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COMMITTEE V.8

REPORT FOR SUBSEA TECHNOLOGY

COMMITTEE MANDATE

Concern for the safety and reliability of subsea production systems for oil and gas offshore. This shall include subsea equipment for production and processing, flowlines and risers, with emphasis to design, fabrication, qualification, installation, inspection, maintenance, repair and decommissioning. Structural design for flow assurance and safe underwater operations shall be considered.

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KEYWORDS

Subsea Production System, Subsea Processing, Flow Assurance, Fabrication, Testing for Qualification, Deepwater Installation, Subsea Operations, Inspection, Maintenance and Decommissioning, Hydrates, Pipelines, Risers and Umbilicals, Reliability and Safety

CONTENTS

1. INTRODUCTION

With rapid development of industry, the world's energy consumption has increased steadily since the 1950s, and the fossil fuels (oil, natural gas and coal) still amount to 80% of the world's energy consumption. Since the 1960s, the increasing demand for oil and the depletion of onshore and offshore shallow-water reserves, fasten the exploration and production of oil in deep waters, and challenge the offshore industries. As an efficient and cost-effective plan for the development of deep-water oil and gas fields, subsea production systems have become more and more important for the exploitation of offshore oil and gas. Due to its huge potential, more and more operators and owners have been attracted by subsea production systems.

A subsea production system consists of a subsea completed well, seabed wellhead, subsea production X-tree, subsea tie-in to flowline system, and subsea equipment and control facilities to operate the well, as shown in Figure 1.1. It can range in complexity from a single satellite well with a flowline linked to a fixed platform, FPSO (Floating Production, Storage and Offloading), or onshore facilities, to several wells on a template or clustered around a manifold that transfer to a fixed or floating facility or directly to onshore facilities. As the oil and gas fields move further offshore into deeper water and deeper geological formations in the quest for reserves, the technology of drilling and production has advanced dramatically. The latest subsea technologies have been proven and formed into an engineering system, namely, the subsea production system, which is associated with the overall process and all the equipment involved in drilling, field development, and field operation. The subsea production system consists of the following components:

- Subsea drilling systems;
- Subsea wellhead and Christmas trees;
- Subsea processing and boosting systems;
- Subsea injecting system;
- Subsea manifolds and jumper systems;
- Tie-in and flowline systems;
- Umbilical and riser systems;
- Subsea power and control systems;
- Subsea installation and decommissioning.

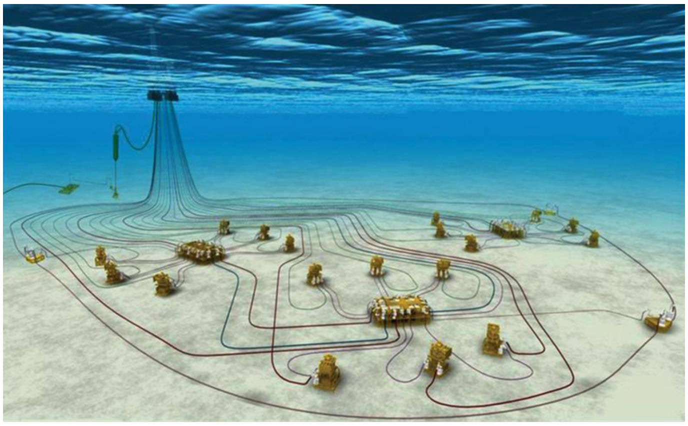


Figure 1.1: Subsea production system (courtesy Petrobras)

Most subsea structures are built onshore and transported to the offshore installation site. The process of moving subsea hardware to the installation site involves three operations: load-out, transportation, and installation. A typical subsea installation also includes three phases: lowering, landing, and locking. After the production system has been installed, numerous operations are in place to ensure safe and pollution-free operations and support the continued flow of hydrocarbons. The following are typical of post installation operations:

- Commissioning and start-up (start-up could be “cold” or “hot”);
- Normal operations;
- Production processing;
- Chemical injection;
- Routine testing;
- Maintenance and repair (remotely operated vehicle - ROV, routine surface);
- Emergency shutdown;
- Securing facilities (e.g., from extreme weather events);
- Intervention.

The complex mixture of hydrocarbon compounds or components can exist as a single-phase liquid, a single-phase gas, or as a multiphase mixture, depending on its pressure, temperature, and the composition of the mixture. The hydraulic theory underlying single-phase flow is well understood and analytical models may be used with confidence. Multiphase flow is significantly more complex than single-phase flow. However, the technology to predict multiphase-flow behavior has improved dramatically in the past decades. It is now possible to select pipeline size, predict pressure drop, and calculate flow rate in the flowline with an acceptable engineering accuracy.

The exploration and production of oil and gas resources entail a variety of risks, which, if not adequately managed, have the potential to result in a major incident. All subsea field development procedures involved in designing, manufacturing, installing, and operating subsea equipment are vulnerable to a financial impact if poor reliability is related to the procedure. Equipment reliability during exploration and production is one of the control factors on safety, production availability, and maintenance costs. In the early design phases, the target levels of reliability and production availability can be controlled through application of a systematic and strict reliability management program.

This report presents recent advances and possible future trends in subsea production system. Papers published since the ISSC 2015 Congress are mainly discussed here, but older publications of 2014 are also included if they are considered to present fundamental and important findings in line with the mandate of the present Committee.

2. SUBSEA PROCESSING EQUIPMENT AND FABRICATION

2.1 Introduction

Subsea processing has been applied in all the four major global offshore oil and gas clusters: the North Sea, Gulf of Mexico, West Africa deepwater and Brazilian Pre-Salt. Major oil and gas companies are active in the campaign for developing new technologies on subsea processing. The operators and their partners have developed different processing systems based on specific project requirements, either to enable economic development of deeper green fields, or to extend production life of brown fields and to enhance oil recovery. Under the former situation, subsea gas-liquid two phase separation combined with subsea boosting of liquids is the common solution, while for the latter, subsea gas/oil/water/sand multiphase separation with water reinjection is used.

As part of the corporate technology strategy Statoil has launched a technology plan for the Subsea Factory concept. The plan describes how to combine subsea production and processing technology elements with key business cases and define enabling and cost-efficient development concepts. Statoil has successfully deployed subsea pumps and subsea separators (Troll Pilot and Tordis) (Radicioni et al., 2016) including the world’s first subsea compressors at both Åsgard and Gullfaks fields. It has also launched an All-Electric Subsea (AES) initiative to prove the feasibility of new flexible, cost efficient subsea production system to meet future demands. And on 4 August 2016, the world's first fully all-electric well of subsea industry, K5F3, has been open to production. The all-electric subsea well consist of an electric subsea Christmas tree, electric downhole safety valve, and associated subsea control modules. (Winther-Larssen *et al.*, 2016; Schwerdtfeger *et al.*, 2017; Abicht *et al.*, 2017; Rubio *et al.*, 2017).

Also, some developments are reported on production optimization in the BC-10 field in Brazil and in Girassol oil field in Angola. Some advanced subsea processing system is empoyed. (Sleight *et al.*, 2015, Delescen *et al.*, 2015).

The fast development of the SPS shall be based on the advances in the fabrication of the components and assembling of the complex subsea hardware, which influence the reliability of the system and the service life of the key components in the HTHP environment of strong corrosion. However, little references have been presented from the academic cycle and the product suppliers do not publish their results due to the confidentiality of their technologies.

2.2 Separators

Although a single multiphase pumping can be considered a subsea processing, many of the related equipment installed up to now provide any type of separation or pre-processing.

2.2.1 Subsea Gas-Liquid Separation

The Pazflor project locates approximately 93 miles offshore Luanda, Angola, at water depth between 600 m and 1,200 m. The Pazflor development involves four fields, Perpetua, Acacia, Zinia and Hortensia. Approximately two-thirds of the oil is heavy oil from the Miocene reservoirs of Hortensia, Perpetua and Zinia fields. The heavy Miocene oil is very viscous and reservoir pressure is relatively low, which requires adequate artificial lift methods. Also, to assure fluid flow in an environment prone to generate gas hydrates, subsea separation units are installed near the initial production well at each field. The subsea separation module consists of a vertical separator for gas/liquid separation and two hybrid pumps for lifting the separated liquids (Figure 2.1).

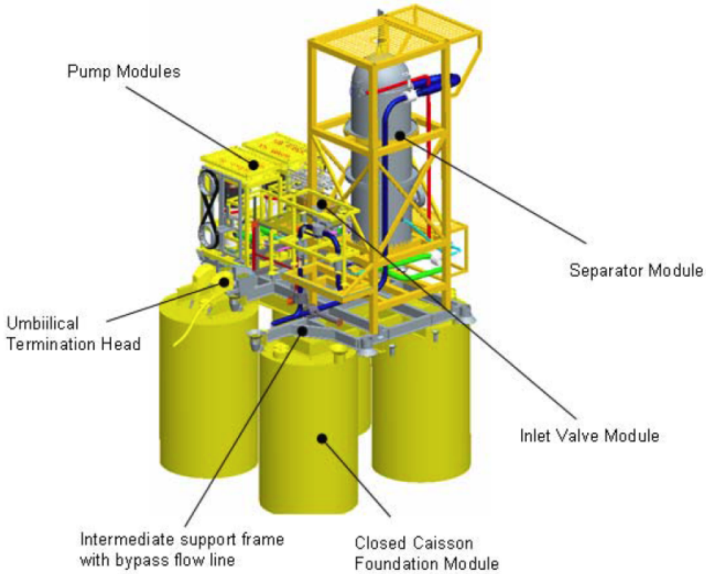


Figure 2.1: Principle overview of subsea separation unit used in Pazflor

2.2.2 *Subsea Multiphase Separation*

The Marlim field has produced its first oil in 1991 and is located at the northeastern part of Campos Basin, Brazil, at a water ranging from 650 to 1,050m. As it approaches the end of production life, extensive water production restricts further development. To debottleneck water processing capacity at production unit, a pilot subsea separation station with 29m length, 10.8m width, 8.4m height and overall assembly weight of 392 ton was installed at water depth of 870m for the pilot well MRL-141 in 2011.

The subsea processing station performs gas/oil/water/sand separation and water reinjection (Figure 2.2). The production stream firstly goes through an inline multiphase sand remover responsible to remove the bulk part of produced solids. Downstream the multiphase sand remover, gas is separated from liquid through a set of vertically arranged pipes, named as "harp". Right downstream of it, there is a long pipe separator of 60m to perform oil-water separation. At the very end of the pipe separator loop, oil is recombined with separated gas and flows free in a multiphase stream to the topside stationary production unit, while separated water with oil content above limits for reservoir reinjection is routed to a polishment system, which comprises another inline sand remover and two stages of hydro cyclones. It reduces the amount of oil in water to acceptable levels for reinjection through a centrifugal pump.

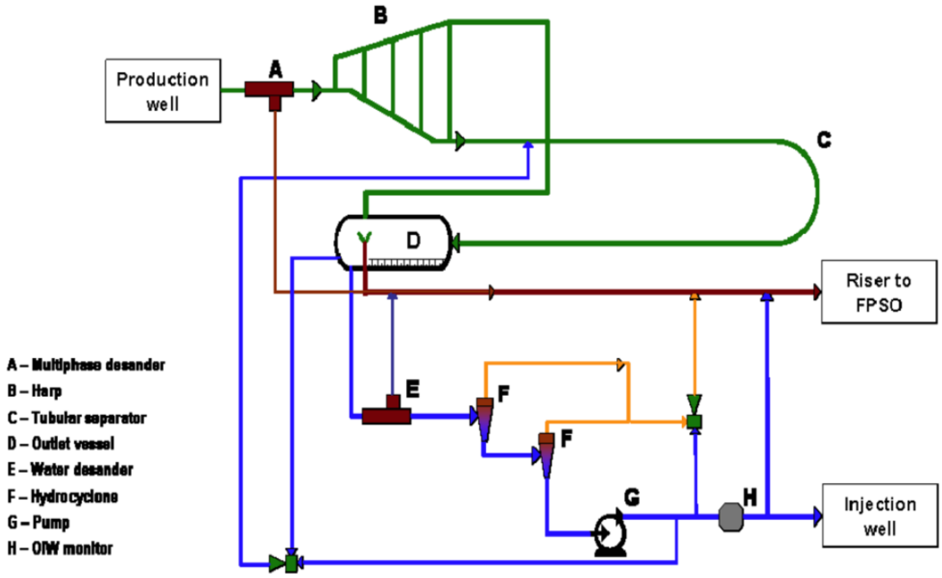


Figure 2.2: Flow diagram of the subsea separation unit at Marlim

2.2.3 *Recent Studies*

Prescott *et al*. (2016) have studied linear pipe separators to propose less expensive solutions that can provide satisfactory phase separation. Two types of separators were studied, gas-liquid and gas-liquid-solid separators under CFD simulations. The results have proved their effectiveness and also showed that pipe separators can be made with standard pipes with cost reduction of up to 500%.

Tamal *et al*. (2017) developed a simplified 6-state model for gravity separator (often used as a first stage separator in subsea separation systems) with lumped fluid properties. The model is used in an Extended Kalman Filter estimator using measurements of levels and densities of fluids inside the separator in order to estimate unmeasured disturbances, namely inlet total flow rate, inlet oil cut and inlet droplet diameter. Results show that the estimated disturbances converge to their true values when process changes.

2.3 Pumps

Homstvedt *et al.* (2015) proposed a new type of electrical submerged pump (ESP) that is different from the vertical concept of BC-10 and Perdido, considering that the concept in vertical caisson is too expensive for installation and maintenance. Instead, they proposed horizontal ESP inside flowline jumpers provided of a system to separate gas before pumping and return it to stream after pumping. Beside the low cost, the proposed new concept can be arranged in serial or parallel configurations.

In order to reduce the cost of umbilical power cable, Margarida *et al.* (2017) have worked in a higher voltage subsea pump (3,2MW), to operate at 13,6kV (before from 4.16 to 6.6kV) and reduce cable amperage. The ongoing project can reduce significantly the cable diameter and consequently the associated cost.

Hjelmeland *et al.* (2017) have developed and qualified the world's first high pressure subsea pump. Three units were installed at water depths around 2,100m to sustain production pressure from the ultra-deep reservoirs Jack and St. Malo to Walker Ridge Regional semi-submersible, the largest in displacement in the world. The 3MW pumps provide a differential pressure up to 4,000psi to a minimum inlet pressure of 1,200psi.

2.4 Compressors

The subsea boosting allows the reduction of the well backpressure and consequently increases the flow rate, improving the total reservoir recovery. In addition, it improves flow assurance issues by increasing velocities in pipeline, increasing temperature and stabilizing production.

The Åsgard compression system was set up in 2015 to deliver the world´s first subsea compression station and provide an additional production of 306 million barrels of oil equivalent up to 2032 (Storstenvik, 2016). The system was installed in a water depth of 270m and comprises two parallel 11.5 MW compressor trains with total weight of 5100 tons that are among the biggest structures in the subsea world (74x45x26m). The system requires a pre-processing of the hydrocarbons stream from manifolds using a gas-liquid vertical separator. The gas is compressed with the aid of a centrifugal compressor while the liquid is pumped by a centrifugal pump and both are recombined in a single multiphase stream to a semi-submersible platform Åsgard B located 40km from compression station. It is controlled by an all-electric control system with chemicals (MEG and N2) from Åsgard B while the power supply is provided from a FPSO of Åsgard A. Time and Torpe (2016) reports the commissioning and Dahle et al. (2016) the installation and intervention procedures of the Åsgard compression system.

In 2015 the world´s first subsea multiphase compression system (gas volume fraction between 95 and 100%) was installed at the Gullfaks field. It is comprised of two 5MW wet gas compressors operating in a water depth around 200m that can deliver 32bar of differential pressure (Hjelmeland and Torkildsen, 2016a). The technology is based in a helico-axial impeller and the gas recovery is foreseen to increase from 62 to 74% (22 million barrels of oil equivalent) by using combined multiphase compression with low pressure production. Different from the Åsgard compression system, no pre-processing is required in this case. The system operation can be changed to a parallel configuration to facilitate high flow rate, as well as a lower flow rate and higher differential pressure provided through serial compressor configuration. The qualification and implementation of Gullfaks compression system was presented by Hjelmeland and Torkildsen (2016b) while the commissioning aspects was presented by Birkeland et al. (2016).

2.5 Electrical Systems

Electrical systems are of increasing application to subsea processing, as the need for large power supply together with reduced infra-structure and extended reach of an all-electric control system.

Hasan *et al.* (2015) compared the conventional electro-hydraulic control system with all-electric options showing the benefits of the new technology. Beside the advantages related to HSE, there were significant CAPEX and OPEX reduction due to the reduced infra-structure needed to the all-electric control system. The comparison was based on new valve actuators, subsea control modules (SCMs) and subsea distribution units (SDUs), where electrical units replaced the hydraulic components. Following similar premise, Dobson and Deighton (2017) stated that both all-electric control system and subsea power supply were needed to decrease production cost in view of reduced oil price and to provide the necessary technology to subsea processing development. All-electric control system provided several applications like heated pipelines that are important to flow assurance in many cases, subsea separators, single or multiphase boosting, seawater treatment to reinjection or disposal, electrical power transmission and subsea chemical storage. The future to control and power supply at long distances will be a combination of DC umbilical (low loss) and fiber optics that can provide data rates of 10Gb/s instead of 10Mb/s of copper cables.

Bugge and Ingebrigtsen (2017) report a JIP for subsea power that has the aim to provide 100MW of power transmission along 600km at 3000m water depth. They are working on qualification of components, sub-assemblies and equipment to achieve the reliability of the developed technology which is comprised of subsea medium voltage switchgear and variable speed drivers with associated controls and low voltage distribution. These new products will provide large amounts of power for applications such as subsea compression and boosting.

The first all-electric subsea Christmas tree was installed in 2016 as repoted by Schwerdtfeger *et al.*, 2017, who showed the development and qualification tests of the all-electric subsea Christmas tree components and stated that not only the costs were reduced but also the environmental impacts were reduced and the safety at topside increased.

2.6 Material for Fabrication of Key Components

Subsea Christmas tree, as an example of SPS, is under the complex conditions of deep water, high temperature, high pressure and strong corrosion. The research is focused on design and type-selection of base material, anticorrosion material and sealing material of key parts of subsea trees. The subsea Christmas tree plant is constructed by a series of production and control channels with high temperature, high pressure and high corrosion resistance of crude oil, including tree body, tubing hanging, hydraulic control valve body, double-hole connector, pipe connector and production cross-pipe and other major components of the key components. In view of the low temperature environment, the external environmental load and the internal high pressure bearing conditions, the key components of the subsea tree are required to have low temperature toughness and thermal resistance and fatigue performance. The key components shall present good overall mechanical properties.

Based on the above-mentioned requirements, several low-alloy steel materials (including 4130, 4140, 4340 and F22) commonly used in subsea equipment were compared. In the design, low-alloy high strength steel material F22 (ASTM A182) was chosen as basic material for key components (Norsok M-001 Materials Selection, 2014).

In order to resist the strong corrosion of crude oil and seawater, taking into account the relevant standard requirements, subsea tree material design shall consider the following anti-corrosion measures:

- Inconel 625 of surfacing layer is selected for fluid infiltration surface of production and sealing surface corrosion layer.
- Inconel 718 for the metal seal material of valve seat, stem and valve plate, the annulus and the center hole of the hydraulic control valve.
- duplex stainless steel is used for spiral cross - tube and chemical injection of pipe materials.
- The Christmas tree is equipped with underwater surface fitting parts and fasteners surface with ultra-thin composite PTFE coating material for surface spraying.

For subsea pipeline systems a total corrosion allowance of 10 mm is recommended as a general upper limit for use of carbon steel. Carbon steel can be used in pipelines where calculated inhibited annual corrosion rate is less than 10 mm divided by design life. Otherwise corrosion resistant alloys, solid or clad or alternatively flexible pipe, should be used. For pipelines with dry gas or dry oil, no corrosion allowance is required. Corrosion during installation and testing prior to start-up shall be considered.

The external atmospheric environment shall be considered wet with the condensed liquid saturated with chloride salts. Material selection and surface protection shall be such that general corrosion is cost effectively prevented and chloride stress corrosion cracking, pitting and crevice corrosion are prevented.

Corrosion allowance sizing for carbon steel in the splash zone should follow the below guidelines (Norsok M-001 Materials Selection, 2014):

- Structures with thin film coating: Min. 5 mm. For design lives > 17.5 years. Corrosion allowance = (Design life - 5 years) x 0.4 mm/year.
- Risers: Min. 2 mm in combination with min. 12 mm vulcanized chloroprene rubber. At elevated temperature the corrosion allowance should be increased by 1 mm pr. 10 degrees C increase in temperature above 20 °C.

3. FLOW ASSURANCE OF SUBSEA PRODUCTION ENGINEERING

Flow assurance technologies could be categorized into different solution types: Thermal management, Chemical injection, Operation and Equipment, and Software and control system.

3.1 Thermal management

Cherkaoui et al. (2016) presented an electrically heat traced flowline that is a pipe-in-pipe enclosing in its annulus high performance thermal insulation and specifically designed electrical heating wires. Powering one of these wires is done with a combined system of electrical subsea connectors and penetrators to access inside the sealed pipe-in-pipe annulus.

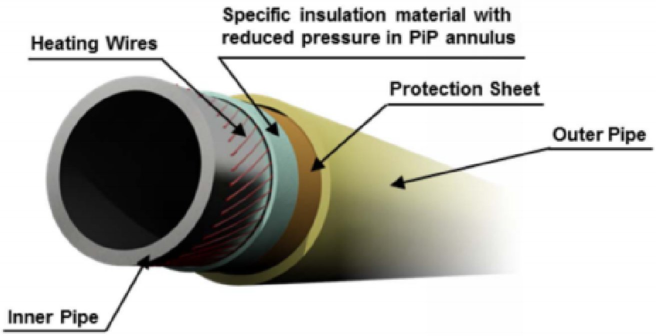


Figure 3.1: Electrically heat traced flowline schematics (Cherkaoui et al., 2016)

The Laboratory of subsea technology (LTS) in UFRJ, Brazil developed a new concept of sandwich pipe, which consist of three layers (Estefen et al., 2016). The mid layer consists of a material with good strength and thermal properties (SHCC), while the external pipe and internal pipe are both carbon steel, to provide the support. As shown in Figure 3.2.

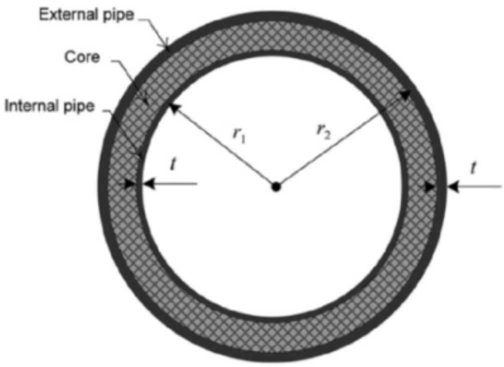


Figure 3.2: Typical section of a Sandwich Pipe (Estefen et al., 2016)

The sandwich pipe could also be applied with thermal insulation layers. Under this condition, the pipe and the insulation layer form multilayer configuration, and the thermal calculation is very important to the insulation design and flow assurance modeling. An and Su (2015) provided improved lumped parameter models for transient thermal analysis of multilayered composite pipeline with active heating, which became an effective analytical tool for the thermal design and analysis of composite pipelines for oil and gas production in deepwater conditions.

The active heating mentioned above is an important way of keeping the flow temperature. Electrically heated flow line systems work on the basis of utilizing the heat generated by the electrical resistance of a conducting material when using an alternating current. There are mainly two types of solutions: Direct electrical heating (DEH) and Trace heated pipe-in-pipe.

In DEH systems the pipe wall is used as the conductor of electric current which directly heats the pipeline (Louvet et al., 2016), as shown in the Figure 3.3.

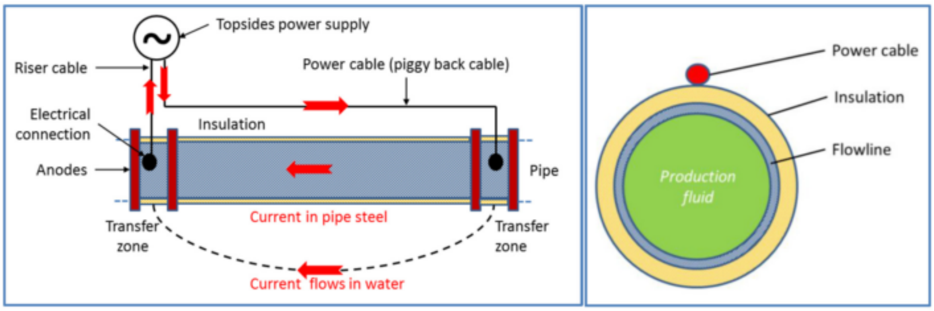


Figure 3.3: DEH system (Louvet et al., 2016)

Tzotzi et al. (2016) discussed the application of electrical trace heated pipe-in-pipe (ETH-PIP) in flow assurance. The ETH-PIP is an improvement of standard Pipe-in-Pipe by adding 4 heat trace cables, and 2 distributed temperature sensing (DTS) optical fibers spiralled against the inner pipe and covered by a high performance thermal insulation, as shown in Figure 3.4.

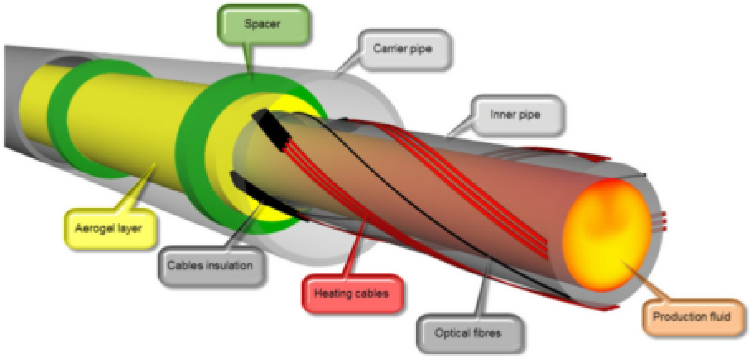


Figure 3.4: Configuration of ETH-PIP (Tzotzi et al., 2016)

Until recently, low voltage (below 1000V) heating elements and low power heating cables have been the typical solutions for down hole and subsea electric heating applications. Wilson (2016), Molnar & Riley (2016) discusses the feasibility and benefits of using medium voltage technology for flow assurance and hydrate prevention applications. This kind of technology could bring reduction of cost, power consumption and line loss.

Subsea components such as X-tree and manifold also need insulation and the thermal dynamic calculation is very important to design and monitor the insulation performance. Gharaibah et al. (2016) combined the experimental and numerical results and recommended a robust thermal modelling procedure for subsea components that allows a favorable balance between conservatism and accuracy. Janoff et al., (2014) introduced a non-destructive evaluation technique used for dielectric materials can be used to detect cracking, voids, and other defects in the installed insulation systems that may cause a degradation in performance.

3.2 Chemical injection

Chemicals are injected to the subsea system or directly to the well bottom to change the property of fluid, thus prevent the formation of wax, hydrate and other type of solids that may block the pipeline or wellbore. Commonly used chemicals could be categorized into nine types based on the function thermodynamic hydrate inhibitors (TDI), Low dosage hydrate inhibitors (LDHI), Defoamers, Asphaltene inhibitiors, Paraffin inhibitors, Scale inhibitors, H2S scavengers, chemical demulsifiers and Drag reducing agents. Actually, chemical injection is relatively a mature technology, and many works focus on the property of chemical and the injection process (Alharooni et al., 2017; Vershinin et al., 2017).

3.3 Operation and equipment

Some subsea equipment could be applied to help ensure the flow assurance through designed operation process. For example, subsea separator could separate oil, water and gas, thus helping prevent the formation of hydrate slug flow and erosion, and the amount of injected chemical could be reduced (Kondapi et al., 2017; Prescott et al., 2016).

Pigging is the practice of using devices known as "pigs" to perform various maintenance operations, including cleaning the pipe due to blockage. Carvalho and Rotava (2017) evaluate the simulation effectiveness to estimate pig total travel time and pig speed profile for a gas pipe line, and Wan et al. (2017) summarized the pigging solution of subsea wet gas pipeline, providing method of calculating pigging period, and scheme of reduce instantaneous slug.

Subsea Cooler technology is usually used for subsea gas dehydration, anti-surge cooling, cold flow and so on. It is getting increased attention primarily due to cost benefits realized by reducing or controlling temperatures. The simplest and most matured cooling device would be a long un-insulated flow line, as shown below.

Figure 3.5: Subsea passive cooler, from NOV: subsea cooler systems

Carrejo et al. (2015) presents a kind of high-strength dissolvable metal (HSDM), to operate as a fluid-loss barrier that can be run-in on the liner. The HSDM dissolves, acts as a screen equal in filtration performance but better than current sand control alternatives in its erosion resistance, and is good to sand and erosion management. An application of this kind of material is shown in Figure 3.6.

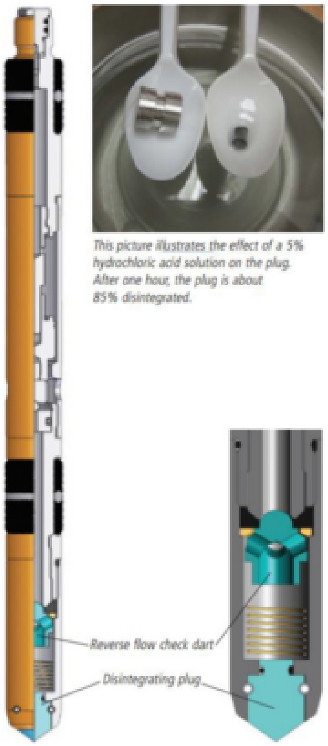


Figure 3.6: Gas lift valve with HSDM (Carrejo et al., 2015)

3.4 *Software technology*

Software technology does not immediately contribute to flow assurance, but it helps monitoring and decision making, which is very important during operation.

A Flow Assurance System (FAS) is installed on Ormen Lange in order to give information about the multiphase flow through the entire subsea production and pipeline system and onshore slug catchers to support the operation of the field (Dianita et al., 2015)

Osokogwu et al., 2014, Wilfred and Appah, 2015, presented a quick and easy tool, PROSYS, which helps in the preliminary screening of asphaltene, to determine if the operator will experience severe or mild problems arising from deposition of asphaltene and also estimates the dissociation temperature of hydrate in a pipeline during depressurization and the thickness of the melted ice in the pipeline.

Brower et al. (2014) introduced a post installed subsea monitoring system for flow assurance evaluation, providing real time operation data, thus helping decision making for flow assurance.

Zhang et al. (2014) discussed an application of integrated management strategy of flow assurance for digital field. An innovative rating system covering all types of flow assurance problems by design of experiments (DoE) and Fuzzy Logic methods was presented firstly. And then this system was combined with the digital field technologies, helping address various flow assurance issues.

3.5 Prospective approach

There are some newly proposed approaches dealing with the flow assurance of subsea production system. For example, the phase change material is a kind of potential alternative for the insulation layer. It can effectively regulate fluid temperature during production fluctuations or increase the cool-down time during production shutdown. Parsazadeh and Duan (2015) introduced a nano-enhanced phase change materials that allow thermal energy storage in the pipeline system.

Wax deposition begins from the pipe wall and generally form a wax layer. If the inner pipe wall is oleophobic, the wax molecule is hard to absorb into the pipe wall. Therefore, it becomes one way of assuring fluid flow. Liang et al. (2015) developed a bio-inspired composite coating with excellent wax prevention and anti-corrosion properties. The prepared coating is composed of three films, including an electrodeposited Zn film for improving corrosion resistance, a phosphating film for constructing fish-scale morphology and a silicon dioxide film modified by simply spin coating method for endowing surface with superhydrophilicity.

As for hydrate formation, a kind of technologies using nano-scale membrane to dehydrate the natural gas attract many attentions. Shirazian and Ashrafizadeh (2015) obtained high-quality nanoporous inorganic membranes applicable to dehydration of natural gas through synthesized and three stage modified process of LTA zeolite mem-branes.

Although these approaches have not been applied to subsea production system yet, the concepts and the performance inside the laboratory indicate large potential for the flow assurance of subsea production system.

3.6 Conclusions

In this section, methods about flow assurance in subsea production system were briefly discussed. Practically, these methods are usually applied together for a subsea system, which is an integrated work (Bouamra et al., 2017; Jain et al., 2015). Besides, the uncertainty and risk should also be analyzed carefully (Morgan and Zakarian, 2015; Twerda and Omrani, 2015).

Flow assurance attracts more and more attention due to the harsh environment of subsea. It is a combination of better material, proper facilities, and scientific management. There is still a long way to go, to overcome the flow assurance problems we are facing during the development of offshore field, especially in deep water.

4. TESTING FOR QUALIFICATION OF SUBSEA PRODUCTION SYSTEM

4.1 Qualification

API RP 17Q (2nd Edition, 2017) recommends that all subsea equipment are subjected to qualification to ensure they meet defined reliability, integrity, and operational requirements. A proper technology maturity assessment should be carried out to assess the need for executing a technology qualification.

The purpose of a qualification program is to provide evidence that a selected technology or equipment will meet functional and performance requirements, within specified operational limits, with an acceptable level of confidence. There are ten steps of a qualification program as defined in API RP 17Q 2nd Edition.

- Requirements planning
- Technology Maturity Assessment
- Select Qualification Program
- Qualification FMECA (Q-FMECA)
- Qualification Plan
- Qualification Execution
- Results Evaluation
- Improvements and Modifications
- Qualification Assurance
- End Users Qualification Program

API RP 17N defined eight Technology Readiness Levels (TRL) and Technical Risk Categorization (TRC) to assess technology maturity and technical risk respectively. Eight TRLs range from minimum of 0, corresponding to an unproven idea, to a maximum of 7, corresponding to proven technology as follows.

- Unproven Concept (basic R&D, paper concept)
- Proven Concept (proof of concept as a paper study or R&D experiments)
- Validated Concept (experimental proof of concept using physical model tests)
- Prototype Tested (system function, performance and reliability tested)
- Environment Tested (pre-production system environment tested)
- System Tested (production system interface tested)
- System Installed (production system installed and tested)
- Field Proven (production system field proven)

TRCs are a means of assessing technical risk across a set of change categories. Five change risk factors are defined including reliability, technology, architecture/configuration, environment and organization that are assessed against four different levels of risk (very high, high, medium, low) based on the perceived deviation from previous experience. The TRL and TRC are combined into a matrix to guide the user to the appropriate qualification activities for that specific phase of development.

The technology maturity assessment uses TRL and TRC to evaluate the technical risk and maturity of a concept in line with specified goals and requirements. Four paths are available for qualification based on the technology maturity assessment:

- Research & Development Program (for $TRL < 1$);
- Technology Qualification Program (TQP, for $1 \leq TRL < 4$);
- Standard Qualification Program (SQP, for $1 \leq TRL < 4$);
- Proven Technology (for $4 \leq TRL < 7$);

Selection of a TQP or SQP is mainly based on the assessed TRC and project requirements. TQP uses Q-FMECA to identify necessary qualification activities for technology qualification. TQPs are typically for novel or less mature technology, where the application is new or environment is not well understood, and/or where no existing standard is applicable to that technology. TQPs usually require more efforts and are more complex than comparable SQPs as a result of increased uncertainty in technology or environment.

SQP uses predefined qualification activities in existing applicable standards to qualify technology. Usually SQPs are for components, sub-assemblies, and assemblies using existing technologies that are modified to satisfy an incrementally more stringent requirement.

The TQP and SQP are normally carried out by a technology developer or equipment supplier. As soon as equipment achieves TRL 4, the technology is ready to be applied by an end user, then an appropriate End Users Qualification Program (including testing and monitoring) is to be established to progress the equipment TRL through TRLs 5, 6 and 7.

With the development of the subsea production technology, a lot of advanced testing processes of qualification are employed in the subsea production system.

4.2 Advanced Testing for Qualification of All-Electric Subsea Production

ABB Oil & Gas is running a Joint Industry Project (JIP) together with Statoil, Total and Chevron to develop technologies for subsea power transmission, distribution and conversion at greater distances, in deeper waters, and in harsher environments (Bugge, 2017). The project started up in 2013 and is targeting a 3000-hour shallow-water system test in 2018, including the qualification of pressure tolerant medium voltage switchgear, medium voltage drives, as well as supporting controls and auxiliary supplies.

The project follows the TRL development stages for technology qualification applied to components, sub-assemblies and equipment. For the JIP, this first required a breakdown of the overall subsea power system into separate manageable technology parts, the further to classify these with respect to novelty. Other important aspects of the DNV recommended practice is to be able to identify required design changes at an early stage and also to improve confidence in the new technology by close interactions and traceable documentation, see e.g. documentation process in Figure 4.1.

Since the test matrix is extremely large and difficult to handle considering several hundred unique critical components and various stress conditions, it was necessary to find a pragmatic way to structure the test such as to maximize the risk mitigation before pre-qualifying for full-scale prototypes. The key test philosophies are listed below:

- Test derived from a common understanding of realistic component/equipment specific stresses throughout design life (life-cycle mission profile)
- Comprehensive confirmation of the desired function as well as reliability testing primarily conducted at the level of the component, where a functional failure can be defined, and accelerated conditions applied
- Sub-assemble level testing geared toward confirmation of the overall function, design margins, and the thermal and high-current aspects. Special attention to novel aspects in subsea power, where the use of customized versions of existing standards may be required
- Seek the simplest of conceivable tests for verifying the investigated function, rather than strictly following a standard developed for entirely different reasons or conditions
- Utilize standardized tests for subsea electronics located in 1 atm chambers, unless the impact of meeting these standards introduce a negative impact on the design
- Hypothesis-based testing, with knowledge of how to interpret different possible outcomes of a test, supported by numerical simulations where possible

- Use well-established failure modes and design rules unless theoretical or experimental evidence suggest new adverse effect in subsea environment
- Focus on learning the behavior and limits of design, rather than just "passing tests".

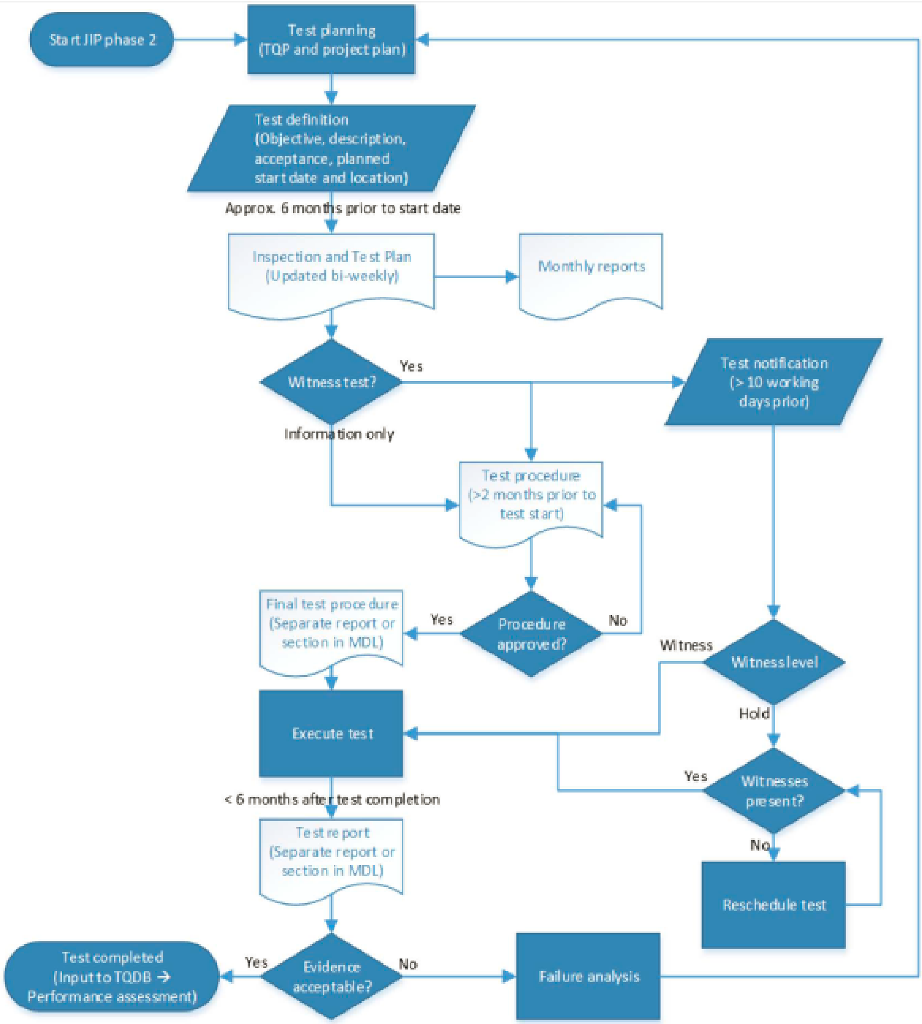


Figure 4.1: Qualification test execution flow-chart (Bugge *et al.*, 2017)

One of the key sub-assemblies is the medium voltage drive cell. This has been pressure tested at 300 bar in Statoil R&D facility in Trodheim as shown in Figure 4.2 below. The first test was performed in 2016, and a second 3000 hours cell test planned for the same year.

Formal qualification of key components and sub-assemblies was also planned for 2017. Key sub-assemblies will also be tested for 162/3 Hz supply in order to demonstrate that developed technology can be used in subsea drive system with LFAC power transmission and distribution. Based on the pre-qualified components, full-scale prototypes will be assembled in 2018 for a 3000hours shallow-water system demonstration.

Figure 4.2: Medium voltage drive cell pressure test at Statoil R&D facility Rotvoll (Bugge *et al.*, 2017)

4.3 Advanced Testing for Qualification of Multiphase Pumping

The Girassol Resources Initiatives (GirRI) is a major brownfield deepwater project, which seeks to optimize the Girassol FPSO production (Bibet, 2016). It is also the third subsea boosting project developed offshore Angola by Total, the operator, and OneSubsea, the contractor. High boost multiphase pumps (MPPs), with an operating ΔP of 110 bar at 53% GVF are deployed subsea on two exiting deepwater oil production loops to enhance the Rosa field reserves and production, a world's first for the oil and gas industry.

The pump system implemented includes two MPP stations on the sea floor (Figure 4.3), one on the production loop P70, and one on the production loop P80. On P70, the MPP station is located near the riser tower while on P80 the MPP station is located 17 km away from the FPSO. Each MPP station holds two MPPs, in a segregated scheme of one MPP per production branch.

Figure 4.3: View of a high boost MPP station (Bibet *et al.*, 2016)

For all subsea equipment, it is standard practice for both the operator and the contractor to validate the pump through a comprehensive pump factory test (FAT). It is also standard to validate the overall pumping system from topside to subsea through a comprehensive system integration test (SIT), with the pump running in shallow water. The standard contractor pump FAT covers performance mapping with a full range of flow/AP/speed in water + nitrogen, then in viscous oil + nitrogen (Exxcol D80 oil used for GirRI), and a 24-hour endurance test under a full load and at full speed.

The philosophy is also to mitigate, through testing, any new risk caused by conditions specified for the application. For this first high boost MPP application, two new major risks were anticipated: the behavior of the pump with a worn balance piston and the proper sizing of the flow mixer. To address these potential risks, dedicated tests were run with one MPP.

4.3.1 Worn Balance Piston Test

The overall objective of this test was to demonstrate the stability of the pump when operating with a worn balance piston, and in so doing ensure acceptable hydraulic, rotor-dynamic, and mechanical performance of the pump.

Conducting tests on the pump involved seven steps:

- Pump performance tests with a new balance piston. The goal of these tests was to map the performance and compare some test results with the ones obtained later with a worn-out liner.
- Dismantling of the pump to install a worn-out balance piston line: inspection of the pump internals during disassembling to detect any marks, wear, etc.
- Reassembly of the pump with a worn-out, bronze piston liner.
- Performance test with the worn-out balance piston.
- Dismantling of the pump to re-install the new balance piston liner. Inspection of the pump internals during disassembling to detect any marks, water, etc.
- Reassembly of the pump to new conditions.
- Standard OneSubsea MPP factory acceptance test program (performance and endurance tests, 24 hours accumulated testing).

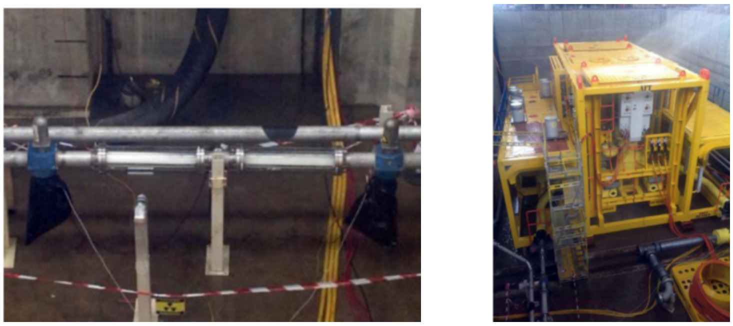
Vibration levels for the worn liner design remain in the same order of magnitude to what was observed for the nominal design, in spite of the wear introduction for the balance piston (double clearance and removal of swirl breaks). Post-test pump disassembly and inspection revealed that all parts were in good condition.

4.3.2 Slug Test

For all MPPs a flow mixer is installed at the pump inlet to homogenize the process fluid and to smooth the gas/liquid transients, which in turn provide optimal inlet condition for the first pump impeller. The design and sizing of the flow mixer depends on the hydrodynamic slug size, GVF, pressure, and flow rate. The slug test was conducted to verify that the GirRI MPP would work well with the slug regime predicted by the flow assurance studies. The expected slug regime was therefore reproduced on the test loop. A slug loop was built in the OneSubsea test facilities, with a length of approximately 130m to enable a fully developed hydrodynamic slug flow at the pump station inlet (Figure 4.4 and Figure 4.5).

Figure 4.4: Slug test loop arrangement (Bibet *et al.*, 2016)

Through the slug test, the Project Team was able to demonstrate that the flow mixer was working well with a slug regime identical to an actual one used on site.



a. “See-through” pipe b. MPP under slug test

Figure 4.5: “See-through” pipe and MPP under slug test (Bibet *et al.*, 2016)

After all the qualification tests (green boxes on Figure 4.6), the pump was deemed ready for development and made available to the project teams for immediate application: GirRI.

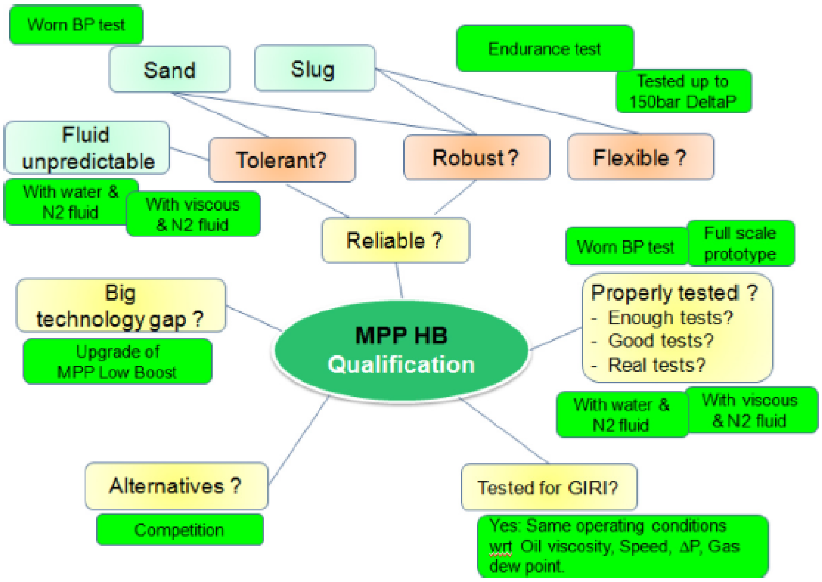


Figure 4.6: High boost MPP qualification process. In the green boxes, all tests done to address the identified risks (Bibet *et al.*, 2016)

4.4 Advanced Testing for Qualification of Subsea Wet Gas Compressor

In May 2009, a two-year contract was awarded for the execution of a TQP for the Gullfaks 2030 Subsea Compression project, to mature the concept of subsea compression, as well as the key building blocks of the system (Hjelmeland, 2016).

The qualification program included engineering, procurement, construction and testing activities of the subsea multiphase compressor, based on the WGC400 compression technology. The first compressor, defined as WG4000 Series 0, was built to fall subsea specification. Other parts of the qualification program comprised a representative cooler bundle element, electrical monitoring system, vibration monitoring, as well as control system interface. For qualification testing of the compressor, a novel high pressure live hydrocarbon flow loop was engineered and built in OneSubsea's facility in Fusa (shown in Figure 4.7), outside of Bergen, Norway. The work was conducted efficiently and successfully, and in close collaboration with the expertise and personal of Statoil's K-Lab.

Figure 4.7: High pressure hydrocarbon test loop (Hjelmeland *et al.*, 2016)

Testing of the compressor post manufacturing was performed at the new hydrocarbon test loop in the period from August 2010 to April 2011.

The test program that formed basis for the machine qualification was as follows:

Test Campaign #1 – Ideal Fluid Performance Test (Nitrogen/Exxol D80)

- Mechanical run test
- Assembled compressor gas leakage test
- Hydraulic performance mapping at 24 bara suction pressure
- Mechanical design verification on ideal fluids

Test Campaign #2 – Hydrocarbon Fluids Performance Test

- Hydraulic performance mapping at 72, 65.3, 36, 24 and 12 bara suction pressure and hydrocarbon fluids
- Acceptance test of hydraulic performance
- Mechanical design verification on hydrocarbon fluids

Test Campaign #3 – Ideal Fluids Endurance Test

- Mechanical Integrity Tests, including minimum flow and no-surge tolerance verification, liquid start-up and operation
- Endurance testing (3000 running hours)
- Machine inspection and verification of mechanical design for acceptance

4.5 Advanced Testing for Qualification of Subsea Transformer

The Jack and St. Malo fields were developed in a deepwater Gulf of Mexico (GoM) setting by Chevron and co-owners and commenced production in 2014, the reservoirs are located roughly 40km apart, about 400km southwest of New Orleans, Louisiana. Water depths in both fields are around 2333m, and the reservoirs are approximately 9km below the water surface (Hjelmeland, 2017). The Jack and St. Malo fields were developed with subsea completions flowing back to the Walker Ridge Regional Platform, the largest, by displacement, semi-submersible floating production unit (FPU) in the GoM.

The power system topology for Jack and St. Malo fields was based on elevated transmission voltage in the umbilical, utilizing step-up transformers on the FPU and step-down transformers on the seabed. A TQP was initiated to qualify the subsea step-down transformer which would reduce the voltage. Transmission at elevated voltage levels results in lower power losses and increased overall efficiency for the power system.

Qualification for the subsea step-down transformer modules (Figure 4.8) was based on testing and qualification of sub-components prior to assembly and qualification of the finished transformer unit. A number of test and qualification efforts were initiated as part of the TQP:

- Qualification of wet mate high power connectors;
- Stress tests of wet mate connector components;
- Vibration test of wet mate connectors;
- Test of high resistance ground;
- Transformer current test;
- Test of instrumentation;
- Test of oil filled transformer core;
- Test of internal components;
- Qualification test of subsea step-down transformer.

Figure 4.8: Subsea step-down transformer modules with electrical flying leads during assembly (left) and during system testing (right) (Hjelmeland *et al.*, 2017)

5. INSTALLATION AND OPERATIONS FOR EMERGENCIES

5.1 Installation for Subsea Hardware

Offshore oil and gas production relies on the subsea systems, and the underwater installation is the foundation for construction of the systems. The combination of deeper offshore field developments and larger, more complex subsea structures results in new requirements and challenges for installation vessels and related deployment systems. The conventional vertical deployment systems are struggling to meet the industries requirement of installing heavy subsea structures in deep water.

5.1.1 Lifting Method

Currently, several techniques are used to carry out the full installation activities. The traditional one is lifting method. The object can be transported on the deck of the barge and then lowered down with a crane installed on the barge or a heavy-lift crane vessel. Such type of transportation is considered to be relatively fast, but at the same time this method is sensitive to weather conditions like wind and wave forces, slamming and current forces. This method is limited by water depth. The self-weight of steel wire increases and axial resonance occurs due to very long length. The requirements of lifting capability, positioning, heave compensating and deck areas also get limited. What is worse, the costs is getting more expensive in deeper waters. Figure 5.1 shows the lifting method.

Figure 5.1: Lifting method

5.1.2 Drilling Riser Method

In 2001 Petrobras installed a 241 ton manifold in 940m water depth with drilling riser method. The manifold is connected to the end of riser and lowered by a semi-submersible. The disadvantages are the high costs, time consuming and high requirements for the vessel. The MODU or drilling vessel also needs the heavy lifting capability, DP system and heave compensating system. Figure 5.2 illustrates the drilling riser method.

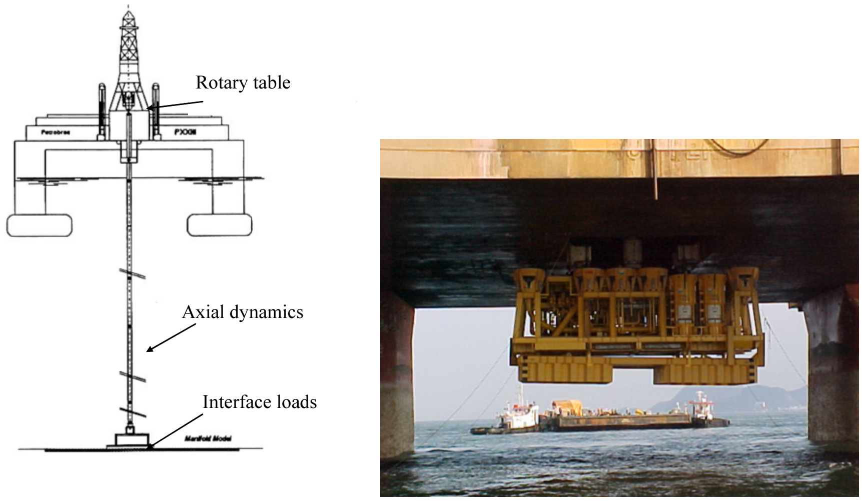


Figure 5.2: Drilling riser method

5.1.3 Sheave Method

The first application of sheave method was in 2002 by Petrobras. A manifold weighted 175ton was installed in 1885m water depth. The manifold is lowered by multi vessels and a sheave was connected to it. A steel wire around the sheave is the main installing line. One end is connected to a drilling platform and the other to an AHTS. When the equipment is lowered to 90m depth the sling is cut and the manifold is lowered to seabed with the steel wire. The other AHTS helps to prevent the wire from damage due to twisting. The dominant disadvantage is the complexity, which makes it difficult to numerical simulation and scheme design. Besides, it needs more vessels and DP and heave compensating. Figure 5.3 shows the sheave method.

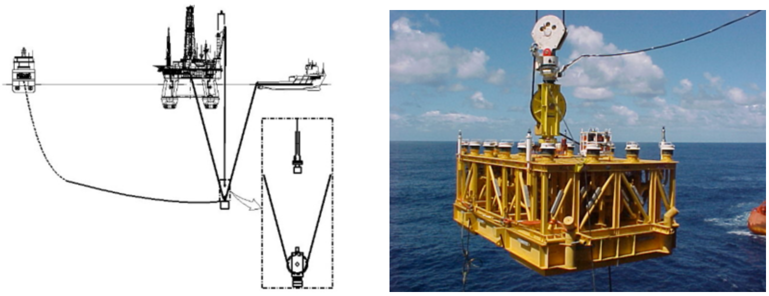


Figure 5.3: Sheave method

5.1.4 Pencil Buoy Method

The pencil buoy method is a subsurface transportation and installation method developed by the company Aker Marine Contractors. The pencil buoy method reduces the offshore installation sequence from a lifting and lowering operation to a pure lowering operation. This is done by wet towing the structure from an inshore load out site to the desired offshore location.

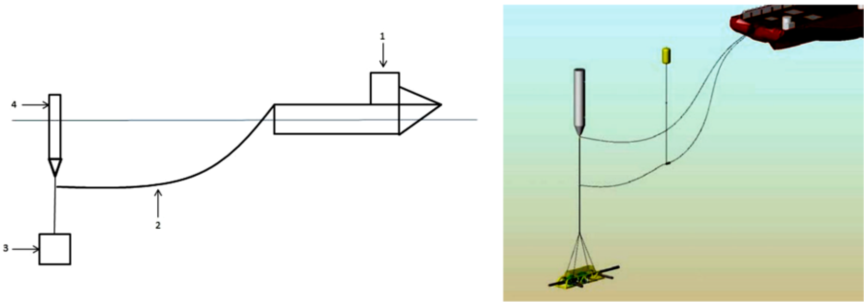


Figure 5.4: Pencil buoy method

This method has several advantages:

- There is no risk of cargo pendulum motions in the air.
- Slamming/uplift loads during lowering through splash zone are excluded.
- Large deck space for transportation is not needed.
- Less crane capacity is required.

5.1.5 Subsea 7 Method

The Subsea 7 method is developed for installation of massive subsea structures in harsh environmental conditions. It enlists the service of a small monohull construction vessel and allows carrying out the installation in a single operation. Subsea 7 promotes this method as more reliable and cost efficient compared to the traditional transportation on the barge.

Towing is done through the moon pool of the vessel, which enables towing of heavy weighted cargos and improves the towing criteria. The hang-off point of the cargo should be as close to the vessels motion centre as possible in order to decrease the effects of the vessels motions, what results in good performance in severe weather conditions. For that purposes, the hang-off tower is installed over the moon pool of the installation vessel. Some operational stages are depicted in Figure 5.5.

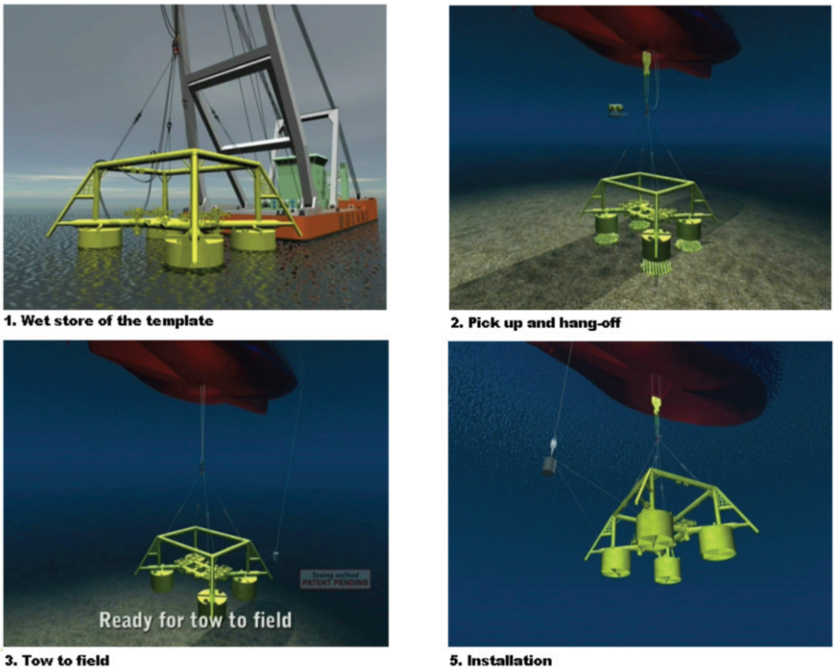


Figure 5.5: Illustration of four operation stages: wet-store, pick up and hang-off, tow to field and installation

The Company reported that installation expenses were significantly lower than the cost of using a heavy lift vessel, and all operations were held in a safe manner because of the limited use of "sophisticated" cranes and crane modes subject to higher risk of technical/software failures and all heavy lifts are performed inshore in sheltered waters. Tow speed can be increased at lower sea states.

5.1.6 Pendulous Installation Method

The Pendulous Installation Method (PIM) was developed by Petrobras to install large manifolds in water depth of 1900m. PIM is a non-conventional technique involving small conventional deepwater construction or offshore support vessels, without drilling platforms. PIM is capable to deploy heavy manifolds or other equipment in water depth up to 3000m.

Numerical simulations by OrcaFlex and model tests were conducted by Fernandes to assess the fundamental aspects and study the feasibility and parameters. Sensitivity studies were carried out by Roveri for pendulous method, where the comparison of numerical analysis and tests were made. The hydrodynamic performance and parameters, including added mass and drag coefficients, were estimated by Fernandes via experimental and numerical methods. Full scale model tests were carried on and finally two subsea manifolds were successfully installed in 1845m and 1900m water depth, respectively.

The PIM is a cost effective solution in comparison with conventional installation methods, for instance, installation with drilling rigs. The resonant motion during deepwater installation can be avoided. However, due to the complex geometry of the manifold, hydrodynamic instability may occur during installation. Therefore, to prevent rotation of the cargo, an anti-rotation system such as counter weights should be installed. Installation process is shown in Figure 5.6.

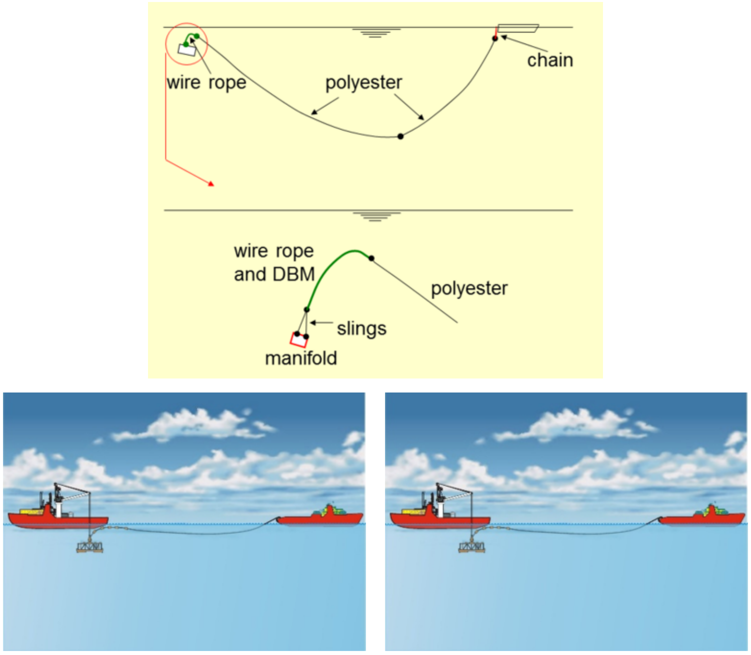


Figure 5.6: Pendulous installation method

5.2 Oil Spill in Gulf of Mexico and Measures Taken against The Accident

Subsea oil and gas exploration and production face many challenges such as harsh weather and working conditions, remote location and lack of infrastructure. These can lead to emergency accidents and present difficulties for handling and rescue. The major accidents are listed in the Table 5.1.

Table 5.1: Major accidents (Basharat *et al*., 2014)

No	Accident	No	Accident
1	Non-ignited hydrocarbon leaks	7	Drifting object
2	Ignited hydrocarbon leaks	8	Structural damage to platform/stability/anchoring/ positioning failure
3	Well kicks/loss of well control	9	Fire/explosion in other areas
4	Leaking from subsea production systems/pipelines/risers/flow lines/loading buoys/loading hoses	10	Damage to subsea production equipment/pipeline systems/diving equipment caused by fishing gear
5	Vessel on collision course	11	Evacuation
6	Collision with field-related vessel/installation/shuttle tanker	12	Helicopter crash/emergency landing on/near installation

On April 20th 2010, the semi-submersible drilling platform "Deepwater Horizon" located in the Gulf of Mexico rented by BP exploded. Thirty six hours after the explosion, the drilling platform sank, and eleven crew died in the accident. From 24th, the oil continued to spill from the oil wellhead, causing a large-scale crude oil pollution.

From April 24th to July 8th, American experts evaluated that 300 thousand tons oil had leaked. On July 15th, BP announced that the newly installed "control cover" had successfully suppressed the underwater oil wells. Eventually, the disaster of the Gulf of Mexico oil spill was put to an end 85 days later.

Preliminary survey results showed that the accident caused nearly a thousand kilometers of coastline to be contaminated, and the polluted area covers more than 20,000 square kilometers. The oil spill caused a severe natural disaster in the ecological environment of the Gulf of Mexico.

Since April 20th after the explosion, the accident developed to become more and more serious. Initially, BP took three measures: the first is to send a ROV to examine and repair the safety valve which was out of service; the second is to send vessels to absorb oil; and the last is to reduce the pressure of oil wellheads by drilling two new wells, in order to reduce the leakage rate. To prevent the disaster from becoming even worse, BP worked with the US government, engaged more than twenty four thousand people, and 1400 vessels in the rescue. Furthermore, more than 610 kilometers water gate was involved, in the manner of "ring oil" to besiege and intercept the oil floating in the sea. In addition, the "capping", "top kill", "hair oil absorption" and other means have been adopted, yet all the means were ineffective or failed at last.

Top kill is one of the method through the assistance of the ROV, the main technical index of the ROV is as follows: four horizontal vector directions and a vertical thruster, five cameras, a LED lamp, a seven functions manipulator and function of automatic directional. A large number of high-density liquid, metal debris *etc*. play a blocking role on the material in oil wells, balancing the pressure in wells, and with the cement injected into the wells, the entrance can be sealed, achieving the effect of plug.

Capping is a method that cuts off the oil spill above the blowout preventer by closing the valves to control the oil spill, and installing an oil drain pipe above the valve to drain and transporting the spilt oil to the waiting vessel.

Faced with this unprecedented environment catastrophe, the US government made considerable efforts in terms of manpower, material resources, and financial resources to clean up pollution. The measures include spraying oil dispersing agent at the surface and under the water, laying out of oil fence and oil absorption railing, using oil recovery machine, burning the spilled oil, *etc*.

5.3 Responses to Oil Spill

After the catastrophic incident in the Gulf of Mexico, the entire oil and gas industry gave much attention to drilling safety and emergency response. The need for safer operations led the industries to promote adequate Emergency Response (ER) System as well as investments in advanced techniques and methodologies to prepare for and efficiently respond to any possible accidental scenarios arising from operations.

The International Oil and Gas Producers Association (IOGP) learned from this and similar accidents, established a program to enhance future prevention and preparedness. They set up an Oil Spill Preparedness Framework, including: risk based plan scenarios, response strategies using NEBA, oil spill response resources, incident management system, and stakeholder engagement. Many new tools and techniques are used in handling oil spill (Flynn, 2016; Coolbaugh, 2017).

5.3.1 Dispersants

Dispersants can be rapidly deployed and are one of the most effective tools in a majority of scenarios (Flynn, 2016). They work just like soap and shampoos, and contain many of the same ingredients. They break the oil into very tiny droplets, which are rapidly diluted and biodegraded by naturally occurring microorganisms in the marine environment. They can avoid floating oil from impacting sensitive near-shore areas and accelerates the natural biodegradation process.

In particular, the application of subsea dispersants for response to well release in deeper water has significantly developed. This technique aims to prevent oil reaching the surface by dispersing the oil close to the point of release. A greater proportion of the released oil breaks into smaller oil droplets that can be dispersed, diluted and biodegraded in the water column, unlike the larger oil droplets will float up to the sea surface.

5.3.2 *In-suit burning of oil*

In-suit burning is a response technique which involves the controlled burning of oil. Prior to the Macondo spill, the technique had not been used in such an operationally complex scenario. In the case of the Macondo response, more than 400 successful individual burns were completed, a number for hours at a time. Now controlled burns of up to 10 hours were routinely used, demonstrating the importance of the new technique for combatting offshore spill.

5.3.3 *Spill surveillance, monitoring and visualization*

Oil Spill Contingency and Response model (OSCAR) is a modelling tool developed by SINTEF to simulate the oil spill behavior; it is a multi-component 3-dimensional oil spill modeling tool to predict the movement of oil both on the water surface and in the water column. The oil spill model is developed for objective analysis of spill response strategies according to the predicted movement of the oil on the water surface and in the environment (Iazeolla, 2016). Two main model methods are used with OSCAR to evaluate the effects of oil spill scenarios.

a). Stochastic modeling

Stochastic simulations predict the probable behavior of potential oil spills under typical historical meteorological and oceanographic conditions, such as database of wind and marine currents speed and direction. Their outputs indicate the probability of where the spill may spread and give statistical information on the possible consequences. They do not indicate volumes of oil. It provides an estimation of the contamination probability and of oil stranding times, stochastic simulation outputs support the selection of the most appropriate response equipment and strategies. Stochastic modeling is used in the ER planning phase, to evaluate the most probable outcomes of a spill and to set up the most appropriate response options.

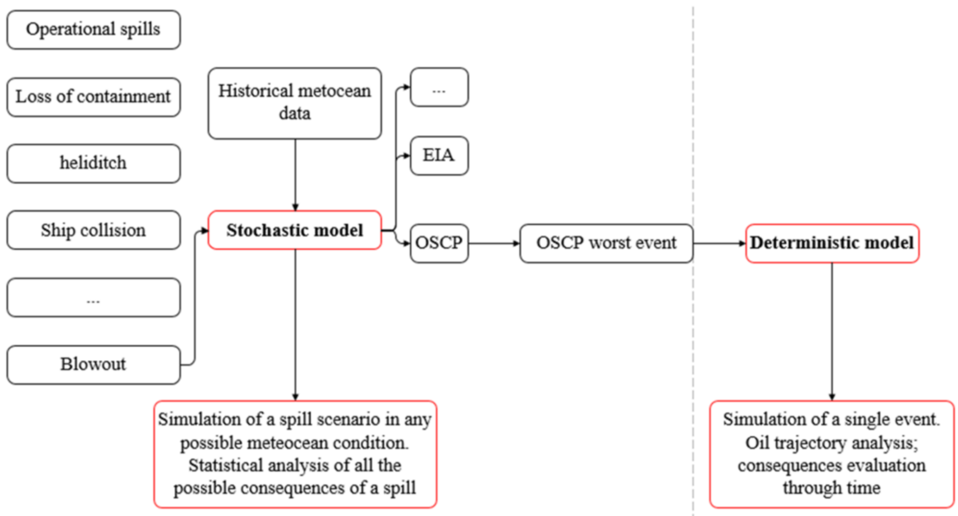


Figure 5.7: Oil spill modeling along Oil Spill Risk Assessment progress (Iazeolla *et al*., 2016)

b). Deterministic modeling

Deterministic modeling is used to predict the route of a hydrocarbon slick over time, and to estimate the oil weathering profile, under a single set of meteorological and oceanographic conditions. It investigates potential beaching or intersection of maritime boundaries under specific (worst case) wind and marine current speed and direction. Result can be integrated into GIS-based systems that enable the crossing of consequence data and response means equipment location and availability. Deterministic modeling is employed during emergencies to predict the development of the spill in the first days after the spill.

5.3.4 Deepwater subsea waterjet

Deepwater subsea waterjet is applied in subsea emergency response situations, and provides an opportunity to prepare for tier 2 and tier 3 oil spill emergencies without depth limitation in the world's deepest water exploration and production sites (Bruce Kivisto, 2014). It can also minimize the risk to the environment during common offshore exploration and production. Waterjet cutting is a cold cutting process and does not generate enough energy to ignite most confined gases, so it is safe and efficient to conduct cutting and repair operations in the presence of hydrocarbons and other combustible gases. Meanwhile, it does not introduce a heat affected zone (HAZ) into the material being cut, this reduces the possibility of introducing stress fractures and other physical deformities to the work piece. A waterjet stream is a soft tool that cannot bind in the cut and can start the cut at any point on the work surface, which allows the waterjet muzzle to place inside the pipe or other hollow subject work piece, and to cut from the inside to the outside. An intensifier-style pump is used to pressurize a stream of water to ultra-high pressure (3,900 bar), and several streams are formed and rotated to produce a uniform application of energy on the subject work piece, which have sufficient energy to remove even the most difficult coatings (epoxy, concrete, marine growth, rust scale,) with minimal risk of cutting into or through. With the addition of abrasive, it is effective at cutting steel up to 250mm thick. It can successfully operate at 1,430m seawater, which allows for cutting of steel and other materials, as well as for hydrate remediation and isolation of valves, ports, caps, boils and weld seams in the deep water subsea space.

Subsea waterjet system is used in emergency response, because of its unique cold-soft tool characteristic, which can rapidly produce a clean cut on the wellhead to make it ready to accept a cap or diversion device.

5.3.5 Subsea emergency response system

Total created the Subsea Emergency Response System Project (SERS), in order to develop and supply tools for use if an intervention was required in response to an uncontrolled hydrocarbon leak (Bourguignon, et al., 2014). This set of tools can be split into two systems: a dynamic killing system and a diverter system.

The dynamic killing system is capable of injecting fluids into a leaking Christmas tree, either directly into the flowing well or through an adjacent well, in the case of the flowing well being damaged or not being accessible. The system can handle an injection flow rate of up to 3,000 lt/mn, aimed to neutralize a leak and bullhead the effluent back into the reservoir. The advantage of this system is that it is reasonably simple and quick to deploy and operate from any available drill ship or light well intervention vessel.

The diverter system can be connected on the top of each subsea Christmas tree for capping shut-in or diverting the fluid to a containment system. It can be used for capping on subsea blowout preventers (BOPs) or subsea wellheads in the case of a blowout. The diverter system can be run from a dynamically positioned drilling rig using an existing installation workover control system with its lower riser package, emergency disconnect package and landing string.

5.4 Responses to Pipeline Emergency

Offshore oil and gas pipeline are important assets for maintaining stable energy supply. Some critical pipeline damages need emergency repairs, these defects include rupture, sabotage, vandalism, material failure, anchor drag damage on any of the operator's critical pipeline.

5.4.1 Temporary by-pass

This method is usually employed as a temporary measure to maintain flow around a damaged pipeline section whilst a more permanent repair method is planned. It is mostly recommended for pipeline defects of significant size by installing the temporary bypass section to allow the pipeline to be put back to service quickly.

5.4.2 Installation of a bolted clamp

Bolted clamps are designed to contain the full pipeline pressures and are generally thick and heavy as a result of the large bolts required to provide the required clamping force. To better contain the pressure for leaking pipelines, these clamps are designed with elastomeric seal. Usually, they are recommended for repairs of minor pipeline defects such as pin-hole leaks, localized corrosion and weld defects.

5.4.3 Lift up and repair/Above water repair

This method is recommended for offshore pipelines installed in shallow waters region in the water depth less than 40m. This method requires the deployment of pipe lay vessel with side mounted davits. The main advantages of this methods are that it minimizes the use of subsea connectors and number of such connectors installed on the pipeline, hence reducing the potential leak points along the pipeline and investment.

5.4.4 Remote welding system

The new remote welding system consist of three main modules: a habitat proving a dry gas filled work location at the tie-in location, a power and control unit launched separately providing all essential services needed for the job and the remote welding tool performing the welding operation itself (Berge, 2015). This new technology uses hyperbaric welding to repair large diameter subsea pipelines in water depth down to 1,300m. The first operational step is to install the remote welding habitat by means of the vessel crane. After landing the habitat on the seabed, the pipe ends are lifted into the habitat and secured by the pipe claws the pipe doors are closed. Then the habitat closure is filled with Argon gas and the atmosphere dehumidified in order to establish acceptable conditions for welding progress. The second stage is to launch the remote welding POCO, using an A-frame launch and recovery system over the vessel side or by means of a module-handling tower through the vessel moon-pool. The POCO will be landed on the habitat side platform and engaged on the connection interface. After verifying the interface seals are tight, the connection system is dewatered and opened to allow

Figure 5.8: Remote welding system in operation (Berge *et al*., 2015)

the remote welding tool to be moved sideways and engaged around the pipe. At last, the pre-heat system then heat the pipe to a specified temperature and the welding path is learnt and logged by the welding tool, the welding is performed under supervision and control by welding operator and a welding engineer.

6. INSPECTION, MAINTENANCE AND DECOMMISSIONING OF SUBSEA SYSTEMS

6.1 Technology Developments of Subsea Systems Inspection

6.1.1 Robotics in Deep Water

Unmanned underwater vehicles (UUVs) and its associated tooling are the most widely used equipment completing different missions under different working conditions and exchange information and data with the ship or station, as they are unoccupied, reliable and highly maneuverable. They have been widely applied to scientific research, acquiring information of oceans and life-forms, and are being increasingly utilized in subsea installation and maintenance operations (Shukla and Karki, 2016). The present UUVs are mainly classified as three types, remote operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs) and autonomous underwater gliders (AUGs), as shown in Figure 6.1.

Figure 6.1: Different kinds of ROVs and AUVs (Shukla and Karki, 2016)

Recently, to response to the lessons from The Deepwater Horizon oil spill accident off Louisiana in the Gulf of Mexico in 2010, an autonomous underwater robot (SOTAB-I) was proposed and tested for early detection and monitoring system as one technological measure around offshore oil and gas production systems (Kato *et al.*, 2017). The mission of this robot

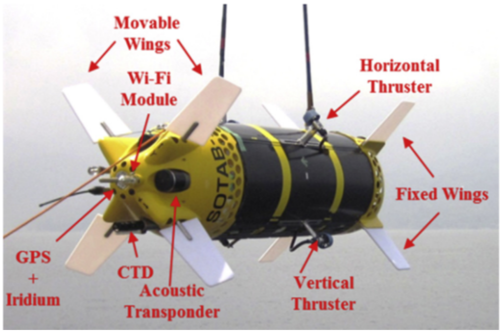


Figure 6.2: SOTAB-I (Kato *et al.*, 2017)

is to monitor not only detailed structure of oil and gas plumes in the water columns, but also time-varying structure of transportation of oil droplets in 3-D space. Technologies of control, communication, navigation and power supply are still the main difficulties in developing UUVs for better subsea inspection and other operations.

6.1.2 3D Laser Imaging Systems

Lockheed Martin has developed the capability to conduct AUV-based structural survey and post-hurricane platform inspection using 3D mapping and change detection with a 3D sonar. The company is now extending its revolutionary 3D modeling and change detection to employ a 3D laser sensor, thereby improving model resolution and accuracy from centimeter scale to millimeter scale. The system about AUV outfitted with 3D laser imaging systems will provide new, high accuracy tools for inspection of flowlines, risers, and other subsea infrastructure.

6.1.3 Non-Destructive Examination of Flexible Risers

There is a significant requirement from operators to have a reliable, high quality method of identifying damage and quantifying the remaining life of aging operating flexible risers. The DRIFT (Digital Radiographic Inspection of Flexible Risers Tool) has been proven to detect the defects of concern in fine detail, including corrosion, cracks, carcass collapse and loss of interlock (Crane, 2016). This technology has significant potential for extension to SCRs, as well as other subsea hardware and for use in greater water depths.

6.2 Advances in Maintenance of Subsea Systems

6.2.1 Risk Based Asset Management (RBAM)

According to Risk Based Inspection (RBI) and Reliability Centered Maintenance (RCM) methodologies, a risk-based inspection methodology for asset management offering an organized analysis with knowledge sharing for collaborative possibilities in a multidisciplinary context is investigated (Kamsu-Foguem, 2016). The RCM process aims to create a precise, targeted and optimized maintenance program in order to achieve optimum reliability from the facility. Compared with RCM, the RBAM approach optimizes the cost of preventive maintenance and the corresponding expected cost of failures. The RBAM focuses on implementing a maintenance and inspection plan which focuses in the possibility of continuous improvement.

6.2.2 Pipeline Maintenance Plan

It is not an easy task to provide timely response and effective maintenance in challenging operating environments for subsea pipelines with the challenges of ultra-deep water, high pressure, corrosive products, and unstable soil conditions. Integrity management programs are used to prevent, detect and mitigate threats in lifecycle of subsea pipelines. The Pipeline Integrity Management (PIM) system includes design, operation, QA/QC, corrosion management, and management of other risks (Liu *et al.*, 2017). The PIM plan has the following responses: preventive response — removes the threat or mitigates the consequence; predictive response — detects and confirms the threat likelihood, its location and characteristics; and corrective response — address the detected threat prior to failure either by non-intrusive means or intrusive repair.

To deal with the emergency and reduce the downtime, an Emergency Pipeline Repair System (EPRS) is introduced. It can put the right material, equipment, resources and construction spreads into place before an emergency occur (Sun *et al.*, 2017), and can make full preparation before the failure and reduce the bad consequence.

6.2.3 Well Maintenance Plan

It is necessary to perform maintenance interventions to avoid leaks and keep safe during well operation. A quantitative and dynamic risk assessment (QDRA) is developed to evaluate the safety of well maintenance activities (Villa *et al.*, 2016). It is an easy method to quantify the available IBS (integrity barriers set) by proper software before operations. The QDRA approach with database containing entire mapped information about barrier components, barriers, IBS, operations and their relationships can be automated to make safety assessment of the well construction or maintenance plan.

6.3 Advance in Decommissioning of Subsea Systems

New technological developments are necessary for the safe and cost effective execution of the project in decommissioning of subsea systems.

6.3.1 Subsea Cutting Technology

Cutting techniques are numerous low-energy solutions including shears, diamond wire, and water-jet cutting. Higher energy solutions include gas cutting and other burning methods. Solutions are chosen on the basis of best-for-task, equipment, safety assessments, and overall energy balance.

6.3.2 Sub Bottom Cutter

The idea of the Sub Bottom Cutter (SBC) has been originated by exploiting diamond wire cutting technology and designing underwater cutting equipment autonomously operating under remote supervision, in response to legislative requirements for the safe and efficient removal of offshore structures such as jacket piles and wellheads below the seabed soil (Buch *et al.*, 2015). The development of the SBC prototype has been sponsored by four oil companies: BP Amoco, Total, Amerada Hess and Shell. The project brings forth:

- A reliably tailored set-up: The robotic platform;
- A low-impact duty-scheme: The dig-and-saw process;
- A new technology: The diamond wire cutting;
- A safe work-cycle: remote monitoring and control of the system functions.

This approach in the unique task of cutting underwater structures below the seabed soil is aimed at reducing the excavation volume to less than 10 cubic meters, enabling the safe disposal of the excavation refuse without disturbance of the surrounding environment.

The SBC (Figure 6.3) leading by Cutting Underwater Technologies Ltd is principally composed of the following parts: The support platform (including bridles, 3 suction anchors, hydraulic/electric junction box); The Main Frame (with tilting rams and frame, sledge guides and rack); The Excavation System (Twin Guide Tubes, sledge frame and feeding system); The Cutting Assembly (the Twin Guide Tubes with the relevant actuation, monitoring and diamond wire cleaning systems).

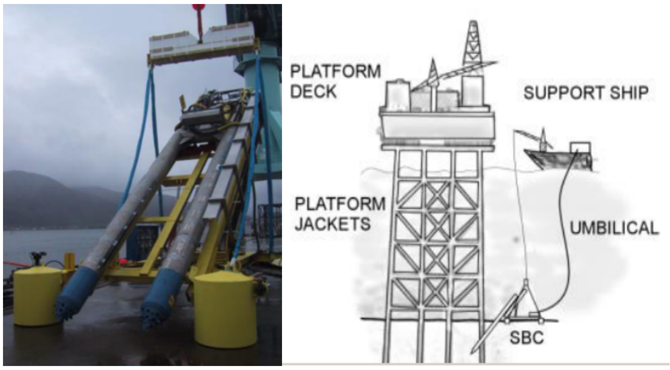


Figure 6.3: The prototype SBC robotic platform (left) and Operating Configuration (right)

The robotic platform developed within the SBC project provides reliable and effective means for underwater oil plants decommissioning, thus giving a positive answer to the market request for new technology.

The operating sequence of the SBC systems (Figure 6.4) is as follows:

- Stand-by, the reference state after deployment on the sea-bed;
- Emergency, if a failure arises, the alarm state is enabled, specifying the originating site;
- Positioning (anchorage), the robotic platform is located and its altitude set to start cutting operation;
- Tilt, the platform cradle is bent up to the selected engagement slope;
- Drilling, the twin pipe drill-and-dig heads perform the required digging beneath the sea-bed soil;
- Cutting, the diamond wire equipment accomplishes the planned task.

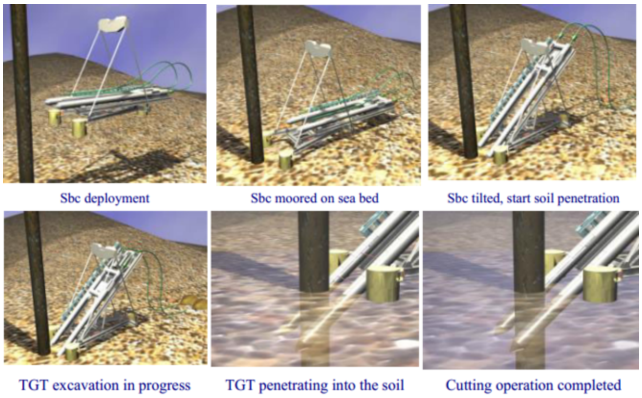


Figure 6.4: Operating Sequences

6.3.3 *Pipe Cutting Tool*

In order to reduce rig time during work-over operations, a new electric line mechanical pipe cutting tool invented by Welltec was designed and tested. This particular mechanical cutter was chosen for its non-explosive design, where a rotating crown removes pipe wall by grinding creating a smooth beveled surface without shavings. This approach made the ability to cut the tubing in compression, without the requirement for the pipe to be put in neutral weight or tension.

A key benefit of mechanical pipe cutters is that they eliminate the use of explosives and chemicals which can pose HSE and operational risks, especially when simultaneous operations are being conducted. In addition, this mechanical solution eliminates the need for dress runs, and tubing recovery is optimized from a rig time perspective. Typically, more than 80% of the pipe wall at the cut must be removed or the rig may be unable to pull the tubing apart, or the pull will prematurely release a packer or other equipment.

The new cutting tools have been operated for the field testing in the Middle East. A series of field testing indicates the tools perform as designed, cutting the pipe on each application with no tool sticking, e-line over-pulls other mechanical problems.

6.3.4 *Plugging and De-oiling*

Conventional methods of decommissioning subsea pipeline infrastructure are inherently very expensive with the mobilization and operation of DSV (Dive Support Vessel), equipment and personnel. In this case the only other viable option was to mobilize a DSV to hot tap the flowlines and circulate fluid from the platform before filling the line with cement. This operation would have incurred considerable expenditure so the operator sought a more cost effective solution (Mackenzie and Jones, 2015).

The solution from Paradigm Flow Services utilized an ultra lightweight, miniaturized coiled tubing system, which was deployable from the platform lower decks with minimal lay-down area required. The system had the ability of traverse multiple bends (360° total), de-oil the line and deliver an expandable cement to plug the pipeline by means of a single operation.

The system had been previously been deployed to remove a 470m sand blockage within a riser and pipeline system from an FPSO in West Africa.

Compared to conventional solutions, the innovative and more cost effective method approach provides an alternative solution for operators to consider when planning pipeline decommissioning. The result of the operation has been outlined as well as the future of this new technology within the decommissioning sector.

6.3.5 External Latch Mechanical for Well Decommissioning

Subsea wells are wells in which the subsea wellhead, Christmas tree and production control equipment are located on the sea bed. At the end of its life cycle, a subsea well and its supporting infrastructure must be carefully dismantled to ensure they pose no safety or environment threats and to salvage useable components. Plug and abandonment (P&A) operation are carried out to close a well either temporarily or permanently. The challenge is to retrieve the wellhead without damage so that it can be used again, minimizing or eliminating damage not only to the wellhead but also to personnel and environment.

There are different methods of severing and removing subsea wellheads. For casing severing, there are explosives severance methods, jet cutting method, and mechanical cutting methods. One such advanced technology system for subsea well abandonment and well suspension, is the external latch mechanical outside single trip (MOST) system which can reduce rig time by cutting and retrieving multiple cemented or uncemented strings in a single trip.

The distinct advantage of the external latch is that it eliminates damage to the internal seal surface of the high-pressure wellhead housing and that it also provides good lateral support for the wellhead assembly thus eliminating any lateral whipping that might impede cutting. Preventing a swarf build-up provides more room for cutting to flow out.

In the Gulf of Mexico, the job was performed in a shallow area (313 ft) with a smaller, inexpensive semi-submersible rig; the well did not require BOP or risers. The production string cuts were done using mud motors since this rig had limited top driver capabilities. The tension cut system offers additional benefits such as where the ocean floor is at an inclination and the wellhead is top-heavy, or the wellhead sticks up higher than normal above the mud-line which could cause the wellhead to list and start the partially cut-section to close in on the knives before the cut is fully severed, a potential additional run can be eliminated by using the tension cut system. The system is currently being used not only in Gulf of Mexico and offshore Australia, but also in other regions such as North Sea, Asia-Pacific region, offshore West Africa, offshore Canada, *etc*.

6.4 Conclusion

The technical evaluation of this field shows that a number of issues require further study such as solid ballast removal techniques, the sealing of conductor penetrations and data delivery in inspection. Such issues would receive the necessary attention during the engineering planning leading up to the inspection, maintenance and decommissioning operation.

The objective of all the technical developments is to reduce the costs in the process of inspection, maintenance and decommissioning of subsea systems. But during subsea structure design for a new project, there is an opportunity to reduce the cost of the operating mentioned above. If the methodology for inspection, maintenance and decommissioning is developed during design, then the design can be amended to ensure that the cost and time for inspection, maintenance and decommissioning is minimized.

7. TECHNOLOGIES FOR HYDRATES AND OTHER SUBSEA RESOURCES

Natural gas hydrate (NGH), ice-like compounds containing methane, which extensively exist in sea-floor, will become an important energy in the future for the fossil fuels owing to the increasing energy consumption. The NGH exists stably in reservoir for the phase equilibrium condition of high pressure and low temperature. The key point of NGH exploitation technology is how to break the phase equilibrium condition destroying the structure of the hydrate and releasing the methane. There are 4 main NGH exploitation technologies widely accepted: depressurization, thermal stimulation, chemical inhibitor and CO_2-CH_4 replacement.

7.1 Depressurization

The technique of depressurization seeks for gas production from NGH reservoirs by lowering the pressure below to the NGH equilibrium pressure at the local temperature. The sustainability of gas production by depressurization depends on the diffusion of pressure, the NGH saturation and effective permeability in the NGHs reservoirs. The latest progress of the technique of depressurization is focused on the numerical simulation aspect.

Konno *et al.* (2016) proposed the cyclic depressurization method. Numerical simulations were conducted and the results shown that gas production rate was high during preliminary stage after primary depressurization; however, the production rate drastically decreased because the sensible heat of the reservoir was exhausted owing to hydrate dissociation.

Yu *et al.* (2017) utilized a one-dimensional mathematical model for methane hydrates decomposition by depressurization in porous media, as shown in Figure 7.1. Ice generation occurred along with the hydrates decomposition process.

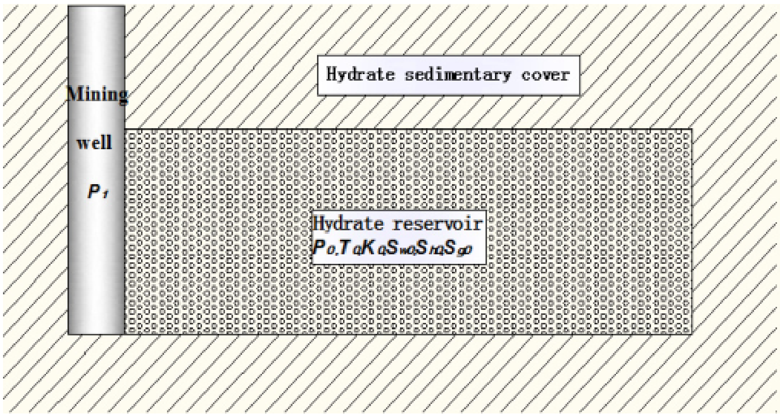


Figure 7.1: Schematic of gas hydrate decomposition by depressurization (Yu *et al.*, 2017)

Zhao *et al.* (2015) analyzed the process of gas production for natural gas hydrate. The methane gas production process can be divided into three main stages: free gas liberation, hydrate dissociation sustained by the sensible heat of the reservoir, and hydrate dissociation driven by ambient heat transfer, as shown in Figure 7.2. Hydrate reformation and ice generation always occur in the reservoir interior due to insufficient heat transfer. The paper found that the sensible heat of the reservoir and ambient heat transfer played a dominant role in hydrate dissociation, and that both were dependent on production pressures.

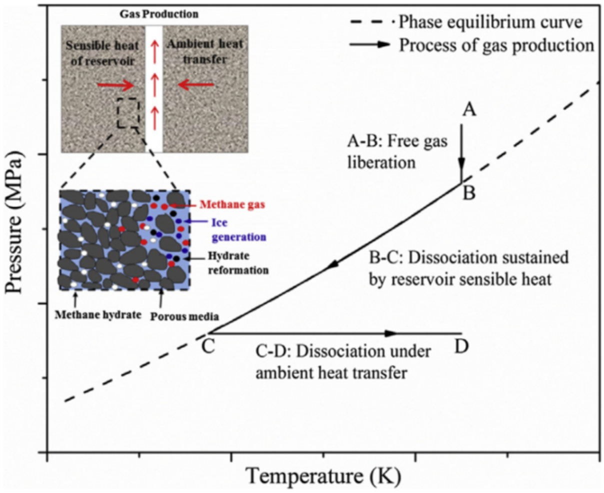


Figure 7.2: Pressure-temperature relationship (Zhao *et al.*, 2015)

Han *et al.* (2017) took siltstone, sand and clay reservoirs in Shenhu area of South China Sea as examples to investigate the effects of the magnitude and anisotropy of reservoir permeability on NGH production process. They found that permeability anisotropy could impede advective interaction of fluids in vertical direction, significantly changing temperature and pressure evolution during NGH dissociation.

7.2 Thermal Stimulation

The local temperature turns to above the phase equilibrium temperature at the local pressure by thermal stimulation, resulting in local NGHs dissociating and natural gases releasing along with water.

Zhao *et al.* (2015) investigated the influence of heat transfer on methane gas production by thermal stimulation. The results showed that during hydrate decomposition, increasing the specific heat capacity of porous media containing hydrate inhibited the gas generation rate.

7.3 Chemical Inhibitor

Chemical inhibitor injection works by shifting the NGH phase equilibrium curve to higher pressure and lower temperature, leaving the NGHs unstable in the local condition of temperature and pressure.

Walker *et al.* (2015) found antifreeze proteins (AFPs) could be effective against structure II (sII) hydrates formed from the liquid tetrahydrofuran, sI and sII gas hydrates formed from single gases, as well as sII natural gas hydrates, as shown in Figure 7.3. For the most part, AFPs were more effective than the commercial kinetic hydrate inhibitor (KHI) polyvinylpyrolidone, even under field conditions where saline and liquid hydrocarbons are present and efforts to overcome the difficulties of recombinant protein production were ongoing.

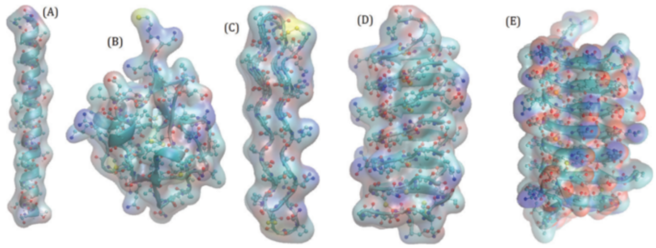


Figure 7.3: AFPs modeled structures, Walker et al. (2015)

Mohamed *et al.* (2017) found new biocompatible gas hydrate inhibitors and tested the gas hydrate inhibition properties of choline acetate (ChOAc), choline bistriflamide (ChNtf2) and choline chloride (ChCl) for methane and a multicomponent Qatari natural gas type mixture (QNG-S1).

Lee et al. (2016) conducted experiments investigating synergetic effect of ionic liquids on the kinetic inhibition performance of poly (N-vinylcaprolactam) (PVCap) for natural gas hydrate formation. The experimental results revealed PVCap and 1-hexyl-1-methylpyrrolidinium tetrafluoroborate (HMP-BF4) showed the best hydrate inhibition effectiveness even under higher pressures, and the combination of 1.0 wt % PVCap and 0.5 wt % HMP-BF4 was found to provide the longest induction time.

7.4 CO_2-CH_4 Replacement

By the CO_2 replacement method, a mutual complementation can be gained between the heat adsorption during the CH_4 hydrate decomposition and the heat release during the generation of CO_2 hydrate. CO_2 hydrate is generated after NGH hydrate decomposition by heat compensation and the secondary hydrate generation can maintain the hydrate reservoir stability.

Khlebnikov *et al.* (2016) proposed a new method combining CO_2 replacement method with thermodynamic hydrate inhibitor technology to accelerate the decomposition of CH_4 hydrate, as shown in Figure 7.4. As a kind of thermodynamic inhibitor for CH_4 hydrate, alcohol showed a more efficient performance than electrolyte.

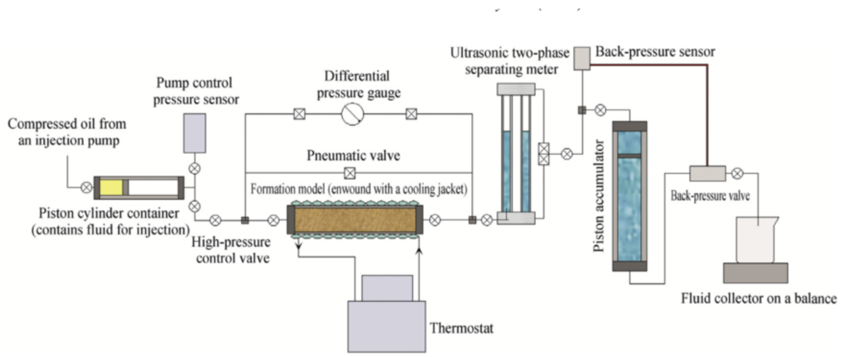


Figure 7.4: Schematic diagram of the experimental apparatus (Khlebnikov *et al.*, 2016)

A novel natural gas hydrate production method combined with methane steam reforming and CO_2/H_2 replacement was proposed to improve the replacement effect and reduce the cost of later gas separation, as shown in Figure 7.5. The experimental results showed H_2 could decrease the partial pressure of methane in gas phase and help to break the methane hydrate stability (Wang *et al.*, 2017).

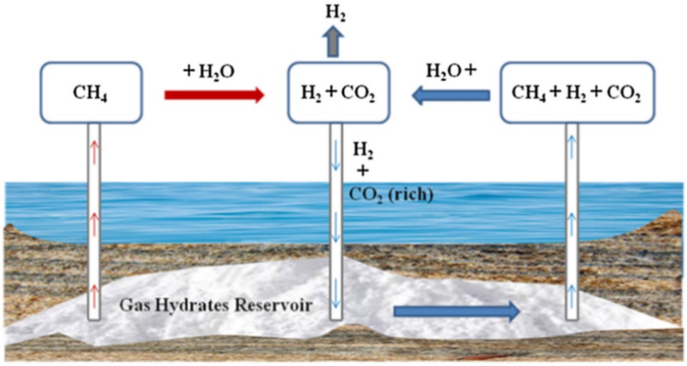


Figure 7.5: Schematic diagram of cyclic hydrogen production from hydrates reservoir (Wang *et al.*, 2017)

8. PIPELINES, RISERS AND UMBILICALS

8.1 Soil-Structure Interaction

8.1.1 Industry Standards

The Addendum 1 of API RP 2GEO 1st Edition (modified from ISO 19901-4:2003) "Geotechnical and Foundation Design Considerations" added a new Section 9 on soil-structure interaction for risers, flowlines and auxiliary subsea structures in October 2014. This section details the recommendations on geotechnical investigation, riser-soil interaction including steel catenary riser (SCR), top tension riser (TTR), riser tower and pipeline-soil interaction.

API RP 17P (identical to ISO 13628-15:2011) "Design and Operation of Subsea Production Systems-Subsea Structures and Manifolds" provides detailed requirements on foundation design for subsea structures, including suction piles, driven piles, skirted structures and non-skirted structures.

8.1.2 Steel Catenary Risers

Riser-soil interaction is one of the major concerns for SCRs design and integrity management as it affects riser strength due to excessive bending and tensile stresses in the riser wall as well as riser fatigue due to cumulative damage to the riser from motion-induced changes in bending stress in the region of the touchdown point.

Clukey and Zakeri (2016) proposed a new non-linear model that considered the soil response for fully-degraded soil based on Zakeri *et al.* (2015) and C-CORE centrifuge results. Yuan et al. (2017) observed the effects of water entrainment and large amplitude cyclic loading in experimental studies.

Model testing for SCR-soil interaction has primary two modules: segment tests and sectional tests. Segment tests are carried out by measuring the response of a moving short pipe section in the soil, such as Aubeny *et al.* (2015) and Yuan *et al.* (2017). Segment tests observe the fundamental soil behavior which is the base of a soil model development. Sectional test simulates the actual SCR configuration by starting a pipe from a point above the seabed to the touchdown zone, for instance the centrifuge tests at C-CORE. The C-CORE test results have been used to validate a fully degraded secant stiffness values based non-linear soil model proposed by Clukey and Zakeri (2016). Three non-linear curves which had slightly higher stiffness values than the curve derived from the segment data provided a very good fit to the measured fatigue data. These curves were then averaged to provide the best overall fit to the results (Clukey *et al.*, 2017).

Consolidation effects have been studied by a number of model tests (Clukey *et al.*, 2017; Yuan *et al.*, 2017). The vertical cyclic motions of a SCR in the touchdown zone (TDZ) induce shearing of the surrounding soil (or soft clays), leading to excess pore pressure building up. The impact of long term consolidation has not been fully resolved, however, it is found that larger numbers of cycles did produce larger initial stiffness values (Clukey *et al.*, 2017).

Field data on SCRs have been collected from a number of real projects, unfortunately none of them are in the public domain. The recent launched STREAM (STeel Riser Enhanced Analytics using Measurements) JIP will use full-scale field data from six deepwater SCR systems to benchmark design, identify gaps and derive calibrated modeling parameters. It is expected that STREAM JIP will provide a measurement-based foundation for SCR modelling to allow for accurate fatigue assessment, especially in TDZ.

Studies were carried out on the trench effect on SCR fatigue damages, such as Clukey and Zakeri (2016), and Wang and Low (2016).However, other recent simulations using different numerical approaches for trench formation for two different SCR systems in different loading conditions showed mixed results. 23 of the 29 cases showed a positive impact on the SCR fatigue lives while only 6 cases showed a negative impact. In addition, centrifuge testing results have shown no impact for a trench to SCR fatigue lives (Clukey *et al.*, 2017).

During the STRIDE JIP, remotely operated vehicle (ROV) surveys of the SCR TDZ in the Gulf of Mexico (GoM) showed the shape and extent of the trench. Consequently, efforts were made to collect other SCR trench videos in GoM and offshore Brazil. The observations showed that the overall trench was shaped like a ladle, with maximum width at the touchdown point typically 5-10 pipe diameters.

8.1.3 Top Tensioned Risers

Top tensioned riser (conductor) design should consider both ultimate and fatigue limit states. Generally, TTR-soil interaction is analogous to that of a laterally loaded pile. Therefore, lateral soil springs provided for offshore piles have often been used for TTR-soil interaction (API RP 2GEO 2014).

However, the soil springs for piles were originally developed for steel jackets subjected to large storm loads. It focuses on the characteristics of the soil near yield, not the soil response at smaller displacement, therefore it is not suitable for TTR-soil interaction.

Procedures in Templeton for developing p-y curves through FEA are recommended by API RP 2GEO. It is also suggested by API RP 2GEO that if the critical bending moments are below the mudline, the curves given by API 2A-WSD, can be initially used. If the critical fatigue point is above the mudline, the p-y curves given by API 2A-WSD, can be non-conservative. For a drilling riser with heavier lower stacks (LMRP, BOP), using stiffer soil (or fixed at mudline) does not guarantee the results to be in the conservative side even if the critical fatigue point is above the mudline (API RP 2GEO).

8.1.4 Hybrid Riser Systems

There are a number of possible foundation options for the subsea hybrid riser system (HRS): gravity base, suction caissons and driven piles. The selection of the HRS foundation is normally based on technical and economic criteria, soil properties, installation methods, as well as the in-place performance of HRS.

The design guidance of driven piles and gravity base is given in API RP 2T (2015) and the design guidance of suction caissons is provided in API RP 2SK (2015) with the considerations of the following aspects:

- penetration and retrieval
- holding capacity including long-term uplift capacity
- long-term displacement
- soil reactions to be used for the structural design

ABS Guidance Notes on Subsea Hybrid Riser Systems also provides detailed guidance on the design and analysis of foundation piles for HRS based on industry common practices (ABS, 2017).

8.1.5 Pipelines

More complex pipeline-soil models are developed in the recent years, especially in SAFEBUCK JIP. Either upper or lower bound values of the pipe-soil interaction forces can be critical for a limit state, therefore each bound should be assessed as recommended in API RP 2GEO.

SAFEBUCK GEO is a JIP dedicated to pipe-soil interaction during lateral buckling, running alongside SAFEBUCK III. The numerical pipe-soil interaction model developed in SAFEBUCK GEO considers pipe embedment, axial pipe-soil interaction, and lateral pipe-soil interaction. Centrifuge tests were conducted at the University of Western Australia to calibrate the numerical results. FEA were also carried out to supplement the centrifuge data and provide the relationship between forces on the pipe and pipe movement (Atkins, 2015 and Rismanchian, 2015).

COFS-MERIWA JIP focuses on the simulation of slide runout and the assessment of the resulting loading and deformation of seabed pipelines. The JIP worked on slide-pipeline interaction with regard to the following aspects (White *et al.*, 2016):

- characterization of soils at the solid-fluid transition
- computational modelling of slide runout – via depth-averaged and continuum finite element methods
- physical and numerical modelling of slide runout and pipeline impact
- analytical studies of pipeline response during slide loading.

He summarized the recent advances in the pipeline-soil interaction from late 1990s to 2017. The review covers submarine slide, pipeline embedment, axial and lateral pipe-soil interaction, scour and self-burial et al. (White *et al.*, 2017).

8.2 Local/Global Buckling and Propagation

Subsea pipelines buckle globally because of their movement relative to surrounding soil. Global buckling is often triggered by high operational temperature of the oil in pipelines, initial imperfections in the pipeline, and/or a combination of both. Global buckling is increasingly difficult to control due to the increase in temperature and pressure. Therefore, location prediction and buckling control are critical to pipeline design.

Liu *et al.* (2014) proposed four numerical simulation methods based on finite element method (FEM) program ABAQUS to simulate pipeline global buckling under different temperatures. An analysis method based on modal analysis that introduces initial pipeline imperfection is also presented to analyze thermal buckling in an initially imperfect pipeline.

Liu *et al.* (2014) introduced energy method to get the analytical solution suitable for the global buckling modes of idealized subsea pipeline and analyze the relationship between the critical buckling temperature, buckling length and amplitude under different high-order global lateral buckling modes. To obtain consistent formulation of the problem, the principles of virtual displacements and the variation calculus for variable matching points are applied.

Experimental and finite element results for buckle interaction in subsea pipelines are presented by Hassan and Albermani (2014). The effect of linear and clad materials on the effective axial force has been determined by analytical deduction. It was concluded that it is important to include the effects of the linear or clad materials in the effective axial force.

Wang *et al.* (2015) studied static and dynamic analysis on upheaval buckling of unburied subsea pipelines. Two analysis procedures are proposed for different stages in buckling. Procedure 1 links Newton- Raphson and arc-length method. Procedure 2 links static and dynamic nonlinear analysis seamlessly which effectively solves the convergence problem when dealing with snap buckling.

Using a preheating method combined with constraints from two segmented ditching constructions which are scheduled before and after preheating, Zhao and Feng (2015) proposed an upheaval buckling solution for high temperature subsea pipelines. In this solution, some selected pipe segments along the route were curve-laid and preserved resting on the seabed in the first ditching construction, while other straight segments were trenched. The subsequent hot water flushing operation induced the curve-laid segments to buckle on the seabed, and then these pre-buckles were laterally constrained by the second ditching operation carried out during preheating. After preheating, the cooling rebound of these pre-buckles was constrained by the new trenches, and axial pretension was induced in the pipe wall to offset the axial compression in service and upgrade the thermal stability of the entire pipeline.

Zhao and Duan (2017) proposed an upheaval buckling prediction approach for high-temperature Cased Insulated Flowlines (CIFs). Based on the tensile cracking and compression crushing analyses of the CIF concrete-weighted coats, the curvature-related nonlinear bending stiffnesses of CIF systems are discussed firstly and a changeable stiffness is included in this buckling prediction approach developed using a transfer matrix method. Using the approach developed, the field-joint stress of a CIF carrier pipe and the interlayer shear forces of the CIF pipe coats can be obtained along the buckling path of the CIF systems by plotting the relationship curves between the carrier pipe axial forces and the CIF buckle lengths.

Zeng *et al.* (2014) noticed that the upheaval buckling pipelines have some different approximation formulas for the critical buckling axial forces. However, these formulas did not take into account of the imperfection out-of-straightness (OOS) as a whole. Based on dimensional analysis and finite element (FE) analysis some brand new formulas were presented for the critical upheaval buckling forces for three typical imperfections, which could be used to estimate the critical forces of the imperfect pipelines quickly. Meanwhile, Zeng and Duan (2014) investigated the laterally buckling behavior of partially embedded submarine high pressure and high temperature (HP/HT) pipelines. They modeled the lateral buckling pipeline by an axial compressive beam supported by lateral distributing nonlinear springs. It is found that the model is governed by a time-independent Swift–Hohenberg equation and that the equation's localized solutions are corresponding to the different buckling modes of the pipelines. Based on numerical results the range of the possible critical axial forces was found out and two critical axial force formulas corresponding to the range boundaries were presented..

Zhang and Duan (2015) studied the upheaval buckling behaviors of eight groups of pipeline segments with different imperfection shapes and different out-of-straightness using the finite element method. A new parameter is defined to express the differences of imperfection shapes. An approximation and universal formula is proposed to calculate the critical axial force which covers the new parameter and the out-of-straightness of pipeline.

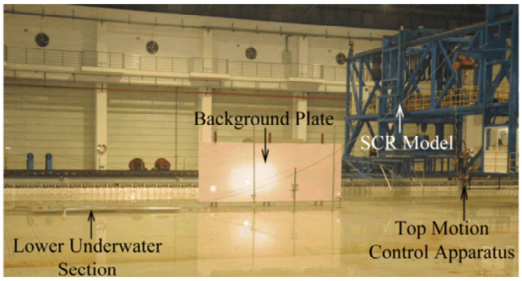
Wang *et al.* (2017) proposed a new nonlinear pipe-soil interaction model and deduced the governing differential equation of an imperfect pipeline on soft foundation. The solution to the governing differential equation is proposed based on nonlinear perturbation expansions. The effect of soil conditions, burial depth and initial imperfections on critical force as well as localization pattern of upheaval buckling are discussed.

Zhang *et al.* (2017) proposed a new lateral pipe-soil interaction model. Three dimensional Finite Element Models are built to simulate the lateral buckling and post-buckling. The effects of pipe-soil interaction parameters, initial imperfection shape and out-of-straightness of pipe on critical buckling force and localization patterns of lateral buckling are discussed.

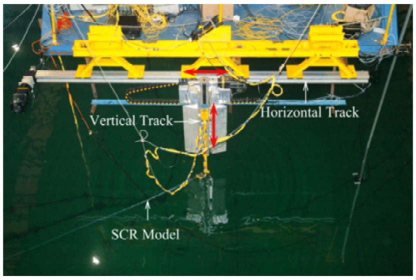
8.3 Vortex Induced Vibration of Cylindrical Structure

Novel model tests on the riser dynamic response under vessel motion have been performed for the steel catenary riser (SCR) by Wang et al. (2015), the water intake riser (WIR) by Wang et al. (2016), the steel lazy wave riser (SLWR) by Cheng et al. (2016) and the free-hanging drilling riser (FHR) by (Wang et al., 2017) recently. A representative experimental setup is demonstrated in Figure 8.1, concerning a large-scale SCR model test under vessel motion. The top end of the SCR is connected to the forced motion system, which simulates the vessel motion time histories. The riser dynamic response is measured by a large amount of Fiber Bragg Gratting (FBG) strain sensors and several underwater cameras. The main contribution of these work is the discovery of out-of-plane VIVs induced by purely in-plane vessel motions, termed as vessel motion-induced VIVs. Vessel motion-induced VIVs were recognized to have greatly amplified the riser fatigue damages compared with the global dynamic response under vessel motion, and would lead to more fatigue damage than steady ocean flow induced VIVs (Wang et al., 2014). These new findings indicated the necessities of including vessel motion-induced VIVs during the riser deign, which is yet to be implemented into the design standards (DNV, 2014). With further experimental investigations, they found some more novel phenomena of VIV under oscillatory flows: unsteady VIV with three developing stages steps of “building up - locking in - dying out”, hysteresis of motion trajectories, and VIV could occur even when the KC number is down to 20 (Fu et al., 2014).

Shur and Strelets (2015) used SRANS method to simulate incompressible flow past a circular cylinder, with a simple and generic geometry. They found by introducing Vortex Generators (VG), flow separations of smooth bluff bodies were significantly delayed together with a substantial decrease of the pressure drag force (up to 60%) of the bodies in the transcritical flow regime. Chen and Gao (2015) also used the RANS method to simulate the VIV of an inclined cable under wind with varying velocity profiles, and found the cable undergoing single-vibration mode with small velocity changes, and multi-vibration modes with large velocity changes.



(a)



(b)

Figure 8.1: Vessel motion-induced VIV modet test of a SCR at SJTU (Wang et.al., 2015)
(a: overview of the experimental setup in air; b: overview of the top motion apparatus)

Quadrante and Nishi (2014) studied the effect of tripping wires on the vibration of a circular cylinder subject to flows. They placed a pair of tripping wires on to the surface of a circular cylinder symmetrically about the stagnation point, and submerged the cylinder clamped or elastically mounted. They determined the angular positions giving the maximum and minimum of the hydrodynamic force. The experiments on the cylinder demonstrate that the presence of tripping wires remarkably alters the response of VIV. In particular, for β=120 degrees, the VIV is completely suppressed throughout the reduced velocity range tested.

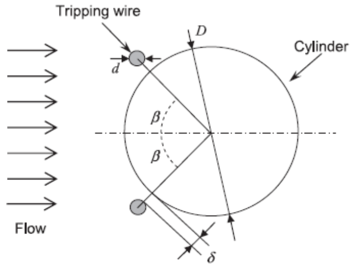


Figure 8.2: Cross section of cylinder and tripping wire (Quadrante and Nishi, 2014)

Chen and Gao (2015) designed four perforated pipes with different numbers of suction/jet holes, as shown in Figure 8.3.

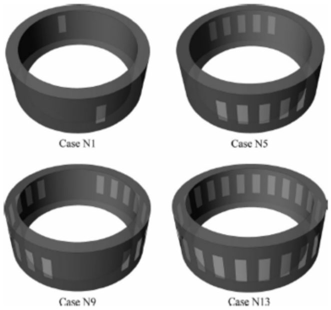


Figure 8.3: Schematic drawing of the passive jet control pipe units (Chen and Gao, 2015)

N represents the number of suction/jet holes on each side of the pipe, the pipes were put around a circular cylinder suffered from incoming air flow. It was found that the passive jet control method is very effective in manipulating the wake vortex shedding process from the circular cylinder. The perforated pipe designs with more suction/jet holes were found to be more effective in reducing drag and suppressing fluctuating amplitude of the dynamic wind loads acting on the test model. The periodicity of the vortex shedding was also observed to be diminished and eventually disappeared with the number increase in the suction/jet holes.

8.4 Dynamic Behavior and Fatigue

Very recently, there have been some studies on the development of fast and reasonably accurate methods for long-term fatigue analysis of risers, spurred by its practical importance.

Song *et al.* (2016) attempted to systematize the blocking method by proposing an approach to determine the equivalent wave height, wave period and probability of occurrence for each block. Giraldo *et al.* (2015) investigated the asymptotic approach for a riser suspended and moored by chains, using time domain analysis. The highly efficient asymptotic approach is found to be generally quite accurate for this application. Giraldo *et al.* (2016) proposed to use the univariate dimension reduction technique, testing it on a steel lazy wave riser (SLWR). This approach requires only 21 stochastic dynamic simulations, and appears to give a reasonable estimation of the long-term fatigue damage. One of its main advantage is that the integration points are pre-determined, and the results are applicable to any stress location. Gao and Cheung (2015) proposed a response surface approach for fatigue analysis of a flexible riser in the time domain. Five environmental parameters were considered, namely the significant wave height, wave period, wave direction, wind velocity, and current.

Methods have also been proposed to improve the efficiency of Monte Carlo simulation. Such methods have the advantage of producing an unbiased estimate of the fatigue damage, and allowing an error estimate. Gao and Low (2016) developed an efficient simulation method based on importance sampling, applying the method on unbonded flexible risers. Low (2016) proposed a variance reduction technique based on control variables. This method has the advantage of being a post-processing scheme, allowing the fatigue damage to be evaluated at multiple stress locations using the same set of simulation results.

Wang and Duan (2017) proposed a 2D nonlinear dynamic model for steel lazy wave riser (SLWR) based on Euler-Bernoulli beam theory with initial conditions and boundary conditions under top excitations considering the effect of ocean current and internal flow. Keller Box finite difference scheme was adopted to solve the partial differential equations and numerical analysis is conducted to investigate the influences of tangential and normal excitations on the dynamic response of SLWR.

Researchers have also explored the use of artificial neural networks (ANN) to reduce the amount of nonlinear time domain simulations required for a full fatigue analysis of moorings and risers. Christiansen (2015) proposed an algorithm to optimize the training procedure, and applied it on mooring lines; however the approach is equally appropriate for risers. Aguiar *et al.* (2015) implemented ANN for fatigue analysis of a buoy support riser, while Chaves *et al.* (2015) used ANN to analyze the bending stiffener of a flexible pipe. In the above mentioned studies, ANN is found to be a promising approach for substantially reducing the computational effort while maintaining an acceptable accuracy. However, further studies are still required to determine whether ANN is sufficiently robust to be used in a wide range of riser systems, for example the highly nonlinear touchdown region of a steel catenary riser.

8.5 Special Issues for Flexible Pipes and Umbilicals

Installation of flexible pipes and cables is normally carried out in the J-lay mode. The wave induced vessel motions give rise to dynamic tension and curvature at the touch down zone (TDZ) limiting the weather window within witch the installation operation can take places. Commonly used acceptance criteria during global installation analysis are the minimum radius of curvature and (API 2014) and the common practice of not allowing compression to occur. An important question for the industry in later years has been whether effective axial compression can be allowed at TDP during installation of umbilicals and power cables. If this can be allowed, the current practice of not allowing compression can be relaxed which will have a direct economic benefit with respect to the installation costs. However, there are several issues that relates to the interaction between local instability of individual helix element and global torsion instability modes, which are not yet fully understood and need to be resolved.

As flexible pipes are normally installed in empty condition, a high external pressure in combination with the empty bore will introduce a large compressive end cap force. This means that the load condition that might lead to kink formation is fundamental different between flexible pipes and umbilicals. For the flexible pipe, local instability can occur even if the cross-section is in effective tension. The global configuration is stable; however, due to local buckling effects resulting from true wall compression, a condition of torsion unbalance occurs gradually by cyclic curvature until severe torsion deformation forces a kink to be formed. This requires either full scale testing or coupled numerical models that are capable of describing the coupling between local lateral transverse helix buckling and global behavior, (Sævik, 2014) and (Zhou *et al.*, 2014), to determine the capacity.

For the umbilical case, due to the lack of an empty bore, local instability cannot occur unless the effective axial force is in compression, which means that the global configuration already might not be stable. The structural analysis model can then in first instance be assumed uncoupled and governed by the global behavior. This is then followed by component capacity checks, which for the case of axial compression also must include the local helix instability modes that include both lateral transverse helix buckling and bird-caging as for the flexible pipe case.

Kink formation might, however, occur even if the effective tension is positive, depending on the amount of torque in the catenary. This will again be influenced by a range of parameters such as the catenary length (water depth), cross-section torsion balance, seabed routing, vessel heading and motions, seabed friction and built-in torque from the manufacturing and installation procedures. If kink formation occurs, permanent deformations in terms of residual curvature will occur due to the friction between the layers, i.e. the friction moment effect. Then any attempt of straightening the kink may result in severe curvatures that may destroy the cross-section components. Neto and Martins developed an FE model based on a geometric exact beam element formulation and addressed the issue of kinking of an elastic cross-section during deep water installation (Neto, *et al.*, 2014). They investigated the effect of the tension distribution and seabed friction on the critical torsion moment with reference to the Greenhill equation for a straight beam. On the basis of the same installation parameters, Koloshkin (2016) addressed the effect of the friction moment and vessel motion, concluding that this significantly influenced the critical torsion moment. A standard Euler-Bernoulli co-rotated beam elements was successfully applied to address the torsion stability problem. The concept of a critical curvature parameter associated to kink formation was also proposed to address the issue during installation analyses. Then Neto *et al.* (2015) developed a finite element procedure describing self-contact as a result of extreme torsion deformation. Good correlation with test data was obtained.

More focus is, however, needed to address the amount of torque that actually occurs during an installation scenario as this governs the amount of tension (or compression) that can be allowed for a given installation scenario.

For deep-water flexible pipes, bird-caging is a limiting factor in addition to lateral transverse helix buckling and associated global instability. Ebrahimi *et al.* (2016), addressed radial buckling of tensile armour wires numerically by developing a 3D FE model in ABAQUS and used this to study the effect of external/internal pressure and pipe damage. Then, Rabelo *et al.* (2015) investigated the role of local shell buckling in the external polymer layer and established a simple criterion for bird-caging, based on the yield stress of the external polymer layer. The criterion was assessed analytically, numerically and experimentally, and compared well with previous experimental observations. Sævik and Thorsen (2017) proposed a simple analytical model considering the interaction between yield stress, elastic buckling and tape/polymer layer yield failure where good correlation with test data was found.

Collapse of flexible pipes is a complex phenomenon that is influenced by the support from all cross-section members. Normally, the pessimistic approach is taken that the external polymer layer is broken such that the carcass is exposed to the full external pressure. Then the pressure spiral layers will act as an additional support leading to a constrained instability mode. Chen *et al.* (2015) proposed an analytical approach for assessing the collapse strength of an unbonded flexible pipe, taking the pressure armour support into account. The results were compared with FEM and experiments proving the analytical model to give conservative results when the radius/thickness ratio was large. Bai *et al.* (2016), studied confined collapse of an unbonded multi-layer pipe subjected to external pressure including the contact/support effect from surrounding layers. They proposed an analytical model where the support effect was included in terms of springs and applied both FEM and experiments to validate the model.

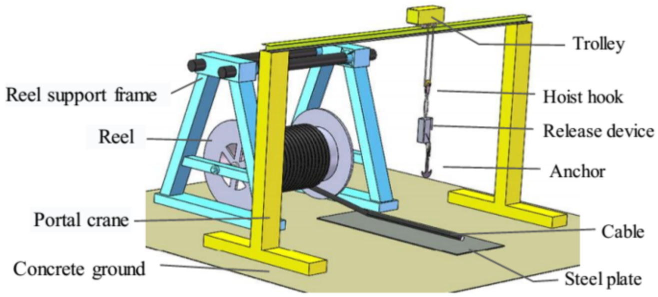
Wang and Duan (2014a, 2014b, 2015a, 2015b, 2015c) have done comprehensive researchers on the mechanic performance and installation analysis on the steel lazy wave riser (SLWR).

The governing equations which consist of conventional small deformation beam theory for the portion of pipeline lying on the seabed, coupled with a large deformation beam theory for the suspended section are established. The deepwater steel lazy-wave riser configuration with ocean current and internal flow in the process of abandonment, recovery and transfer during installation are researched. These are all based on the static analysis. And in the dynamic analysis, a 2D nonlinear dynamic model for SLWR based on Euler-Bernoulli beam theory with initial conditions and boundary conditions under top excitations considering the effect of ocean current and internal flow are proposed. Keller Box finite difference scheme was adopted to solve the partial differential equations. It is an alternative solution for the SLWR dynamic response besides the FEM.

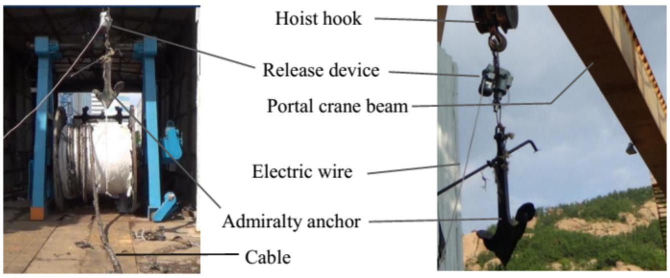
Kang *et al*. (2017) investigated the sealing design of connector at the end of the flexible jumper pipes. The theoretical relationship between the sealing contact load and the amount of compression was obtained from the contact model among the lenticular gasket ring and hubs on the basis of Hertz contact theory. Taking the requirements for sealing and strength into consideration, a design principle for the lenticular gasket structure is proposed to determine the limits of the amount of compression. Finally, an analytical equation for calculating compression limits is developed. The contact model is verified by utilizing the finite element method.

Drumond *et al*. (2018) presented a literature review on failure events experienced by the industry concerning pipelines, risers, and umbilical cables, describing their causes, consequences, and severity. With regard to floating risers, approximately 85% of them are of flexible type. Although flexible risers may fail in different ways, collapse due to external pressure is reported as the most frequent failure mode. For umbilical cables, the major failure modes are found to occur under tension or compression, torsion, fatigue, wear and sheaving.

Gao and Duan *et al.* (2018) designed a test setup to study the structural deformation and resulting performance degradation of photoelectric composite cable impacted by dropped anchors. The nonlinear dynamic finite element model was developed and verified by the tests.



(a) Schematic diagram of test setup



(b) Real photos of test setup

Figure 8.5: Impact test setup (Gao and Duan *et al.*, 2018)

They presented a parametric analysis of different impact directions and impact velocities. The permanent indentation of armor layer increases with falling height, obviously with increase tendency slowing down. From the initial collision contact, the indentation grew with time to its maximum, until the anchor stopped. The anchor began to bounce back under the action of contact reaction force. And the armor layer also partially restored and vibrated with decreasing magnitude, because of energy dissipation by interface friction, leaving some permanent indentation. As falling heights increase, the differences between maximum indentations diminished gradually. And the cable sooner ceased vibrating, especially at higher collision speed.

Zhang et al. (2017a) investigated the sealing design of connector at the end of the flexible jumper pipes. The theoretical relationship between the sealing contact load and the amount of compression was obtained from the contact model among the lenticular gasket ring and hubs on the basis of Hertz contact theory. Taking the requirements for sealing and strength into consideration, a design principle for the lenticular gasket structure is proposed to determine the limits of the amount of compression. Finally, an analytical equation for calculating compression limits is developed. The contact model is verified by utilizing the finite element method.

9. RELIABILITY AND SAFETY IN SUBSEA SYSTEM

9.1 Introduction

The exploration and production of oil and gas resources entail a variety of risks, which, if not adequately managed, have the potential of resulting in a major incident. A recent accident is the Deepwater Horizon drilling rig explosion and oil spill of 2010, which indicate the importance of improving the reliability and safety of the subsea system. This report presents the advances and developing of reliability and safety in subsea system, including the standard, methodology, database and software, which may be referenced by the researchers and engineers related.

9.2 Reliability and Safety Engineering Standards

9.2.1 Standards and Codes for Safety and Reliability of Subsea System

Throughout the 1900s and the early 2000s, there are a number of standards and codes concerning the reliability and safety of subsea system, as presented in Figure 9.1. Along with the development of new technologies and the increase of the occurrence frequency of accidents, particular concerns are raised regarding the reliability and safety of subsea systems achieved by targeted reliability and integrity strategy for large, high risk subsea development projects. These standards and codes aim to provide a common language and approach to the management of safety, reliability and integrity, that subsea projects could accept as recommended practice and guiding documents which would be used to achieve higher levels of safety and reliability performance. In response to these demands, a number of well-known organizations and institutes such as API, DNV and ISO have released a range of standards and codes related to the reliability and safety of subsea system.

The main standards and codes and the timeline are given in Figure 9.1. From the timeline, there are two versions of API RP 17N, three versions of DNV RP A203, and the DNVGL RP 0002 was released in November 2014 after DNV and GL merged into DNVGL. Hence, it is attempted to reflect the advancement of standards and codes through comparison.

9.2.2 Update in the Newer Version of API RP 17N

The first edition of API RP 17N mainly focuses on production reliability and availability and the management of risks to reliable production performance but very little about integrity, and the guidance related to the operation stage was very limited. In consideration of these

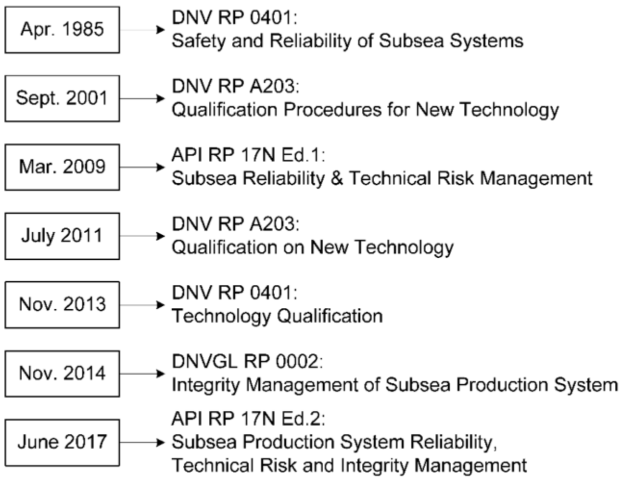


Figure. 9.1: Main standards and codes for subsea system

limitations of the 2009 edition, the updated edition of API RP 17N include the incorporation of integrity management, the inclusion of human factors, the subdivision of life cycle and the extension of the reliability assurance cycle, and these changes make the API RP 17N to has a wider industry implication.

9.3 New progress on reliability and safety evaluation of subsea systems

Several new progresses on reliability and safety evaluation of subsea systems have been reported recently. Various methodologies were developed to analyze and evaluate the reliability and safety of subsea system. The following parts address some cases.

A fatigue reliability analysis of dented pipeline subjected to internal pressure load has conducted by Garbatov (2017). Based on limited experimental data, different failure criteria considering the dent size and applied load are analyzed and reliability as a function of number of load cycles is defined.

Rowland (2014) studied the effects of systematic faults in the development phase of a safety instrumented system, especially the relation between systematic faults and operational common cause failures.

Failure Elimination and Prevention Strategy (FEPS) was designed to prevent failures and improve the reliability of valves and the overall reliability of Wet Christmas tree. Ellen *et al.* (2014) presented and discussed analytical approaches that can be used to quantify the PDF_{avg} of a specific HIPPS implementation, and to study how the various input parameters influence the value of the PFDavg.

Pearse (2014) focused on the financial impacts of subsea equipment failure and how real time data improves subsea equipment availability.

Anietie *et al.* (2014) focused on subsea tree-mounted electro-hydraulic (E-H) SCM responsible for the underwater control of oil and gas production.

Bailey (2014) utilized some of recent extensions of standard Cox formulation to analyze components of ESP systems where multiple competing risks from individual components exist (intra-component correlations, intra-installation correlation and time-dependent explanatory variables). These model extensions utilize a more involved analysis undertaking and demand some careful preliminary data treatment. The work illustrates the concept of time-dependent competing risks with an example of an individual component, a specific motor, from its first deployment and subsequent re-deployments in different ESP system in a systematic and unbiased manner.

Liu *et al*. (2015) published a monograph related to reliability modeling and evaluation methodologies of subsea blowout preventer systems. For improving the accuracy of reliability evaluation, some important factors and actions, such as common cause failure, imperfect coverage, imperfect repair and preventive maintenance were considered.

Blount (2015) described the optical fiber "health" monitoring program, reviewed case histories, emphasized the importance of this diagnostic information, and monitoring program, review case histories, emphasized the importance of this diagnostic information, and summarizes developments to improve FO system reliability.

Cai *et al.* (2015) proposed a real-time reliability evaluation methodology by combining root cause diagnosis phase based on Bayesian networks and reliability evaluation phase based on dynamic Bayesian networks. The application of the proposed methodology was demonstrated using a case of a subsea pipe ram blowout preventer system. A novel fault diagnosis methodology of non-permanent faults including transient faults and intermittent faults for the control system of subsea blowout preventers were also developed by the same authors (Cai *et al*. 2017), increasing the reliability of subsea system greatly.

Okaro *et al*. (2016) proposed an enhanced Weibull-Corrosion Covariate model for reliability assessment of a system facing operational stresses. The newly developed model was applied to a Subsea Gas Compression System planned for offshore West Africa to predict its reliability index.

Choi *et al*. (2016) proposed the concept of subsea production systems with a seabed storage tank to provide an alternative to conventional floating facilities and performs the reliability, maintainability and availability study for the seabed storage tank. The reliability assessment of the seabed storage tank performs a four-step procedure by using fault tree analysis. The four-step procedure is to define the system boundary, collect the reliability data, construct a fault tree and estimate the reliability. Reliability of the seabed storage tank was estimated with a consideration of critical events.

Low *et al.* (2016) developed a joint probability density function of the variables based on experimental data. A new fast reliability approach is proposed for the VIV fatigue reliability analysis, while Monte Carlo simulations are performed for comparisons. Case studies of a vertical riser in a uniform flow show that the proposed method compares favorably with Monte Carlo in terms of predicting the failure probability as well as safety factors conforming to prescribed reliability levels. Moreover, this study reveals that the randomness of wake coefficients leads to large variability in the riser fatigue damage. The correlation between the coefficients should be properly incorporated as it affects the fatigue reliability of risers experiencing VIV.

Dave (2015) presented an overview of the development and implementation of a Topsides safety and control system to mitigate the risk of a downhole caprock breach in the BC-10 Phase 2 waterflood development.

Cai *et al.* (2016) developed a novel safety integrity levels (SILs) determination methodology based on multiphase dynamic Bayesian networks for safety instrumented systems of subsea systems. Proof test interval phase and proof test phase are modeled separately using dynamic Bayesian networks, and integrated together to form the multiphase dynamic Bayesian networks. The proposed model solves the problems of binary variable constraint and state space explosion of traditional methods, is considered to be important supplements to the calculation methods of international standard IEC61508. The target failure measures, that is, probability of failure on demand, average probability of failure on demand, probability of failing safely, average probability of failing safely, and SIL of safety instrumented systems operating in a low demand mode, are evaluated using the proposed multiphase dynamic Bayesian networks.

Akyuz (2016) performed a comprehensive human reliability assessment during cargo operations of a mooring unit to enhance maritime safety in off-shore units. The paper prompts a methodological extension of human error assessment and reduction technique by incorporating interval type-2 fuzzy sets which overcome more of the uncertainty of experts' judgement and expression in decision-making. In 2014, United States Department published NTL to authorize the use of the Barrier Concept as the basis for using alternate procedures or equipment in the safety systems for subsea production operations and to clarify the differences between topsides and subsea production operation.

Zhang et al. (2017b) presented the possibilities of success or failure in the installation process of subsea collet connector. Risk matrix method is adopted to analyze the risk of installation failure event of subsea collet connectors. Accurate values of occurrence probabilities and impact levels of risk factors must be provided in traditional risk matrix analysis, while risk factors in the installation process of subsea connector are lack of these data. To solve this problem, the authors introduced expert evaluation and fuzzy theory into risk matrix analysis. And finally, a fuzzy risk matrix analysis method is put forward. Based on the fuzzy risk matrix method, the offshore installation trial of a subsea connector is guided and conducted successfully.

Li *et al*. (2018) proposed a computational framework to calculate the reliability of subsea pipelines subjected to a random earthquake by using subsea simulation, which is an advanced Monte Carlo simulation approach. This framework takes full account of the physical features of pipelines and the earthquake, and also retains high computing precision and efficiency.

10. CONCLUSIONS AND RECOMMENDATIONS

Subsea production system is a relatively new concept developed from difficulties and cost effective strategies in moving to deeper waters for oil and gas. The emerging problems quite different from shallower waters have been challenging the industry to improve both the reliability of the SPS and the service life of all the hardware, and to reduce the CAPEX/OPEX by managing the risk and safety of the system. The technological progresses are characterized by requirements for severe service, multiphase processing, high reliability and low-maintenance solutions. This report reviews the recent advances of the past years in subsea technology area including subsea processing equipment, flow assurance, key components fabrication, qualification testing, installation and operations for emergencies, inspection and maintenance, hydrate exploitation, flowlines and umbilicals, reliability and safety.

The following recommendations are made for future work in the area of innovative technology in the subsea industry.

•It is confirmed that All-Electric Subsea complies with or even exceeds current safety and reliability requirements. CAPEX and OPEX savings have been identified for application of the All-Electric subsea production system while more efforts shall be made to improve the maturity of the AES.

•Efforts are recommended to develop new multiphase compressor system which enables gas compression directly from the well stream without upstream separation, and will be an attractive technology to increase the recovery factor for remote gas field to make gas fields development more profitable.

•New strategies are necessary to simplify the system design, installation and intervention to reduce weight and cost of subsea boosting systems, which is promising for brownfield application.

•Innovative material technologies have cost-efficient potential to be utilized to deal with the flow assurance issues such as remediation of wax deposits or hydrate inhibition in deep-water and long subsea tiebacks.

•Condition and performance monitoring offers critical real-time data to the operator which can avoid unplanned shutdowns saving expenses in lost production and ensuring system integrity. More efforts should be conducted to develop monitoring system to gain feedback on the mechanical fitness, electrical condition and operating performance of subsea rotating machinery such as subsea pumps, boosting and compression systems.

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