Moving the Immovable: Practical Offshore Appraisal Testing of Heavy and Sour Oil

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Abstract

Saudi Aramco has recently embarked on an exploration program targeted at evaluating potential heavy oil reserves, offshore Saudi Arabia’s eastern coast. The oil being tested is classified as heavy oil with an API gravity as low as 10 degrees (field measurement). Appraisal well testing in an offshore setting of such low API oil is difficult, especially when environmental considerations are of outmost importance. The tests objectives were to obtain accurate reservoir parameters, collect representative reservoir samples, and dispose of all produced hydrocarbons (heavy oil) without adversely impacting (spill/polluting) the offshore environment. Being offshore, with limited space availability on jack-up rigs, it was also crucial that the design of the test equipment and procedures take into account the potential presence of Hydrogen Sulfide (H₂S).

This paper will present best practices, experience gained, and lessons learnt from appraisal well testing of heavy oil at offshore locations. Several offshore heavy oil well tests were successfully carried out, where all produced hydrocarbons were flared off without causing spills or polluting the sensitive marine environment.

Introduction

It is known that offshore oil or gas operations are much more complicated compared to those onshore. Besides the challenges associated with logistics and limited space availability, there are others that come from strict yet essential, marine and environmental regulations. To promote environmental responsibility, Saudi Aramco has implemented a zero-discharge policy, where harmful discharge into the marine eco-system is strictly prohibited. Saudi Aramco’s offshore appraisal testing procedures; therefore, had to be modified and optimized to ensure full adherence to environmental regulations.

It is important to recognize that heavy oil does not burn efficiently as compared to conventional oils. Standard flaring practices of such heavy oil in an offshore environment can lead to incomplete combustion of the oil, leading to hydrocarbon fall-out into the sea, thus causing pollution.

The presence of Hydrogen Sulphide (H₂S) makes offshore testing even more challenging. Test equipment and procedures have to be designed to ensure full H₂S containment and safety of the personnel on the confined and limited space of an offshore drilling rig.

In order to comply with a zero-discharge policy during heavy oil tests, alternate designs such as flowing the produced hydrocarbons into a small storage tanker or a test barge (dedicated for the entire duration of well testing heavy oil to the drilling rig) were evaluated. These alternatives were deemed unacceptable due to their unavailability at the time. Another alternative was to design the test equipment and procedures in a way that ensured that all produced hydrocarbons were completely flared-off to adhere to policies of zero discharge into the sea.
The plan was to work with the limited space on offshore rigs and efficiently utilize all available space to put onboard all the test equipment, along with a temporary heavy oil production and treatment package. Prior to full implementation of this system to offshore wells, the concept was trial tested in analogous onshore wells to ensure its feasibility and applicability for offshore operations.

The team carried out several successful offshore heavy oil well tests. All produced hydrocarbons were efficiently and completely flared-off without causing any harmful discharge into the marine environment. This paper will share lessons learnt, equipment used, operating procedures, and best practices that led to this success.

Background & Challenges

Offshore oil & gas operations are recognized as more difficult than those on land, in many aspects. Logistics, transportation, and space availability on offshore drilling rigs are always an issue during routine operations. The involved and complex operations associated with exploration appraisal testing on an offshore rig adds a bigger challenge to the success of the overall objective.

Strict regulations pertaining to environmental responsibility, having to deal with and dispose of heavy oil, and the potential presence of Hydrogen Sulfide (H2S) calls for a non-conventional test design (equipment & procedures) to achieve the appraisal test objectives.

Marine Environment Regulations

When an oil drop is placed on water surface, it forms a thin layer called sheen which is normally less than 1μm in thickness. The surface area of sheen formed as a result of oil being placed on water is very large compared to the surface area of the oil drop. However, repeated development of sheens as a result of minor oil spills can have an adverse impact on the marine environment as it will affect the local eco-system at spill locations.

Saudi Aramco's environment protection policy states that “The Company will assure that its operations do not create undue risks to the environment or public health, and will conduct its operations with full concern for the protection of the land, air and water from harmful pollution...” And hence, harmful discharge into the sea regardless of its quantity, including hydrocarbon fluids, shall not be allowed. Therefore, appraisal testing equipment and disposal procedures must be modified to ensure full adherence to environmental regulations. Since flaring off produced hydrocarbons was the only viable alternative at the time, all flared hydrocarbons had to be burnt efficiently, such that no liquid hydrocarbon, regardless of its amount or severity, would fall-out into the sea while flaring.

Space Availability

Unlike the case for land rigs, space on offshore rigs is very limited. In addition to the well test equipment, heavy oil tests may also require coiled tubing and stimulation equipment. There is not sufficient space on board the drilling rig to accommodate all this equipment simultaneously. This required moving equipment on board at the required time while simultaneously unloading other temporarily surplus equipment. This movement of heavy equipment many times during the test is a logistical and safety concern. All operations have to be designed and planned to ensure the safety of personnel. Sea conditions and weather also impose restrictions on this movement of equipment and can lead to time delays and cost escalation.

Heavy Oil

The chemical composition of heavy oil is characterized by large and long hydrocarbon molecules resulting in lower combustion efficiency. This combustion efficiency is variable and is governed by the amount of heat required to burn large hydrocarbon molecules, the retention time during which such molecules are exposed to flame, and the amount of oxygen present during the combustion stage. Incomplete combustion can be easily identified by a cloud of black smoke being emitted while flaring, which signifies that some hydrocarbon molecules are being released into the environment un-burnt or partially burnt. Such un-burnt molecules fall-out (spill) into the sea creating a thin film of hydrocarbon layer called sheen. Depending on its size and severity, sheen can have an adverse impact on the local marine eco-system at spill locations.

Another challenge with heavy oil is that its mobility is dramatically reduced when it cools off. Plugging of surface flow lines and test equipment and/ or downhole test equipment is a potential risk associated with heavy oil testing. Heavy oil may solidify in pipes as it cools at surface or even downhole if the well is lifted with nitrogen through
coiled tubing. A properly designed test procedure along with a proper surface heating system can help reduce this risk.

Conventional techniques for determining fluid properties of typical oil do not work very well with heavy oil. Inaccurate measurements of fluids properties will eventually lead to inaccurate rate measurements obtained through a multiphase flowmeter. Therefore, identification and breakup of water emulsion in heavy oil is essential to obtain accurate rate measurements.

**Hydrogen Sulfide (H₂S)**

Presence of H₂S poses a big challenge from a safety perspective. This is especially true on offshore rigs where escape options are limited. The test plan must take into consideration that heavy oil and sour gas with H₂S concentrations as high as 20% may be encountered during testing some of the zones; therefore, all surface equipment must be designed to provide complete containment of any produced heavy oil and unvented sour gases in pressurized storage tanks (150 psi internal yield pressure).

**Test Equipment**

Well test tools and equipment are generally divided into two main sets: surface and downhole. The primary functions of downhole test tools (Packer, downhole shut-in valves, circulating valves, etc.) are not affected by the state of oil being tested. However, conventional surface well test equipment packages cannot be used when testing heavy oil with API densities as low as 10 °API. For example, a horizontal separator can not provide efficient separation of such heavy oil, especially with short retention time, and therefore, flow rate measurements may not be accurate.

Furthermore, wellhead pressure of heavy oil wells is usually significantly lower than the optimum operating separator pressure, and therefore, the automated flowrate measurement logic loop of a separator does not function.

The importance and the design concept of surface well test equipment and treatment package will be presented in the subsequent discussion. A complete description outlining the entire test process (flow, storage, and flaring) will be presented.

**Surface Well Test Equipment**

- **Skimmer (Vertical Separator)**

Since heavy oil wells are not expected to naturally flow to surface at high rates, basic flow rate measurement techniques can be used. This objective can be achieved by a skimmer, where fluid rates are calculated manually by measuring incremental volumes over time. If done correctly, it can provide very accurate measurements of flow rates. If water is present, skimmer rate measurements represent the total flow rate (oil and water), but by capturing continuous wellhead samples and determining the oil-water-ratio, individual phase flow rates can be determined from the total flow rate. If gas is present, gas rates can be measured through a low-rate measurement skid connected to the gas vent line of the skimmer.

Because of its vertical design with two separate vertical compartments, a skimmer provides an advantage over a horizontal separator in terms of longer retention time and larger capacity with a smaller foot-print on an offshore rig. Being able to switch flow from the well between the two compartments ensures continuous rate measurements in the event one vertical compartment is full and needs to be transferred to onboard storage tanks for later treatment and disposal.

Determining liquid level via regular transparent sight-glass is impractical since oil will stain the sightglass and makes it very difficult if not impossible to determine the fluid level in the skimmer. Removing this oil coating/residue from the inner wall of the sight glass requires rigorous cleaning as simple flushing of the sight glass is insufficient.

The functionality of magnetic fluid level Indicators is also impaired by the viscosity of the oil and and makes it very difficult to determine fluid level. This problem can be dealt with by flushing the tubulars with solvents to clear the heavy oil.
Ultrasonic level indicators will provide the ultimate solution to resolve problems associated with determining fluid levels.

- **Multiphase Flowmeter**

Even with the advanced technology of multiphase flowmeters, heavy oil still presents a challenge to the accuracy of their measurements. The challenge is even exacerbated when dealing with low flow rates as the accuracy of multiphase flowmeters is further reduced. However, using a multiphase flowmeter gives the advantage of being able to continue to measure (qualitatively) well effluents and functions as another source of flow rate data to validate/compare rate measurements obtained by the manual skimmer measurements.

In case of high H2S concentrations, continuous liquid sampling of well effluents to determine flow rates by the skimmer’s manual method becomes riskier as human exposure to H2S must be minimized. The frequency of fluids sampling at the wellhead can be reduced significantly by obtaining multiphase flowmeter data which can be checked and validated with reduced sampling frequency by the manual method.

- **Heat Exchanger**

Because fluid viscosity is strongly dependent on temperature, heating the heavy oil keeps it in a mobile state. Heat also ensures that when heavy oil is mixed with lighter hydrocarbon fluid (diesel), a homogeneous, lighter and less viscous mixture is created. This change in fluid characteristics enhances its burn efficiency and helps in achieving complete combustion.

Breaking of water emulsion in heavy oil is difficult to achieve with the addition of emulsion breaker chemicals alone. Heat is required to facilitate maximum emulsion breakup.

Heating heavy oil should start immediately as soon as it comes to surface because it becomes very difficult to move the heavy oil when it cools off. Once the heavy oil’s viscosity is permanently reduced by diluting it with lighter fluids; maintaining the mixture at high temperature is not necessary. However, prior to flaring off the heavy oil-diesel mixture, its temperature must be increased for better burn efficiency.

The mixture’s temperature must not be increased beyond the maximum allowable operating temperatures of the surface equipment to ensure their integrity throughout the test duration.

- **Burners**

The flare burner is likely the most critical piece of equipment since it is here that the actual flaring of oil takes place. Any deficiency in the burner will result in incomplete combustion and fallout, which violates the environmental policies. It is critical that the burner and all associated equipment are checked and maintained prior, during and after the heavy oil test.

**Heavy Oil Treatment Package**

- **Storage Tanks**

As we have seen from the previous discussion on heavy oil, the produced heavy oil can not be flared off in its raw state because it will not go through complete combustion.

Heavy oil has to be conditioned and high graded to a quality where it burns efficiently. Initially, the well’s effluent is accumulated in the skimmer, but later it is transferred from the skimmer to onboard oil storage tanks, where the conditioning process takes place.

Four skidded and pressurized horizontal storage tanks (150 psi internal yield pressure) were used. Each two tanks were stacked on top of each other in order to save space and ensure uniform weight distribution on the rig’s main deck.

Each tank had a total volume capacity of 100 barrels, but an effective capacity of only 60 barrels. This is due to the horizontal design, where there is 40 barrels of dead volume (below the liquid outlet line and the volume above the gas outlet line). The total usable volume is therefore 240 bbls for all four tanks combined.
Most of the produced gas with oil (if any) is separated at the skimmer, measured, and flared off directly; however, more gas is released by the heating and agitation process. This gas has to be vented and flared off to prevent pressure build up inside the storage tanks. To achieve this, the gas outlet line in each tank is kept closed until it is needed to reduce the tank pressure to below the internal yield pressure. The gas vent line can not be kept open all the time because through the agitation process some liquid may get carried over in the gas line and eventually falls out into the sea. It is important to stress out that the gas vent line should be opened only when a tank’s contents settle down after agitation. This tank vent must be hot-flared using a flame arrestor in the line to prevent flashback. Cold venting of sour gas is dangerous and should not be attempted.

- **Diluents**

Keeping heavy oil in a mobile state requires adding diluents in addition to the previously discussed heating of the oil. Diesel (or equivalent) can be used to achieve that purpose. In addition to reducing the oil viscosity, diesel can significantly improve the combustibility of flared hydrocarbons.

- **Pumps**

Since heavy oil has to be stored and treated before it is flared off, it requires pumps to transfer it during the treatment phase and when it is finally flared off. Two pumps are required; one to transfer the oil from the skimmer to the storage tanks and another to be used for agitating, conditioning, and flaring the oil.

Smaller, low rate/low pressure pumps are also required for chemical injection.

- **Air Compressors**

Efficient flaring of the oil requires that the oil be atomized by the addition of air. Field trials (on land) indicated that 1500 scf/min of air is required to efficiently burn hydrocarbon/diesel mixture being sent to the flare at a rate of 1000 bpd. It is imperative to modify the burner head to optimize flaring at such low rates. This can be achieved by reducing the number of nozzles being used at the burner head to achieve 150 – 200 psi back pressure at the discharge point of the burner head.

**Operating Procedures—Testing Heavy Oil**

The following sections outline general operation guidelines for testing heavy oil exploration wells and addresses the different flow scenarios (natural or artificial) that may be encountered while testing heavy oil wells. Discussion of heavy oil conditioning, storage, and flaring is also presented.

**Flow Period**

Heavy oil wells may or may not naturally flow to surface. If wells do not flow naturally, an artificial lift method like nitrogen lifting via coiled tubing is required. The following operating guideline is designed for 10°-12° API oil exhibiting considerable emulsion. However, different scenarios may require some modifications to the general operating procedures.

- **Natural Flow**

If the well flows naturally, the following test procedures should be implemented:

1. Check and maintain burner head condition and do a test burn with diesel to check for system efficiency.
2. Ignite the gas pilot at the flare boom downstream of the wind direction and ensure that the skimmer’s gas vent line is open and lined up to the correct flare.
3. Line up the flow through the heat exchanger, multiphase flowmeter, choke manifold, and collect returns in one compartment of the skimmer to recover the test string’s fluids (cushion) while continuously monitoring BS&W.
4. Frequently measure and record flow rates (every 10 minutes) using the multiphase flowmeter and the skimmer manual technique.
5. Upon recovering 80% of total volume of the cushion, expect heavy oil traces and start injecting low volumes of diesel. Heavier oil may require higher volumes of diesel. The injection point must be downstream of the choke manifold to allow for capturing untreated, representative samples.
6. Multiphase flowmeter measurements need to be continuously monitored and validated by the manual rate measurement techniques using the skimmer.

7. Shortly after heavy oil is observed at surface, start to periodically flush the fluid level magnetic indicators on the skimmer with diesel.

8. As soon as one side of the skimmer’s twin compartments is full, divert the flow to the other side and continue sampling and measuring flow rates.

9. Pump out the contents of the already filled compartment to a predetermined minimum level into one oil storage tank. Record the volume pumped into the storage tanks.

10. If the initial string’s fluid (cushion) was diesel, distribute the recovered cushion volume equally between all storage tanks and later pump the heavy oil into those tanks in order to approximately have 70% oil and 30% diesel in the mixture (see section on conditioning and processing optimum oil/diesel ratio). If the initial cushion was clean water, mud, or brine, drain into rig tanks or off board if possible and no pollution is to be created.

11. If the cushion volume is less than 30% of the overall tanks capacity, add more diesel to any tank to ensure that 30% by effective volume is diesel.

12. Fill the first two storage tanks with the suggested ratios of oil and diesel mixture and immediately start processing and conditioning the oil for flaring.

13. Continue flowing the well into the skimmer and transferring oil into the remaining storage tanks (effective volume already filled with a predetermined volume of diesel). When 100% of the effective volume of storage tanks’ is filled, shut-in the well and start processing and conditioning the oil for flaring.

14. Flaring is a critical step and it is suggested that the flow be halted while flaring to permit the full concentration of the test crew on this critical task. Never flare at night as visual indication of inefficient burn is difficult and may result in significant oil spills.

- Flow Assistance (Coiled Tubing)

If the well does not naturally flow, the following procedure should be implemented.

1. Ignite the gas pilot at the flare boom downstream of the wind direction and ensure that the skimmer’s gas vent line is open and lined up to the correct flare.

2. Line up the flow through the heat exchanger, multiphase flowmeter, choke manifold, and collect returns in one compartment of the skimmer to recover the test string’s fluids (cushion) while continuously monitoring BS&W.

3. Start running in hole with coiled tubing while injecting nitrogen to unload the string fluids at three stages (1/3, 2/3, and maximum allowable lifting depth).

4. If the well starts to flow naturally, proceed with steps 4 through 14 in the natural flow section; otherwise, proceed to next step.

5. Upon recovering 50% of the cushion volume, start injecting the diesel at a rate of 0.05 bpm via a high pressure injection pump into the nitrogen stream to reduce the oil viscosity as it is being lifted.

6. If the well starts to continuously offload oil, but only with nitrogen assistance, frequently measure and record flow rates (every 10 minutes) using the multiphase flowmeter and the skimmer manual technique.

7. continue lifting and testing the well according to the above mentioned procedure in the natural flow section.

Conditioning and Processing

Before the produced heavy oil is flared off, it requires conditioning such that it burns efficiently. This can be achieved by mixing a lighter fluid (diesel) with oil and at the same time heating and agitating the mixture to ensure a homogeneous blend. Trial tests showed that a blend of heavy oil and diesel resulting in 25° API mixture is sufficient for effective flaring. The following equation determines the amount of diesel required as a percentage of each tank’s effective volume:

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\text{Diesel requirements (\% by volume) } = \frac{25V_{\text{effective}} - (\text{Oil}_{\text{API}} \times V_{\text{effective}})}{35V_{\text{effective}} - (\text{Oil}_{\text{API}} \times V_{\text{effective}})}
\] (1)

For example, an effective volume of 60 barrels will have API density of 25° by blending 36 barrels of 35° API diesel (60% by volume) with 24 barrels of 10° API heavy oil. Therefore, in this example, the heavy oil total volume to be recovered and stored in the tanks must not exceed 40% of the total effective volume of all storage tanks. The well has to be shut-in or nitrogen lifting must be stopped until more storage space is availed by flaring off the tanks’ contents.
The conditioning and processing stage is performed as follows:

1. Add the predetermined volume of diesel to the oil storage tanks to change the mixture’s API to 25° using equation 1.
2. One at a time, circulate each tank’s contents of heavy oil diesel mixture through the heater until the mixture temperature increases to 55°C.
3. While circulating each tank measure and record API and BS&W. If BS&W is greater than 20%, stop circulating the tank, wait for the water to separate and drain the water into the rig tanks if possible to do so; otherwise, this water must be flared off (see section on flaring)

**Flaring Operations**

When flaring off heavy oil, the goal is to achieve zero discharge into the sea. The previous section described how to condition the oil and high grade it to a certain quality that ensures complete combustion when it is flared off. However, reducing the oil API alone will not ensure that the oil burns completely. The most important factor in ensuring complete combustion and no fallout is the flaring operation itself. A lot of coordination is required in order to have a successful flaring whereby all hydrocarbons are completely burnt.

Oil storage tanks must be circulated and heated before they are sent to the flare. Their fluids properties must be measured to ensure that they can be efficiently flared off. The most important parameters to be measured are the mixture’s API and its BS&W. As stated earlier, achieving a mixture density of 25° API should be sufficient for efficient flaring. The mixture’s BS&W must not exceed burner head’s manufacturer recommendation. If the oil storage tanks’ BS&W is higher than the recommended operating limits by the burner head manufacturer, clear diesel must be continuously supplied to the flare to ensure that the mixture’s BS&W at the burner head is within the operating limits for maximum efficiency.

Flaring operations must be well coordinated by an experienced person to ensure a complete combustion of the flared oil. Visual attributes of the flared hydrocarbons determine the requirements (air & diesel) for efficient flaring. This section will outline the flaring process and provide general guidelines to achieve efficient burning of the oil.

It is essential to have the outlets of the oil storage tanks and the clear diesel tank gather into one control manifold that feeds the suction inlet of the transfer pump, which in turn is controlled by a series of valves to manipulate the amount of oil and diesel volumes to be sent to the flare. In addition, the plumbing of the oil storage tanks individuals’ outlets should allow for control of which oil storage tank is to be directed to the control manifold.

- **Flaring Process:**
  1. Start the burner boom water cooling system.
  2. Start the air compressors and the gas pilot on the burner head.
  3. Slowly introduce the air supply to the burner head.
  4. Slowly introduce diesel to the diesel pilot on the burner head.
  5. Increase the air supply to the burner head so that the diesel pilot flare shapes into a spear.
  6. Start the transfer pump and begin sending clean diesel to the oil line of the burner boom by slowly opening the diesel supply control valve to the pump’s suction line. Simultaneously, increase the amount of air supply to the burner head. Repeat this step until the diesel supply line is fully open.
  7. Fine tune the flare by adjusting the air supply to ensure clean burn (no black smoke)
  8. Line-up one the oil storage tank desired for flaring to the control manifold.
  9. Slightly open the oil storage tank control valve (25% open) to the suction line of the transfer pump.
  10. Adjust the air supply line to ensure clean burn.
  11. Increase the oil storage tanks’ control valve to 50% open. Monitor the flare and adjust air supply, if needed.
  12. Start reducing the diesel supply by controlling the diesel supply valve to 50% open.
  13. Increase the oil supply to 100% open and close the diesel supply line.
  14. Monitor the flare to ensure efficient burn. If black smoke starts to develop, slightly open the diesel supply line and reduce the oil supply by the same amount.
  15. Continue flaring all oil storage tanks utilizing the techniques listed above.
  16. When the flare starts to show signs of water (thick white cloud), start reducing the oil supply and increasing the clear diesel supply by the same amount.
  17. Continue flaring all the tanks by following the steps above.
  18. When the contents of the last tank are almost completely flared off, start to slowly open the control valve of
the clear diesel supply line, while simultaneously adjusting the air supply to the burner head.
19. Continue sending clear diesel to the burner head until the last tank’s contents are completely flared off.
20. Close the oil supply line from the control manifold.
21. Start reducing the clear diesel control valve while simultaneously adjusting the air supply.
22. Shut-down the transfer pump, reduce the air supply and close the diesel pilot at burner head.

Best Practices

Flaring

1. Shut-in well prior to flaring. Do not do both operations concurrently.
2. Perform a test burn with diesel prior to commencing each major flaring operation.
3. Ensure that the flaring personnel are trained and experienced in flaring heavy oil.
4. Condition, heat and mix the fluid to ensure a consistent and favorable flaring condition.

Stimulation Volumes

1. Minimize the volume of stimulation fluids.
2. Recommended practice is to restrict stimulation volumes to 1/3 of the surface effective storage volume.

Conclusions

Heavy oil testing in an offshore setting is very complex and requires the full cooperation and interaction of all stakeholders.

The key to success is having the right equipment, the correct procedures, and continuous vigilance at all times until the last drop of oil has been flared efficiently.

Planning is essential. Communication is vital.

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Nomenclature

\[ V_{\text{effective}} \] : Effective volume of each individual oil storage tank
\[ \text{bpd} \] : Barrels per Day
\[ \text{scf/min} \] : Standard Cubic Feet per Minute