

Design and Evaluation of Floating Production Storage Offload (FPSO) Systems for Decommissioning and Reuse

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Abstract

Field development schemes for FPSO's involving subsea well/manifold systems are increasing in numbers because of lack of a mature field (or area) infrastructure or marginal field life situations. However, FPSO/subsea systems may be too expensive to support just one field alone. Further, FPSO systems may only be economically justifiable if it can be decommissioned and sold to another "project" or user. Hence, industry interest is growing with respect to decommissioning and reusing FPSO/subsea systems (Figure 1). However, how and where to reuse these systems poses a challenge because their designs are usually site specific (both technically and commercially). This paper addresses the site specific nature of the equipment by grouping various parts of the system into operating classes to better understand where they can be reused.

Ideally, FPSO/subsea equipment systems would be designed to accommodate the most demanding of all known conditions, so that it could be transferred from any one field to another field for reuse. In reality, such a system would be far too large and expensive to be justified for starting out on a marginal field or a benign environment.

Using a classification process, FPSO/subsea systems can be grouped into various defined categories to better illustrate where they can and cannot go after their first "purpose built" job is completed. From these categories, jumps to other classifications with either minor or major cost modifications can be identified. The paper also describes what will be required to make FPSO's/subsea systems more decommission / reuse "friendly". Equipment that is typically consumed for "one field" use is also identified. Through the defined classification process, a technical evaluation tool, to help end users and designers better address FPSO/subsea requirements and understand the design philosophy, which maximizes overall system flexibility beyond "first field" requirements.

FPSO Topsides

Process facilities are usually tailor made to suit characteristics of reservoir fluid and production plan. They are not designed to be relocated and reused for production at other oil fields. However major components such as pressure vessels, piping and equipment can be reusable because of similarity of fluid

characteristics at fields. In many cases provisions for future expansion and/or longer design life can be built in facilities at initial design, so long as production fluid properties are similar. Decommissioning/reuse costs are often manageable because the facilities are easily mobilized to a conversion yard and the modification work can be carried out at a conversion yard with help of sufficient infrastructure. This minimizes offshore work and is one of the substantial advantages of an FPSO. These factors allow production facilities to be modified easily and reused at other fields in an economical way.

Category

Topsides facilities are specifically designed and fabricated to comply with requirements for production which vary for each field and are difficult to be categorized. However the following categories will be considered from the viewpoint of system compositions:

- Conventional production systems
- Enhanced production systems

Conventional production systems consist of a production manifold, several stages of two or three phase separators including a test separator, water treatment system, gas flare/disposal system, heat exchangers, crude transfer pumps and control system. Usually this system is used for small fields to minimize capital investment. Enhanced production systems feature a gas compression system for gas lift, gas injection and gas export, water injection system, desalters, NGL recovery systems, etc., in addition to the "conventional production system." In many cases (but not all), some of the systems listed above will be added to a "conventional production system" to increase oil recovery rate or to satisfy other requirements. In general, enhanced production systems have a large processing capacity. Enhanced production systems will also have more chances to be utilized with small modifications. Still, there are many parameters to govern specification of topsides facilities which can thwart the reuse possibilities without major modification.

Normally it is very difficult to incorporate versatility into a topsides facility because of a project's economic constraints and vagueness for requirements derived from future assignment. However the following are recommended for consideration during the initial design:

- Provide space for future expansion of additional equipment
- Provide additional space in pipe racks and cable racks
- Provide spare I/O ports for control panels
- Provide spare branches on piping for future connections

Planning for Re-utilization

To start the re-utilization process, key parameters for the new field are reviewed and compared with the functional specifications and the remaining life of the existing production facilities to determine the level of suitability. Key parameters include:

- Production rate and profile
- GOR
- Produced Water Rate
- Field Life
- Fluid Characteristics (Operation Pressure, Shut-in Pressure, Temperature, Specific Gravity, Viscosity, Pour Point, Components, Amount of H₂S and CO₂, Wax, Salt, and Sand Contents, etc.)
- Requirements for crude stabilization (RVP, TVP, BS&W, Salt Content, etc.)
- Allowable oil content in discharged water
- Requirements for NGL Recovery
- Requirements for gas lift and water injection
- Requirements for gas injection
- Chemical injection requirements
- Slugging characteristics of incoming flow
- ESP requirements and their power supply requirements
- FPSO vessel motions at operating condition and survival condition
- Shut down philosophy in case of survival condition
- Operational constraint especially at survival condition
- Safety requirements, Safety Case
- Operator's policy and preference for operation, maintenance and safety

Next, the engineering documents such as PFD, P&ID, plot plan, equipment data sheet, etc. of the existing facilities, sizes, flow rate, pressure rating, temperature, internals for ship motion, and material service of the following equipment is checked for compatibility with the new produced fluid composition and design conditions:

- Manifolds
- Pressure vessels
- Valves, Piping
- Pumps
- Heat Exchangers
- Water treatment facility
- Flare system

- Gas compression system
- E & I system

This is followed by a thorough inspection and survey of existing equipment and infrastructure to look for:

- Condition of existing equipment (corrosion, erosion, mechanical failure, leakage, etc.) for reusability
- Space availability on FPSO main deck for new equipment, piping and wiring
- Reclassification/relocation of hazardous areas due to new equipment
- Strength of structural members
- Impact to existing utility system such as electricity, steam, cooling water, compressed air, etc.
- Impact to safety system such as deluge fire fighting system

After the existing and new requirements are investigated for suitability, a revised PFD and P&ID is developed along with an appropriate modification plan. The plan outlines the necessary removal replacement or addition of facility equipment such as gas injection compressors, water injection system, gas lift compressors, desalter, etc. The plan will also be verified by flow simulation for recovery efficiency and checked by a HAZOP study for operability and safety.

Decommissioning

Following well abandonment of the subsea trees, wellheads, and flowlines/risers, valves segregating topsides facilities from the risers will be depressurized and fluid in pressure vessels and piping will be drained or flushed by water, while gas will be flared or vented. Hydrocarbon gas remaining in pressure vessels and pipe will be replaced with inert gas to well below low explosion level. Utility systems such as electricity, steam, etc. also disconnected or segregated from the topsides facilities. After this work the facilities are ready to be opened for inspection. This work is normally carried out at the field prior to decommissioning of the mooring system and departure to a conversion yard.

Refurbishment and Conversion Work

After demobilization of an FPSO to a conversion yard, refurbishment and conversion work commences.

Following clean up work, the condition of the topsides equipment (especially pressure vessel internals) are surveyed which would include thickness gauging of pressure vessels and piping. Equipment to be reused will be overhauled and reconditioned. Reusable instruments are recalibrated, and new equipment, instruments, piping, tubing, and electric cables are added to the existing facilities per the modification plan.

FPSO Vessel

The vessel part is the easiest part of the FPSO for decommission and reuse. After the disconnection from the mooring system, the vessel can be towed by a tug, or sail under her own power to the next assigned field or a shipyard for refurbishment. As with topsides facilities, decommissioning and reuse is manageable because the vessel is easily mobilized to a conversion yard where extensive work for refurbishment and conversion is carried out more economically with a shorter duration.

Normally it is very difficult to design vessels at the initial stage with higher grade standards and enough spare capacity of equipment because of economic constraints of a specific project. Practicality also dictates the design and construction of the vessel be tailored to site specific requirements (considering that the vessel can be mobilized to a shipyard and economically converted for the next assignment).

Besides initial design considerations, maintenance during operation is very important. Adequate maintenance will extend the residual life of the FPSO and reduce refurbishment costs for future assignments.

Category

The FPSO vessel is categorized by size of its storage capacity. Vessel categories follow classical groups for trading tankers:

- Small vessel
- Medium vessel
- Large vessel

The small vessel category includes tankers with a deadweight range less than 90,000 dwt. Examples of small vessels include the Aframax and Panamax. Crude oil storage capacity is less than 700,000 bbls. The medium vessel category includes mostly Suez Max tankers. Deadweight range is from 100,000 dwt to 150,000 dwt. Crude oil storage capacity is between 700,000 bbls to 1,000,000 bbls. The large vessel category includes VLCC and ULCC size tankers. Deadweight range is from 160,000 dwt to 400,000 dwt. Crude oil storage capacity is more than 1,000,000 bbls.

In almost every case, a "large vessel" has more versatility than a "small vessel".

Planning for Re-utilization

The following requirements are key factors to judge reusability of an FPSO vessel for a new field:

- Operation duration requirement at the new field - The residual life of the FPSO to be utilized will be assessed against this requirement. As a general tendency, older vessels need more steel renewal of hull construction to satisfy operating life requirements for the next assignment. In cases where the vessel is too old, and the required life is long, the plan to reuse the FPSO will not be an economical solution.
- Crude storage capacity requirements - Smaller storage capacity will require more frequent shuttle offloadings and cause potential production shutdowns due to limited storage capacity.
- Double hull requirement - IMO regulations do not require double hulls for FPSO's and FSO's. If local regulations or the Operating Company requires a double hull, it is not practical nor economical to convert a single hull vessel to a double hull.

If an FPSO is judged to be reusable for the next assignment, the following factors are studied and the conversion plan will be developed accordingly:

- Life Extension and Repair - Considering expected operation duration without drydocking in the next field, life extension and repair plan will be established based on detailed condition surveys of the vessel.
- Conversion of Utility System - Available utilities such as electricity, steam, cooling water, compressed air, etc. will be assessed for new duty, and if they are not sufficient, capacities will be increased and necessary redundancy features will be added. Usually a vessel has enough space for such expansion.
- Conversion of Offloading System - Depending on required offloading rate, size of shuttle tankers and requirements for the metering system; suitable conversion work will be carried out.
- Conversion of Tank Heating - In the case of high pour point crude, tank heating is required for cargo tanks.
- Conversion of Safety Facility - Safety requirements are becoming more severe year by year. Upgrading of safety systems/equipment will be carried out depending on regional regulations and operators' requirements. Compatibility of certification for equipment in hazardous areas shall be checked. A Safety Case study will be mandatory for some regions, and necessary upgrading and modification will be carried out in accordance with the results of the Safety Case.
- Regulations - Generally FPSO's are built in compliance with International regulations and rules, such as IMO, which are compatible to local regulations. However sometimes requirements for safety and environment are dictated by the new field's local regulations and upgrading of the facilities are carried out for these

requirements.

- Site Environment - Vessels can withstand most harsh environments. However special consideration is required for applications in an arctic environment (low temperature and ice) and shallow water especially for large FPSO's/FSO's. Crude oil loading conditions may be restricted due to environmental conditions.

Decommissioning

After the completion of decommissioning of the topsides facilities, as much of the remaining crude oil stored in the cargo tanks will be offloaded to a last shuttle tanker. Following the decommissioning work of the mooring system, the vessel will sail or be towed to a shipyard for conversion work. Prior to arrival at a shipyard, the vessel's cargo tanks will be gas freed and sludge will be removed. Decommissioning work for the vessel is minimal.

Refurbishment and Conversion Work

At a conversion shipyard, refurbishment and conversion work will be commenced. Refurbishment and life extension work is very similar to the work periodically done to trading tankers. Plate thickness of hull structure is measured, with a close up survey for all hull structure especially inside the cargo and ballast tanks. Residual strength and fatigue life of the hull structure will be assessed. A steel renewal plan will be prepared if necessary. Piping is opened up for inspection and wall thickness is also measured. Pipe will be renewed according to the results of the survey. Machinery is overhauled and damaged or worn parts will be replaced. Concurrent to these refurbishment and life extension works, conversion work will be carried out in accordance with the conversion plan.

FPSO Mooring: On-Vessel Turret

Turret facilities can vary tremendously in type, size and function. For the purposes of this discussion, all turrets will be treated together. Turret facilities may be the external or internal type, and may be either permanent or disconnectable. External turrets are typically cantilevered off the bow or stern of a vessel. Internal turrets penetrate the body of the vessel and may be located near the bow, near the stern or near amidships. This discussion will not specifically address permanent vs. disconnectable since the discussion presented will generally be applicable to both. In general, these turrets perform the same basic functions although more functions may also be served. Generally, the turret is the structural interface between the off-vessel anchoring system and the weathervaning vessel and the turret also houses the flow path for the riser fluids. A further function related to the flow path is to support the piping/manifold system and swivel stack.

Given these basic common characteristics, it is reasonable to relocate and reuse a turret system if functionality and load carrying requirements are satisfied.

Most projects cannot financially support reuse implementation in the detail design of the initial turret system. However, within the categories defined some reuse plans are reasonable. For example, a turret's chain support interface is a relatively inexpensive item which could be made suitable for a range of potential successor fields. For some turrets, where the chain support is tucked above the keel, the chain support range of motion, increased size, and load factors for deeper and/or more severe mooring requirements may require more consideration and trade-offs during turret design work. External turrets are best suited for shallower water moorings for which chain/keel interference may require investigation.

Turret design standardization further facilitates reuse in that plans for additional (future) risers may be well thought out avoiding the complications due to structure or piping interference in a future modification.

Swivel and piping/manifold requirements are usually too field specific to employ much planning for reuse. However space control planning (similar to topsides space planning) will aid in future modifications. Standardization of swivel mounting interfaces will aid swivel stack changes.

As with the FPSO vessel, turret maintenance during operation is very important. Adequate maintenance will extend the residual life of the turret system and reduce refurbishment costs for the next assignment.

Category

Given that the most basic capabilities of a turret are governed by load capacity and riser space availability, turrets may be categorized accordingly. The categories will then be somewhat independent with cross correlation required to examine suitability. They are not totally independent since increased load capacity of most turret bearing systems is sometimes most easily achieved by increasing bearing diameter which yields more space for risers as well.

- Load Capacity - Turret load capacity may be categorized as either "Low Load Capacity" or "High Load Capacity" for simplicity. "Low Load Capacity" may be considered when the total maximum resultant load due to off vessel moorings plus risers is less than approximately 1,200 tonnes. These categories are somewhat correlated to water depth although this correlation is not absolute. Likewise, external turret systems were originally considered to be relatively low load capacity systems. However, in recent years, external turret systems for

extreme environments have been installed which could qualify as "High Load Capacity" systems.

- **Riser Capacity** - Here, the extremes are so far apart that three categories may be more reasonable. Turret systems have been designed to house from one to more than sixty risers. Recently, turret systems have become more compact however the space required remains a primary consideration in determining the number and size of risers which may be accommodated. Therefore, turret categories based on riser capacity may be "Few Risers" (less than 10), "Moderate Number of Risers" (between 10 and 25), and "Many Risers" (greater than 25).

Planning for Re-utilization

Realizing that the turret forms a part of the flow path, a review of the new field key parameters to assess turret system suitability will include most of the key parameters listed in the Topsides section of the paper.

For the turret system, more specific information must be examined in relation to the interfaces with the subsea production equipment. In particular, the specific quantity and size of risers and their plan view arrangement must be considered. In addition, a very detailed review of the metocean data must be performed to determine suitable design environments, especially considering the development of "crossed environments" in which the wind, waves and current are not aligned. System mooring plus riser loads may then be computed and compared to the current capacity of the system. Metocean data must also contain design temperature that may affect the applicability of the turret structural materials.

The turret system piping, manifold, swivels, and safety features must be evaluated for compatibility with the new field requirements following a thorough inspection to determine the existing condition. Evaluation of the swivels, piping, manifold, etc. must consider materials (i.e. corrosivity), pressure, size, pigging requirements, etc. A modification plan may be developed considering that most of these turret system features are usually above the vessel's main deck and may be more easily accessed for modification.

The turret system structural and mechanical condition must be determined. This inspection may be performed as an integral part of the vessel survey although more detailed attention should be given to the turret bearings. The residual load capacity and life expectancy of the turret structure and mechanical parts must then be assessed against the new field requirements.

Because the turret system is the structural interface with the off-vessel mooring, particular attention should be given to this

interface. In most systems, this interface consists of a freely rotating chain support. The size and capacity of this chain support must be assessed. If considered in the original system design (i.e. when system reuse is foreseen), the chain support may be designed to accommodate a range of chain sizes/grades with little modification.

Decommissioning

Prior to disconnection of the mooring and riser systems, the machinery related to anchor leg or riser installation/de-installation is reconditioned. Following disconnection of the mooring and riser systems, little effort is required to decommission the turret system. Piping, including swivels and any tanks on the turret, are drained or flushed by water. Any gas pipes, etc. are vented, flared or otherwise gas freed. Any hydrocarbon gas remaining in these components will be replaced by inert gas to well below explosion level. Utility systems such as electricity, steam, air, hydraulic, etc. are disconnected and drained as appropriate. These components may then be opened for inspection.

Refurbishment and Conversion Work

Turret system refurbishment is best carried out at a shipyard. Drydocking may be required depending on the modification plan.

Any upgrade/modification needed to the turret mounted installation machinery is performed. Clean-up work and inspection of the turret equipment will follow the same procedures outlined for the topsides facilities. In addition, a structural evaluation of the turret foundation will also be performed including the vessel's superstructure, according to the modification plan. The turret system structure will be inspected with thickness gauging performed in any areas where corrosion is excessive. Plate renewal similar as for the vessel will be performed if required. Coating and cathodic protection renewal is required for all applicable components.

Marine growth and its removal after decommissioning should play an important factor both technically and commercially. Equipment residing in water depths less than 75 meters is exposed to sunlight from the surface, encouraging the establishment and growth of marine organisms. Affected equipment should be inspected and chemical/mechanical removal should be evaluated against replacement.

Turret swivels should be disassembled and inspected. If necessary re-machining of seal grooves may be carried out. All seals are replaced and tested. Swivel bearings are inspected and replaced as necessary. Reconditioning of the lubrication system and any leak detection and buffer systems will also be performed. Swivel addition, replacement, or

deletions are made according to the modification plan. Commensurate modifications to the swivel access are also carried out.

FPSO Mooring: Off-Vessel Anchor Leg

Anchor leg patterns and component sizes, grades and lengths are generally specific to a certain site. However, with proper consideration of corrosion, wear, fatigue and handling, modern anchor chain and wire components may be considered for reuse. Drag anchors have been recovered and reused for many years in the mobile offshore drilling industry. Suction anchors may be retrieved and reused if planned for and providing the soil properties of the sea floor are favorable. Driven pipe anchor piles are not suitable for reuse.

In the initial design, it is important to properly allow for corrosion and wear to enhance the potential for future reuse.

Connection design which allows for ease of modification or adaptation to different sizes may facilitate reuse.

Category

FPSO mooring systems may be categorized as below:

- All Chain System - An all chain system may contain one or more sizes/grades of chain and the chain may be stud link or studless. Typically these systems will be applicable to shallow water.
- Combination System - Combination systems typically contain chain and wire and may contain multiple segments of each. Subsurface buoys may also be used to achieve an 'inverted catenary' shape.
- Polyester System - Polyester systems may be taut, semi-taut, or catenary and will usually contain some chain segments at the upper and lower ends.

Planning for Re-utilization

The following are key parameters for judging the reusability of the off vessel mooring components:

- Field Life - Is residual life adequate for new field life?
- Strength - Is size and grade adequate?
- Design Temperature - Is material suitable?
- Installation Equipment - Can it be properly handled?

A thorough inspection plan must be carried out for recovered anchor leg components intended for reuse. Re-certification by the classification society should be obtained.

Used anchor chain has been used many times although seldom for an FPSO permanent mooring system. However, inspection

programs to re-certify anchor chain exist and should be adopted or modified to meet the new field's functional requirements.

For some types of wire rope, the cost to recover, re-spool, and inspect the wire rope may be too high to consider reuse. Also wire rope end connections are more difficult to adapt than chain. Except in rare cases for which the initial use is of short duration, it is not recommended to reuse six strand wire rope.

Insufficient experience with polyester is available to state its potential for reuse. It is not expected to be sufficiently robust to withstand multiple handling offshore.

Drag anchors for permanent moorings are not generally as robust (i.e. in terms of shank strength, recovery connections, etc.) as drilling vessel anchors; however, FPSO anchors may be recovered and inspected for structural damage. Corrosion will not usually be a problem. If satisfactory upon inspection, drag anchors must be assessed against the soils and holding capacity requirements at the new site.

Recovered anchors require a structural inspection of the shaft/padeye.

Decommissioning

Careful planning for the recovery of the anchor legs must allow for handling operations which will not damage the components. Generally, these procedures may be a reversal of the original installation procedures. Any wire rope to be considered for reuse must be very carefully handled especially when handling the spelter ends to avoid overbending of the wire rope. Suitable reels must be used considering the spooling load required and the wire rope minimum D/d ratio.

The pullout load on drag anchors must be applied inline with the shank to avoid out-of-plane bending loads on the shank. In cohesive soils, a sustained pullout load is preferred to an overly high pullout load. If a chaser is used, deployment operations must be careful to avoid abrasion damage to any anchor leg components to be reused.

Refurbishment and Conversion Work

Anchor chain may be inspected dockside or it may be returned to the factory for a more detailed assessment of its condition. A detailed inspection plan is required. Specific reject/accept criteria must be developed in cooperation with the classification society for the new field. Acceptable reconnection details for any link(s) removed must be developed compatible with the strength and fatigue requirements of the new field. Any new links which are

forged into the existing chain must be properly heat treated and proofloaded without detriment to the existing links.

Wire rope inspection will usually require a spooling operation for good access. An expert in the particular type of wire rope should be consulted for this inspection. Particular attention should be given to areas of abrasion, loss of galvanizing, broken wires, loss of blocking compound, or kinks. Spelter connections must be inspected.

All connections including splatters, D-shackles and link plates must be thoroughly inspected. NDE techniques should be used similar to those for newly manufactured components. Evidence of wear or plastic deformation must be detected and evaluated.

Subsurface steel buoys should be subjected to a detailed structural inspection program and repaired as required. Syntactic foam buoys should be inspected for surface skin damage. An accurate weighing of each buoy should be carried out and compared to the original as-built weights in order to assess water absorption. The water absorption must be compared to the original extrapolated long term performance expectation to determine if it is acceptable. If necessary the syntactic foam may be repaired. Small repairs may be made dockside. Larger repairs may require return to the manufacturer or a new section of foam may be manufactured and epoxied into place dockside by manufacturer representatives.

Drag anchors or suction anchors will require structural refurbishment based on their inspection results.

Risers

Typically risers are custom designed for a specific site. The design of the structure and the configuration is a complicated function of fluid service, site water depth and environment, and floating vessel response characteristics. However, careful design in the choice of riser configuration, size and interface between vessel and the well heads can allow the re-utilization of the FPSO without major modifications at the riser interface. In addition, with proper consideration of the remaining service life, wear and corrosion, and installation methods, the riser itself can be reused.

In the initial design, it is important to properly design the structure and configuration to enhance the potential for reuse. Configurations like the lazy wave and free hanging catenary risers are more readily adaptable to re-utilization as the riser forms part of the flowline after touchdown; thus the length of the riser is not too dependent on water depth. However, shallow water configurations like the steep-S and the pliant-wave have a riser length that is designed for a particular water depth and field layout, and may not be readily adaptable to re-

utilization for a different water depth. The shallow water configurations also come with additional hardware (mid-support arch and clump weight) that may not be easily removed or adaptable to another site.

Flexible pipe can be used for both riser and subsea flowlines. Often one installation vessel can be used to install (or retrieve) both riser and flowlines. Flexible pipe also has been readily decommissioned and reused, such as Brazil. An all-steel riser design is usually found in deepwater applications and are ideal for long offset distances between the FPSO and subsea hardware. However, these lines are usually not recoverable.

Hybrid risers (free standing spars with steel lines and flexible pipe jumpers) have been used and re-used. An example of a re-deployed riser is the Placid hybrid riser. It was initially designed and deployed for Placid's Green Canyon development in 469 meters of water. Later it was re-fit for Enserch's Garden Banks 388 development in 670 meters of water.

Category

Riser systems for FPSO's can be categorized as follows:

- Flexible risers - Most FPSO's use flexible risers made of thermoplastic materials and steel layers. The riser structure and configuration can be designed to allow use for a variety of water depths, environment, and vessel response. Typical flexible riser configurations are the lazy wave and free-hanging catenary riser for intermediate to deep water depths, and the pliant wave, steep-wave, and steep-S configurations for shallow water.
- Steel Risers - Rigid steel risers have been used extensively for Tension Leg Platforms in water depths up to 1,200m. Steel catenary risers have also been used and proposed for use with TLP's and semisubmersible based floaters, and have been demonstrated to be viable for FPSO's in deep water and mild environments like Offshore West Africa and Brazil.
- Hybrid risers - Hybrid risers are riser designs that incorporate the light weight and cost of steel risers, and the flexibility of composite pipe risers. One example is a riser system that consists of bundles of steel pipe supported by external buoyancy, and connected to the FPSO with flexible pipe jumpers.

Planning for Re-utilization

The following are key parameters for judging the reusability of the riser system:

- Service Life- Is the residual life adequate for the new field life?

- Type of Service - Is the product type similar (sweet or sour)?
- Design Temperatures and Pressures - Is the riser structure suitable?
- Site Particulars - Water depth and metocean environment?
- Riser Configuration - Does the riser configuration allow for use at another site?
- Installation equipment - Can it be properly handled?

A thorough inspection plan must be carried out on the recovered riser. This includes the end fittings, external sheath wear, external buoyancy modules, and possible NDE inspection of the inner carcass. Re-certification of the riser by the riser manufacturer or the certifying authority may also be required.

Decommissioning

Similar to the anchor leg recovery, the recovery operation must be carefully planned to allow for handling operations that will not damage the riser. These procedures may be a reversal of the original installation procedures.

Refurbishment and Conversion Work

A detailed inspection plan with specific reject/accept criteria must be developed with the riser manufacturer and/or classification society for the new field. A detailed examination of the external sheath and the end fittings will be required. Buoyancy modules will need to be removed, refurbished, and replaced during re-installation. NDE of the riser may be required to confirm the condition of the internal carcass. Minor repairs may be carried out dockside; however, major repairs or refurbishment may have to be carried out at the riser manufacturer's plant.

Subsea Systems

Subsea systems typically are a much lower cost consideration relative to the pipeline / riser and FPSO counterparts, but still play an important role to project costs and flexibility for reuse. Subsea systems are a packaged system designed around very specific reservoir and metocean requirements. Because they are a packaged system, they incorporate intricate machined hardware sized for the flow rates, well shut in pressures, installation vessel interfaces and intra field connections (flowline and control umbilicals).

Suitability of subsea hardware for decommissioning and reuse is primarily a function of its valve size, material class and its remaining useful design life. Another obstacle to reuse may be the tree's flowloop configuration (circulation, pressure measurement, hydrate remediation, pigging, gas lift, etc.) and, the number of valves (including chokes and isolation valves,

chemical injection, sensor monitoring requirements at the tree and downhole, etc.), as it passes from one field's requirements to another. Since subsea hardware is a packaged system, it becomes most versatile when these requirements are packaged in a separate subsea assembly, leaving the tree and its connection point(s) untouched.

Category

Subsea trees can be broken down into four major types and two sub-categories in order to better understand and categorize where they can be reused: water depth, and trim (material callouts). Water depth is the primary category for describing the type and complexity of a subsea system:

- | | |
|-----------------|------------------------------|
| • Mudline | < 120 m |
| • Diver Assist | < 200 m |
| • Diverless | 200-800 m |
| • Guidelineless | > 100 m, but usually > 800 m |

Mudline systems (Figure 2) are very simple rudimentary designs, often with stacked valve configurations, and rely heavily on human (diver) intervention to connect equipment together and play a key role in subsequent interventions and decommissioning. As its name suggests, these wells are placed on mudline wellhead equipment and normally accessed by a jack-up rig (in addition to the divers). These systems also tend to be low cost because of their relative simplicity (leaving most work tasks to human intervention), and small size (small flanged/clamped connections, lesser environmental load requirements, and usually nominal 4" valving or smaller).

Diver Assist systems (Figure 3) are still rudimentary but become a little more complex and larger in size because they are usually placed on top of subsea (floating drilling) wellheads. Because of the drilling vessel, these wells can venture out to deeper water depths than their mudline counterparts, but still carry the diver intensive intervention features to keep complexity, size and costs down. These trees tend to get more complex with depth because they are designed after weighing the economic viability of various tasks using divers in the offshore spread vs. doing tasks remotely through running tools (ROT's) and/or ROV's.

At around 200 meters, the economics of diver intervention vs. remote operation give way to our third group of subsea trees, diverless systems (Figure 4). These trees, as their name implies uses ROT's and ROV exclusively to perform all installation and intervention tasks. As technology and reliability of equipment and systems has progressed over the last 20 years, this class of subsea tree has become the most widely specified version, not only because well sites have gotten deeper, but operators and suppliers have become used

to subsea operations and recent innovative strides in control line and flowline connection technology has made them extremely versatile.

The last group of subsea trees is the guidelineless tree (Figure 5). These trees are also diverless, but they do not require the four guidepost /guideline guidance from surface to the subsea well site, as the others. These trees rely on upward and/or downward "looking" funnels to capture and orient equipment connections and are primarily used by surface vessels who conduct stationkeeping through some sort of dynamic positioning method. Guidelineless systems have been installed as shallow as 100 meters (in areas where moored vessels find it difficult to put out a safe anchor pattern), but are usually found in deepwater areas where drilling vessels are unable to properly deploy and tension guidelines or maintain an adequate watch circle using conventional moorings. Guidelineless subsea trees have now been in service for about ten years, and the advancements made in these systems have gone a long way to improving the technology in diverless subsea systems, resulting in their widespread use today.

Under these four groups, there are two sub-categories which distinguish subsea trees: high and low material trim. Low trim refers to simple low carbon steel alloy components which make up the pressure containing and pressure controlling equipment. As its name implies, trees using these types of materials are for lower flow / lower corrosive service applications (where corrosive chlorides and CO₂ constituents are minimal). Most subsea trees routinely feature low hardness materials to qualify for low to moderate H₂S environs, so impact of sour vs. sweet service is usually not important. This trim is also found in lower design life applications where "using up" the tree and keeping costs down vs. long life and reuse. As the flow rate and/or corrosivity increase, the use of high trim materials (corrosion resistant alloys - CRA's) come into play. As the flow rates rises, the bore size of the tree and piping or the erosion constant "C" needs to be increased to keep fluid (and gas) velocity under the recommended erosion velocity limit. Low hardness materials give way to higher hardness CRA's which are both stronger and still compatible with H₂S service. CRA's also allow higher "C" values to be used for erosion velocity calculations and may be required for moderate to high chloride (>20,000 ppm) and/or CO₂ (>7 psi partial pressure) levels. The amounts of CRA's increase as the levels of corrosion or erosion increase, always keeping an eye on minimizing costs to specify only what is necessary. The higher CRA trimmed trees tend to have higher design lives because of their material's resistance to wear and metal loss over time.

Planning for Re-utilization

There are some caveats on use and reuse of subsea equipment which should be highlighted. First mudline trees are, by definition, smaller, minimal wall thickness design systems. Their designs are more susceptible to metal loss and pitting corrosion because of the minimal wall thickness unless CRA's are used. They also are limited in their production capacity by their smaller bore configurations. The other three subsea tree categories are typically designed with composite valve blocks, offering considerably more metal (to withstand environmental loads, multi-bore configurations, etc.) which is available for metal loss without sacrificing pressure containment or pressure control for longer design lives at the lower trim levels. The other trees are also capable of accommodating larger bore sizes as well, because of their larger size.

From a broad perspective, one may assume that a guidelineless CRA subsea completion should be specified for all but the shallowest of FPSO jobs so that this hardware may be decommissioned and reused anywhere in the world. From a purely technical standpoint, this may be true. However, as repeatedly illustrated for other FPSO equipment, deeper water equipment may be commercially unfeasible for projects in shallower water. Diverless trees are probably the most versatile tree since remote intervention can be accomplished from many different types of vessels in a wide variety of water depths. Diverless trees are also designed for greater water depths and harsher environments, but work just as well in shallower depths, since their design requirements exceed the shallower depth requirements. Guidelineless drilling vessels are often scarce and some operators may be unfamiliar with their installation methods or trust in dynamic positioning operations. Suitability of a diverless tree for decommissioning and reuse is primarily a function of its valve size, service trim and its remaining useful design life. The only other stumbling block may be the tree's flowloop configuration (circulation, pressure measurement, hydrate remediation, pigging, gas lift, etc.) and, the number of valves (including chokes and isolation valves, chemical injection, sensor monitoring requirements at the tree and downhole, etc.), as it passes from one field's requirements to another. The most versatile subsea tree may be a diverless guideline tree that features many ROV and guidelineless re-entry features for smaller components such as chokes, control pods, instrumentation packages, wireline re-entry, etc. taking advantage of small vessels for intervention for all but the most well intrusive operations.

Mudline and diver assist trees reign supreme in shallower water, milder environment, lower production / corrosion service applications. Mudline and diver assist trees are driven principally by small budget scenarios. Reuse of these subsea trees should only be considered for other "small budget" projects in similar environmental and water depth locations. Here too, the thought of a throw away tree or minimal design

life tree may be more cost effective than specifying a higher life (higher cost) tree then adding the cost for refurbishment for the new assignment field.

Other Subsea Equipment Factors

There are three other subsea equipment areas that should be mentioned which could affect successful reuse: wellheads, foundations, control systems, and flowline connection techniques.

Subsea wellhead systems have been widely used for decades and are considered a readily available "off the shelf" commodity worldwide. In many parts of the world, subsea wellheads must be removed several meters below the mudline during decommissioning and well abandonment. By design, mudline wellhead systems are designed with below mudline abandonment in mind. They simply unscrew the landing string from the casing hanger joints inside the well, and leave the rest behind. Subsea (floating drilling) wellheads have the high pressure and low pressure housings recovered during abandonment work. Casing hangers and packoffs are generally discarded. Reworked wellheads and housings are cost effective for drilling programs where a single wellhead may be used for three or more successive drilling programs over a short period of time. However, a wellhead housing that has been subsea for a long period of time may suffer enough wear and tear over time that prohibit repair costs over new build equipment. In addition, many subsea completions often specify metal sealing equipment. If so, seal bores in a wellhead only need to suffer minor corrosion or mechanical damage to prohibit its reuse. Many wellheads are made of low alloy steel with CRA inserts or weld overlays in only a few critical locations. Therefore, mudline or subsea wellhead equipment should be considered a new-build commodity item when planning decommissioning and reuse.

Mudline trees can fit on most any mudline wellhead since the completion interface is usually casing joints threaded together between the mudline wellhead's landing sub and the tree completion hardware. Therefore reused mudline trees can be used on any number of different mudline wellhead systems so long as the casing program is the same. Subsea wellheads are a different matter. Subsea wellheads have an external profile in either one of two categories, clamp hub or mandrel profile. The subsea tree has a special hydraulic connector that fits over and locks on to one of these external profiles. The operator of the reuse trees should make sure that the same wellhead profile for the new field's wells is the same as was used in the initial field. In the wellhead vs. tubing head completions there is another problem area due to the proprietary designs between wellhead manufacturers having different seal bore and load shoulder interfaces. An expensive tree refurbishment may be the result if similar subsea wellhead equipment is not used.

Subsea foundations are pieces of equipment designed to structurally support subsea equipment on the sea floor for the life of the field. Several systems are in use today including drilled or hammer founded piles, flat mudmats and skirted mudmats, auger bit anchors, caisson silos, and various suction anchor designs. The thing to remember is, the more permanent the foundation design is, the harder it may be to recover later.

Subsea control systems are a huge wild card when considering decommissioning and reuse. There are three basic types of subsea control systems: direct hydraulic, piloted hydraulic, and various forms of electro-hydraulic controls. Direct hydraulics are multi-line hose bundle hydraulic controls where one line controls one function on a subsea tree or manifold valve. This is the lowest cost system, but also the most limiting on flexibility for re-use. It is ideal for a limited number of wells feeding an FPSO, roughly less than six trees, and work best where the lateral offset distance from the tree to the FPSO is kept within 5 km. Their rework and replacement criteria is straightforward and simple and can be accomplished most anywhere worldwide. Piloted hydraulic control systems can extend the offset distance roughly 3 km and help reduce the size of the control umbilical between the FPSO and the tree, using smaller pilot lines to trigger pilot valves to hydraulic storage accumulators and single larger diameter supply lines to operate functions on the tree(s). The smaller umbilical sizes may also allow for the operation of more trees from the FPSO as well. Piloted systems also require a pod on the tree to house the pilot valves and hydraulic accumulators. Piloted systems are slightly more expensive than direct hydraulics but again are straightforward for refurbishment. Electro-hydraulic control systems are the most flexible and adaptable control system, although the most expensive and complex of the group. There are no offset distance or number of wells criteria, if properly planned up front. They are also extremely adaptable for a wide variety of sensor monitoring and data collection and can be wired into many automated processing functions. However, electronics become quickly obsolescent and changes to any of the sensors (both on the tree and/or downhole) may require new computer programming or new circuit boards. Electro-hydraulic control systems also have subsea pods. Rework and reuse of these pods are becoming more commonplace and are becoming relatively depth insensitive through stronger and better pressure vessel housings and prudent use of CRA materials. Again, the amount of overhaul and refurbishment to the FPSO and the overall control philosophy of the new field will dictate how much repair and new build is required.

Flowline and umbilical decommissioning and reuse should address a fundamental question at the beginning of an FPSO project, "Can (or should) the intra-field flowlines be

abandoned in place, or should they be recovered for economic and/or regulatory reasons?" If recovery is the answer, then subsea flowline and umbilical tie-in methods should be carefully examined for their abandonment capabilities without excessive damage to the flowline or umbilical. There are a wide variety of flowline and umbilical connections available, depending on the size of the flowline, availability of divers (water depth) and whether the subsea connection is a "first end" or "second end" connection. Each method should be carefully considered if decommissioning and reuse is one of the design requirements. Drilling vessels are ill-equipped to handle flowlines and umbilicals, especially when recovering equipment. They have relatively limited deck space and load. Furthermore picking up the flowline may be difficult because it requires a complex dynamic rig move laterally as the flowline is being brought to the surface; operations better suited for a construction barge or pipelay vessel. Backing the flowline out away from the subsea tree prior to tree recovery may also be difficult if the flowline is extremely stiff (like steel pipe) which was initially pulled in. Ideally, a system which can in some way jettison the end of the flowline, leaving it in place for later recovery with the pipe after the tree is gone is preferred. Removing a diver installed spool piece between the end of the flowline and the tree is the simplest method to decouple and recover the two subsea components separately. Similarly a ROV installed U-jumper system can perform the same function during abandonment. First end connection methods, such as the stab-and-hinge over method or first end pull-ins could be "reverse installed" for easy abandonment.

Interface Tinkering and the "Off Tree" Concept

If an operator truly wants to reuse existing equipment, he either: 1) builds in all the "what ifs" (and pays a higher price for it at the front end of the project), 2) pays for an overhaul of the tree to change its configuration (trading off new build vs. refurbishment costs), or 3) works hard to live within the bounds with what is given him and work around potential equipment limitations. Therefore, there is the ever present drive (and fear) to wind up with option 1 or 2 when option 3 was the goal. From a subsea hardware prospective, option 1 and 2 are almost unavoidable unless stringent design philosophies are followed. Changes downstream of the tree should be handled by the "off tree" concept (Figure 6). The "off tree" concept stated simply is, "Move any of the design and hardware variables that may change the tree's hardware configuration, off the tree, leaving the basic tree and its interfaces intact." In this way the tree can be easily refurbished with spare parts, pressure tested, and cleaned up with minimal fuss. If a new production choke is needed, or changing the flowline size, or adding insulation, or adding flowline pigging requirements, or adding a control pod are necessary, then place all of the changes on a new flowline termination sled, installed adjacent to the tree. When adding

functioning components, make sure the control system can be easily modified to take on the additional tasks.

Upstream changes are more difficult to handle. Downhole equipment interfaces through the tree and the tubing hanger should stay the same, if at all possible. Standardization of porting also pays big dividends by making room for as many ports as practical up front in the initial tree and tubing hanger design, if later reuse is planned. Ideally, a tree and tubing hanger should be designed with up to four hydraulic and one wet mate electrical connections. Unused ports should be blind flanged off. The biggest problem with standardized downhole porting is the hydraulics. Many SCSSV's come with a second lockout function, a balanced line function, or a redundant control line. It may be further complicated by the operator specifying one or two SCSSV's, quickly doubling the count. In addition, many wells are requiring one or two downhole chemical injection ports to mitigate corrosion or flow problems. Any changes that require remachining of the hardware in this critical area may be better served by new build equipment. One area that is showing promise is that the machined access port for electrical connectors are approaching that of its hydraulic counterpart as wet mate connectors become smaller in size. Standardizing the port profiles will give some more flexibility in trading one hydraulic for an electrical or vice versa. The advent of smart wells to subsea also presents interface challenges. Many smart well scenarios now being considered may require up to nine interface ports.

Decommissioning

Subsea hardware decommissioning is accomplished during well abandonment. After the well is controlled and killed, cement is usually circulated into the well through prepared perforations in the tubing string. Once the well is dead, the flowlines and associated subsea hardware (such as subsea manifolds, flowline connection hardware, etc.) are circulated with water (pumping from the FPSO to the tree and drilling vessel or from the drilling vessel to the FPSO) to purge all equipment from hydrocarbons and allow all equipment to flood to hydrostatic pressure. Then flowline and control umbilical connections are disconnected and the subsea tree is recovered. Subsea wellheads are then cut approximately 3 meters below the sea floor and pulled up as a single salvaged unit (wellhead, guide bases, casing hangers, packoffs, and casing joint stubs). All remaining subsea hardware is either removed from the sea floor, or abandoned in place, depending on local regulation requirements, water depth, proximity to shipping lanes or anchorages, and abandonment costs. In some cases, properly purged subsea hardware has been donated to coastal agencies to serve as an artificial fishing reef. An example is Florida's artificial reef program where salvaged platforms and subsea structures have been placed in barren sea floor areas to promote the growth of marine

ecosystems.

Subsea flowlines are either recovered with the FPSO riser, or abandoned in place with the ends buried downward, again based on regulations and abandonment costs.

Refurbishment and Conversion Work

A detailed inspection plan with specific reject/accept criteria must be developed with the subsea hardware manufacturer. A detailed examination of all piping and valves will be required. As a minimum, flushing, internal pressure testing and function testing of components, and NDE of piping, thin wall areas, and erosion prone areas are performed, after cleaning. If sand or other by-products were present in the produced fluids, disassembly and further inspection of component parts may be warranted. Framework and non-pressure containing structures are usually removed and repaired or replaced. The framework repair/replacement work may coincide with new build subsea hardware to meet the new field's interface requirements, including refits for different flowline connection equipment and/or control systems. Coating and cathodic protection renewal is of course required for all applicable components.

Marine growth and its removal after decommissioning should play an important factor both technically and commercially. Equipment residing in water depths less than 75 meters is exposed to sunlight from the surface, encouraging the establishment and growth of marine organisms. The affected equipment may extend all the way down to the subsea tree and flowlines for shallow water completion schemes. Removal and refurbishment of encrusted equipment can be both time consuming and costly in labor and chemical removal and should be evaluated against scraping and new build of hardware.

Many subsea controls in use today rely on water based hydraulic fluids to operate subsea equipment. Special care should be given to flushing out all of these lines (both umbilicals and trees) with biocides soon after the equipment is decommissioned and replaced with a manufacturer recommended storage fluid. This will help prevent the growth and possible clogging by bacteria in these lines.

Nomenclature

bbl	barrel (0.159 m ³)
BS&W	basic sediment and water content
CRA	corrosion resistant alloy
dwt	dead weight ton (1.016 tonne)
E & I	electrical and instrument
ESP	electrical submersible pump
FPSO	floating production storage and offload
FSO	floating storage and offload

GOR	gas oil ratio
HAZOP	hazards to safe operations (study or review)
I/O	input/output
IMO	International Maritime Organization
NDE	non-destructive examination
NGL	natural gas liquids
PFD	process flow diagram
P&ID	piping and instrumentation diagram
ppm	parts per million
psi	pounds per square inch (.069 bar)
ROT	remote operated tool (subsea)
ROV	remote operated vehicle
RVP	Reid vapor pressure
SCSSV	surface controlled subsurface safety valve
TLP	tension leg platform
TVP	total vapor pressure

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