ADVANCED PRODUCED WATER TREATMENT

1ST ANNUAL UPSTREAM ENGINEERING AND FLOW ASSURANCE CONFERENCE

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

ADVANCED PRODUCED WATER TREATMENT

APRIL 2, 2012

HOTEL OF AMERICA, HILTON, HOUSTON, TEXAS

AUTHORED AND PRESENTED BY TIM DAIGLE

CO-AUTHORS BRIAN PHILLIPS, SAVANNA HANTZ, RAFIQUE JANJUA

FLUOR OFFSHORE SOLUTIONS
# TABLE OF CONTENTS

## 6.0 STATE OF THE ART REVIEW OF PRODUCED WATER TREATMENT TECHNOLOGIES

- 6.1 Produced Water Sources and Constituents ................................................................. 6
- 6.2 Produced Water Separation and Treatment ................................................................. 8
- 6.3 CONVENTIONAL OIL AND GREASE REMOVAL ...................................................... 8
  - 6.3.1 Separator ................................................................................................................. 10
  - 6.3.2 Filtration .................................................................................................................. 11
  - 6.3.3 Hydrocyclone ......................................................................................................... 13
  - 6.3.4 Gas Flotation ......................................................................................................... 14
  - 6.3.5 Membrane Filtration .............................................................................................. 14
  - 6.3.6 Other De-Oiling Technologies ................................................................................. 15
- 6.4 Best Available Technology for Produced Water Treatment ....................................... 23
  - 6.4.1 Treatment Methods for Constituents ....................................................................... 25
  - 6.4.2 Vendors .................................................................................................................. 29
  - 6.4.3 Oil in Water Monitoring Techniques for Produced Water Treatment Systems ........... 29
- 6.5 Pictorial History Of Seabed Processing ...................................................................... 43
- 6.6 Installed and Planned Subsea Separation Systems ...................................................... 45
  - 6.6.1 Introduction ............................................................................................................. 45
  - 6.6.2 Troll C Subsea Separation System ............................................................................ 46
  - 6.6.3 Petrobras Marimba - VASPS Prototype .................................................................... 50
  - 6.6.4 Statoil Tordis - Subsea Separation Boosting and Injection (SSBI) ......................... 52
  - 6.6.5 Shell Parque das Conchas (BC-10) .......................................................................... 55
  - 6.6.6 Shell Perdido - Gulf of Mexico ................................................................................. 56
  - 6.6.7 Total PazFlor Subsea Separation System ................................................................. 57
  - 6.6.8 Petrobras Marlim Subsea Separation System ......................................................... 58
  - 6.6.9 Petrobras Congro, Malhado & Corvina ................................................................. 59
  - 6.6.10 Petrobras Canapu .................................................................................................. 60
  - 6.6.11 Multiple Application Re-injection System (MARS) ............................................... 62
- 6.7 Subsea Separation, Oil/Solid Removal from Water and Other Related Technologies Under Development ........................................................................................................... 63
  - 6.7.1 Aker Solutions DeepBooster with Subsea Separation .............................................. 63
  - 6.7.2 Alpha Thames Subsea AlphaPRIME Incremental Field Developments - KeyMANTM .... 64
  - 6.7.3 Cameron Subsea Compact Electrostatic Separator ................................................... 68
  - 6.7.4 Cameron Two-Phase and Three-Phase Compact Subsea Separators ....................... 69
  - 6.7.5 FMC InLine Electrocoalescer .................................................................................. 69
  - 6.7.6 FMC InLine DeWaterer .......................................................................................... 70
  - 6.7.7 GE Nu-Proc Test Separator with Electrostatic Coalescer ........................................... 71
  - 6.7.8 Saipem Subsea Separators Concept - Vertical Multi-Pipe (VMP) ............................... 72
ADVANCED PRODUCED WATER TREATMENT

6.7.9 In-Line Rotary Separator (IRIS).........................................................................................................75
6.7.10 Other On-Going Developments........................................................................................................77

6.8 Additional Considerations for Subsea Processing and Water Treatment...............................77
6.8.1 Sand Handling – A Fundamental Subsea Processing Challenge.................................................77
6.8.2 Examples of Sand Handling System in Installed Subsea Processing Systems......................78
6.8.3 Operating principle of the FMC InLine DeSander ........................................................................80
6.8.4 Process Controls of Subsea Separation Systems.........................................................................81
6.8.5 Subsea Power Distribution .............................................................................................................81
6.8.6 Separation Building Blocks for the Future ...................................................................................81

6.9 Summary ........................................................................................................................................84

REFERENCES.........................................................................................................................................86
ADVANCED PRODUCED WATER TREATMENT

TABLE OF FIGURES

FIGURE 1 - PRODUCED WATER CONSTITUENTS (HAYES, 2004) ................................................................. 7
FIGURE 2 - TYPICAL PRODUCED WATER TREATMENT PACKAGE (COURTESY OF PROSEP) ............... 8
FIGURE 3 - TYPICAL PRODUCTION SEPARATOR AND PROFILE (COURTESY OF PRODUCED WATER SOCIETY) ........................................................................................................................................ 11
FIGURE 4 - MODERN WALNUT SHELL FILTRATION PACKAGE (COURTESY OF PRODUCED WATER SOCIETY) ........................................................................................................................................ 12
FIGURE 5 - PILOT COMPACT WALNUT SHELL FILTER PACKAGE (COURTESY OF PRODUCED WATER SOCIETY) ........................................................................................................................................ 12
FIGURE 6 - BASIC CONCEPT OF A HYDROCYCLONE (COURTESY OF WWW.CRONIN-COOK.COM) ... 13
FIGURE 7 - TURNER DESIGNS PICTURE OF TD-4100 XD UNIT .................................................................... 31
FIGURE 8 - SIDE STREAM TECHNIQUE AND EQUIPMENT DESIGN. (COURTESY OF ADVANCED SENSORS) ........................................................................................................................................ 32
FIGURE 9 - ADVANCED SENSORS INLINE PROBE MEASUREMENT. (COURTESY OF ADVANCE SENSORS) ................................................................................................................................. 33
FIGURE 10 - PROANALYSIS INSTALLATION ILLUSTRATION (COURTESY OF PROANALYSIS) ................. 33
FIGURE 11 - LASER PARTICLE COUNTER (COURTESY OF SPECTREX WEBSITE) .................................. 34
FIGURE 12 - JM CANTY INITIAL SUBSEA INLINE CONCEPT (COURTESY OF JM CANTY) ......................... 35
FIGURE 13 - IMAGE OF JORIN METER COMPONENTS (COURTESY OF JORIN) ......................................... 36
FIGURE 14 - ILLUSTRATION OF THE ABB INDUCTANCE LEVEL MONITORING SYSTEM USED FOR TORDIS (COURTESY ABB SENSORS) ........................................................................................................ 37
FIGURE 15 - AGAR’S MICROWAVE WATER CUT METER. (COURTESY OF AGAR) ...................................... 38
FIGURE 16 - TYPICAL INSTALLATION POINTS FOR THE RED EYE WATER CUT METER (COURTESY OF WEATHERFORD). ....................................................................................................................................... 39
FIGURE 17 - CUT AWAY OF THE RED EYE WATER CUT METER (COURTESY OF WEATHERFORD) ........... 40
FIGURE 18 - OPTEK PHOTOMETER (COURTESY OPTEK) ............................................................................. 41
FIGURE 19 - SONICGAUGE ILLUSTRATED (COURTESY OF NIMTECH) .................................................. 42
FIGURE 20 - PICTORIAL HISTORY OF SEABED PROCESSING .................................................................... 45
FIGURE 21 - TROLL C SUBSEA PRODUCED WATER RE-INJECTION PUMP MODULE - FRAME ............. 47
FIGURE 22 - DESIGN PARAMETERS FOR THE TROLL C SUBSEA SEPARATION STATION .................... 47
FIGURE 23 - EXPLODED VIEW OF TROLL PILOT SYSTEM. ......................................................................... 48
FIGURE 24 - THE AMOUNT OF PRODUCED WATER FROM THE SUBSEA SEPARATION STATION INJECTED IN PERCENT OF THE TOTAL WATER HANDLED THROUGH THE TROLL C TOPSIDE AND SUBSEA. .................................................................................................................................................. 49
FIGURE 25 - THE AVERAGE MONTHLY AMOUNT OF WATER INJECTED (B/D) ............................................ 49
FIGURE 26 – (1) VASPS - INSTALLED IN MARIMBA FIELD 2001 (OTC 18198), (2) VASPS CONCEPT (OTC 18198) ........................................................................................................................................ 51
FIGURE 27 – VASP LAYOUT .......................................................................................................................... 52
FIGURE 28 - CDS SAND JETTING SYSTEM - GRAVITY SEPARATOR internals ........................................ 53
FIGURE 29 - TORDIS SSSI - SUBSEA SEPARATOR (COURTESY OF FMC TECHNOLOGIES) ...................... 54
FIGURE 30 - TORDIS SUBSEA SEPARATOR FLOW DIAGRAM (COURTESY FMC TECHNOLOGIES) ........ 54
FIGURE 31 - SHELL BC-10 SEPARATION CAISSON .................................................................................. 55
FIGURE 32 - SHELL PERDIO SUBSEA CAISSSON SEPARATOR .................................................................... 57
FIGURE 33 - PAZFLOR VERTICAL SUBSEA SEPARATOR LOAD-OUT (COURTESY OF FMC TECHNOLOGIES) ................................................................................................................................. 58
FIGURE 34 - FMC - 2 PHASE GAS / LIQUID SEPARATION USING INLINE TECHNOLOGY ....................... 59
FIGURE 35 - INLINE HYDROCYCLONE ........................................................................................................... 59
FIGURE 36 - PETROBRAS CANAPU ................................................................................................................ 60
FIGURE 37 - .................................................................................................................................................. 61
FIGURE 38 - TWISTER – SUPersonic SEPARATOR .......................................................................................... 61
ADVANCED PRODUCED WATER TREATMENT

FIGURE 39 - MULTI APPLICATION RE-INJECTION SYSTEM .................................................................63
FIGURE 40 - AKER SOLUTIONS DEEP BOOSTER WITH SEPARATION SYSTEM FLEXSEP ...............64
FIGURE 41 - KEYMAN™ - PASSIVE MANIFOLD BASE .................................................................. 64
FIGURE 42 - FEATURES OF A 3-PHASE SEPARATION & WATER INJECTION SYSTEM-MODULE .... 65
FIGURE 43 - CAMERON SUBSEA COMPACT ELECTROSTATIC SEPARATOR .......................................68
FIGURE 44 - CAMERON THREE PHASE SUBSEA SEPARATION PROCESS ........................................ 69
FIGURE 45 – FMC TESTING LOOP FOR ELECTROCOALESER .........................................................70
FIGURE 46 – IN LINE DEWATER PRINCIPLE AND PERFORMANCE ..................................................70
FIGURE 47 – ADVANCE SEPARATION TECHNIQUES ..................................................................... 72
FIGURE 48 - ELECTROSTATIC COALESCENCE, VIEC ..................................................................... 72
FIGURE 49 - ELECTROSTATIC COALESCENCE, LOWACC .................................................................72
FIGURE 50 – SAIPEM SUBSEA SEPARATORS CONCEPTS – VERTICAL MULTI-PIPE (VMP) ............73
FIGURE 51 – CONFIGURABLE SUBSEA SEPARATION AND PUMPING SYSTEM ............................. 75
FIGURE 52 - IRIS CROSS-SECTION SHOWING COMPONENTS AND FLOW PATH ............................76
FIGURE 53 - HYBRID SEPARATOR (STEEL + COMPOSITE) FOR SUBSEA SYSTEM LIGHTENING .......77
FIGURE 54 - INLINE CYCLONIC SEPARATION EQUIPMENT - CLOCKWISE: LIQUID-LIQUID SEPARATION, PHASE SPLITTER, DE LIQUIDIZER, DE-SANDER (REF. OTC 20080 PAPER, 2009) .... 79
FIGURE 55 – FMC IN LINE DESANDER OPERATING PRINCIPLE .................................................... 80
6.0 STATE OF THE ART REVIEW OF PRODUCED WATER TREATMENT TECHNOLOGIES

Upon review of the worldwide produced water (PW) treatment industry, Fluor performed a high level screening study to identify current produced water treatment technologies, along with their respective vendors. In addition, the study included the latest developments in subsea processing systems with an emphasis on subsea produced water and sand handling.

This information will be used to recognize the needs of the offshore oil industry to deliver treatment technologies to the seafloor and grasp how those technologies operate throughout the subsea system.

6.1 Produced Water Sources and Constituents

Oil and gas reservoirs have a natural water layer (called formation water) that, being denser, rests under the hydrocarbons. Oil reservoirs frequently contain large volumes of water, while gas reservoirs tend to produce only small quantities. Furthermore, to achieve maximum oil recovery, additional water is often injected into the reservoirs to help force the oil to the surface. Both formation and injected water are often produced along with the hydrocarbons. As an oil field becomes depleted, the amount of produced water increases as the reservoir fills with injected water. (www.netl.doe.gov)

Oil is made up of a number of different hydrocarbons, including BTEX (benzene, toluene, ethylbenzene and xylene), NPD (naphthalene, phenanthrene, and dibenzothiophene), PAHs (polyaromatic hydrocarbons) and phenols. The hydrocarbons are largely insoluble in water, and most of the oil is therefore said to be ‘dispersed’ in the produced water. However, the different components of the oil do dissolve partially in water to differing extents. For example, BTEX and phenols are the most soluble in water of those mentioned above. When oil is said to be dissolved in water, it is largely being referred to these components. PAHs and some of the heavier alkylphenols, in contrast, are considerably less soluble in water and therefore are to a greater relative extent present in the dispersed oil.

In addition to its natural components, produced waters from oil production may also contain groundwater or seawater (generally called “source” water) injected to maintain reservoir pressure, as well as miscellaneous solids and bacteria. Most produced waters are more saline than seawater. They may also include chemical additives used in drilling and producing operations and in the oil/water separation process. Treatment chemicals are typically complex mixtures of various molecular compounds. These mixtures can include:

- Corrosion inhibitors and oxygen scavengers to reduce equipment corrosion
- Scale inhibitors to limit mineral scale deposits; biocides to mitigate bacterial fouling
- Emulsion breakers and clarifiers to break water-in-oil emulsions and reverse breakers to break oil-in-water emulsions
- Coagulants, flocculants, and clarifiers to remove solids
- Solvents to reduce paraffin deposits
ADVANCED PRODUCED WATER TREATMENT

In produced water, these chemicals can affect the oil/water partition coefficient, toxicity, bioavailability and biodegradability. With increased development of subsea oil fields many of these additives will be required in larger amounts for flow assurance in subsea pipelines. Figure 1 shows the typical constituents of produced water.

Figure 1 - Produced Water Constituents (Hayes, 2004)
6.2 Produced Water Separation and Treatment

On a typical offshore facility, the produced water from the primary oil-water separation process has to be further treated before discharge. Separated water from all sources (HP / MP / LP separators, wash water from desalter / dehydrator, crude stabilizer overhead separator, condensate collection drum, condensate-stripper-overhead drum, gas dehydration units) are collected and sent to a produced water treatment package (PWTP) for recovery of oil and treatment of water. From the PWTP, the treated water is injected into subsea disposal wells or discharged to sea. The separating efficiency depends largely on the quality of the water being treated, i.e. on the concentration of oil and the average size of the oily particles. A typical host facility process flow diagram for the PWTP is shown below:

![Diagram of a typical produced water treatment package](image)

Figure 2 - Typical Produced Water Treatment Package (Courtesy of Prosep)

6.3 CONVENTIONAL OIL AND GREASE REMOVAL

Oil and grease from the production flow occur in at least three forms:

- Free oil: large droplets - readily removable by gravity separation methods
- Dispersed oil: small droplets - somewhat difficult to remove
- Dissolved oil: hydrocarbons and other similar materials dissolved in the water stream - very challenging to eliminate

The primary de-oiling process involves an oil/water separator or free water knockout vessel for separation of the free oil. Oil/water separators and skim piles are deployed to remove oil droplets
ADVANCED PRODUCED WATER TREATMENT

greater than 100 microns in diameter. After the primary separation from the oil, the water may still contain drops of oil in emulsion in concentrations as high as 2000 mg/l, so additional physical separation steps are added to remove any remaining free oil and some dispersed oil.

To achieve compliance with applicable discharge limits, additional treatment iterations may require a PWTP. A PWTP consists of additional separation technologies that remove oil, grease and other organics from the 1st and 2nd separation stages of produced water. These technologies are deployed at offshore facilities where produced water is treated prior to ocean discharge. (Ciarapica; www.netl.gov)

Current offshore practices to remove oil and grease from produced water are summarized in Table 1.

Table 1 - Produced Water Treatment Processes for Oil & Grease Removal (Hayes, 2004)

<table>
<thead>
<tr>
<th>UNIT PROCESS</th>
<th>TECHNOLOGY DESCRIPTION</th>
<th>STATE OF DEVELOPMENT</th>
<th>STRENGTH</th>
<th>LIMITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Separator</strong></td>
<td>A gravity oil-water separator tank (basin) that is designed to promote full separation of water and free oil. Oil is mechanically collected as a floated material or as a settled mass in the process. Often used in conjunction with chemical pretreatment employed to break emulsions. Useful as a first line treatment process. A variant of the process uses corrugated plates (CPI) to collect oil.</td>
<td>Very well established treatment process used in the oil and gas industry.</td>
<td>Performs well in the treatment of high oil concentrations; at percent levels: achieves 50 - 99% removal of free oil. Particulates above 150 μ are removed (see Note below table).</td>
<td>Soluble components of the TPH parameter are not efficiently removed with the process. Free oil concentration can be in the range of 15-100 ppm.</td>
</tr>
<tr>
<td><strong>Filtration</strong></td>
<td>A bed of sand or walnut shell granular media that is at least four feet deep in a vertical tank.</td>
<td>Well known and established technology in the oil and gas industry.</td>
<td>Able to remove small diameter oil droplets from produced water. Useful for polishing the effluent.</td>
<td>Soluble TPH components are not removed; not recommended for influent oil concentrations over 100 ppm.</td>
</tr>
</tbody>
</table>
## ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th>UNIT PROCESS</th>
<th>TECHNOLOGY DESCRIPTION</th>
<th>STATE OF DEVELOPMENT</th>
<th>STRENGTH</th>
<th>LIMITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocyclone</td>
<td>A device of cylindrical construction that is fitted with one or more tangential inlets which cause the fluid entering the cyclone to follow a circular path around the wall of the process. Rotation of the fluid generates a centripetal acceleration field which is thousands of times greater than earth's gravity. Heavier water and solids move toward the outer wall; lighter material moves toward the center and the light oil is rejected from the process.</td>
<td>Well known and established technology in the oil and gas industry.</td>
<td>Capable of reaching low levels of free oil below 10 ppm. Low space requirements. Lowest cost de-oiling device in many cases. Removes particles larger than 5μ.</td>
<td>Highly soluble oil components of TPH, such as naphthenic acids, are not removed. May not be able to meet NPDES permit effluent oil and grease limitations.</td>
</tr>
<tr>
<td>Induced Gas Flotation</td>
<td>Fine gas bubbles are generated and dispersed in a chamber to suspend particles which ultimately rise to the surface forming a froth layer. Foam containing the oil is skimmed from the surface.</td>
<td>Well known and established technology in the oil and gas industry.</td>
<td>Oil removals of greater than 93% have been demonstrated with chemical additions.</td>
<td>Does not remove soluble oil components.</td>
</tr>
<tr>
<td>Membrane Filtration</td>
<td>Ultra filtration is a membrane process that is capable of retaining solutes as small as 1000 daltons (1 dalton is 1/16 of the mass of an oxygen atom) while passing solvent and smaller solutes. Surfactant addition enhances oil removal. Operating pressures of 140-410 kPa (20-60 psi) are far lower than reverse osmosis pressures.</td>
<td>Widely practiced on a large scale in industry. Developmental for O&amp;G applications. Micelle-enhanced version of this process is an emerging technology.</td>
<td>Compact. Removes about 85-99% of total oil. Effluent oil &amp; grease can consistently be reduced to below 14 ppm.</td>
<td>Iron fouling can be a problem. Effective cleaning is critical to preventing membrane fouling and reduction in permeate flux.</td>
</tr>
</tbody>
</table>

Note: Most likely the lowest removable particulate size is 500 μm.

### 6.3.1 Separator

Separators rely on the difference in specific gravity between oil droplets and produced water. The lighter oil rises at a rate dependent on the droplet diameter and the fluid
ADVANCED PRODUCED WATER TREATMENT

viscosity (Stokes Law). Smaller diameter droplets rise more slowly. If sufficient retention
time is not provided, the water exits the separator before the small droplets have risen
through the water to collect as a separate oil layer. Corrugated plate separators can
remove more oil than a standard API gravity separator. Likewise, inclined plate
separators show better performance. Advanced separators contain additional internal
structures that shorten the path followed by the oil droplets before they are collected. This
gives smaller oil droplets the opportunity to reach a surface before the produced water
overflows and exits the separator. (www.netl.doe.gov)

Figure 3 - Typical Production Separator and Profile (Courtesy of Produced Water Society)

6.3.2 Filtration

Filtration is a widely used technology for produced water. Filtration does not remove
dissolved ions, and performance of filters is not affected by high salt concentrations.
Removal efficiencies can be improved by employing coagulation upstream of the filter.
Several types of media filtration devices are used for offshore produced water treatment,
including up-flow sand filters, walnut shell filters, down-flow sand filters and multimedia
filters containing anthracite and garnet. Media filters operate until they reach a pre-
determined level of solids loading, then they are taken offline and backwashed to remove
the collected material. Membrane filters have also been used offshore. They are typically
deployed as cartridges, which can be replaced when filled. (RPSEA 07122-12, 2009)
ADVANCED PRODUCED WATER TREATMENT

Figure 4 - Modern Walnut Shell Filtration Package (Courtesy of Produced Water Society)

Figure 5 - Pilot Compact Walnut Shell Filter Package (Courtesy of Produced Water Society)
6.3.3 Hydrocyclone

Hydrocyclones have been used for surface treatment of produced water for several decades. By the mid-1990s, over 300 hydrocyclones were deployed at offshore platforms. Hydrocyclones, which do not contain any moving parts, apply centrifugal force to separate substances of different densities. Hydrocyclones can separate liquids from solids or liquids from other liquids. The liquid/liquid type of hydrocyclone is used for produced water treatment. Depending on the model of hydrocyclone being used, they can remove particles in the range of 5 to 15 microns. Hydrocyclones will not remove soluble oil and grease components.

![Diagram of a Hydrocyclone](https://www.cronin-cook.com)

**Figure 6 – Basic Concept of a Hydrocyclone (Courtesy of www.cronin-cook.com)**

Hydrocyclones do not require any pre- or post-treatment. They do not require any chemicals or energy. There are no energy requirements unless the setup requires a forwarding pump to deliver water to the hydrocyclone. Depending on the size and configuration of the device, a large pressure drop can occur across the hydrocyclone. The waste generated from a hydrocyclone is a slurry of concentrated solids. This is the only residual that requires disposal.

Total residence time of the liquid in the hydrocyclone is only 2-3 seconds. Hydrocyclones can provide significant savings in weight, space, and power usage. They are particularly
ADVANCED PRODUCED WATER TREATMENT

effective where system operating pressures are high. If system pressures are low, booster
pumps are required to increase the operating pressure for the hydrocyclone. This however
induces a shearing action on the oil droplets and will reduce overall system efficiency.
Hydrocyclones also require relatively high and constant flow rates. If flow rates are low
or variable, a recycle flow stream through a surge tank can be added. (Mastouri, 2010;
RPSEA 07122-12, 2009; www.netl.doe.gov)

6.3.4 Gas Flotation

Flotation technologies introduce bubbles of air or other gas into the bottom of a sealed
tank. As the bubbles rise, they attach to oil droplets and solid particles and lift them to the
surface where they can be skimmed off.

Gas flotation technology is subdivided into dissolved gas flotation (DGF) and induced
gas flotation (IGF). The two technologies differ by the method used to generate gas
bubbles and the resultant bubble sizes. In DGF units, gas (usually air) is fed into the
flotation chamber, which is filled with a fully saturated solution. Inside the chamber, the
gas is released by applying a vacuum or by creating a rapid pressure drop. IGF
technology uses mechanical shear or propellers to create bubbles that are introduced into
the bottom of the flotation chamber. DGF units create smaller gas bubbles than IGF
systems. However, they require more space than IGF systems and more operational and
maintenance oversight. Because space and weight are at a premium on offshore
platforms, IGF systems are used at most offshore facilities. In the past few years, some
new types of pumps have been introduced that generate a large number of small bubbles
in an IGF system to improve performance. Many IGF systems use multiple cells in series
to enhance the hydraulic characteristics and improve oil and solids removal. Chemicals
are often added to aid the flotation process. They can break emulsions, improve
aggregation of particles, and serve other functions.

The efficiency of the flotation process depends on the density differences of liquid and
contaminants to be removed. It also depends on the oil droplet size and temperature.
Minimizing gas bubble size and achieving an even gas bubble distribution are critical to
removal efficiency. Flotation works well in cold temperatures and can be used for waters
with both high and low total organic concentrations (TOCs). If high temperatures are
present, a higher pressure is required to dissolve the gas in the water. It is excellent for
removing natural organic matter (NOM). Dissolved air flotation (DAF) can remove
particles as small as 25 microns. If coagulation is added as a pretreatment, DAF can
remove contaminants 3 to 5 microns in size. Flotation cannot remove soluble oil
constituents from water. (RPSEA 07122-12, 2009; www.netl.doe.gov)

6.3.5 Membrane Filtration

Membrane filtration systems operate under microfiltration (MF) and ultrafiltration (UF)
conditions. These methods give rise to a filtrate with an oil concentration of less than 5
mg/l and also remove any solids in suspension. Other advantages lie in the modularity of
the systems and their smaller dimensions, this latter characteristic being extremely
important on offshore oil facilities. Their main disadvantage has to do with fouling, i.e.
the pores in the membrane become occluded, calling for frequent flushing and chemical
cleaning, and the installation of pre-treatment and/or pre-filtering units upstream from the
system, thus increasing the complexity and cost of such solutions. (Ciarapica)
ADVANCED PRODUCED WATER TREATMENT

The removal capabilities of offshore separation methods are shown in Table 2.

### Table 2 - Particle Size Removal Capabilities

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Removes Particles Greater Than Size Indicated (in microns) Ref. Hayes, 2004</th>
<th>Typical Oil in Water Concentration in Outlet Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>API Gravity Separator</td>
<td>150</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Corrugated Plate Separator</td>
<td>40</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Induced Gas Flotation</td>
<td>25</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Induced Gas Flotation with Chemical Addition</td>
<td>3-5</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Hydrocyclone</td>
<td>10-15</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Media Filter</td>
<td>5</td>
<td>[HOLD]</td>
</tr>
<tr>
<td>Membrane Filter</td>
<td>0.01</td>
<td>[HOLD]</td>
</tr>
</tbody>
</table>

### 6.3.6 Other De-Oiling Technologies

There are other available de-oiling technologies not currently used on offshore facilities. These technologies are listed in Table 3.

### Table 3 - Other De-Oiling Treatment Technologies (Hayes, 2004)

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced Gravity: Enhanced gravity separation relies on gravity forces (settling and floating) and uses different techniques to enhance the forces of gravity. Such techniques include subjecting the contaminated water to G forces greater than normal gravity (hydrocyclones, centrifuges), attachment of contaminants to lighter (gas bubbles) or heavier (sand, clay particles) substances such that the phase containing the contaminant will travel up or down in water than it would otherwise. This accelerates separation and generally reduces equipment size.</td>
<td></td>
</tr>
<tr>
<td>Weighted (or Ballasted) Flocculation</td>
<td>Consists of attaching suspended particles, especially organic, to heavier ones using coagulants and flocculants. The aggregates are thus weighed (or ballasted) and can be settled down in a clarifier.</td>
</tr>
</tbody>
</table>
### ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th><strong>TECHNOLOGY</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commercial Availability</strong></td>
<td>Weighed flocculation, using materials such as clay, are available as engineered systems. However such systems have not gained popularity. There exists a proprietary system that uses micro sand instead, and where the clarifier sludge is pumped through a hydro-cyclone to recover and recycle the micro sand. This proprietary system has been successful in the market.</td>
</tr>
<tr>
<td><strong>Uses and Strengths</strong></td>
<td>The proprietary ballasted flocculation system has gained popularity in the domestic water and wastewater industries. Its main advantages are a small footprint relative to gravity or air flotation clarifiers, and a very good quality effluent (turbidities of about 0.1 NTU are possible).</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Uses relatively large amounts of polymers, which are expensive, and “leaking” of polymer droplets into the effluent has been reported. This poses a concern for systems where a membrane filter follows clarification. The high quality of the effluent means that depth filters, which usually follow clarification, will require long “ripening” times, during which leaked polymer droplets may not be retained and could be detected in filtered water particle counters, as they are of the same size as certain undesirable micro-organisms.</td>
</tr>
<tr>
<td><strong>R&amp;D Needed</strong></td>
<td>Technology is well understood for normal applications. Has potential for removal of low to moderate concentrations of hydrocarbons in water, perhaps including asphaltenes. Work needed to develop correct combination of ballasting material and polymer, to minimize and simplify treatment of waste, recover hydrocarbons, and maximize recovery of ballasting material. This R&amp;D work would consist of both laboratory and pilot studies.</td>
</tr>
</tbody>
</table>

*Size Exclusion: Consists of separating a solid phase from a fluid (gas or usually liquid) phase by retaining the solids on a porous material (thin plate, cloth or mesh, or deep bed of particles) that allows the fluid to pass through. The smaller the solids the more impervious the material would need to be in order to retain the particles. Particles may be removed by many mechanisms other than simple size exclusion, including interception, deposition or others. Some contaminants may be retained on the porous material by surface adsorption, and sometimes particle retention is enhanced using chemicals (polymers that act as “binders”) added to water.*
## Adsorptive Filtration

### Description
Adsorptive filtration consists in using granular material in a depth filter that can adsorb contaminants. Operation is similar to other depth filters, but the regeneration of the adsorptive capacity varies depending on the material. Some granular materials (e.g., walnut shells) adsorb contaminants (free oil) on the external surface. Others (e.g., GAC) adsorb contaminants mostly on the internal surface, in pores and fractures. Such internal surface area may be several orders of magnitude greater than the external.

### Commercial Availability
These systems are commercially available, usually as skid-mounted packages, and their use is widespread. Filters with walnut shells and other materials with an affinity for oil are regenerated by slurring and pumping the media through high turbulence into an oil/water/solids separation system. GAC may be regenerated using steam stripping (volatile adsorbents) or pyrolysis (non-volatile). Anionic resins used for organics polishing are regenerated with a caustic solution. Inexpensive adsorbents may be simply replaced.

### Uses and Strengths
Granular activated carbon (GAC) is used to adsorb dissolved organics. Walnut shells are used to retain small oil droplets. Clay pellets have been used in the lube oil recycling industry. Weakly anionic resins are used to adsorb organics upstream of deionization resins. Adsorption produces some of the best polished treated water, with concentrations down to a few ppb and lower. Most of these systems are expensive to install and operate, and their application is generally limited to situations that require polishing to such high quality. Walnut shell filters would be an exception, both regarding the cost and the quality of the treated water.

### Weaknesses
Most of these filters are expensive to install and operate. The regeneration of the media and the eventual disposal are expensive and require skilled operator attention. Regeneration can produce waste streams that are difficult and expensive to treat and dispose. Adsorption bed life depends on the contaminant loading. Justification for the high cost of this technology usually depends on having very low concentration of contaminants (longer life) and the need to polish to very high quality.
## ADVANCED PRODUCED WATER TREATMENT

### TECHNOLOGY

<table>
<thead>
<tr>
<th>R&amp;D Needed</th>
<th>The technology, in its many variations, is well understood and requires little if any R&amp;D work prior to full size implementation. However, given the complexity of produced water contaminant matrices, it is advisable to complete bench top and pilot studies before implementing new applications, particularly for GAC, given that different components will compete for the adsorption sites in the granular material.</th>
</tr>
</thead>
</table>

### Evaporation / Distillation: These classes of technologies effect separation of two or more substances by making at least one of them change from the liquid to the gaseous phase (vapor), and may recover the evaporated substance by condensation or other means. Different techniques can be used to evaporate a substance (usually a liquid such as water). The driving force for the process is the difference between the substance vapor pressure in the liquid phase and its partial pressure in the gaseous phase. These techniques seek to increase the former (i.e. by increasing the temperature) or decrease the latter (e.g., by applying vacuum or by stripping with an inert gas). |

### Description

| The process consists in evaporating the water, leaving non-volatile contaminants in the liquid phase. The vapors are then condensed, producing a high quality condensate (or distillate) than may contain volatile components. Water is generally heated with steam or with the vapors produced. The heat exchangers may be internal (e.g., vertical falling film or calandria / flooded, tubular or dimple plate) or external (tubular or plate). Liquid recirculation is generally needed in either case. |

### Commercial Availability

| Two basic types of evaporators are in widespread use. Multiple effect evaporators consist in a number of evaporation vessels connected in series for the flow of water, which gets more concentrated in contaminants as it moves from one to the next. These vessels usually operate under vacuum. Steam is used in the last one. The vapors produced in this last vessel are fed to the previous one (in the liquid train), and so on. Each “effect” produces some condensate, the sum of which is the “distilled” water. A single effect (classic still) requires almost twice as much steam as a two effects evaporator. The other type is mechanical vapor recompression (MVR). The vapors generated in the vessel are compressed using a blower, which also heats them up, and fed to the vapor side of the exchanger, where they condense at a higher temperature (and pressure) than the liquid phase. |

| Evaporation / Condensation | -- |
| Description | -- |
### ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Uses and Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This technology is generally used for treatment of water with higher concentrations of solids, particularly salts, and is widely used for sea water desalination. It has been used to process water produced at SAGD operations into boiler feed water quality. A pulp mill in Saskatchewan treats its effluent in this manner to produce fresh water for process uses. Gas fields in Texas that use water to fracture tight formations and displace the gas use MVRs to treat the brine. Sask Power uses evaporators at one of its generating stations to produce boiler feed water. The quality of the condensate can be quite high, with extremely low TDS concentrations. It is possible to design the system to produce more than one condensate streams, with volatile contaminants concentrated in one of them.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evaporation / Condensation</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Some contaminants cause foaming, and the froth could be entrained in the vapors. Anti-foaming agents and washing (scrubbing or fractionating) columns above the vapor space can be used to deal with foams. Mist entrainment can be controlled with such columns or with demisters. The concentration of solids in the liquid leads to a waste stream that needs treatment and disposal. Some evaporator systems concentrate the solids to the point of crystallization, separating the crystals in other equipment. Forced circulation (external heating) units are particularly exposed to corrosion and erosion. Many contaminants cause fouling and scaling that degrade performance. Even with the use of anti-scalants, these need periodic cleaning, which also produces waste streams that need treatment and disposal. Technology is capital intensive and normally would not be economic for non-saline produced water, except for concentrated treating waste management. Small operations may not justify the complexity of these systems. And simple stills, whether with steam or electrical heating, may have significantly higher operating costs.</td>
</tr>
</tbody>
</table>

| R&D Needed | The technology and the science behind it are well understood. However, pilot testing would be advisable prior to implementation on new applications, particularly water with complex contaminant matrices. |
**TECHNOLOGY**

Chemical Treatment: In the context of water treatment, this set of technologies requires the addition of chemical substances that react with water or contaminants to effect the separation. In some cases, the chemical reacts with a contaminant forming a less soluble substance (e.g., addition of lime to precipitate calcium sulphate for sulphate removal). Other techniques consist in adding acids or caustics to modify the pH and in this manner change the ionic or other properties of contaminants, which causes the latter to become less soluble or to change certain properties (such as surface charges), which facilitates separation. Yet other type of chemicals may react with contaminants changing their oxidation state into one where their chemical and physical properties are significantly different (e.g., oxidation or reduction). A very large number of chemicals are utilized in water treatment, and the manner in which they act is equally varied.

<table>
<thead>
<tr>
<th>Other Chemicals</th>
<th>Description</th>
<th>Commercial Availability</th>
<th>Uses and Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Many chemical may be added for different water treatment needs. Usually, they are used to enhance or enable the performance of various separation processes.</td>
<td>A large variety of chemicals are available in the market. Some, such as anti-foaming agents or polymers, are proprietary and the expertise for their use generally resides with the manufacturers. Others, such as sodium bisulphite, are commodities and water chemists and water engineers normally understand their use well.</td>
<td>There are too many uses to list. For example, antifoaming agents can used in evaporators or other equipment where frothing may be a concern. Bisulphite is frequently added to the feed of RO systems to neutralize any residual chlorine from pre-treatment, scavenge oxygen, dissolve and prevent the oxidation of iron or manganese that could foul the membranes, and provide a slightly negative oxidation-reduction potential (ORP) such that aerobic bacteria (which grow fast in the presence of dissolved oxygen) will not cause a biofouling problem.</td>
<td>Even though most chemicals are used in small quantities, most are very expensive. Most chemicals present health and safety hazards, and require containment and adequate handling both for safety and for environmental protection (to avoid spills). Some chemicals are incompatible with each other, and their combination may render them ineffectual, or could result in undesirable or violent reactions, or the release of toxic fumes.</td>
</tr>
</tbody>
</table>
**TECHNOLOGY**

| R&D Needed | New applications of chemicals generally require bench top and pilot studies. |

*Other Technologies: There are technologies that may be applied to water treatment. Under this entry are novel or less well known in the industry, but which could find application in certain situations. Their principle of operation is described in each case.*

<table>
<thead>
<tr>
<th>Electro-Flocculation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-flocculation is a novel technology also called electro-coagulation. It consists in passing the water between two electrodes where a DC voltage differential is applied. Water conductivity allows the current to circulate, leading to water electrolysis. At the sacrificial anode (aluminum or iron), the metal dissolves, hydrolyzes and coagulates particles. The gas generated (hydrogen and some oxygen) is in the form of micro bubbles, which attach to the coagulated solids and rise together to the surface, from where they are removed similarly to a gas flotation system.</td>
<td></td>
</tr>
</tbody>
</table>

| Commercial Availability | The technology is not new, but is available from a small number of vendors, in the form of proprietary packages. To the author’s knowledge, the technology has not been scaled up for use in large water treatment systems, however most produced water applications would be small by water industry standards. |

| Uses and Strengths | The technology has not been used extensively (see “weaknesses” column). At the pilot and small system level, it has demonstrated good removal of particulate (including organic), oil (including emulsified), metals and certain anions (such as phosphate). It provides the benefits of dissolved gas flotation for coagulated materials, but without the addition of coagulant (the dissolving metallic anode provides the coagulating agent), and produces less sludge that is less bulky and easier to dewater. |
# ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>The gas generated and used to float the flocs is largely hydrogen with some oxygen (not necessarily stoichiometrically balanced). This gas is flammable and potentially explosive and the hazard should be considered in designing the installation. The main reason why the technology has not been scaled up and widely adopted is that it consumes large quantities of electric power. Power consumption is inversely proportional to the water conductivity. For example, treatment of fresh water may consume 10 to 100 kWh/m³ treated, depending on the application. A similar application in sea water would consume about a tenth as much.</td>
</tr>
</tbody>
</table>

| **R&D Needed** | The technology could be of interest for the treatment of produced water to remove certain contaminants that may be difficult to remove by other means. Electrical power costs are of concern, but possibly manageable for the more brackish end of the non-saline spectrum. The theory of electro flocculation is well understood, but well planned and executed pilot studies would be required prior to implementation. Scale up of existing commercial equipment may be required. |

| **Adsorptive Bubble (Foam Fractionation)** | The technology uses a bubble column where water to be treated is injected at mid height. Air or other suitable gas is injected at the bottom using diffusers that produce small bubbles (say 1 mm). A surfactant (the “collector”) is usually metered into the water feed stream, unless surface-active substances are already present. Treated water exits at the bottom of the column. In the lower section (adsorptive bubble) the rising bubbles adsorb contaminants (the “collagens”) and take them to the upper (foam fractionation) section. This upper section contains froth only, but collapsing bubbles provide for internal reflux and further concentration of contaminants. Foam at the top (the “foamate”) is directed to a separate tank where it is totally collapsed. Some of this contaminant stream may be used for reflux for greater concentration and water recovery. |
The technology is not new, but is available from a small number of vendors, in the form of proprietary packages. To the author’s knowledge, the technology has not been scaled up for use in large water treatment systems, however most produced water applications would be small by water industry standards.

Adsorptive bubble separation has been used to separate metals, dyes, pesticides, organic colloids (algae) and other contaminants. Reduction in contaminant concentration in the treated water can be greater than 90%. Other than the power required to pump the liquids into and out of the column and to collapse the foamate, the only other source of energy is to blow air into the diffuser, and the consumption of air is relatively small. The only chemical needed (other than adjustments such as pH that might be needed) is the collagen (surfactant). Their consumption would be in the same order of magnitude as polymers that would be required in other technologies, but surfactants are generally less expensive, and if the water naturally foams they may not be needed at all.

The bubbles at the bottom are small, with a small upward velocity. On the other hand, the water is moving downward, and its velocity needs to be subtracted from that of the bubbles relative to water in order to obtain the actual rising velocity. This is a limiting aspect of design, which could make the column quite large. The collapsed foamate would contain the contaminants as a liquid concentrate that will require further treatment and disposal.

The technology could be of interest for the treatment of produced water to remove certain contaminants that may be difficult to remove by other means. The theory of adsorptive bubble separation is well understood, but well planned and executed pilot studies would be required prior to implementation. Scale up of existing commercial equipment may be required.
ADVANCED PRODUCED WATER TREATMENT

If the produced water is returned to the field (reinjected), there are typically no legislative restrictions, but it is advisable to remove as much of the oil and solids (sand, rock fragments, etc.) in suspension as possible in order to minimize the risk of clogging the pore space in the reservoir.

The US Environmental Protection Agency (EPA) has designated IGF treatment as the best available technology (BAT) for removal of oil from produced water that is to be discharged to sea. Table 4 shows typical concentrations of pollutants in treated offshore produced water samples from the Gulf of Mexico (EPA 1993).

In North Sea, [HOLD]

The data in Table 5 was compiled by the EPA during the development of its offshore discharge regulations and is a composite of data from many different platforms in the Gulf of Mexico. The first column of data represents the performance for a very basic level of treatment (best practicable technology, or BPT) while the second column of data represents a more comprehensive level of treatment (BAT). The data indicates that the organic and inorganic components of produced water discharged from offshore wells can be in a variety of physical states including solution, suspension, emulsion, adsorbed particles and particulates.
ADVANCED PRODUCED WATER TREATMENT

Table 4 - Pollutants in Treated Offshore Produced Water (Veil, 2004)

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration (mg/L) (BPT)</th>
<th>Concentration after IGF Treatment (mg/L) (BAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and grease</td>
<td>25</td>
<td>23.5</td>
</tr>
<tr>
<td>2-Butanone</td>
<td>1.03</td>
<td>0.41</td>
</tr>
<tr>
<td>2,4-Dimethylphenol</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Anthracene</td>
<td>0.018</td>
<td>0.007</td>
</tr>
<tr>
<td>Benzene</td>
<td>2.98</td>
<td>1.22</td>
</tr>
<tr>
<td>Benzo(a)pyrene</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>0.019</td>
<td>0.008</td>
</tr>
<tr>
<td>Di-n-butylphthalate</td>
<td>0.016</td>
<td>0.006</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>0.32</td>
<td>0.062</td>
</tr>
<tr>
<td>n-Alkanes</td>
<td>1.64</td>
<td>0.66</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>0.24</td>
<td>0.092</td>
</tr>
<tr>
<td>p-Chloro-m-cresol</td>
<td>0.25</td>
<td>0.010</td>
</tr>
<tr>
<td>Phenol</td>
<td>1.54</td>
<td>0.54</td>
</tr>
<tr>
<td>Steranes</td>
<td>0.077</td>
<td>0.033</td>
</tr>
<tr>
<td>Toluene</td>
<td>1.901</td>
<td>0.83</td>
</tr>
<tr>
<td>Triterpanes</td>
<td>0.078</td>
<td>0.031</td>
</tr>
<tr>
<td>Total xylenes</td>
<td>0.70</td>
<td>0.38</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.078</td>
<td>0.050</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.11</td>
<td>0.073</td>
</tr>
<tr>
<td>Barium</td>
<td>55.6</td>
<td>35.6</td>
</tr>
<tr>
<td>Boron</td>
<td>25.7</td>
<td>16.5</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.023</td>
<td>0.014</td>
</tr>
<tr>
<td>Copper</td>
<td>0.45</td>
<td>0.28</td>
</tr>
<tr>
<td>Iron</td>
<td>4.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Lead</td>
<td>0.19</td>
<td>0.12</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.12</td>
<td>0.074</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.2</td>
<td>0.13</td>
</tr>
<tr>
<td>Radium 226 (in Ci/L)</td>
<td>0.00023</td>
<td>0.00020</td>
</tr>
<tr>
<td>Radium 228 (in Ci/L)</td>
<td>0.00028</td>
<td>0.00025</td>
</tr>
</tbody>
</table>

6.4.1 Treatment Methods for Constituents

Table 5 identifies the some treatment technologies that are used to reduce the concentration of the constituents in produced water. Only the treatment technology that are relevant to subsea discharge are listed.
## Table 5 - Treatment Technologies for Identified Constituents (PTAC, 2007)

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Description</th>
<th>Commercial Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cake Filtration</td>
<td>Consists of passing a liquid through a porous filtration surface that retains suspended solids. As solids accumulate, a cake is formed that becomes the actual filtration surface. At some point, the cake is mechanically removed and the cycle repeated.</td>
<td>Cake filters are readily available in many configurations, including batch or continuous; gravity belt, filtering centrifuges, pressurized (filter press, filter leaf, cartridge), or vacuum (drum, belt, pan); with manual or automatic discharge or cleaning, and others. Filtration surfaces may be dynamically formed over sieves (diatomaceous earth slurry) or consist in a variety of materials such as filter clothes (plastic or other fibers), paper, felts, and others.</td>
</tr>
<tr>
<td></td>
<td>Uses and Strengths</td>
<td>Widely used in most industries, they are an efficient and cost effective means of separating solids from water.</td>
</tr>
<tr>
<td></td>
<td>Weaknesses</td>
<td>Small particulate and amorphous (gel) solids produce cakes with low permeability and require high filtration pressure differentials, which induces compaction. The presence of free oil, particularly heavy (bituminous and wax-like) hydrocarbons and similar contaminants can cause clogging of the filtration surface.</td>
</tr>
<tr>
<td></td>
<td>R&amp;D Needed</td>
<td>Requires examination of potential for clogging at the bench top level. Similarly, the permeability and compaction tendency of the cake may need to be studied for high solid contents.</td>
</tr>
<tr>
<td>Media Filters</td>
<td>Description</td>
<td>Also known as “depth filters”. Consists of one or more layers, usually 0.3 to 0.9 m total depth, of granular material such as activated carbon, anthracite, sand, garnet or others, in a vertical tank or vessel. As the water passes through the voids between granules, suspended solids are retained in the bed, accumulating on and between the granules. Air scouring and back washing with filtered water is used for regeneration, producing a high solids stream.</td>
</tr>
</tbody>
</table>
## ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th>Media Filters</th>
<th>Commercial Availability</th>
<th>Uses and Strengths</th>
<th>Weaknesses</th>
<th>R&amp;D Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Widely used in the water treatment industry for removal of fine suspended solids. Large plants use gravity media filters in concrete tanks. Small plants usually have pressurized media filters in closed vessels, and the water is pumped into them. The latter are usually skid-mounted packaged systems.</td>
<td>Widely used for domestic water and wastewater treatment. Have found limited applicability in the oil and gas industry because they do not tolerate even small concentrations of free oil. Applicable to the clarification of turbid water. There are proprietary systems using sand moving beds where the sand and retained particles are extracted at the bottom, separated, and the sand is washed and recycled to the top of the filter. See also adsorption technologies below.</td>
<td>Concentration of solids in the feed should be &lt; 10 mg/L - ideally &lt; 1 mg/L. Media filters clog rapidly even with small concentrations of free oil. Filters require large footprint, as particles are not retained or are scoured at high filtration rates. The backwash waste requires separate treatment for solids separation and disposal. Separated water may be recycled. In the presence of certain contaminants, such as oil, bed may clog beyond the ability clean it by conventional means. Excessive use of coagulants (alum), the presence of certain algae, and bacterial growth can lead to the formation of “mud balls” that are difficult to disintegrate, and this degrades filter performance.</td>
<td>Pilot plant studies are done to determine performance, design criteria, and effect of filtration aids, such as coagulants and polymers.</td>
</tr>
</tbody>
</table>

### Adsorptive Filtration

<p>| Description | Adsorptive filtration consists in using granular material in a depth filter that can adsorb contaminants. Operation is similar to other depth filters, but the regeneration of the adsorptive capacity varies depending on the material. Some granular materials (e.g., walnut shells) adsorb contaminants (free oil) on the external surface. Others (e.g., GAC) adsorb contaminants mostly on the internal surface, in pores and fractures. Such internal surface area may be several orders of magnitude greater than the external. |</p>
<table>
<thead>
<tr>
<th>Adsorptive Filtration</th>
<th>Commercial Availability</th>
<th>Uses and Strengths</th>
<th>Weaknesses</th>
<th>R&amp;D Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>These systems are commercially available, usually as skid-mounted packages, and their use is widespread. Filters with walnut shells and other materials with an affinity for oil are regenerated by slurring and pumping the media through high turbulence into an oil/water/solids separation system. GAC may be regenerated using steam stripping (volatile adsorbents) or pyrolysis (non-volatile). Anionic resins used for organics polishing are regenerated with a caustic solution. Inexpensive adsorbents may be simply replaced.</td>
<td>Granular activated carbon (GAC) is used to adsorb dissolved organics. Walnut shells are used to retain small oil droplets. Clay pellets have been used in the lube oil recycling industry. Weakly anionic resins are used to adsorb organics upstream of deionization resins. Adsorption produces some of the best polished treated water, with concentrations down to a few ppb and lower. Most of these systems are expensive to install and operate, and their application is generally limited to situations that require polishing to such high quality. Walnut shell filters would be an exception, both regarding the cost and the quality of the treated water.</td>
<td>Most of these filters are expensive to install and operate. The regeneration of the media and the eventual disposal are expensive and require skilled operator attention. Regeneration can produce waste streams that are difficult and expensive to treat and dispose. Adsorption bed life depends on the contaminant loading. Justification for the high cost of this technology usually depends on having very low concentration of contaminants (longer life) and the need to polish to very high quality.</td>
<td>The technology, in its many variations, is well understood and requires little if any R&amp;D work prior to full size implementation. However, given the complexity of produced water contaminant matrices, it is advisable to complete bench top and pilot studies before implementing new applications, particularly for GAC, given that different components will compete for the adsorption sites in the granular material.</td>
<td></td>
</tr>
</tbody>
</table>
6.4.2 Vendors

Table 6 shows the some of major vendors that provide water treatment technology and/or equipment.

Table 6 – Some of the Major Produced Water Treatment Vendors

<table>
<thead>
<tr>
<th>PRACTICE</th>
<th>VENDOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocyclone</td>
<td>Cameron</td>
</tr>
<tr>
<td></td>
<td>Siemens</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td></td>
<td>FL Smith</td>
</tr>
<tr>
<td></td>
<td>EnerScope</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>EVTN</td>
</tr>
<tr>
<td></td>
<td>Alpha</td>
</tr>
<tr>
<td></td>
<td>Laval</td>
</tr>
<tr>
<td>Filtration</td>
<td>Cameron</td>
</tr>
<tr>
<td></td>
<td>New Logic</td>
</tr>
<tr>
<td></td>
<td>Siemens</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td></td>
<td>Ecodyne</td>
</tr>
<tr>
<td>Coalescence</td>
<td>ACS Industries Inc</td>
</tr>
<tr>
<td></td>
<td>Siemens</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td></td>
<td>ProSep Technologies</td>
</tr>
<tr>
<td>Flotation</td>
<td>Enviro-Tech</td>
</tr>
<tr>
<td></td>
<td>Siemens</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td></td>
<td>IDI</td>
</tr>
<tr>
<td>Combined processes</td>
<td>MI-Swaco</td>
</tr>
<tr>
<td></td>
<td>ProSep Technologies</td>
</tr>
<tr>
<td></td>
<td>Cameron</td>
</tr>
<tr>
<td></td>
<td>Siemens</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>VWS MPP Systems B.V.</td>
</tr>
<tr>
<td></td>
<td>Veolia</td>
</tr>
<tr>
<td></td>
<td>Ecodyne</td>
</tr>
<tr>
<td>Adsorption</td>
<td>CETCO</td>
</tr>
<tr>
<td></td>
<td>MyClex</td>
</tr>
<tr>
<td>Oxidation</td>
<td>Ecosphere Technologies</td>
</tr>
</tbody>
</table>

6.4.3 Oil In Water Monitoring Techniques For Produced Water Treatment Systems

Introduction

One of the most important aspects of seabed discharge of produced water will be the oil-in-water monitoring system. With the treatment system being subsea, several thousand
feet below the surface, it is imperative that accurate oil-in-water monitoring systems are present to inform operators of an upset, and to ensure that regulations are being met.

There are five methods currently used to measure oil-in-water which will be discussed further in the following sections. Each of these methods measure different properties of the produced water, and all can be done in the field, with the exception of the direct weight measurement method. This method is the official regulatory method required for compliance in the US and is typically done in a lab.

**Typical Properties of Oil-in-Water Monitoring**

**Direct Weight Measurement**

The direct weight measurement method is best known for being the required test method used for the US EPA. It is known as Method 1664 and is the only test that can be done to verify that discharge in the US meets EPA oil-in-water standards. This test must be done in a laboratory and if it is being used to meet EPA requirements, it must be done in an accredited lab. The procedure for the direct measurement method is to acidify a one liter water sample to pH 2 or less, then extract it using n-hexane. N-hexane is the extractant used for the 1664 method, but other extractants may be specified. The extractant is then evaporated and the remaining residue is weighed. The mass of this residue is recorded in milligrams, and this gives a direct mg/L concentration. The following methods described are indirect methods of measurement, meaning that the recorded value of whatever property is being measured must be correlated to a standard in order to determine the oil-in-water concentration.

**Colorimetric Method**

Colorimetric method oil-in-water tests measure the absorption of energy in the visible light range. This test only works well with dark oils. The measurement is then correlated to a sample with a known concentration to determine the concentration of the test water. One major problem associated with this method is that a calibration sample of the oil is needed, and if the sampling quality or process flow changes the hydrocarbon ratio in the sample, the analysis can have a large uncertainty and degree of error associated with the final resultant oil-in-water measurement.

**Top Industry Resources**

The HACH company provides portable test kits with a colorimeter that can perform this test method, as well as other analytical suppliers. Many different analytical vendors are familiar with the testing method and can perform the test by request using field personnel. It is also common for operators to have their own personnel use this type of equipment for verification of equipment and process performance. A brochure has been included in the Appendix for further reference.

**Infrared Method**

Infrared (IR) measurement of oil-in-water uses instruments that target carbon hydrogen (C-H) bonds. C-H bonds adsorb IR energy at a 3.41 micron wavelength. The instrument measures the absorption of IR energy and correlates that measurement to an oil concentration using a standard. The standard must be free of carbon and hydrogen. Originally, Freon was used, and today several other chemicals are used as reference. What is important is the procedure to create the calibration fluid in each sample. The
ADVANCED PRODUCED WATER TREATMENT

process is not easy to perform and consists of inherent user errors contributing to the final result. Due to the challenges associated with this method, it is not commonly used today and should not be considered a preferred method for subsea discharge of produced water.

Ultraviolet Fluorescence Method

Ultraviolet (UV) Fluorescence measurement methods look at the aromatic compounds in a sample and how they absorb UV radiation and fluoresce at another wavelength. “The amount of fluoresced light is proportional to the concentration of aromatic compounds in the water. Therefore, the amount of fluorescence measured is proportional to the oil in the water sample.” (Tyrie, 2007)

Top Industry Resources

In the industry today, this method is one of the preferred methods. Technologies are continuously improving with this measurement and competition to provide the technology is robust. Two top industry providers, Advanced Sensors and Turner Designs both offer equipment that performs this type of measurement and both are considered reliable. Both require a side stream installation where the flow in a pipe is routed through the unit with a smaller liner and then once through the measurement system, is sent back into the flowline. One of the challenges of using this technology is keeping the sensor windows free of built up oil/solids or wax residue which can skew the results of the measurement. Turner Designs has delivered the technology with the successful implementation of flushing methods to keep the sensors free of build up.

FIGURE 7 - TURNER DESIGNS PICTURE OF TD-4100 XD UNIT.
Advanced Sensors has employed the use of an internal ultra sonic agitation technology which keeps the sensor window clean and free of build up. Advanced Sensors suggests using both the UV Fluorescence technique along with the particle counting method to provide the best part per million oil-in-water readings.

FIGURE 8 - SIDE STREAM TECHNIQUE AND EQUIPMENT DESIGN. (COURTESY OF ADVANCED SENSORS)
ADVANCED PRODUCED WATER TREATMENT

FIGURE 9 - ADVANCED SENSORS INLINE PROBE MEASUREMENT. (COURTESY OF ADVANCE SENSORS)

Another vendor, ProAnalysis, uses a probe type measurement of UV Fluorescence spectroscopy and has many successful installations in the UK and Middle East. The provider claims low cost and virtually no maintenance requirements.

FIGURE 10 - PROANALYSIS INSTALLATION ILLUSTRATION (COURTESY OF PROANALYSIS)

Particle-Counting Method

The particle counting method can be further broken down into three techniques: measuring turbidity, Coulter counter, and visual recording of particles and their size characteristics.

Measuring turbidity was one of the earliest particle counting methods. Dispersed particles cause water to appear cloudy due to the scattering of transmitted light. An upper turbidity limit would often be specified to limit the maximum particle size and number of particles per unit volume in water to be injected.
The Caulder counter uses a small circular orifice with known dimensions and an electrical current. The particles that pass through reduce the area of the current in proportion to the size of the particle. This method must be performed in a laboratory and has limited usefulness as an oil-in-water monitor because it does not differentiate between solid particles and oil droplets.

Lastly, microscopic video cameras can be used to actually look at particles in a stream. Then computer algorithms are used to count, size and identify those particles. This method can determine if a particle is a solid, oil, or gas bubble. The size and volume of all of the oil droplets seen in a volume of water can then be added together to determine the oil-in-water concentration.

One limitation to all particle counting methods is that usually any particle below two microns cannot be seen, and therefore cannot be counted. As a result, soluble oil concentrations cannot be determined using particle counting methods.

**Top Industry Resources**

The two top vendors using this technology today with the most promise for using them in the subsea processing systems is JM Canty and Jorin. Both companies employ a video camera type method that has early engineering research for subsea applications.

JM Canty International uses a dynamic imaging based oil-in-water particle analysis and has begun to design a subsea version of the technology. Their system combines a vision based technique with the latest Ethernet camera technology, a trademark fused glass and lighting technology and a custom built software package to provide real time
ADVANCED PRODUCED WATER TREATMENT

measurements of oil in water. This technology works on the basic principle of presenting
the produced water stream between a high intensity light source, and microscopic camera.

JM Canty believe their major challenges to subsea marinization and function is in the
design of the remote connectivity of the instrumentation to the process line. Also, the
electric design and data handling need investigation and the testing and verification of
performance needs testing.

Jorin utilize a high quality camera and lens assembly looking through a flow cell an LED
(normally red ~ 680nm) light source. The images of suspended material are back lit by a
highly reliable light emitting diode (LED). Jorin suggests both the light source and
camera on their unit has a MTBF of more than 100,000 hours. The flow cell is made of
316 stainless steel or duplex, rated from 1800 psig and 120 °C. The cell windows are
made of industrial sapphire and are highly scratch resistant. The unit gives a live image
for instant process diagnosis, similar to the JM Canty unit. The Jorin unit is called the
VIPA (Visual Process Analyzer).
Jorin is working with several operators in the industry to initiate a design and develop a subsea version of their technology.

Another imaging particle counting method has been recently developed by MIT students through a RPSEA funded study 9303 which is titled Digital Holographic Imaging (Sensor for Oil-in-Water, etc.) and has been headed up by George Barbastathis of MIT. This is encouraging technology to be used to see multiphase flow. Here, students are modeling light propagation to image, 2 – 40 microns of water/oil droplet size. This method could benefit the water quality monitoring technologies as it is capable of very small resolutions, down to 9 microns. At present, the technology cannot differentiate bubbles and solid particles, but it has potential use in the future development of particle counting analyzers.

Subsea Requirements
Marinizing topside technologies for use on the seafloor can be difficult to do. Most of all the above mentioned technologies require hands on implementation and frequent service, and most are manually performed. Subsea systems have unique requirements that may not have ever been considered for topsides developments.
ADVANCED PRODUCED WATER TREATMENT

For this study, the target water depth is 5,000-8,000 feet, meaning that all equipment must be able to withstand up to 4,000 psi of external hydrostatic pressure. More importantly, all devices must be able to operate without maintenance and have a lifespan that justifies the price of installation. Obviously, any oil-in-water measurement method that must be performed in a lab would not be suitable for subsea, so one of the major challenges will be how to ensure the environmental safety of the produced water discharge to the regulatory agencies.

New and Non Typical Methods to Measure Oil-in-Water

The subsea processing system will require a good understanding of the interface position of gas, oil and water within vessels and piping in the subsea system to properly determine the processing effectiveness and efficiency. Topside systems can be manually and visually inspected by operators. Subsea systems will require remote measurements to provide the inspection. Level detection and phase determination can be done by other types of measurements such as gamma densitometer, capacitance, inductance, microwave, fiber optic and ultrasonic type measurements.

Inductance Type Sensors

While the use of inductance and capacitance measurements is well known and has been most commonly used in multiphase flow metering techniques, their use in level monitoring in separators is new. This type of sensor provides a comparison by measuring the conductivity of process water which is much higher than the conductivity in oil.

The ILMS is made up of a vertical stack of sensor elements, each measuring the conductivity in its vicinity.
Microwave Type Sensors

In addition, microwave sensors are being used to measure level and water cut detection. They have not performed to accuracy levels of parts per million readings that can be used in water quality measurements required for discharge, but can be useful in level control and water cut readings in process pipe and vessels.

FIGURE 15 - AGAR’S MICROWAVE WATER CUT METER. (COURTESY OF AGAR)

Microwave sensors used to measure oil-in-water can differentiate the water molecules’ movement from other particles. They do this by understanding the interaction of the microwaves with matter. This interaction can be in different forms such as reflections of the microwaves, refraction, scattering and absorption of the microwave, or even look at the emission of microwaves from the matter, including the change of speed and phase of the microwaves. They can be divided into different groups such as resonators, transmission sensors, reflection and radar sensors, radiometers, holographic and tomographic sensors and special sensors. They are often used to measure a wide range of quantities such as distance, movement, the shape of an object, the particle size of a particle and most commonly the material properties of an object or medium.

Permittivity and Permeability of the medium being measured are the two main properties that a microwave sensor will have an affect on interaction. Knowing that different materials have different permittivity and permeability is an identifying parameter. Some sensors will also use additional sensors for density and temperature to help identify the medium.
NIR Absorption Type Sensors

Near Infra Red Absorption methods are used by many different vendors throughout the industry. One of the most popular types of instruments using this technology is Weatherford’s Red Eye Water Cut Meter which is a near infrared absorption method type measurement for an inline probe installation.

FIGURE 16 - TYPICAL INSTALLATION POINTS FOR THE RED EYE WATER CUT METER (COURTESY OF WEATHERFORD)
ADVANCED PRODUCED WATER TREATMENT

Photometry

Vendors like Optek use a photometer to perform various fluid measurements for turbidity, UV absorption, colorimetric and conductivity type measurements. This technology uses a precisely focused light beam to penetrate the process medium. A photoelectric silicon cell measures the resulting light intensity. The change in light intensity caused by light absorption and/or light scattering is described by the Lambert-Beer law.

Lambert Beer's law states that the amount of light emerging from a sample is diminished by three physical phenomena:

1. The amount of absorbing material in its path length (concentration)
2. The distance the light must travel through the sample (optical path length OPL)
3. The probability that the photon of that particular wavelength will be absorbed by the material (absorptivity or extinction coefficient)
Due to the dark oils and the “dirty” nature of measuring oil flow in flowlines and pipelines, this technology has significant challenges for use in the subsea environment.

**Ultrasonic Frequency Measurements**

NIM Tech is a new provider of a technology measurement device that is labeled as a SonicGauge Sensor System that uses a multispectral ultrasonic measurement to see through pipelines and containers and track the chemical fingerprint of the substances flowing in the process pipe, whether they are solids, liquids, or a gas. The non invasive solution uses two or more ultrasonic transducers clamped onto the outside of a pipe. By carefully selecting the design of the multi frequency ultrasonic signals, various properties of the material are derived. This in turn creates a unique pattern profile of the substance and unique data signature. The technology is unique and has a strong potential to be used for oil-in-water monitoring.
Section Conclusion

The oil and gas industry has relied upon the 5 typical measurement principles to distinguish oil-in-water and perform water quality measurements. Direct weight measurement (being the preferred EPA method), colorimetric, infrared, ultra violet fluorescence and particle counting have all been the typical methods used throughout the industry. However reliable, their use in the subsea environment is nonexistent and methods, designs and tests need to be performed to bridge the gap of subsea oil-in-water quality monitoring.

While new methods have recently been developed using the techniques of inductance, microwave, near infrared absorption, ultrasonic and photometry methods, the widely used and proven 5 typical measurement principles can be used in combination with the new methods to improve the reliability of instruments deployed subsea. The industry has many options but new designs and testing for the subsea environment need to be developed.
6.5 PICTORIAL HISTORY OF SEABED PROCESSING

Kvaerner Booster Station (Mid 80’s)

Petrobras VASPS Technology (2000 – Ongoing)

Texaco Highlander Subsea Slug Catcher and Vertical Separator (1985)  
Alpha Thames -AESOP (1999 – 2000 Successfully Tested)
ADVANCED PRODUCED WATER TREATMENT

Good-fellow Assocs. subsea production (GASP) project
(1986 – 1990 Successfully tested)

Statoil Troll C - SUBSIS (2000 – Ongoing Pilot)

Marimba VASPS - 2001

Statoil Tordis SSBI - 2007

Shell BC-10 Separation Caisson and Boosting 2009

Shell Perdido – Separation Caisson and Boosting 2010
6.6 Installed and Planned Subsea Separation Systems

6.6.1 Introduction

The earliest subsea processing came in the form of seabed separators, the first of which was installed in 1970 on BP's Lower Zakum field off the United Arab Emirates. This installation was followed in the 1980s by the Highlander and Argyll fields in the North Sea. More recent applications include the GE / Framo Troll Pilot subsea separator off Norway on Norsk Hydro's Troll C field (Ref: Douglas-Westwood, The Subsea Processing Gamechanger Report 2003-2012). There are about a dozen examples of installations worldwide, but the number of subsea processing units installed are expected begin to increase rapidly as the technology matures and installation track records grow.

As the technology for the multiphase booster pumps improves and is able to handle a fairly high gas volume fraction, the efficiency requirements for the gas-liquid separation is lessened. However, there is still a large potential to improve the separation efficiency and design more robust subsea processing systems. Better efficiency will lead to high pump reliability and less equipment down time.
ADVANCED PRODUCED WATER TREATMENT

The overall cost of a subsea processing station can be significantly reduced by use of compact separation technologies. The Statoil Tordis and Total Pazflor separators are located at relatively shallow water depths of approximately 200 and 800 meters respectively. It is not feasible to install or manufacture large vessels when developing fields at excessive water depths. This is one of the reasons why ultra deepwater projects such as Perdido (Gulf of Mexico) and BC-10 (Brazil) are using caisson separators. A caisson separator is comprised of components that can be used at extreme water depths. This solution is however not optimal as it has limited performance and capacity. Hence, the industry needs more efficient separation technology to enable cost efficient exploitation of this technology at all water depths. (OTC 20080 paper, 2009)

Table 7 summarizes the installed and planned subsea separation systems.

Table 7 - Listing of Subsea Separation Installations

<table>
<thead>
<tr>
<th>OPERATOR / YEAR</th>
<th>FIELD NAME</th>
<th>TECHNOLOGY USED</th>
<th>TECHNOLOGY TYPE</th>
<th>TECHNOLOGY SUPPLIER</th>
<th>WATER DEPTH ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statoil 2001</td>
<td>Troll C</td>
<td>Horizontal SUBSIS</td>
<td>Separator</td>
<td>GE / Framo</td>
<td>1,116</td>
</tr>
<tr>
<td>Petrobras 2001</td>
<td>Marimbá</td>
<td>VASPS</td>
<td>Separator &amp; ESP</td>
<td>Saipem</td>
<td>1,265</td>
</tr>
<tr>
<td>Statoil 2007</td>
<td>Tordis</td>
<td>Horizontal</td>
<td>Separator</td>
<td>FMC/CDS</td>
<td>689</td>
</tr>
<tr>
<td>Shell 2009</td>
<td>BC-10</td>
<td>Caisson</td>
<td>Separator &amp; ESP</td>
<td>FMC/CDS</td>
<td>6,562</td>
</tr>
<tr>
<td>Shell 2010</td>
<td>Perdido</td>
<td>Caisson</td>
<td>Separator &amp; ESP</td>
<td>FMC/CDS</td>
<td>9,600</td>
</tr>
<tr>
<td>Petrobras 2011</td>
<td>Marlim</td>
<td>Inline</td>
<td>Separator</td>
<td>FMC</td>
<td>2,881</td>
</tr>
<tr>
<td>Total 2011</td>
<td>Pazflor</td>
<td>Vertical Separator</td>
<td>Separator</td>
<td>FMC/CDS</td>
<td>2,625</td>
</tr>
<tr>
<td>Petrobras 2012</td>
<td>Congro</td>
<td>VASPS</td>
<td>Separator &amp; ESP</td>
<td>FMC</td>
<td></td>
</tr>
<tr>
<td>Petrobras 2012</td>
<td>Malhado</td>
<td>VASPS</td>
<td>Separator &amp; ESP</td>
<td>FMC</td>
<td></td>
</tr>
<tr>
<td>Petrobras 2012</td>
<td>Corvina</td>
<td>VASPS</td>
<td>Separator &amp; ESP</td>
<td>FMC</td>
<td></td>
</tr>
<tr>
<td>Petrobras TBA</td>
<td>Canapu</td>
<td>Inline Supersonic</td>
<td>Separator</td>
<td>FMC Twister</td>
<td>5,579</td>
</tr>
</tbody>
</table>

6.6.2 Troll C Subsea Separation System

Ref: Offshore Magazine Published: Nov 1, 2002 Terje Horn, Norsk Hydro ASA Nils Arne Soelvik, ABB Offshore Systems Inc.

The world's first subsea water separation and injection system – the Troll C subsea separation system is tied back 3.3 km to the Troll C platform in 350 m of water. The subsea station makes it possible to separate water from the wellstream on the seafloor and re-inject it into a low-pressure aquifer so that the water does not have to be transported
ADVANCED PRODUCED WATER TREATMENT

back to the main platform. Eight wells can be routed through the processing station, which is designed to process four wells at a time.

How it works

FIGURE 21 - TROLL C SUBSEA PRODUCED WATER RE-INJECTION PUMP MODULE - FRAME

The main processing modules are the horizontal gravity-based separation vessel and the subsea water re-injection pump. A fully automated control system with separation level instrumentation and variable speed drive system provides the main functional blocks for control of the process system.

The wellstream is routed into the separator from one of the main production lines. Pre-processing is done in an innovative inlet mechanism called a low-shear de-gassing device. Its purpose is to split the gas and liquids to reduce the speed of the liquids and limit the emulsion formed. Once past the inlet device, the liquid is allowed to settle in the separator vessel, and the separated water is taken out directly to the water re-injection pump. From there, the oil and gas is commingled and forced back to the Troll C semi by the flowing pressure in the separator and pipeline system. The separated produced water is re-injected into the disposal reservoir by the subsea water injection pump via a dedicated injection well.

FIGURE 22 - DESIGN PARAMETERS FOR THE TROLL C SUBSEA SEPARATION STATION

Design parameters for the Troll C subsea separation station

Total liquid capacity: 10,000 cu m/day (~ 63,000 b/d)
Water capacity: 6,000 cu m/day (~ 30,000 b/d)
Oil capacity: 4,000 cu m/day (~ 25,000 b/d)
Gas capacity: 800,000 cu m/day (~ 20 MMscf/d)
Max water cut: 90%

Key performance requirements for the Troll C subsea separation station

Max oil in water (re-injection product): 1,000 ppm
Max water in oil (produced to host): 10%
ADVANCED PRODUCED WATER TREATMENT

The water/oil interface is read by the level detection system, and the reading is fed back to the process controller topside via a fiber-optic communication system. The communication system calculates the required pump speed, feeds that data to the frequency converter that sets the pump speed, and the main loop of the process control is closed.

How it performs

The primary purpose of the subsea separation station is to separate and remove as much water as possible, hence the injectivity and rate into the injection well is very important. The subsea water re-injection pump was required to enable adequate injection. The required pressure at the water injection wellhead shows a downward trend. This is positive for the injectivity and indicates that the injection well completion and formation is capable of taking the increased water production.

Another positive consequence of the improving injectivity is low power consumption for pumping the produced water into the reservoir. This reduces the energy cost per injected barrel of water and shows that there are substantial margins of the pump for later increasing water cut.

In the operation regime for the subsea separation system, the separator efficiency is measured by the amount of water left in the wellstream and the remaining oil in the produced water. Looking at the water in oil first, the system proves its functionality for total oil rates at or below the specified requirement of 4,000 cu m/day. When the system
ADVANCED PRODUCED WATER TREATMENT

is producing up to 75% to 80% of the design oil rate, the amount of water in the oil is consistently in the range of 4% to 6% of wellstream volume. When producing at 100% oil rate, the water content reaches the maximum water-in-oil content of 10%.

FIGURE 24 - THE AMOUNT OF PRODUCED WATER FROM THE SUBSEA SEPARATION STATION INJECTED IN PERCENT OF THE TOTAL WATER HANDLED THROUGH THE TROLL C TOPSIDE AND SUBSEA.

The produced water quality is measured from ROV samples taken from a sampling point at the subsea processing station and brought back to surface for analysis. Over a year, five samples were brought back to surface and showed results from 15 to 600 ppm. The 15 ppm, was taken when the subsea processing station was producing at 100% design liquid flow rate.

FIGURE 25 - THE AVERAGE MONTHLY AMOUNT OF WATER INJECTED (B/D)
ADVANCED PRODUCED WATER TREATMENT

The stable pressure and temperature in the separator, together with the performance results, demonstrate how quickly the process operators were able to determine how to operate and maintain stable processing conditions. The Troll C subsea separation station has performed to specification and with nearly 100% availability. These results can be attributed to a combination of skilled operators, the robustness of the subsea processing system, and the emphasis StatoilHydro has put on training and knowledge transfer. It is a proven investment in new technology that has and will generate payback for the operator.

6.6.3 Petrobras Marimba - VASPS Prototype

Ref: SPE 95039, “VASPS Prototype in Marimba Field—Workover and Restart,”

The Vertical Annular Separation and Pumping System (VASPS) represented an innovative concept for subsea gas/oil separation and pumping. A Joint-Industry Project (JIP) involving AGIP, ExxonMobil, and Petrobras developed the VASPS prototype was installed in 2001 in the Marimba field in the Campos basin.

After the gas/liquid mixture is separated by passing through a helical channel, the liquid phase is pumped by an ESP, and the gas is vented to the platform. In July 2001, Well MA-01 was producing 750 m³/d of fluid with 100,000 m³/d of gas from gas lift. Wellhead pressure was 36 kg/cm². After VASPS installation, the subsea phase separation allowed the wellhead pressure to be reduced to 11 kg/cm². This resulted in a production increase of 1000 m³/d without gas lift. The performance and operating stability of the subsea separator was proved.

- Gas-Liquid Separation
- Oil and Water Not Separated
Vertical Annular Separation and Pumping System (VASPS) Installation Data

**Operation Parameters**
- Design liquid flow rate – up to 1,500 m$^3$/d
- Design gas flow rate – up to 190,000 m$^3$/d (20 °C @ 1 atmosphere)
- Separation temperature – 40 to 70 °C
- Seabed temperature – 5 °C
- Maximum fluid temperature – 89 °C
- VASPS separation pressure – 8 to 12 bar (typical)
- Design pressure – 3,000 psi
- Pump head & power – up 70 bar & 150 kW
- Platform arrival pressure – 7 bar
- Sand – 1 m$^3$/year (maximum rate)
- Power supply – 480 V @ 60 Hz
- Step up transformer – to 1,375 V in the ESP motor
- Level control – Subsea control valve & VFD on the ESP motor supply

**Well Fluid Properties**
- GOR – 74 to 60 Sm$^3$/m$^3$
- PI – 32 m$^3$/d/kgf/cm$^2$
- Gas lift rate – GLIR of 60 Sm$^3$/m$^3$
- Oil Density – 29°API
- Dead oil viscosity – 14.3 cP (at 38 °C) 7.6 cP (at 60 °C)
- Oil-water emulsion potential – yes (inhibitors are needed)

**Umbilical**
- Length – 1,750 m
- Features – Nine hydraulic function + power cable

---

*FIGURE 26 – (1) VASPS - INSTALLED IN MARIMBA FIELD 2001 (OTC 18198), (2) VASPS CONCEPT (OTC 18198)*
The results showed that the separation feasibility increased with temperature and with the watercut. The oil at Marlim is very viscous (395 cP @ 25°C), reasonably heavy (19°API), with a very strong tendency to form stable oil-water emulsions. Tests performed in the laboratory, on stable water-oil emulsions with up to 80% watercut showed the need for chemicals to break the emulsion.

The subsea separation system needs to be installed close to the producer wellhead where the water depth is around 1,000 m, the fluid pressure is 85 bar and the fluid temperature is 55°C. These conditions contribute to the separation process because the higher the temperature, the easier the separation and the higher the pressure, the more light oil fraction will continue in solution, which keeps the fluid viscosity low. Chemicals are still necessary to break the emulsion.

Ref: OTC 18198 Application of Subsea Processing and Boosting in Campos Basin

6.6.4 Statoil Tordis - Subsea Separation Boosting and Injection (SSBI)

The StatoilHydro Tordis project in the North Sea uses a semi-compact gravity based separation concept that has been specially developed for subsea applications. The design is designated as semi-compact because the gas is removed in a cyclonic inlet such that the main settling portion of the separator operates flooded. The vessel is 17 meters long, with a diameter of 2.1 meters. With a total liquid retention time of approximately 3 minutes, this separator was designed for a capacity of 100,000 bwpd and 50,000 bopd. It does not have strict quality requirements for the hydrocarbon stream, as the concept is primarily focused on removing the water from the total liquid, thus reducing the hydrostatic head on the oil flow line.
ADVANCED PRODUCED WATER TREATMENT

The water stream was designed to meet a maximum of 1,000 mg/l. At project start up, an ROV sampling system was used to confirm how well the separator was performing and it seemed to surpass the design specification with a water sample that contained about 500 ppm of the original oil.

The Tordis system is a water and sand separation and re-injection system. The water and sand are separated from the well-stream in the separator vessel, where the sand separates and accumulates at the bottom. The vessel includes a sand removal system which is operated by high pressure water from the water injection pump. This system is a dual redundant system with two independent technologies:

- A CDS Sand Jetting system as the primary sand removal
- A cyclonic sand removal system which can be operated as a back-up in case of a potential failure to the main sand removal system.

It was found that the separator risked having solids clog and stick to the bottom of the vessel without the use of the internal sand jetting system. An important lesson learned was that the sand jetting system would be required to operate more often than originally designed.

The removed sand is transported to a desander and sand accumulator vessel in batches. The sand collected was originally disposed of with the water into an injection well, but after having problems with the injection well, that stream was sent to the surface production via an alternate flow line. The sand handling system was qualified for continuous operation with 1100 lbs/d sand.

Ref.: OTC 20080 paper, 2009

The sand handling system applied for Tordis was qualified through a Subsea Separation and Sand Handling System qualification program executed at FMC’s facilities in the Netherlands during 2003 and 2004. The In Line De Sander/sand accumulator was qualified as part of the Technology Qualification Program of the Tordis project in 2005.
ADVANCED PRODUCED WATER TREATMENT


FIGURE 29 - TORDIS SSBI - SUBSEA SEPARATOR (COURTESY OF FMC TECHNOLOGIES)

FIGURE 30 - TORDIS SUBSEA SEPARATOR FLOW DIAGRAM (COURTESY FMC TECHNOLOGIES)

Tordis Summary

Produced Water Separation and Injection + Oil and Gas Boosting
Water depth: 650’
Step-Out: 6.9 mile
Design Pressure: 3,000 psi
Liquid Capacity: 100,000 bwpd and 50,000 bopd
Multi-Phase Pump: Helico-Axial to 68% GVF x 2.3MW x 450 psi
Water Injection Pump: Single Phase 2.3 MW x 1,100 psi
Installation: 2007

Scope of Work: Subsea Separator Station, Pump, control

- First sand management system
- First density profile (sand, water, emulsion, oil and foam sensing system)
- First semi-compact separator (centrifugal gas separation and by-pass)
- Semi-compact separator 2.0 m OD x 12 m t/t
- Horizontal separator; water for re-injection
- Design Spec
  - 1000 ppm oil-in-water; observed performance of 500 ppm
- 17 m Long, diameter 2.1 m; liquid retention time 3 minutes
- Capacity 100 K bwpd, 50 K bopd
- Sand was disposed with water to injection well, then surface facility
- Lessons learned
  - Sand jetting was required more often than designed.
  - A CDS Sand Jetting system as the primary sand removal
  - A cyclonic sand removal system as a back-up
  - The removed sand is transported to a desander and sand accumulator vessel in batches.
  - The accumulated sand is pressurized and transported to the discharge side of the water injection pump.

6.6.5 Shell Parque das Conchas (BC-10)

Parque das Conchas, also called BC-10, is in the north of the Campos Basin, offshore Brazil. The project consists of five fields: Production from phase one began on 13 July 2009. The fields have estimated reserves of 400 million barrels of heavy crude oil. Phase two is expected to come on-stream in 2013.

The project needed an economic design for linking productions from different reservoirs to the central facility. It involved a vertical caisson separator system developed by FMC and Shell. The separator had an artificial lift (AL) and subsea gas and oil separation system. A 300 ft caisson, which consisted of a cylindrical cyclonic gas and liquid separator and a 1,500 hp electrical submersible pump, was driven into the seabed.

FIGURE 31 - SHELL BC-10 SEPARATION CAISSON
ADVANCED PRODUCED WATER TREATMENT

Ref. E&P Magazine Seabed production boosting systems push the limit – July 1, 2010

The development concept is to tie back to artificial lift manifolds. Production from two manifolds will be co-mingled in electric submersible pump (ESP) caissons, which provide boost. Production will be sent up oil and gas risers to the floating production, storage, and offloading vessel (FPSO).

Caisson ESPs boost the production in reservoirs with a low gas volume, while the separator caisson ESPs will separate the gas from the liquids at fields, where higher gas volumes could cause decreased ESP efficiency. Both the caisson ESP and the separator caisson ESP are 100m long by 42in with a 32in internal liner. Shell is using Centrilift ESPs.

It's essential, to measure the fluid levels in the caissons to operate the pump effectively. To do so, multiple pressure gauges in the caisson system measure liquid levels. Based on the results, Shell can adjust the pump speeds to ensure a continuous stream of fluids to the pump and to minimize any liquid carryover in the gas riser.

To make the ESPs function more efficiently and produce better, Shell is using two-phase subsea separation to separate gas from liquids. Production goes into a caisson with a tangential separator, oil drops to the bottom, and gas goes to the top. Liquid is then pumped through the large ESPs that are inside the caisson and pumped to the surface.

Shell is investigating twin screw pump technology and multiphase pump technology but pointed out that it is possible that ESP caisson technology may work in Phase 2 as well. All the fields require a substantial amount of boosting in the range of around 2,000 psi to overcome the backpressure on the well at the seafloor.

6.6.6 Shell Perdido - Gulf of Mexico

This is FMC Technologies second full field development with Shell using five Caisson Separator Assemblies for subsea oil and gas separation and boosting, following the award of the Shell BC-10 project in offshore Brazil. The Perdido project has a SPAR-based processing hub moored in an estimated 7,874 ft of water, making it the deepest production SPAR in the world.

(Ref Oil & Gas Financial Journal Article Apr 1, 2010):
ADVANCED PRODUCED WATER TREATMENT

Description of the Vertical Caisson Separator System
- Multiphase flow from subsea wells enters Top End Assembly (TEA) through Manifold Multibore Interface (MMI)
- Multiphase flow introduced to Vertical Caisson Separator (VCS) through a purposefully angled and tangential inlet
- Separation of multiphase inlet flow into liquid and gas components occurs as stream spirals down inside of VCS.
- Centrifugal and gravitational forces cause heavier elements (solids, liquids) to be thrown outward to VCS wall and downward to Caisson Sump (CS).
- ESP suspended from ESP Hanger on tubing pumps liquids and associated solids from CS to TEA flowloop, through MMH and downstream through in-field flowline to Production Host Facility (PHF)
- Gas liberated from multiphase stream rises naturally through annulus created between OD of ESP tubing and ID of VCS into TEA flow-loop, through MMH and downstream through in-field flowline to PHF.

ESP string, TEA and VCS may be retrieved sequentially from permanently installed Manifold.

6.6.7 Total Pazflor Subsea Separation System
The Pazflor system is a subsea gas liquid separation and liquid boosting system. The purpose of the separator is to remove the gas from the liquid, such that the liquid can be pumped while gas flows free to the surface. The Pazflor project includes three subsea separation stations, each including one separator and two hybrid boosting pumps. The separator is designed to ensure no sand accumulation. In addition, a sand handling system including a proprietary sand flushing arrangement is installed as a back-up solution to remove any build-up of sand during operation. The sand handling was qualified as part of the Technology Qualification Program during an extensive separation and sand handling qualification program in 2008.
ADVANCED PRODUCED WATER TREATMENT

The Pazflor vertical subsea separator designed by FMC stands 9 meters tall and 3.5 meters wide. Its use of booster pumps able to accommodate high gas volume fraction liquids helps the unit operate more effectively.

(OTC 20080 paper, 2009)

FIGURE 33 - PAZFLOR VERTICAL SUBSEA SEPARATOR LOAD-OUT (COURTESY OF FMC TECHNOLOGIES)

Subsea produced water treatment in ultra deepwater developments will have to consider the higher pressure requirements. Vertical separators, extended flow pipe loops and separation caissons can increase a system working pressure design and allow for more effective separation.

Summary:

- Vertical Gas-Liquid Separation
- Purpose is to reduce gas volume fraction to enable multiple pump use
- Vessel design including curved lower section to prevent sand accumulation
- A sand handling system including sand flushing is installed as a back-up solution to remove sand build-up

6.6.8 Petrobras Marlim Subsea Separation System

The Marlim system is the most complex subsea processing project executed to date. The water is separated from the well-stream and re-injected back into the reservoir. This is the first application where the produced water is used for pressure maintenance of the reservoir as part of the subsea separation operation and also the first subsea heavy oil application.

The system includes a Pipe Separator concept for the separation of the water from the well stream and a water treatment system using InLine HydroCyclones. The sand
handling system includes an InLine De Sander at the inlet of the separation system. The purpose of this is to remove the majority of the sand, from the multiphase well stream, to protect the downstream equipment and to avoid sand accumulation. It also contains a dual redundant Sand Jetting System in the outlet section of the Pipe Separator and an In Line De Sander for removal of the smallest particles in the water stream from the separator to protect the re-injection well and reservoir. The separated sand is routed with the oil up to the topside facility.

All the separation and sand handling equipment has been tested as part of the technology qualification program started 4Q 2009, and completed 2Q2010.

FIGURE 34 - FMC - 2 PHASE GAS / LIQUID SEPARATION USING INLINE TECHNOLOGY

FIGURE 35 - INLINE HYDROCYCLONE

6.6.9 Petrobras Congro, Malhado & Corvina
- VASPS with Horizontal ESP
ADVANCED PRODUCED WATER TREATMENT

- The control system incorporates an innovative subsea robotics technology, designed by Schilling Robotics, to operate the manifold and separation station valves.

6.6.10 Petrobras Canapu

- Twister BV. In-line supersonic
- Process steps in a compact, tubular device
  - Expansion
  - Cyclonic gas/liquid separation
  - Re-compression
- Dehydrate gas and removes heavy hydrocarbon components
- Technology is not applicable to oil-water separation

FIGURE 36 - PETROBRAS CANAPU

How it works

The Twister® Supersonic Separator has thermodynamics similar to a turbo-expander, combining the following process steps in a compact, tubular device:

- expansion
- cyclonic gas/liquid separation
- re-compression

Whereas a turbo-expander transforms pressure to shaft power, Twister achieves a similar temperature drop by transforming pressure to kinetic energy (i.e. supersonic velocity):

- Multiple inlet guide vanes generate a high velocity vortex, concentric swirl (up to 500,000 g)
- A Laval nozzle is used to expand the saturated feed gas to supersonic velocity, which results in a low temperature and pressure.
- This results in the formation of a mist of water and hydrocarbon condensation droplets.
- The high velocity vortex centrifuges the droplets to the wall.
- The liquids are split from the gas using a cyclonic separator.
- The separated streams are slowed down in separate diffusers, typically recovering 70 - 75% of the initial pressure.
- The liquid stream contains slip-gas, which will be removed in a compact liquid de-gassing vessel and recombined with the dry gas stream.
Simulations demonstrate that, when expanded through a Twister tube, H₂S and CO₂ gases condense and can be removed in the liquid phase. Twister can therefore be considered for pre-treatment of high concentration sour gases prior to conventional amine-based sweetening processes, freeing up capacity and reducing size and cost. Twister is currently involved in various strategic co-operations for developing new sour gas treatment technologies. The era of easily recoverable sweet gas is closing, and Twister may become the technology differentiator, enabling new ways for processing sour gas.

ADVANCED PRODUCED WATER TREATMENT

6.6.11  Multiple Application Re-injection System (MARS)

MARS is a unique wellhead interface that allows any processing equipment, e.g. (multiphase pump, multiphase meter, chemical injection, etc) onto any wellhead (platform, subsea or land based). This technology delivers multiple production optimization solutions where it’s needed and when it’s needed.

Since incorporating in 1999, DES has had global success with its MARS™ and POSSibilities™ technologies. Several major operators, including BP and Shell, have incorporated these products to optimize production from both new and existing fields.

MARS offers strategic flexibility and maximum productivity in a cost-effective package. DES, have developed a cost-effective well intervention system which allows operators to significantly minimize the cost, downtime and risk normally associated with subsea chemical stimulation operations.

The patented MARS system is a Cameron technology, supplied by DES. The technology enables multiple processing technologies to be retrofitted onto subsea trees and is being applied by Chevron to perform subsea chemical squeeze operations on existing wells in Angola. Chevron and DES have integrated the MARS system into an existing subsea infrastructure enabling chemical scale squeeze operations from an ROV support vessel, eliminating the need for MODU support.

The MARS interface is adaptable to any subsea tree enabling the integration of a variety of processing equipment to an operator’s asset. MARS is a cost effective well intervention system which allows us to significantly minimize the downtime associated with subsea chemical stimulation operations. DES provides customers simplified subsea processing for both on and off the wellhead applications.
In November 2008, Shell selects the MARS System for well stimulation operations on the Pierce field in the North Sea. The order followed the successful installation in their Bittern field. In the Pierce installation, the MARS system will allow subsea chemical squeeze operations from an ROV-support vessel, eliminating the need for MODU support. This capability increases safety, saves time and reduces costs over traditional intervention methods. The patented MARS system enables multiple processing technologies such as pumps, meters or chemical injection skids to be retrofitted onto any wellhead at any time during the life of the field.

In August 2007, Chevron selects MARS for the long-term subsea production optimization strategy on Chevron’s Lobito Tomboco Field in Angola. MARS had been previously used by BP for subsea multiphase pumping in the Gulf of Mexico by Total in Angola and Shell in the North Sea for subsea multiphase metering and well stimulation respectively.

6.7 Subsea Separation, Oil/Solid Removal from Water and Other Related Technologies Under Development

6.7.1 Aker Solutions DeepBooster with Subsea Separation
- Compact degassing and scrubbing as a first separation stage
- Compact Electrostatic Coalescer, CEC
ADVANCED PRODUCED WATER TREATMENT

- Technology is qualified and has several topside applications
  - Compact separator due to the CEC
  - Cyclonic Separation, Multistage cyclonic separation
    - Reduces oil content in water down to 40-100 ppm.
    - Liquid booster: Multistage centrifugal pump concept

FIGURE 40 - AKER SOLUTIONS DEEP BOOSTER WITH SEPARATION SYSTEM FLEXSEP

6.7.2 Alpha Thames Subsea AlphaPRIME Incremental Field Developments - KeyMAN™

This is a low cost approach using Standardized modules. It does not need every eventuality to be included up-front. The CAPEX is reduced and the re-configuration of equipment during the field’s life enables production to be optimised to significantly increase the amount of recoverable reserves. It has the following features:

- Simple, passive manifold
- All field-proven, industry-standard equipment
- Fully rated for field shut-in pressure
- Low cost, future-proof “Insurance Policy”
- Local fabrication
- Standard design
- Simple System, standardised manufacture, quick and easy to install
- Bypass facility enables production to continue during upgrade/reconfiguration, system maintenance and repair

FIGURE 41 - KEYMAN™ - PASSIVE MANIFOLD BASE

Retrievable Modules
- Standardized Interface
- Electric Operation
ADVANCED PRODUCED WATER TREATMENT

- Processing
- Boosting
- Water Injection
- Gas Compression
- Metering
- Can Include HIPPS

FIGURE 40: KEYMAN™ RETRIEVABLE MODULES

Boosting & Gas Compression  Processing & Water Injection

Metering & HIPPS  Dummy Module

FIGURE 42 - FEATURES OF A 3-PHASE SEPARATION & WATER INJECTION SYSTEM-MODULE

This configuration contains 1st stage separation and fast acting electric actuators to control level. It includes simple single speed liquid pumps for boosting oil, re-injecting produced water and injecting make-up water. The module includes an autonomous control system to monitor the process and provide prompt response to signals.
- Nodal developments – making best use of existing infrastructure
- Electric Power distribution – subsea ring main for power and services
- Smart Controls – ability of the system to accommodate new devices
- Electric Trees – combining the operation of electric trees with seabed processing
- Sand management – simple inclusion of sand management devices to avoid damage to subsea equipment
- Dispense with Well test lines
- Specify gas lift and injection water lines with lower pressure rating
- Develop single wells with the benefit of seabed processing
ADVANCED PRODUCED WATER TREATMENT

• Transportation of heavy oils or the mitigation of emulsions, whilst avoiding topside processing bottlenecks
• Plug and play HIPPS – avoiding expensive pipelines
• Dynamic Separation and Slug control – ensuring that the installed process equipment can accommodate the current production conditions
• Modular Systems – Integrated processes/machines operating with minimal interfaces for optimum reliability
• Deployment System Architecture
• Enabling Technology – Electric Actuators, High Power Electric Connectors, Subsea Gas Compressors

Benefits of the AlphaPRIME approach to the industry:
• Faster sanction / low initial CAPEX / Early First Oil
• Optimised solution throughout field life
• Increases recovery from new and existing fields
• Plug-and-Play processing
• Accommodate the unexpected – highly flexible
• Faster sanction / low initial CAPEX
• Planned maintenance / leasing opportunities
• Suitable for marginal field developments
• Standardised approach – faster regulatory approval
• Allows all contractors / manufacturers / equipment suppliers to participate
• Trial new equipment
Table 8 – Listing of Alpha Thames Patents

<table>
<thead>
<tr>
<th>AlphaPRIME™ Field Development</th>
<th>AlphaPRIME™ CPU</th>
<th>Individual Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Importance</td>
<td>Strength</td>
<td>Patent (Item no.)</td>
</tr>
<tr>
<td>III</td>
<td>5</td>
<td>S</td>
</tr>
<tr>
<td>1</td>
<td>W</td>
<td>Figgion (3)</td>
</tr>
<tr>
<td>3</td>
<td>VS</td>
<td>Electric Tires - Power &amp; Control (4)</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>Disposal Of WH Test Line (6)</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>Downloads 1st Pump (7)</td>
</tr>
<tr>
<td>4</td>
<td>VS</td>
<td>Fluid Transportation (9)</td>
</tr>
<tr>
<td>3</td>
<td>MS</td>
<td>Sand Management (9)</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>Low Pressure Water Injection on Line (10)</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>Single Well Development (14)</td>
</tr>
<tr>
<td>1</td>
<td>W</td>
<td>Early Production (13)</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>Low Gas Injection Line (16)</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>Node/Grill Development (20)</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>Smart Control Development (31)</td>
</tr>
</tbody>
</table>
The Compact Electrostatic Separator allows rapid separation of oil from water in a subsea environment by reducing the entrained water. The skid consists of a 14” compact electrostatic separator capable of processing 2,500 Bbl/day of oil and water. The skid is 10’ x 24’ and weighs approximately 27,500 lbs. The temperature can range from ambient to 200° F, and the pressure can be up to 300 psig 2500 Bbl/day at 20 cps. The unit can intake up to 70% water and output oil with less than 10% water and water with less than 200 ppm oil.

FIGURE 43 - CAMERON SUBSEA COMPACT ELECTROSTATIC SEPARATOR
ADVANCED PRODUCED WATER TREATMENT

6.7.4 Cameron Two-Phase and Three-Phase Compact Subsea Separators
- Without ESP
- With ESP
- Using Electrostatic Method

![FIGURE 44 - CAMERON THREE PHASE SUBSEA SEPARATION PROCESS](image)

6.7.5 FMC InLine Electrocoalescer
This uses electric fields to encourage water-in-oil droplet growth and emulsion breakdown to enable effective oil-water separation. It is designed to be fitted into pipe spool upstream of the separator. High voltage power systems and process designs results in more efficiency and compact design and lower high voltage power consumption. There
ADVANCED PRODUCED WATER TREATMENT

are no moving parts which minimize the downtime and periodic maintenance. Material selection enables long lifetime without need for maintenance. Since pressure vessels can be reduced in size, or sometimes even be eliminated when applying inline separation equipment, compact equipment is ideal for subsea separation and other high-pressure applications.

ElectroCoalescer test:

- 50 m$^3$/h through 4” unit
- Residence time: 0.14 s
- Crude oil
- 20% water cut

6.7.6 FMC InLine DeWaterer
- Axial flow cyclone design
- Specially designed swirl element - low energy loss and shear.
- An oil core is formed by the oil droplets
- The separated oil is removed through a reject (overflow) opening
- The clean water leaves the cyclone through a water outlet (underflow)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil in Water at inlet</td>
<td>1 - 50 %</td>
</tr>
<tr>
<td>Oil in Water after separation</td>
<td>200 - 2000 ppmv</td>
</tr>
<tr>
<td>Gas Volume Fraction at inlet</td>
<td>0 - 50 %</td>
</tr>
<tr>
<td>Total Flow rate at inlet</td>
<td>10 - 40 m$^3$/h</td>
</tr>
<tr>
<td>Water removal efficiency</td>
<td>&gt; 95 %</td>
</tr>
<tr>
<td>Pressure drop reject</td>
<td>0.3 - 2.5 Bar</td>
</tr>
<tr>
<td>(from inlet to oil outlet)</td>
<td></td>
</tr>
<tr>
<td>Pressure drop underflow</td>
<td>0.1 - 2.0 Bar</td>
</tr>
<tr>
<td>(from inlet to water outlet)</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 46 – In Line Dewater Principle and Performance
ADVANCED PRODUCED WATER TREATMENT

6.7.7  GE Nu-Proc Test Separator with Electrostatic Coalescer

- GE
- DEMO 2000 – 2004
- Made to fit Statoil Hydro’s test loop
- Length: 5200 mm
- Diameter: 630 mm
- Capacity: 6000 bl/day (as test loop)
- Max Pressure: 100 bar (as test loop)
- Max Temp: 120 ºC (as test loop)
- Dual VIECS, Dual LOWACCS

Installation of NuProc™ Test Rig in Hp Test Loop

Subsea Compression (Ormen Lange, Åsgard)

Inductive Level Profiler

NuProc Test Deep Water Separator
Volume 6 m³

Nucleonic Level Profiler
ADVANCED PRODUCED WATER TREATMENT

FIGURE 47 – Advance Separation Techniques

FIGURE 48 - ELECTROSTATIC COALESCENCE, V1EC

FIGURE 49 - ELECTROSTATIC COALESCENCE, LOWACC
6.7.8  

**Saipem Subsea Separators Concept - Vertical Multi-Pipe (VMP)**

- COSSP (2-Phase Gas/Liquid Separation & Boosting System)
- 3-Phase Separation Module

![Image](image.jpg)

**FIGURE 50 – SAIPEM SUBSEA SEPARATORS CONCEPTS – VERTICAL MULTI-PIPE (VMP)**

Saipem has developed a subsea gas/liquid separation and boosting station integrating a gravity separator made of pipes, specifically designed for the deepwater environment. The Vertical Multi-Pipe Separator is composed of an array of vertical pipes that provide the required separation and liquid hold up volume. The reduced diameter and wall thickness of the vertical pipes, as compared with the equivalent single separation vessel, is designed for deep and ultra-deep water applications and/or high pressure services. Furthermore, the system relies on the gravity separation whose efficiency is less prone to the input flow rate and the unsteady regimes than dynamic separation processes. Validation of the separation performances was carried out, within the framework of a JIP sponsored by BP and Total, in a pressurized multiphase loop handling crude oil, natural gas and water.

The subsea separation of the associated gas and the subsea boosting of the liquid through pumps in deep water, allows longer tie back distances. The separator is also beneficial in the management of the slugs that may be generated in the subsea flowline network and some flowing conditions. The capability of handling large slug volumes is in many cases the sizing criteria for the subsea separators that also provide the residential time for the gas and liquid phase to separate.

The combination of large volume and diameter separators in deep water is associated to very thick wall separator shells to resist to collapse when operating in low or depressurized conditions. The novel approach to the deep water separation aims at avoiding costly, long lead pressure vessels and using line pipes to provide the separation and slug handling volumes.
ADVANCED PRODUCED WATER TREATMENT

Ref: OTC 21394
A Novel Gas/Liquid Separator to Enhance Production of Deepwater Marginal Fields

This concept consists of 7 vertical cylindrical pressure vessels grouped in a circular bundle interconnected at the top, middle and bottom. The vessels are 42” dia. and 15 m tall. The production enters the vessel group in the center, allowing the gas and liquids to separate. The foundation is a suction pile with two diametrically opposed caissons for ESPs attached to it. The liquid outlet from the vertical separators is piped to the ESPs for transmission to the FPU. The separated gas is taken off the top of the separator bundle and piped to the FPU.

Design parameters:
- 530 cu m/hr (about 80,000 b/d)
- ESPs ΔP is 180 bar
- Radar level controls
- Separators weight bundle = 160t
- Suction pile foundation weight = 200t
ADVANCED PRODUCED WATER TREATMENT

FIGURE 51 – CONFIGURABLE SUBSEA SEPARATION AND PUMPING SYSTEM

- Compact System Design
- Does not require Large Pressure Vessels
- Suitable for Deep and Ultra Deepwater
- Reliable Process Design (Gravity Separation)
- “Off the Shelf” Components
- Good Slug Handling Capabilities
- Proprietary Design for Radar Based Level Sensors
- Suitable for ESPs or Twin Screw Pumps
- Retrievable Manifolds and Pump Modules

6.7.9 IN-LINE ROTARY SEPARATOR (IRIS)

Introduction
The IRIS, developed by Multiphase Power & Processing Technologies, is an ultra-compact in-line separation device designed to “scrub” liquids from a wet gas stream. The technology provides high quality separation at significantly smaller equipment size than current technology. A cross section of this device is shown below. Separation is achieved by a free-spinning rotor wheel, which derives power from process pressure. Requirements are a 1-7% pressure drop for operation, depending on the liquid content. Maximum inlet liquid content that can be handled is 4% by volume.

It can operate equally well at the wellhead or pipeline, and will provide significant advantages in retrofit, debottlenecking, and new installations. The compact size produces the highest throughput-to-size ratio of any scrubbing equipment and greatly reduces liquid inventory hold-up over vessel based technology. In-line installation eliminates support skid and allows fast changeout. Envisioned applications for the IRIS include gas transmission and metering runs, compressor suction or discharge, absorber/contactor inlet or outlet, well testing and proving, or as a standard or secondary scrubber.

Testing Of An In-Line Rotary Separator
**Operation Description**

The general layout of this device is similar to an axial flow cyclone. It has an axial arrangement consisting of a swirl generator, separation zone, diffuser section, and liquid collection belt, as shown in the figure above. The inlet gas/liquid stream travels through a set of stator vanes in the swirl generator that directs the flow to a larger radius while increasing the tangential velocity component. The stream then enters a separation zone, which is an annular region with a static inner wall, and a rotating outer wall formed by the inside of the rotor drum. The vortical flow subjects the fluid stream to a field of up to 3,000 “g”, which centrifuges the liquids (or particles) to the outer wall.

The rotating outer wall provides several important benefits. The primary advantage is a radially outward force continually applied to the separated liquid forcing it to “stick” to the moving wall. Secondly, because the outer wall and fluid are moving at approximately the same rotational speed, no significant fluid shear boundary forms. This results in a more distinct and smooth liquid layer compared to static walled cyclones, and provides significantly improved separation. Finally, the moving wall actively forces the separated liquid to a drain location. A combination of viscous drag on the drum and momentum transfer from the fluid stream passing through axial spokes on the rotor provides the energy for rotation.

After traversing the separation zone, the dry gas exits through a vaned diffuser section to recover a portion of its kinetic energy and to minimize exit swirl. The separated liquid on the rotor drum moves to a collection ring. Liquid exits the collection ring through four radial holes. It jets radially outward into an annular collector band, which directs it toward a tangential drain opening.
ADVANCED PRODUCED WATER TREATMENT

Ref: Presented by Hank Rawlins at 52nd Annual Laurance Reid Gas Conditioning Conference
The University of Oklahoma February 24-27, 2002 By permission of Author

6.7.10 Other On-Going Developments

3C cyclone (Saipem patent)

- CFD simulations and tests to develop a new compact cyclonic separation system

Process dynamic simulations

- Define subsea station control philosophy
- (Matlab-Simulink model)

Subsea power transmission

- Selection of subsea electrical network architecture

Hybrid separator (steel + composite) for subsea system lightening

- Alternative to heavy steel vessel for deep & very deep water (reduction of steel wall thickness)

FIGURE 53 - HYBRID SEPARATOR (STEEL + COMPOSITE) FOR SUBSEA SYSTEM LIGHTENING

6.8 Additional Considerations for Subsea Processing and Water Treatment

6.8.1 Sand Handling – A Fundamental Subsea Processing Challenge

Handling sand at the seabed is a huge challenge. The sand can clog separation equipment and if not properly removed from the produced water used for reinjection, can plug a formation and well bore causing a failure in the injection well completion, which was a result of operations for Tordis. The system was changed so that Tordis is re-injecting the sand slurry into the oil line for transport back to surface for disposal.

(OTC 20080 paper, 2009)

Sand can wear out pumps, subsea meters and flow piping over time. If sand is separated from the production stream, a major challenge is where to send it. Is it re-injected with the water, re-combined with the oil and transported to the surface or being stored / disposed in another way? This is important to understand when designing a subsea system and when sand is expected to be a problem.
ADVANCED PRODUCED WATER TREATMENT

The following information from a recent OTC paper is helpful in understanding the challenges in sand management of a subsea production system.

- The uncertainty of knowing the actual sand production rate and how this can be estimated in the basis of design is a big challenge. It is difficult to estimate the actual volume of sand production a system must handle and effective models do not appear to be readily available to the industry, which results in costly and complex system designs.

- Sand detection tools can be used, but are not well understood and are often improperly operated. This can result in underestimating high sand production rates, making it hard to properly handle the sand.

- Because of the lack of reliability of performance in sand detection equipment, subsea systems need to be simple and efficient.

- The technology to handle sand subsea and discharge it at the seabed does not exist today, but such a technology could be a solution where other options struggle to work. For instance, applications with water separation and re-injection. The typical solution is to handle the sand at the topside facility. Ideally, engineers would prefer to re-inject the sand in the reservoir, but little agreement can be found in the industry on how that can be done without having major problems. More work is needed to better understand this problem.

- Not having sufficient liquid to handle the sand transportation can also be a problem.

This has already been a major concern in the existing subsea separation projects of Tordis and Pazflor. Both projects have executed extensive sand handling test exceeding normal practices for topside separation processes. This will continue to have a high focus as the industry will use more advanced separation equipment for new applications.

(OTC 20080 paper, 2009)

6.8.2 Examples of Sand Handling System in Installed Subsea Processing Systems

Installed subsea separation systems either have included extensive sand handling system, or have managed sand through flow velocity. For example

- Tordis Subsea Separation Boosting and Injection (SSBI) system, for Statoil in the North Sea: Sand jetting and flushing system
- Marlim Subsea Separation System, for Petrobras in Brazil: desander included
- Pazflor Subsea Separation System (SSS), for Total in Angola: avoid sand accumulation, sand flushing system as backup.
- Shell BC-10 (Brazil) and Perdido (US Gulf of Mexico): avoid sand accumulation, large debris are collected in caisson sump.

The Tordis subsea separation system was originally designed for re-injection of sand with the water. That advanced sand handling system used a bypass to route the sand around the water injection pump to increase the pump life.

Being the most advanced sand handling concept to date, Tordis addressed the problem one step at a time.
ADVANCED PRODUCED WATER TREATMENT

- Sand enters the separation station as part of the inlet well stream.
- Sand is separated to the bottom from the fluid stream in the large gravity separator.
- Sand is removed from the bottom of the gravity separator by a sand removal system.
- A static jet pump driven by pressurized water from the water injection pump helps to transport the sand to the injection pump.
- The de-sander vessel is pressurized by water from the water injection pump enabling removal of the sand to the downstream side of the pump.

By this process, three important features are achieved:

1) Sand is separated from the oil and gas stream.
2) Sand is not routed through the pumps, extending the lifetime of the pumps.
3) Sand is re-injected with the water.

This process has been proven and tested and is becoming a recommended oilfield practice.

The sand handling solution of the Pazflor system was simply to allow the sand to follow the liquid through the separator and be pumped to the topside facility, but it is a challenge for the system to avoid high volumes of sand.  
(OTC 20080 paper, 2009)

For future projects, it is important to realize that simple sand handling systems are essential for low cost and high availability. Some of the new sand handling technologies that follow will make a subsea produced water treatment system easier to design.

FIGURE 54 - INLINE CYCLONIC SEPARATION EQUIPMENT - CLOCKWISE: LIQUID-LIQUID SEPARATION, PHASE SPLITTER, DE LIQUIDIZER, DE-SANDER (REF. OTC 20080 PAPER, 2009)
6.8.3 Operating principle of the FMC InLine DeSander

Upon entering the cyclone, the fluids are given a swirling motion by a specially designed swirl element. Light phases (water, oil and gas) leave the separation section through the centre opening. The solids collect on the outside of the middle pipe section. This pipe section is tapered and thus guides the solids into a concentrated stream, which is taken to the solid outlet. The multiphase (gas-liquid) stream that was separated into the inner pipe is passed to the outer pipe through openings in the swirl element blades.

The Swirl element imparts swirl flow and G-forces for separation. The sand is pushed out to the side wall while the liquid or multiphase flow leaves the separation section through centre openings.

For a given flow a single or a few large units can be used or multiple smaller units. The benefit of using multiple smaller units is that the G-force will be higher and thus smaller size particles can be separated. The advantage of the larger units is that these are more robust when separating larger particles and are better at handling large amounts of sand.

The unit achieves a solid content of less than 30 ppm (wt) based on an inlet condition of less than 500 ppm (vol) of solids. The oil content is approximately 400 ppm (vol) of oil in water. The collection vessel is equipped with a Sandwash System for automated disposal of the sand.


FIGURE 55 – FMC In Line Desander Operating Principle
ADVANCED PRODUCED WATER TREATMENT

6.8.4 Process Controls of Subsea Separation Systems
Many experts in the industry believe that the subsea control system is the most critical part of any subsea production system. Because of location, the subsea control system tends to be less complicated than a typical topside control system. Retrievalability and redundancy have been major issues and data transfer rates from subsea instruments to a topside control system have also been a challenge due to the limited bandwidth that comes with the use of traditional umbilical cables. The use of fiber optic cables alleviates this problem by providing lightning fast data transfer rates, high data volume and the ability to transmit data over distances exceeding 100 miles without a repeater (amplifier). The control system designed to handle a produced water treatment system subsea will require a significant effort and will most likely come with a high cost as seen on the Tordis project.

(OTC 20080 paper, 2009)

6.8.5 Subsea Power Distribution
Another major challenge for subsea processing systems that handle produced water treatment will be in the distribution of power to operate the pumps, coalescence devices, measurement systems and control valves. Pumps in particular are a fundamental component of the subsea processing system and require a lot of electric power. The conventional subsea pump concept uses power generation at the host.

Additional concepts providing a transformer, switchgear and a variable speed drive system on a floating control facility located directly above the wells would be a good idea for a long tieback of 50 miles. In this way the umbilical is as short as possible.

(OTC 20080 paper, 2009)

6.8.6 Separation Building Blocks for the Future
New compact technologies that can be used for separation have been developed for topside applications. Oil companies and equipment suppliers have been working on bringing the compact technology to subsea application:

- Inline separation technology applying high G-forces
- Separation in pipe segments instead of in large vessels
- Use of electrostatic coalescence techniques

Table 9 summarizes the existing inline technology. Subsea water treatment applications require liquid/liquid separation technologies, the current status of which are summarized in Table 10. The discussions earlier on technologies under development provided additional details.

The overview in Tables 9 and 10 identifies the key components required to effectively design a subsea processing system to handle bulk separation of oil and water. It will be a challenge for the industry to use these components in new subsea applications, but as the industry matures, technologies are meeting those challenges and evolving into a process system that is more reliable and capable of performing with a wider range of flow regimes. As the industry is pushing the technology to meet oil-in-water requirements
between 5 - 20 mg/l, subsea applications will benefit from using these technologies, such as hydrocyclones and compact floatation units. (OTC 20080 paper, 2009)

Table 9 – Overview of Existing Inline Technologies (OTC 20080 paper, 2009)

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>FEATURE</th>
<th>TECHNOLOGY STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degasser</td>
<td>Enables separation of gas from a liquid stream.</td>
<td>Qualified and Field Proven Technology - 3 commercial applications</td>
</tr>
<tr>
<td>De-liquidizer / Phase Splitter</td>
<td>Enables liquid separation from a gas stream / separating two uniform phases.</td>
<td>Qualified and Field Proven Technology - 20 commercial applications</td>
</tr>
<tr>
<td>De-sander</td>
<td>Separation of solids from a liquid, gas or multiphase stream</td>
<td>Qualified technology - 3 commercial installations to be set in operation during 2009, already experiencing successful operational performance.</td>
</tr>
<tr>
<td>Bulk de-oiler</td>
<td>Separates oil from w water stream (&lt; 50% water cut)</td>
<td>First offshore system being manufactured.</td>
</tr>
<tr>
<td>Inline Electrostatic Coalescers</td>
<td>Increases sizes of water droplets in oil.</td>
<td>Conceptual design developed, ready for qualification for topside applications.</td>
</tr>
<tr>
<td>De-watering</td>
<td>Separates water from an oil stream (&lt; 50% water cut).</td>
<td>First generation conceptual design established.</td>
</tr>
</tbody>
</table>
# ADVANCED PRODUCED WATER TREATMENT

Table 10 – Comparison of Liquid-Liquid Separation Technologies *(OTC 20080 paper, 2009)*

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>PROS</th>
<th>CONS</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| Gravity Separation | - Simple concept, gravity vessels applied topside.  
- Sand separated from fluid stream, efficient de-sanding concept if sand needs to be separated from the water stream. | - Typical subsea application not applied topside. Design subsea needs to be different than topside. Experience from topside therefore less vital.  
- Large units, large diameters, difficult to install and manufacture.  
- Large unit, high total system cost.  
- Sand settles from the liquid stream – need sand removal system in vessel. | - This is a topside solution - Solutions tailor made for subsea applications that are more suitable already exists. |
| Semi-Compact Gravity Separation (Gas-Liquid Separation in Inlet Cyclone / Liquid/Liquid Separation in Vessel) | - Uses building blocks proven from topside, arranged in a more optimal way for subsea applications compared to conventional gravity separator.  
- Applied for the Tordis SSBI separation system.  
- Sand separated from fluid stream, efficient de-sanding concept if sand needs to be separated from the water stream. | - Also resulting in a large separator vessel, even though significantly more compact than a conventional gravity separator.  
- Sand settles from the liquid stream – need sand removal system in vessel. | - Tailor made subsea concept. Will need water treatment technology to meet strict oil-in-water requirements.  
- Advantage compared to conventional gravity separation larger for high gas flow rates. |
### ADVANCED PRODUCED WATER TREATMENT

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>PROS</th>
<th>CONS</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| Pipe Separation          | - Smaller diameter components, more suitable for large water depths, high design pressures.  
                           |  
                           | - Efficient separation due to favorable flow conditions, therefore suitable for separation of difficult fluids. | - Sand handling a major challenge and currently a technology gap.  
                           |  
                           |  
                           | - Only diameter reduction compared to a vessel, overall system mechanical structure still bulky. | - De-sander and sand flushing technology associated technology that may be important facilitator for use of pipe separation technology.  
                           |  
                           |  
                           |  | - Needs upstream gas/liquid separation.  
                           |  
                           |  
                           |  | - Needs water treatment technology to meet strict oil-in-water requirements.  
                           |  
                           |  
                           |  | Use of ejector technology may limit consequence of pressure drop. |
| Cyclonic Liquid-Liquid Separation | - Very compact technology, especially suitable for large water depths, or applications with high design pressures.  
                           | - Easy sand handling, sand will follow the water stream and not accumulate in the separator | - Requires pressure drop to achieve high G-forces for separation.  
                           |  
                           |  
                           |  | - Challenge to both meet very strict requirements both for oil-from-water and water-from-oil separation at the same time. Currently a focus area in technology development.  
                           |  
                           |  
                           |  | Needs upstream gas/liquid separation.  
                           |  
                           |  
                           |  | Needs water treatment technology to meet strict oil-in-water requirements.  
                           |  
                           |  
                           |  | Use of ejector technology may limit consequence of pressure drop. |

#### 6.9 Summary

From the review of the state of art in topsides and subsea technologies relevant to seabed produced water treatment and discharge, we have the following main findings:

- Available offshore water treatment technologies are primarily used in topsides, which treat the produced water for discharge to sea. There is a very limited amount of subsea projects which separate oil and water. There is no subsea water treatment for discharge.
- Topsides water treatment generally requires a tertiary systems which involve separator, CPI separator / hydrocyclones / skimmer, and Induced Gas Flotation. Filtration is sometimes
ADVANCED PRODUCED WATER TREATMENT

required after the tertiary systems as a polishing step to achieve low oil and grease concentrations. Membrane filtration is sometimes required to remove dissolved organics. A recent technology on filtration is to infuse hydrophobic polymer to filters to reduce the effluent oil and grease concentration.

- Subsea separation technologies have focused on two-phase gas liquid separation. The installations with oil/water separation were intended for injecting water to wells, which allow much higher oil in water content than discharge limitations. Suspended solids in the water are major challenges for injection.

- Compact subsea oil/water separators and desander for deepwater have been developed and to be installed in the near future. Multiple technologies in this area are under development.

- Currently subsea oil/water separation systems do not meet discharge limitations on oil and grease concentrations. They can achieve oil in water concentration of several hundred ppm, which is about 10 times the discharge limit.

The control and monitoring of the process will be critical in providing confidence to the industry that such processes are working and effective. Subsea sampling of separated water have been practiced.

Deepwater seabed treatment and discharge of produced water and/or solids will likely require significant power for pumping the large volume of water and to overcome the pressure difference between the seabed hydrostatic pressure and the treatment system pressure, which may be much lower. Current technology can provide the power required since several deepwater projects already use significant power to seabed pumping.

The industry appears to have very capable vendors that supply these technologies and understand the challenges they face with delivering them to the seafloor. They well understand the requirements to provide reliable products to the subsea processing system and most of these vendors have a research and development program that is being coordinated with various operators within the industry.
REFERENCES


3. The Treatment of "Produced Water" in Offshore Rig: Comparison Between Traditional Installations and Innovative Systems, F. E. Ciarapica, G. Giacchetta, Department of Energy, Faculty of Engineering, University of Ancona via Brecce Bianche, 60131, Ancona, Italy.


8. Introduction to Produced Water Treatment by Nature Technology Solution


11. Study of Beneficial Reuse of Produced Water, Water Innovation Planning Committee (WIPC) of the Petroleum Technology Alliance Canada (PTAC), August 2007


13. OTC 20080 Comparison of Subsea Separation Systems

14. Van Khoi Vu, Total; Rune Fantoft, CDS Engineering; and Chris Shaw and Henning Gruehagen, FMC Technologies
ADVANCED PRODUCED WATER TREATMENT