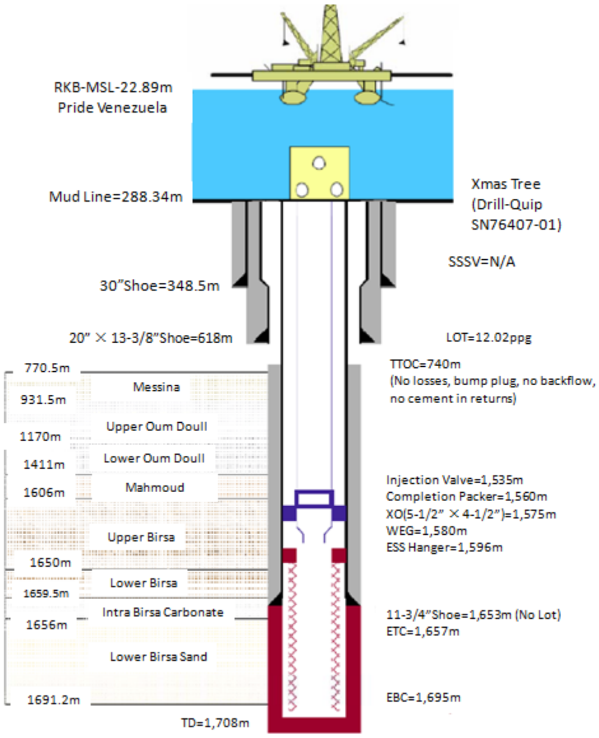

Fig. 3-3 Scheme of Injector Well (W-2)

Theoretical top of cement TTOC of both wells is based on a certain cement volume. The actual cement volume pumped in the well for cementing the production casing has a substantial excess, hence cementation may be better than reported with a higher cement level.

It could be that section below 20 inch casing is not fully cemented off to inside 20 inch casing. A maximum of 182 m in producer and 122 m in injector of formation may not be cemented around the production casing. These possible un-cemented sections are formed of clays, anhydrite, and gypsum completely un-permeable formations. For such type of formations there is no requirement for cement remedial. All abandonment plugs are designed, and set to be in compliance with, or to exceed the local and international codes and regulations.

These are outline detailed in the following pages of this document and are supported by schematics and narrative that are designed to enable the reader to understand clearly the intention and commitment to the abandonment process meeting the regulations. Further to this document initiating abandonment approvals, more detailed operational procedures will be developed for the actual abandonment operations. For well abandoning operation a 5 ½” work string inclusive of the following items from top down:

- Flow head
- Lubricator valve
- Slip Joints
- Subsea test tree
- Tree Running tool

A 3 inch flexible return line will be connected to the tree annulus access.

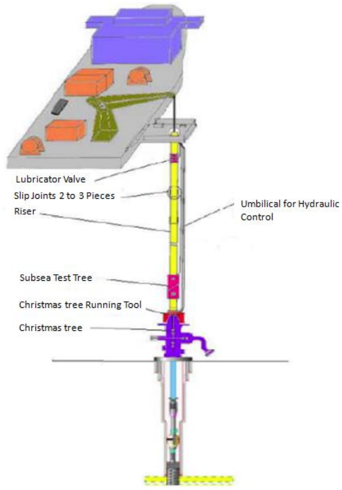

Fig. 3-4 Scheme of Work Barge

3.3.3 Well abandonment scheme

3.3.3.1 Primary reservoir section isolation cement plug & secondary tubing cement plug

- Perforate tubing some 9 m above Kobe Jet Pump level to enable fluid returns from annulus.
- With the annulus closed bullhead/squeeze 55 bbls Litecrete/CaCl or Class G/CaCl cement plug into the ESS 150 micron section, covering the reservoir section, lower casing above the shoe and into the lower/upper completion tubing section from 1627.58 m MD (ESS bull plug depth) up to 1370 m MD .

If refusal is seen before full cement displacement volume is achieved the annulus can be opened and fluid returns taken to surface for one casing/riser/annulus return line volume.

The Basic Stepsfor the Abandonment of Wells it is considered that this cement plug meets the requirements of Placement, Cross flow and Height.

- Allow cement to set, then pressure test to 3,000psi for to prove isolation plug and production packer. If required, tag top of cement in the tubing with wire line at theoretical depth and confirm actual depth.
- If required, tag top of cement with wireline at theoretical depth and confirm actual depth.

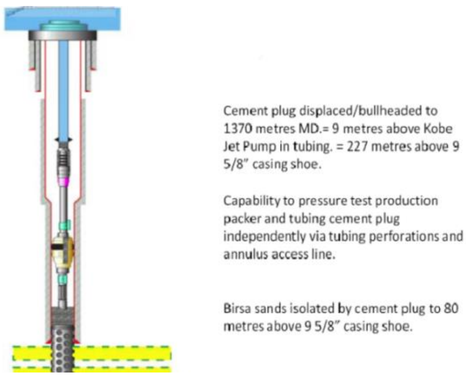

Fig. 3-5 Primary Cement Plug in Reservoir and Mechanical Barrier in Casing Section

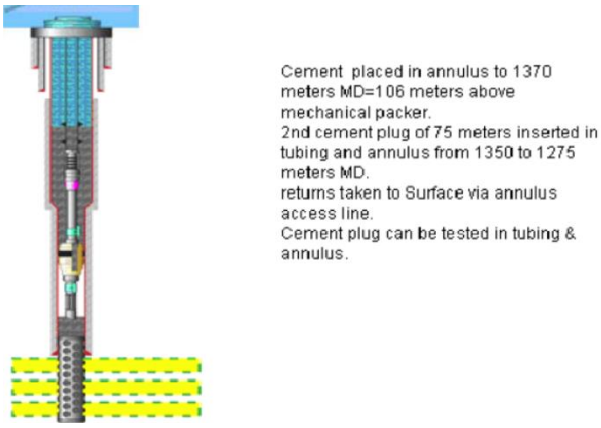

Fig. 3-6 Secondary Cement and Mechanical Barrier in Casing Section & Cement in Tubing

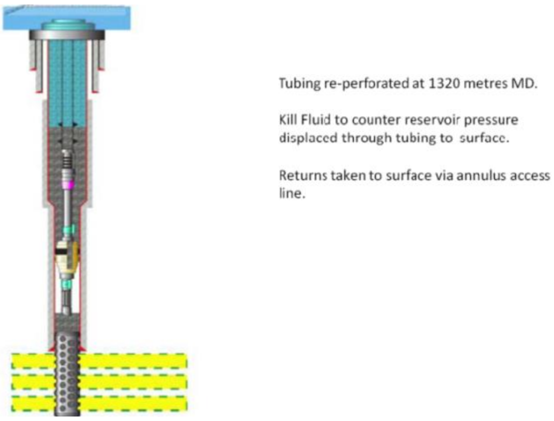

Fig. 3-7 Kill Fluid Displaced to Tubing & Annulus above Cement Plugs

3.3.3.2 Secondary annulus cement plug above mechanical element

- With the annulus returns line to surface open, 50 bbls Class G cement (considered the well depth, formation temperatures, formation properties, and wellbore mud properties, etc) to be pumped slowly. This would enable cement to fill annulus above packer and ensure a 75 m cement plug above jet pump.
- Allow cement to set, then pressure test to 3,000 psi in the tubing and the annulus to prove test casing isolation cement plug and production packer and the tubing isolation test plug.

3.3.3.3 Complimentary seal barrier

- Perforate tubing above cement plug in tubing.

Displace tubing and annulus to inhibited sea water to provide Complimentary Seal Barrier to counter reservoir pressure.

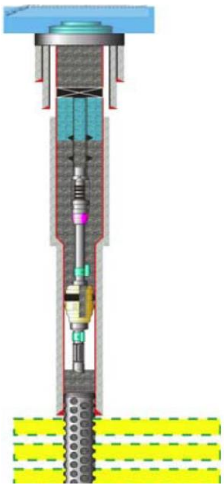

Fig. 3-8 Bridge Plug in Casing and Environmental Cement Plug Set

At this stage the well abandonment seal barriers are considered fulfilled.

3.3.3.4 X-mas tree retrieval

- X-mas trees will be retrieved with the work string.
- Cut tubing 50 m below wellhead with jet cutter and retrieve tube portion.

3.3.3.5 Environmental surface plug

- Set 11 3/4 inch casing bridge plug 50m below well head.

Set 50 m environmental cement plug above bridge plug.

3.3.3.6 Seabed condition

- Remove all guide posts to 12 inches above permanent guide base, leaving only 18 ¾ inch mandrel and guide base plus remaining guide post stubs.
- Run over-trawlable protection structure on wire or tubing to top of 18¾ inch wellhead mandrel. Place cement if necessary.
- Video all sea bed operations with ROV and to a radius of 30 m around wellhead removing all debris.

3.4 Well intervention support means

Three options were considered and studied for the means to support the well abandonment operations:

- Semi-Submersible drilling unit: This option is the conventional mean for deep subsea well abandonment operations. Consideration for well intervention will strongly depend on availability in the nearby area for reasons of high mobilization costs for the drilling unit and the large anchor handling vessels at substantial high rates.
- Dynamic Positioned Vessel: This option was discarded at an early stage for reasons of

difficulties to adapt the equipment to well application and also for unavailability outside North Sea environment.

- Deck Barge with Cantilever: This option has been thoroughly reviewed and assessed through Micoperi 30 vessel capabilities and past experience with similar type of work in a similar environment. The option viability is fully assessed and has strong technical capabilities while remaining cost effective.

3.5 Sign posting and notice to navigators

Marine authorities will be informed about the work planning in order to diffuse the information to navigators. As the well abandonment operation will be carried out later on, at the second stage after the production installations decommissioning , the area of producer and injector wellheads will be marked by suitable signposting means (buoy at water surface) until dismantled. This plan of well abandonment as well as the coordinates and the size of the installations to be laid down on the sea bed will be communicated to the authority for display on the marine maps and to inform navigators. In case other measures are required by the relevant authorities, these measures will be taken into consideration and studied in time.

3.6 Environment impact

For the dismantling and the removal of the installations of the oil field, a thorough analysis of the various options and an Impact study on the Environment were carried out in order to define the most adapted options to this case and which take into account the respect of the environment, safety, technical and technological constraints. These analyses and studies were established in agreement with the Tunisian rules and standards and also with the international directives and rules used in the oil industry in particular.

The assessment of eventual impacts of oil field abandonment focuses on an appraisal of the gains and losses expected to ensue from the planned activities, as far as the various components of the natural and human environment are concerned. The main impact mitigation measures taken by operator in order to preserve the environment are as follows:

- Separating the biodegradable and the non-biodegradable waste and disposing of the same in accordance with the regulatory requirements;
- Transporting the non-biodegradable waste for disposal on an authorized dumping ground;
- Treating residual fluids (draining water and domestic water) in conformity with the applicable standards prior to dumping at sea;
- Recovering in specific tanks and shipping to the shore of used lubricants for reprocessing;
- Taking the necessary actions to avoid the spilling of chemical products, hydrocarbons and lubricants;
- Covering drilling wellheads with gravels &/or Cement to avoid damage to the trawling nets;
- Informing the maritime authorities of the abandonment program to enable them to control embarkations in the area affected;
- Communicating the coordinates and dimensions of the facilities left over on the sea bottoms to the relevant authorities to enable them to record the same in the nautical charts;
- Conducting the abandonment operations in accordance with the oil industry practices and the International Maritime Organization (IMO) recommendations, in such a way as to minimize the environmental impact and risks in terms of navigational security.

Based upon knowledge of the existing environment, possible interactions with the project and taking into account proposed minimizing steps, the project to be acceptable is judged as far as the environment is concerned. The environment study was sanctioned in December 2008 with approval from the environment authorities.

4. Conclusions

The procedure of decommissioning and well abandonment for FPSO, TCMS, subsea system have been analyzed. Meanwhile, the environment impact and mitigation measure have been proposed. These will provide a guide line for the offshore facilities decommissioning and abandonment.

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