Development and Qualification of a Subsea 3,000 Barrel Pressure Compensated Chemical Storage and Injection System

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Abstract

This paper presents important findings while executing a detailed qualified design of a large (3,000 + barrel), subsea (to depths of 10,000 fsw) production chemical storage and injection system. The design drivers for the system were safety first, extensive utilization of existing commercially available equipment / tools / methods, and a re-usable shuttle system that allows for delivery of production chemicals as a service versus the current approach where an operator / owner makes a capital investment. The system is designed to be compatible with existing production chemical formulations and features multiple barrier design between the chemicals and the environment. Placement of the storage and injection system directly on the seafloor in close proximity to the point of need eliminates expensive chemical umbilicals, removes significant topside chemical storage and injection kit weight and space requirements at host facility and isolates hazardous chemicals from platform workers. The re-deployable shuttle economically allows inspection, repair and maintenance to take place quayside with the ability to upgrade equipment as technology progresses and / or quickly and cost effectively adjust to ever-changing field requirements.

Subsea wells have been proliferating over the last decade with ever-longer tie-backs to enable commercial recovery of small resource pools that are unable to support a traditional floating system development. Virtually all wells, especially subsea, require various volumes and types of production chemistries during their operational life. For subsea wells, the incumbent technology is chemistry delivery via umbilicals. In rare occasions, small volumes are sometimes delivered via single trip, disposable containers, principally during intervention activities. As tie-back distances have increased, so have the technical challenges with their attendant mushrooming costs. These challenges include the needs for; special corrosion resistant materials, resistance to high pressures differentials, material flexibility and ‘crimp – resistance’, and long term reliability. Additionally, some of these chemicals are high viscosity and as the tie-back distances increase, so does the pressure drop of the flowing fluids. In some cases, the risks of plugging and the magnitude of the delta-pressure drop in ½” – ¾” chemical tubing within the typical umbilical can preclude tie-backs of long offsets from the host / hub facility.
The subject system overcomes many of these challenges by locating a large, pressure compensated storage and injection facility directly on the seafloor in close proximity to the point of need, thus qualifying it as enabling technology for extra-long tie-backs and enhancing technology for short tie-backs, de-bottlenecking, or early production system usage.

Introduction

Overview.

Virtually all wells require various volumes and types of production chemistries during their operational life. This is particularly the case with subsea wells. Figure 1 is a photo of a hydrate plug being removed from a flowline. Many flow assurance experts (Koh, 2015) (Volk, 2008) have declared hydrates to be the number one problem with flow assurance; they are costly to prevent and to remove and pose safety concerns (Figure 1).

Of course in-situ deposition of paraffin and asphaltene, along with corrosion effects can also cause significant problems. Onshore, chemical treatment companies frequently maintain local storage near the wellhead and can readily and at low cost refresh supplies via truck delivery. Offshore, the logistics / supply chain is much longer, more complex and costly. Starting at quayside, chemicals are loaded onto supply boats that then transport offshore to the destination platform. Then rigging is hooked up to the chemical containers and cranes are utilized to hoist on deck and position into place chemical transportation totes. Alternatively, in some situations hoses and pumps are utilized to transfer the chemicals from boat to platform deck (Figure 2). From the storage systems, chemicals are then pumped to point of consumption subsea via complex and expensive umbilicals. As reliable and constant supply of chemical often means the difference between production and shut-in wells, large stocks of chemicals are frequently kept on hand; taking up expensive platform space and creating additional personnel exposure risks.

Figure 1: Hydrate plug removed from gas pipeline offshore Brazil, courtesy of Petrobras
Figure 2: The journey of production chemicals from quayside to subsea wells

The vision of project success:

- Safe and Environmentally friendly
  - Dual barrier chemical containment
  - Order of magnitude lower number of installation days (compared with numerous smaller containers)

- Low cost (operating and capital)
  - Low cost installation vessels of opportunity (vessels of opportunity to deploy / recover); anchor handlers / tugs
  - Short duration for installation; minimize weather-window risks
  - “Redundancy” and safe-guards designed in

- High availability and reliability
  - Common Off The Shelf (COTS) technologies
  - Shorter design life; lower costs & simpler design
  - Systems approach; fleet of shuttles to service a region

The business drivers for development of this game-changing solution were to develop a safe and environmentally friendly method of supplying production chemicals to long offset subsea wells, too deep and too far offset to be supplied by umbilicals. Additionally, the technology has applications to supplement existing umbilical solutions which may be undersized due to; a) ‘missed’ original estimates in well requirements, b) changing reservoir production characteristics, c) further field delineation d) damaged / fouled / corroded / plugged tubes within an umbilical. The subject solution may enable development of smaller satellite fields that cannot bear the complexity, cost (Operations – ‘OPEX’ and Capital – ‘CAPEX’), and operational risks associated with a traditional system. The solution may also enable early production from exploratory wells in advance of full field sanction when umbilical purchase and installation could be delayed until full field assessment and / or development is complete. Additionally, the technology could prove useful with support services for subsea construction, commissioning, and decommissioning and for use in well containment / spill response activities.
System differentiators for the subject project versus other industry efforts are presented below (Figure 3).

- Large volume (3000 bbls) vs multiple small (30 - 200 bbls)
- Low-cost vessels of opportunity vs massive derrick barge
- Safe & environmentally friendly
  - SIGNIFICANTLY less marine ops (comparable volumes)
  - Dual barrier containment

Figure 3: System differentiators

Size of the prize, tie-back of long offset subsea wells.

DOE’s Energy Information Agency (EIA) has developed data that shows that while ‘small’ fields are by definition small, the very large number of small fields can contribute significantly to the overall resource base – if they can be economically developed. It is likely that more of these ‘small’ fields will be developed with subsea wells and tied back to production / surface hosts. (Figure 4).

Figure 4: Undiscovered Resource Base by Field Class size

Work done by Knowledge Reservoir, LLC funded by RPSEA and the DOE (Knowledge Reservoir, 2007) shows that 20% of the Original Oil In Place (OOIP) is contained in 80% of the number of reservoirs, meaning there are many small reservoirs containing the remaining oil (Figure 5). The clear takeaways:

1. There are a very larger number of smaller resource pools that in aggregate represent a significant resource
2. New game-changing technology and business practices will be required for cost effective development.

![Figure 5: Cumulative % of Neogene OOIP vs. cumulative number of reservoirs](image)

**Description and Function of Major Systems**

The project was divided into four major systems, and integrated by system interface management to achieve project goals. The Stage 1 report provides the design basis that carries through to work described herein as well as trade-off studies with other alternative approaches (Chitwood, 2015). The “Shuttle” was developed to provide for reliable and reusable transport for the payload from the dock to its subsea worksite and back. Its design is based upon compliance with various applicable industry codes, guides, rules and regulations including ABS rules and guidance. In the subject work, the payloads are the Subsea Chemical Storage System (SCSS) and the Subsea Chemical Injection Unit. The SCSS (base case) consists of three (3) 1,100 bbl chemical storage bladders which are contained within pressure compensated steel containers. These 3 individual bladders may hold a common chemical or they may each hold a different chemical depending upon the field’s flow assurance needs. Bladder designs and materials have been tested and qualified for use with seven different production chemicals. The Subsea Chemical Injection Unit (SCIU) mainly consists of Common Off The Shelf (COTS) components but does leverage some existing technology (commercially proven topside methanol pump) via a marinization qualification program to meet industry needs subsea. Transportation, installation and recovery include all ROV subsea interfaces during intervention and deployment operations. The shuttle design has been through an extensive set of Computational Fluid Dynamics (CFD) exercises and demonstrates good stability and maneuverability within expected installation conditions. Additionally, the systems have been subjected to Design; Failure Mode, Effects and Criticality Analysis (DFMECA) and the identified risks have been determined to be within acceptable limits. A companion paper, OTC-Number-MS presents in detail the Shuttle marine operations which are summarized below.

**Shuttle.**

The Shuttle’s function is to deliver production chemicals from dockside to the ocean floor / point of use and return to dockside; all in a safe, reliable, repeatable and economic fashion. It is designed to
deliver a net volume of 3,000+ bbl of any of several production chemicals. All of these chemicals are in use today, but are classified as hazardous from a regulatory point of view. Hence the Shuttle is specifically designed to ABS Rules for Hazardous Cargo Barges and Emerging Technologies. The Shuttle includes a double hull providing isolation and protection to the SCSS.

The Shuttle is of standard steel construction with four columns protruding above the deck (Figure 6). The four columns are internally fitted with flotation elements, thereby raising the underwater center of buoyancy above the unit’s vertical center of gravity. This configuration will provide stability during the lowering and raising of the Shuttle through the water surface and while transiting through the water column across a wide range of met-ocean conditions (Cooper, 2014). The current design water depth is 5,000 feet with the intention of additional future validation to allow for use in water depths up to 10,000 feet.

Figure 6: Shuttle showing Subsea Chemical Storage System payload of 3 x 1,100 barrel chemical bladders

**Hull Design.**

The structure of the barge is designed to ABS Steel Barge Rules to provide the basic structural design. Global bending and shear strength was checked to ABS Steel Barge Rules for Stillwater bending and shear stresses and to ABS Steel Vessel Rules less than 90 meters for wave loading. Global bending and shear strength in both the longitudinal and transverse directions were analyzed for shear and bending when the Shuttle is fully submerged. The column design was analyzed to verify that they have sufficient strength to support the shear and bending moment that would occur in the worst case scenario that the submerged barge should take an attitude of 90 degrees in the transverse or longitudinal direction. The column design was also checked for wind loading to ABS MODU Code. Buckling checks were applied in plating where there was any potential for buckling. Note that the double-sided and double-bottomed hull provides protection for the bladder and contained chemical in the unlikely event of a collision or grounding accident.

**Topsides.**

Sufficient clear deck space and structural support is provided for topside payload / equipment. The Shuttle is designed to carry up to 60,000 lbs. of topside equipment. This load is assumed to be within an 8’x 8’ x 20’ ISO module frame but could be varied depending upon need. The Shuttle also has the ability to attach a small (<200 bbl) deck tank to store low volume use chemicals. This tank is assumed to be an 8’ x 8’ x 40’ module that, when submerged, is almost neutrally buoyant. One, two, or more of these deck tanks (depending on size/volume and chemical specific gravity) may be installed and recovered with the Shuttle. Alternatively, the deck tanks may be installed post Shuttle deployment with the Shuttle as a foundation.

**High Pressure Buoyancy Design.**
To provide buoyancy for the Shuttle, carbon fiber cylinders are utilized. These provide the most efficient and cost effective buoyancy for deeper water depths. Per the manufacturer the cylinders have a working pressure of 3,626 psi and a max fill pressure of 4,714 psi, thus allowing the future possibility of using this buoyancy technology in 10,000 feet water depth applications. These cylinders have already been certified by ABS, in conjunction with the U.S. DOT, for the transport of compressed natural gas (CNG) on U.S. highways.

For application in the Shuttle, the cylinders will be filled with nitrogen, as opposed to air, to avoid any potential risks of using oxygen under high pressure. As the Buoyancy Cylinders expand radially and longitudinally when pressurized, they are supported on their ends. One end is fixed while the other end is only supported perpendicular to the cylinder’s longitudinal axis to allow longitudinal growth or contraction of the cylinder in different pressure environments (Figure 7).

**Figure 7:** High pressure composite buoyancy cylinders

**Water Column Transit System.**

A system of polyrope, chain and connectors are utilized in the Shuttle deployment and retrieval process. Unlike a traditional platform mooring system, the chain in the Shuttle system is used for weight and control, not for ultimate strength. The chain is a standard 3” Stud Chain with 600’ of deployable chain on each end of shuttle with a total net submerged weight for both at 88,000 lbs. Standard shackle and padeye connections common in mooring systems are used. Winches are used to deploy or to pull these chains aboard the Shuttle during operations. The Chain Catenary serves two functions;

1. Disconnects or decouples the motion between shuttle and surface vessel
2. Allows the mass of the shuttle to be adjusted during transit through the water column to control ascent/descent speed

Additional discussion is included in the transportation, deployment and retrieval section.

**Winches.**

The Shuttle design is equipped with a winch on both its forward and aft ends. The winches are capable of handling the free hanging submerged weight of 600 feet of 3” studded chain (51,000lbs dry). The winches are powered using a hydraulic stab from either the ROV or the work boat. As a typical work class ROV is rated between 150 and 250 HP, and the maximum capable output is 85% of these values; the winches are designed for a maximum power supply of 127 HP.

**Foundation / Securing to Seafloor.**

Using soil data for the Gulf of Mexico (Fugro, 2014), the on bottom condition of the Shuttle was analyzed to determine if some form of mechanical anchoring, such as pin piles, were needed to prevent current forces from moving the Shuttle on the seafloor. Analyzed against the maximum current speed of 2.43 knots (1.25 m/s) – (velocity corresponding to the topographic Rossby waves generated by a 100-year event for a Gulf of Mexico installation in 5,000 feet of water), CFD analysis determined that no equipment such as pin piles or shear skirts are necessary.
**Piping Systems.**

The Ballast System piping runs are specified to fully flood all of the Shuttle’s compartments to submerge the Shuttle below the water’s surface. Pipe and valves are sized to provide a controlled rate of sinking while minimizing pressure head on the tanks. Remotely operated (design completed for both hydraulic and electric) gate valves are specified for ballast hull penetrations to allow positive closure of compartments during surface transit.

All compartments are fitted with vents sized to prevent buildup of internal pressure due to the maximum filling flowrate. Each vent is fitted with a closure valve to allow compressed air to be used to deballast the compartment once the shuttle is recovered to near the surface.

Piping for the cargo system is to be kept to a minimum. The cargo piping system consists of a universal flanged connection at the deck to allow flexibility in pipe size depending on the chemical being used and its desired flowrate.

**Instrumentation.**

The design includes instrumentation for monitoring the condition of the Shuttle and its various systems (i.e., valve positions, roll and pitch of Shuttle while submerged, cylinder pressure, etc.). Instrumentation between the Shuttle and process systems will interface through a “standard” interface flange and port through which all required process instrumentation may be added and linked back to the SCIU controls. Not all instrumentation will be remotely reported back to the hub facility. ROVs can observe valve positions, pressure gauges, etc. The system is to be kept simple, maximizing use of a ROV (or AUV) for data collection. Remote Instrumentation will be limited to items that require real time information and / or control.

**Four (4) Phase Computational Fluid Dynamic (CFD) Study.**

A four (4) phase CFD study was conducted to thoroughly investigate the Shuttle’s stability across a wide range of conditions (Figure 8). CFD was used to explore operational boundaries of the submerged Shuttle in ways that are not possible with physical wave tank models. Operating limits were 2 knot currents from any direction and vertical transit speeds (up or down) of 0.5 knot while under full position control of the two surface vessels using the shuttle chains.

<table>
<thead>
<tr>
<th>Phase</th>
<th>CFD Setup</th>
<th>CFD Results</th>
<th>Status</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steady Flow Analysis</td>
<td>Overturning Forces</td>
<td>Complete</td>
<td><img src="image1" alt="Steady Flow Analysis" /></td>
</tr>
<tr>
<td>2</td>
<td>Forced Shuttle Motions</td>
<td>Damping of Shuttle Motions</td>
<td>Complete</td>
<td><img src="image2" alt="Forced Shuttle Motions" /></td>
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<tr>
<td>3(^1)</td>
<td>Free Rotation of Shuttle</td>
<td>Evolution of Shuttle Forces</td>
<td>Complete</td>
<td><img src="image3" alt="Free Rotation of Shuttle" /></td>
</tr>
<tr>
<td>4(^4)</td>
<td>Full Ascent</td>
<td>Full System w/ Lowering Lines</td>
<td>In Progress</td>
<td><img src="image4" alt="Full Ascent" /></td>
</tr>
</tbody>
</table>

\(^1\) = Laminar Flow physics (still have viscosity)

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**Figure 8:** A set of comprehensive CFD studies were conducted across a wide range of potential conditions.
Answers to key questions:

- Will the Shuttle remain stable? Yes, the Shuttle remains upright while submerged in swift currents and does not require lowering lines to remain in acceptable catenary.
- Will shuttle rotate? How much? Results show negligible rotation. Lowering lines only control position, Shuttle stays upright during transit to/from seabed.
- The shuttle is highly damped subsea and consequently will not flutter (oscillate) during installation. The damping further enables seafloor positioning of the shuttle with projected good performance.

DFMECA – Design; Failure Mode, Effects and Criticality Analysis of the Shuttle Design.

A DFMECA and API RP 17N Technology Risk and Readiness Assessment was performed by the contractor group and then subjected to third party review. Each Component of each system was given a Technology Readiness Level (TRL). The TRL numbers range from 0 for an unproven concept with no analysis or testing having been performed, to 7 for a routine field proven system. The system was then assigned a TRL number based on the lowest number from each of its components (Figure 10).

The shuttle’s TRL analysis was a natural extension of the API methodology when it was used to review the shuttles structural design and was used to evaluate the required marine operations for deployment and recovery of the shuttle. The SCIU and shuttle equipment analysis was a direct application of the API TRL methodology as applied to equipment or kit. This TRL analysis quickly identified where the maturity of the facility equipment or processes were less mature.

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Ref Dwg No.</th>
<th>TRL of Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1</td>
<td>Steel Piping</td>
<td>B1228-1-506-001</td>
<td>6</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Flanges</td>
<td>B1228-1-506-001</td>
<td>6</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Gate Valves</td>
<td>B1228-1-506-001</td>
<td>6</td>
</tr>
<tr>
<td>2.1.4</td>
<td>Pressure Relief Valve</td>
<td>B1228-1-506-001</td>
<td>6</td>
</tr>
<tr>
<td>2.1.5</td>
<td>Hydraulic Actuator</td>
<td>B1228-1-506-005</td>
<td>6</td>
</tr>
<tr>
<td>2.1.6</td>
<td>Compressed Air Connection</td>
<td>B1228-1-506-005</td>
<td>6</td>
</tr>
</tbody>
</table>
Additionally, for each component in the design, a probability of failure and consequence of failure analysis was made. These attributes were then characterized at different levels as shown in the figure below (Figure 11).

The two scales together form a risk matrix, as follows:

<table>
<thead>
<tr>
<th>Probability:</th>
<th>Consequence:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlikely</td>
<td>Minor</td>
</tr>
<tr>
<td>Remote</td>
<td>Moderate</td>
</tr>
<tr>
<td>Occasional</td>
<td>Significant</td>
</tr>
<tr>
<td>Frequent</td>
<td>Severe</td>
</tr>
<tr>
<td>Very Frequent</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

- Never heard of in the Oil & Gas Offshore Industry (but still is a possibility).
- Heard of in the Oil & Gas Offshore Industry (unlikely but has still happened to others).
- Incident has occurred in Company Operations.
- Incident has occurred several times a year in Company wide Operations.
- Happens several times a year at an individual asset.
- Less than $100,000: Insignificant damage to plant and equipment.
- $100,000 - $1,000,000: Limited damage to plant and equipment.
- $1,000,000 - $10 million: Significant damage to local area or essential plant or equipment.
- $10-100 million: Damage extending to several areas/significant impairment of installation / equipment integrity.
- >$100 million: Severe and extensive damage to plant and/or total asset loss.

Figure 10: Example of Technology Readiness Level (TRL)

Figure 11: Probability – consequence matrix used in DFMECA

Failure Mode, Effect, Indicators etc. were defined for each system in the spreadsheet excerpt shown below (Figure 12).

Consequence and probability are assigned for each component and provided a Risk Color per the matrix shown earlier. Below is an example (Figure 13).
The DFMECA results indicate there are no unmanageable risks within the design. A peer level review of the results of the analysis is scheduled after the submission of this paper.

Class Society; Approval in Principal.

While not complete at the time of submission, the design validation process includes Class review for Approval in Principal (AiP) for the Shuttle Design. The AIP is an intermediate approval step to provide proof of feasibility to project partners and regulatory bodies. It is a statement of fact that a proposed novel concept or new technology complies with the intent of the most applicable ABS Rules and Guides as well as appropriate industry codes and standards. It may also include an Approval Road Map which defines a list of submittals necessary to be completed in later phases of the project in order to obtain full Class approval.

Subsea Chemical Storage System – SCSS.

Design.

The Shuttle is designed to carry an array of chemical cargo. Three 1,000-barrel net (1,100-barrel gross) separate cargo cells allow the delivery of multiple chemicals from the same Shuttle. The chemicals are contained within a flexible Product Bladder that is supported by the walls of the cargo cells. The maximum allowable cargo cell pressure is a 10 psi differential and the working differential pressures are to be held below 5 psi. The average cargo density range is from 0.79 to 1.025 Specific Gravity (SG.) Examples of chemicals that meet this are as follows:

- 100% Methanol (0.79 SG)
- 100% LDHI (0.98 SG)
- 67% Monoethylene Glycol, 33% Methanol (average 1.0 SG) where the different chemicals are held within separate tanks.

The Product Bladders of course ‘collapse’ as the chemical is pumped out. Depending upon the SG of the chemical, the Product Bladder can either collapse ‘up’ or ‘down’ as shown below (Figure 14).
Engineered flexible materials have been utilized in numerous applications, from consumer products, aerospace and defense. Below it can be seen on an amphibious assault boat capable of traversing very challenging beach landing environments (Figure 15). For decades, engineered fabrics have also been utilized for inexpensive fluid storage in remote and harsh environments, though mainly in land-based applications (Figure 16). The flexible Product Bladders specified for the subject design have been engineered to be fit for purpose and for specific chemical use with both the material manufacturers and Product Bladder fabricators, and then validated with third party testing (Figure 16 is an example of bladder testing for previous applications).

Double containment for the Shuttle is achieved through the use of a double bottom and wing tanks in way of the cargo spaces, i.e., the Product Bladders. To prevent contamination of the seawater in the hold surrounding the Product Bladder, a containment system with an Expansion Bladder will be used as described below.

**General concept, pressure compensation with flexible bladders subsea.**

At the beginning of deployment (Figure 17), the Expansion Bladder is void of air and liquid and
the valve leading to it is closed. The seachest valve is open and the isolation valve is closed. The check valve allows seawater to enter the Bladder Cell to compensate for compression of the chemical and seawater in the compartment as the ambient water pressure increases during descent.

During the discharge (production) (Figure 18) of Chemical the check valve also allows seawater to enter the Bladder Cell to displace the discharged Chemical. When the Shuttle is ready for recovery the seachest valve is closed and the valve to the Compensation Bladder is opened. As the liquid inside and surrounding the Chemical Bladder expands it fills the Compensation Bladder. For in-situ refilling (Figure 19) the isolation valve is bypassed to allow seawater to flow out of the Bladder Cell while the Chemical Bladder is filled. During all phases a contamination sensor monitors the water surrounding the Chemical Bladder for any possible leaks.

During discharge, the annular space around the Product Bladder will be progressively filled with sea water. The hull provides a containment barrier (double on bottom and sides) in the event of a bladder leak. Seawater is now allowed to flow into the annular space as the liquid inside the Bladder Cell compresses or the cargo is dispensed. However, an inline check valve prevents the seawater from leaving the Bladder Cell in case there is any contamination, providing additional barrier to chemical leakage.

For recovery (Figure 20) the seachest valve is closed and a valve leading to an Expansion Bladder is opened. The Expansion Bladder is located outside the Bladder Cell in the wing space of the barge. The Expansion Bladder is void until the valve leading to it is opened. As the liquid in the Bladder Cell expands during recovery it flows into the Expansion Bladder.

Figure 17: Deployment configuration

Figure 18: Seafloor installation, during discharge (production of chemical)
Figure 19: *In-situ refill configuration*

Figure 20: *Recovery to surface configuration*

**Chemical / fabric third party validation.**

A very important performance aspect of the system is the long term integrity of the Chemical Bladder. Early in project execution a series of qualification tests were developed to ensure adequate validation of chemical compatibility as well as proper examination of other mechanical and physical attributes. One of the project’s cost share partners provided results of their testing (done for other purposes) to help winnow the potential combinations. Additionally, the Chemical Bladder fabric manufacturers and product fabricators (two groups, one utilizing a plastic base material and the other an elastomeric material) also brought their extensive research and development and field experience to the project design. The project is design qualified for methanol and Low Dosage Hydrate Inhibitor (LDHI), but several additional chemicals were examined for potential utilization including; Scale Inhibitor, Corrosion Inhibitor, Asphalten Inhibitor and Dispersant. Of course in all cases there was need for compatibility with Seawater. Project validation work is planned to confirmed suitable materials and design / fabrication for field use.

**Scale Model Test Apparatus.**

In addition to chemical – fabric compatibility, the geometries and physics of Product Bladder collapse (production) and expansion (fill) are important for a number of reasons. While it is very difficult to ‘get the last drop’ out of the Product Bladders, efforts have been made to reduce the non-producible volume of chemical which in essence ‘goes along for the ride’. The main point of the Scale Model Test Apparatus was to investigate bladder performance at the boundaries of expected conditions, chemical volume removal and fill operations, operation on surfaces up to 5-degree slope and looking for any mechanical component interferences. The system layout is shown below (Figure 21). Construction of the 1/5th scale apparatus was underway at time of submission.
The SCIU is simply stated a pump(s), controls, instrumentation, sensing and metering equipment packaged together as a unit that takes suction from the SCSS (Chemical Bladders) and then pumps (or depending upon pressure differentials) allows chemical to flow to the point of use. Specifically, a design has been qualified for two (2) major scenarios; one for methanol injection during which large volumes of methanol are quickly pumped during well transition conditions (start-up, shut-down). The other scenario is for Low Dosage Hydrate Inhibitor (LDHI) in which chemical is continuously injected (in small volumes). Additionally, the SCIU design has the capability to inject other chemicals such as corrosion, asphaltene and scale inhibitors that may be used at lower rates. The injection system might also be configured to inject large volumes of dispersant if there is a need.

Pipes and related equipment such as flanges, valves, and connectors are required to be rated to 10,000 psi. The piping systems are designed and specified in accordance with API RP-1111 Recommended Practice for Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design). According to API RP-1111 section 2.1.7 (c), injection lines are covered by this code. Design pressure, burst pressure, allowable incidental overpressure, and test pressure are defined by this code. In compliance with this code, lower pressure rated portions of the overall unit are protected by high-pressure shutdown or pressure relief devices. The valves can be actuated either by an ROV (or AUV) or with electric actuators.

The SCIU is mounted to the shuttle such that it can be removed entirely and replaced subsea without having to move the Shuttle. Critical equipment sparing was specified to help ensure overall reliability. If the existing Christmas Tree subsea umbilical can supply the required power, then this is the
preferred option because of minimal added cost. The small power demands, a few kilowatts total for all continuous chemical injection, will likely mean that LDHI and other continuous low-dosage chemical injection can be powered using power which is available in-situ. The much higher power demand for methanol injection, several hundred kilowatts to supply a 3 bbl / minute flowrate may make the use of available installed power a challenge. Depending on the installation, it is likely that additional power will need to be supplied to the SCIU, using one of the options below.

**Subsea Power Umbilical from fixed existing surface assets.**

A new subsea umbilical can be deployed, which provides one or more of the following:

- Electrical Power
- Communications
- Low Pressure Chemical Resupply

This umbilical, while expensive, would be less expensive than a conventional umbilical which needs to supply all of the above and several chemical types.

**Subsea Power Umbilical from a new surface buoy near the drill center.**

A power-producing buoy, for example a diesel generator, can be located at the surface above the drill center, providing continuous electrical power over a shorter and thus less expensive umbilical.

**Subsea battery storage.**

For Methanol the required power is large but for a short amount of time. Subsea batteries (Figure 22) can be stored near the SCIU and trickle charged from a small umbilical. Subsea battery storage is not required for LDHI injection due to the continuous nature of the power demand.

![Figure 22: Subsea pump and battery package utilized on similar project](image)

**Leveraging existing Common Off The Shelf Technologies.**

At the conclusion of the SCIU design program it was determined all of the necessary components are commercially available and qualified for design service (Figure 23) with one exception. The singular exception is the methanol pump. The limiting factors are the 10,000 fsw and the low viscosity of methanol. A surface pump that has been proven with hundreds of thousands of hours of high reliability service with methanol was selected for adaptation to subsea use. Working closely with the manufacturer a Cost, Time and Resources (CTR) has been constructed to guide marinization and qualification for this project. Under this CTR, considerable design and engineering work has been accomplished, including design of a pressure compensating enclosure and pairing with an equally suitable electric motor.
A six-well configuration with individual jumpers to each well was selected for development as it is the most complex arrangement (Figure 24). Figure 25 depicts the LDHI configuration. A similar configuration will be utilized for other low dosage chemicals such as corrosion inhibitors, biocides, asphaltene inhibitors, demulsifiers, scale inhibitors, etc. Some installations may only require a single large chemical jumper to a subsea facilities existing chemical distribution system while others would have several pumps and umbilicals pumping different chemicals at different flow rates simultaneously.
In summary, via a detailed sweep across numerous manufacturers it was determined that existing, field proven kit can be integrated together to produce a fully qualified system to meet project design conditions – with the exception of the high pressure methanol pump, for which a detailed CTR has been developed and the initial stages already completed to close that single gap.

**Transportation, installation & recovery**

Design and simulation studies, supplemented with an industry Subject Matter Expert (SME) populated Qualitative Risk Assessment (QRA) followed with a Design; Failure Mode, Effects and Criticality Analysis (DFMECA) have validated the features and functional performance for installing and recovering subject facilities (~1,000mT). It is also instructive to point out that with minor engineering, similar procedures would be suitable for the cost effective installation and recovery of other large and heavy subsea facilities.

The business driver to mature this technology is the operational cost savings that is achieved by using two anchor handling vessels of opportunity for operational support. Conventional operations would employ heavy lift vessels, with their full spread costs at nearly an order of magnitude higher, plus mobilization and de-mobilization costs and time delays. In addition, the same installation spread is capable of recovering the installed facilities should facility repair, maintenance or refurbishment be required. This feature allows the payload owner to basically design for a much shorter design life and/or to take advantage of technology improvements during the life of the field.

Thus, the potential exists for this deployment technology to create an environment for game changing conditions impacting the architecture, installation and maintenance of major subsea installations as the technology is matured and field utilized. The project has recently completed detailed system design and CFD verification. This significant development project is being monitored and advised by industry representatives through the active representation of operators, service companies and OEMs participating in the project’s technical advisory committee and through the significant contribution of data and expertise. Below is a short summary of the operation as the details of the topic are the subject of OTC-26904-MS; A New Subsea Large Load Deployment System

**Concept of Operations.**
The deployment methodology developed utilizes a two vessel deployment system as shown below in Figure 26. The two primary vessels will likely be anchor handler vessels with stern rollers or vessels with stern A-frames. The Shuttle system will be set up with fixed flotation/buoyancy modules, which remain fixed on the Shuttle. The Shuttle will be configured at about 20-30mT positively buoyant during subsea descent. A pair of catenary chains connected from the primary deployment vessels to the shuttle system will provide additional ballast for submersion of the positively buoyant Shuttle system. This will allow for a catenary decoupling of the primary vessels from the Shuttle system mass (including “added-mass” effects). The catenary chain section provides self-compensating shuttle system descent and load control as the Shuttle system’s buoyant properties continually auto balances with the chains’ catenary mass. This allows more flexibility with vessel selection, not requiring large costly vessel(s) for shuttle system deployment. The recovery operations are basically the reverse of deployment.

![Figure 26: Shuttle deployment utilizing two anchor handling vessels of opportunity for operational support](image)

**Marine Summary.**

Based on single line hoisting loads with the expected mass of the payload shuttle system, a decoupling method is required. Otherwise, single vessel crane size requirements would become cost prohibitive and vessel of opportunity limiting. De-coupling through the use of a catenary arrangement is ideal for large payload deployment and multiple vessel deployment is ideal for shuttle system positioning during subsea land-out and recovery near subsea infrastructure.

Positively buoyant shuttle system is the most manageable configuration with catenary line loads from the anchor handler vessels. Fixed buoyancy in/on the shuttle system is necessary to help neutralize the shuttle’s steel weight in water, payload weight in water, and ancillary equipment weight in water. Variable buoyancy or ballast in/on the shuttle system is necessary to aid with deployment and recovery of the varying payload specific gravities.

While actual deployment and recovery of the subject Shuttle have not been performed to date, all of the individual marine operations required have been safely performed in numerous other projects. The combination of the four (4) phase CFD study and a comprehensive DFMECA, and peer level review of the same give good confidence of marine and economic success.
Conclusions

Leveraging work provided as cost share by DeepStar™ and thanks to funding from National Energy Technology Laboratory (NETL), United States Department of Energy through the Research Partnership to Secure Energy for America (RPSEA), a detailed qualified design of a large (3,000 + barrel), subsea (to depths of 10,000 fsw) production chemical storage and injection system has been successfully developed. The design makes extensive use of existing commercially available equipment, tools, methods, and features a re-usable shuttle system that allows for delivery of production chemicals as a service. Mid-project, Qualitative Risk Assessments (QRAs) with some 50+ SME participants – recommended proceeding with no ‘un-manageable’ risks identified. Just completed are DFMECAs on the Shuttle and transportation systems and a separate DFMECA on the chemical storage and injection equipment. Peer reviews are scheduled, as is a validation test via a Scale Model Test Apparatus.

CFD analysis has demonstrated the Shuttle system to be easy to maneuver with stability and predictable performance during both installation and recovery operations. ABS Approval in Principle (AiP) is planned to be conducted in February / March 2016. Additionally, 4 US patents plus European equivalents have been filed with 2 US patents having been issued. A summary report will be presented in the summer of 2016 and will be made available via RPSEA as well as from the authors.

In a low product price environment, there is an even greater need to develop and commercialize a game-changing solution to radically reduce costs while properly managing risks. These chemical systems developed provide an enabling solution where significant off-set distances and high injection pressures into subsea wells is not possible with conventional umbilicals and an enhancing solution in other situations such as early production and where existing umbilicals may be damaged and / or undersized. Additionally, as the equipment is designed for cost and time effective recovery and redeployment, it can be relocated from field to field as needed and therefore can be provided as a service with an operating expense fee, saving the field owner the usual and costly capital expense associated with this activity.

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research universities, five national laboratories, other major research institutions, large and small energy producers and energy consumers. The mission of RPSEA, headquartered in Sugar Land, Texas, is to provide a stewardship role in ensuring the focused research, development and deployment of safe and environmentally responsible technology that can effectively deliver hydrocarbons from domestic resources to the citizens of the United States. Additional information can be found at www.rpsea.org.

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