Subsea Water Treatment and Injection for IOR and EOR
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Abstract

The patented SWIT technology enables production and injection of treated sea water directly from the seabed in a flexible and cost effective manner. The technology, proven and ready to use, enables a step change in reservoir and asset management that can accelerate production and increase recovery. Recent testing has proved that a combination of SWIT and membranes can produce low salinity and sulphate free water for extended periods of time without any degradation in membrane performance.

The Subsea Water Intake and Treatment (SWIT) technology offers a different approach to how reservoirs and assets are managed and produced. Cleaning the surrounding sea water at the seabed and feeding directly into subsea injection wells is a completely different concept than the traditional topside approach. The benefits are significant from many aspects; reduced weight and area required topside; no long reach platform water injectors (WI) required; acceleration of production; increased recovery through flexible and phased deployment of the WI capacity required.

From 2009 – 2010, a 15 months full scale pilot test was carried out at the seabed in the Oslo fjord. The SWIT treated water was pumped to the onshore NIVA Marine Research Centre for monitoring and testing. The results exceeded expectations and documented superior water quality for WI compared to traditional topside facilities.

The superior quality water achieved (including the ability to control the chlorine level very accurately), paved the way for developing a process for producing low sulphate and low salinity water at the seabed. A second Joint Industry Project completed mid 2013 has proved that SWIT feeding RO membranes can enable long membrane lifetime without any degradation in water quality.

Both Joint Industry Projects (JIP) were verified by the oil company participants and have provided the data required to enable the technology to be passed through their own technology qualification programs.
Introduction

Maximizing recovery of the limited (and not renewable mineral) oil resources is vital in order to meet future demand. Rate of new discoveries, size and recovery factor will be key to future supply, pricing of oil and project economics. Maximizing oil recovery is an important issue in both existing and new fields, to optimize project economics and for resource management at a corporate and national level.

Recovery mechanisms range from pure primary depletion to secondary and more sophisticated tertiary methods. Primary depletion will recover only some 15 – 20% of Original Oil in Place (OOIP), depending on reservoir and fluid characteristics. Water Injection (WI) is by far the most used secondary recovery method, providing pressure support and sweeping oil towards the producers, resulting in recovery of some 35 – 50% of OOIP (or higher) depending on reservoir and fluid characteristics.

Location of the WI wells in the reservoir, well spacing and distribution of the water are critical factors to achieving efficient waterflooding. Unfortunately, planning and optimization of the waterflood requires dynamic data, gained by ongoing production history. Production and pressure development give insight into the nature of the reservoir, faults and heterogeneities – and basis for optimizing the waterflood. As such, the investment decision on WI capacity required, number of slots and wells, is premature at platform design stage.

Treatment of water for WI systems and wells represents a significant part of development and operational cost. In some cases field development projects become uneconomic. Therefore, reducing cost and increasing flexibility and regularity are vital to economic and robust developments, and to maximize recovery in both existing and new fields.

Current global offshore water injection is some 270 Million bpd of water, about 3 times oil production (Guan, L. et al, 2005, Rystad Energy UCube). As more and more major oil fields mature, oil wells begin to produce more water because of aquifer encroachment and breakthrough of widely applied WI. By 2030 WI is expected to approach a total some 500 million bpd of water, some 7 times the oil production (Rystad Energy UCube). The scale of the business and the opportunity for improvements and ‘changing the game’ are significant, as indicated in Figure 1, based on evaluations carried out by Rystad Energy.

An increasing number of new discoveries are made in deep water. Subsea solutions are required to develop deep water fields. The industry is pushing the boundaries for new subsea technology and some Operators are aiming at moving the entire development subsea. Statoil use the term ‘Subsea Factory’ – reflecting the ambition to cover all functions and processes at the seabed and tie production and communication through pipelines and umbilicals to an onshore hub (Økland, O et al. 2013).

While most functions are covered or in the process of being developed, water treatment at the seabed is ‘a missing link’ in the factory. The SWIT technology is closing that gap.
This paper will present and discuss SWIT – a subsea water treatment technology which opens new ways of developing oil fields – to reduce cost and emissions whilst maximizing oil recovery.

**Reservoir Management and Water Injection**

WI is increasingly becoming the base case development to maintain reservoir pressure and to deliver a high ultimate recovery. As such, the term secondary drainage method may be misleading (Guan, L. et al, 2005). Pressure support is important to maintain energy in the reservoir, to lift the liquid column in the wells and to maintain pressure above the bubble point. Allowing pressure to decline below the bubble point of the reservoir fluid may severely affect ultimate recovery.

Injected water also sweeps the oil towards the producers. With increasing understanding of the architecture and properties of the reservoir, and aquifer strength, new WI wells can be better placed in the reservoir for an optimum waterflood and oil recovery. The ability to gather information from the reservoir and to build numerical reservoir models has enabled a much greater understanding of reservoir drainage in recent years. Flexibility to act on new reservoir information and understanding, phasing in more WI capacity where and when needed, has a potentially significant impact on recovery and value.
Water flooding sweeps movable oil in the reservoir. The sweep efficiency and ultimate oil recovery are dependent on location and number of injection points in the reservoir, and the nature and complexity of the reservoir and fluid. Efforts to optimize recovery of movable oil is normally referred to as Increased Oil Recovery (IOR). A certain amount of OOIP is bound to the rock. The wettability characteristics of the rock determine how much of the oil is bound. A number of techniques are available to influence the wettability and release oil from the rock. Surfactants, polymers and low salinity water are examples. These techniques are normally referred to as Enhanced Oil Recovery (EOR), or tertiary drainage methods\(^1\) (Dake, L.P. 1978 4.9). Unfortunately, one thing they all have in common that they are costly to implement with current technology.

The SWIT technology, enables subsea water treatment and injection of water from the seabed. It therefore offers a new flexible and cost effective approach to both IOR and EOR.

During millions of years, a chemical equilibrium between ‘crude oil, brine and rock’ (CBR) has been established in the reservoir. The distribution of oil and water in the porous system in the reservoir is linked to the wetting properties of the CBR-system, i.e. the contact between the rock surface and the two fluids, oil and brine. The wetting properties have strong influence on the two-phase fluid flow in the porous medium because they dictate the capillary pressure and the relative permeability’s of oil and water (Austad, T. 2012).

Today most of the oil reservoirs are waterflooded in order to improve oil recovery. As discussed above, the main reasons for performing a waterflood are:

- Pressure support to keep the reservoir pressure above the bubble point pressure
- Displace the oil by water by taking the benefit of viscous forces, sweeping the oil towards the producing wells

Significant studies have been conducted over the last two decades on wetting properties on different CBR systems. Injection water has a different composition compared to the initial formation water and disturbs the established chemical equilibrium of the CBR-system. By establishing a new chemical equilibrium, the wetting properties will also be changed, which may result in improved oil recovery. Therefore, it follows (Austad, T. 2012):

- Secondary recovery process - Injection of formation water will affect the chemical equilibrium insignificantly, only the relative saturations are affected. This is normally the case with cleaned sea water as well, and categorized as Increased Oil Recovery, IOR.
- Tertiary recovery process – Injection of water with a different composition than the initial brine, may change wetting properties and act as a tertiary recovery process. This is normally categorized as Enhanced Oil Recovery, EOR.

Reducing the salinity of injection water is a method to alter the wettability, in order to increase oil recovery. Different reservoirs and fluid systems respond different on injection water with low salinity, i.e. some gives a positive net effect on recovery while others show marginal effect.

Clair Ridge in the North Sea, operated by BP, is an example where significant investments have been made to implement a low salinity water injection project. However, this is based on traditional topside facilities.

The maturing UK offshore continental shelf is an example of the ongoing initiative regarding Low Salinity EOR. The ongoing PILOT scheme ([www.itfenergy.com/index/news](http://www.itfenergy.com/index/news)) underlines the attention and commitment low salinity and EOR receives from both industry and authorities.

Combining SWIT with membranes, enables dissolved ions to be removed as well as suspended particles in a combined treatment process that can be expected to work reliably on the seabed.

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\(^1\) Some techniques has an effect on both movable and non-movable oil, like miscible gas injection and water alternating gas, WAG, as examples.
Water Treatment is a Prerequisite

Water quality is an important factor for maximizing sweep efficiency during waterflooding and also preventing reservoir souring. Untreated (raw) seawater naturally contains a variety of dissolved and suspended solids – typical composition and values of dissolved solids are shown in Figure 5.

In addition to these naturally occurring dissolved solids, a variety of suspended solids can be found which are dependent on prevailing site conditions. Changes in prevailing site conditions can mean huge variations in suspended solids. Factors like: time of year, time of day, seawater temperatures, tidal currents, storm conditions, depth etc. can have significant effect on both suspended ‘organic’ and ‘non-organics’ solids.

Preventing the reservoir from plugging via solids removal, is one of the key factors in maximizing sweep efficiency. However, very little data exists on the difference in plugging the pores in the reservoir with organic solids and non-organic solids. It is logical to assume that non-organic solids will cause decreased / loss of injectivity by one of the following means (Gao, C. 2007):

1. Adsorption (typically small colloidal particles via Brownian motion, and electrostatic interaction),
2. Gravity settling, and
3. Size exclusion

It is natural to assume that organic solids will be softer in composition and less susceptible to the above blocking mechanisms for pressurized flow. However, at certain times of the year, factors such as plankton blooms can cause significant problems with filtration plant due to the huge volumes of marine organisms present.

Preventing reservoir souring is another key factor in required water treatment prior to injection. Of the many types of bacteria, the presence of Sulphate Reducing Bacteria (SRB) is the major contributor to reservoir souring. Treatment to prevent souring can take several basic directions e.g.: destroying the bacteria, providing non favourable conditions for the bacteria to multiply, or depriving the bacteria of nutrient or sulphate. The more of these techniques that can be applied simultaneously, the less the likelihood is of reservoir souring, thus avoiding the serious corrosion, integrity and HSE consequences.

Depending on the reservoir, scaling tendencies can be experienced due to the interaction of naturally occurring salts in the reservoir and injected water. Additional treatment can therefore include chemical dosing with scale inhibitors.

In later years, the removal of dissolved solids in injection water via membrane treatment has been used to good effect:
• The removal of sulphate ions from injected water is sometimes required to prevent scaling and reduce the possibility of reservoir souring.
• The ability to inject low salinity water into reservoirs has in some cases shown to significantly increase the recovery factor of the oil in place in a reservoir

Basic Principles of how SWIT works

Traditional water treatment at topside involves extensive equipment and processes. The size and weight of the water treatment plant drives size of structure and cost. Figure 8 gives a comparison of main components for a water treatment and injection system topside and at seabed using SWIT.

By using SWIT, the water treatment is moved from topside to the seabed. At the seabed weight and space limits are not as restrictive as for topsides equipment. The SWIT technology take full advantage of that freedom at the seabed, using a large still room and a system with practically no rotating or moving parts. An experienced regularity of almost 100% reflects the inherently simplistic and robust treatment system.

Figure 9 and 10 illustrate the main components of SWIT and how it works (numbers below correspond with numbering in the figures): Flow is induced through the SWIT unit by starting of the downstream pump. Placing the SWIT unit on the pump suction ensures that there are no additional feed pumps and hence no moving parts are required for the treatment process. A typical power consumption to operate the electrochemical cells is 10 kW for 40,000 bpd.

1. Raw sea water enters the SWIT through large proprietary electro chlorination (EC) grids that produce sodium hypochlorite. All water flows through the grids.
2. The large treatment volume (typically 8m x 8m x 7m) of 448 m³ for a 40,000 bpd capacity gives the disinfectant sodium hypochlorite over 1-2 hours’ residence time (chlorine soak) to react with any organic material and bacteria.
3. Very low velocity and the controlled flow through the SWIT provides optimum conditions for settling of particles via sedimentation (Stokes law) and thus removes particles without any filters.
4. Hydroxyl Radical Generator (HRG) produces OH⁻ molecules that instantly kills any bacteria surviving the chlorine soak and mineralizes organic material at the outlet (Kraft, A. 2007. 367)

The combination of the factors above leads to a superior water quality compared to traditional topside solutions. This is further discussed in section below ‘Development and Qualification’.

The use of a large area EC and the large volumes of water passing over it enables a very accurate control of the chlorine content – adjustable to within 0.01 mg/l. This is particularly important if the water is used as feed to low salinity (RO) or low sulphate (nano) membranes.
The illustration in Figure 10 is based on a 40,000 bpd unit. While it is easy to scale the technology to any capacity desired, a typical size of 40,000 bpd has been considered appropriate for most applications. One of the benefits using SWIT and subsea WI is the distributed and decoupled (from topside) approach where a SWIT will typically serve one to two injectors. This will allow simplified vertical water injection wells and treatment of sea water next to the wellhead.

The SWIT unit consists of two main parts – Still Room and Treatment Unit (TU). The Still Room is simply a box made of non-corrosive GRE type of material and will stay at the seabed – either until end of field life, or moved to another injection well site. All critical components with an operational lifetime are placed in the TU, which can be seen detached from the Still room in Figure 11. Intervention intervals are estimated to 4 – 5 years, when the 7 tons TU will be replaced by light intervention vessel. The dimensions of the TU are such that it fits standard containers and make logistics easy.

The design of the EC and HRG cells are such that it is easy to build in redundancy (e.g. 2 x 100%) to ensure that requirements for adequate subsea lifetime and that intervention intervals are met.

The SWIT unit will, in most cases, operate together with a subsea water injection pump to deliver required delta pressure at wellhead. The injection pump, downstream from SWIT, will draw the water through the SWIT unit. Pressure loss across the unit is only a few centimetres water gauge.

Solids are accumulated at the bottom of the unit. At certain intervals they are removed by a system which slurries the solids and jets it out. ‘TORE’ is an example of such device, already installed and in operation on similar subsea duties. Given the large footprint of the unit it may not be required to remove solids during the life of the field in areas with low or medium amount of suspended solids.

SWIT is qualified for water depth down to 3000 m.

**Monitoring and Control**

SWIT has an advanced subsea treatment control system, developed around existing robust and reliable technology. The system has a large degree of autonomy built in with distributed control. Operating instructions are passed to / from topside host platform (or from a regional or global operation centre) to the SWIT treatment unit. The control system in SWIT will then monitor and perform adjustments or corrective actions automatically within a defined envelope.

All connections and interfaces are based on standard communication protocols to simplify hook-up with existing systems or to be integrated with other systems as required by the Operator.

The system is very suitable for integrated operations where an operation centre could monitor and control operations on multiple treatment sites globally. The pilot projects run in the period 2009 to 2013 were monitored and controlled via the net from Seabox office in Stavanger, some 500 km away from the site.
Configurations

Figure 11 illustrates a standard typical 40,000 bpd SWIT unit. In most cases a pump is required to deliver the required injection pressure at the wellhead for injecting the desired volume of water. In a relatively shallow area like the North Sea, dropped object protection and over trawling protection are required. Standardized integrated solutions into 4-slot frames as indicated in Figure 12 are often considered an effective solution (Pinchin, D. and Olsen, J.E. 2013). The 40,000 bpd unit is designed such that it fits into one of the 4 slots. The water injection pump will be placed in the second slot and 2 slots are available for injection wells. Studies have been conducted together with AkerSolutions to ensure all interfaces and integration issues between treatment and pumping are addressed.

At other locations, modular approach is considered appropriate, as indicated in Figure 13. Different seabed soil conditions would also require different solutions, from suction pipes to simplified steel frame where seabed has good integrity.

The Subsea WI and SWIT are flexible and can be adjusted and configured to any application and site.

![Figure 12 SWIT and pump integrated in a standardized 4-slot frame](image1)

![Figure 13 Modular Approach](image2)

Business Case

In general, new discoveries are getting smaller and are found at deeper water locations, development costs are therefore getting higher. Existing fields in production represent infrastructure with a limited design life. The time window for developing marginal near field opportunities is therefore limited (and running out in mature basins such as the UKCS). Combined, the nature of the business is very dependent on new and more cost effective ‘tools in the toolbox’ to sustain production.

SWIT, enabling Subsea WI, is such a ‘tool in the toolbox’. Subsea WI (using untreated / raw seawater) is already in operation at few places in the world. Since subsea water treatment has not been feasible before the arrival of SWIT, the few places with raw sea water injection have been a balance between pressure support requirements and risk of injectivity problems and souring of the reservoir.

Two examples of ‘raw’ subsea WI are Tyrihans Field in Norway (Grynning, A. et al. 2009) and Albacora Field in Brazil (Buk Jr, L. et al. 2013). Tyrihans is somewhat a special case where the water is injected into the water leg far from the reservoir. At the time this was considered as the only way to get some pressure support.

Subsea water treatment is seen as a ‘missing link’ in the ‘subsea factory’, pursued by many Operators - Statoil in particular (Økland, O. et al. 2013).

Moving water treatment from top side to subsea has a number of inherent benefits to all involved disciplines including facilities engineers, well engineers and reservoir engineers. This is in contrast to the normal expectations of moving equipment and processes subsea which results in compromises, increased costs, and risks of reduced regularity and performance. This is not the case with SWIT.
SWIT adds value to all major asset dimensions as illustrated in the conceptual spider diagram in Figure 14.

Figure 14 Large operational and economic benefits compared to topside WI solution

Subsea WI and SWIT has the potential to significantly reduce cost. The reduction in power required for WI also leads to reduced emissions. Cost, HSE and regularity are all important factors for using Subsea WI and SWIT. However, the flexibility to add water injection capacity when and where needed, particularly for sweep purposes, will lead to increased production and recovery possibilities. This will in most cases be the biggest value driver.

Optimization of waterflood in mature fields are often constrained by topside water treatment and injection capacity, and available well slots. Subsea WI and SWIT allows for phasing in further capacity when and where needed, independently from topside. The only support required is electrical power from host or other nearby infrastructure.

A new development can take advantage of a number of knock-on effects by selecting Subsea WI and SWIT, as indicated in Figure 15. Production and Water Injection will be ‘decoupled’. The topside will focus on production with simpler vertical wells. Water treatment is moved to the seabed using SWIT. The structure (jacket or floater) will be reduced in size and weight, and cost, due to no water treatment facility or long reach drilling (for water injection) capacity. The water injectors are drilled as vertical wells where and when needed. This approach will reduce cost and provide flexibility to adapt and optimize reservoir management as understanding of dynamic nature of the reservoir is gained with production history.

Figure 15 Subsea WI – ‘De-coupling’ production and injection
Using Subsea WI and SWIT allows for phased investments, avoiding upfront investments in water injection capacity prematurely. Flexibility leads to a gentler investment profile with a total investment corresponding to actual capacity required. The ‘decoupled’ approach also allows for parallel activities where production wells can be drilled by rig at topside and water injectors by jack-up or floater in parallel, resulting in quicker build-up of production to plateau production.

As such, the approach with Subsea WI and SWIT reduces the total development Risk, and can increase the NPV.

**Satellite Fields and Area Development**

Most fields and developments have a number of discoveries and prospects nearby. Development of nearby satellites often suffer lack of capacity at host facilities, including water treatment and injection capacity. Even if such capacity is available, the cost of providing water injection service to satellites increases dramatically with step-out distance. In particular the high pressure water injection pipeline is expensive.

The SWIT technology requires only power and monitoring from a host facility. Both CAPEX and OPEX costs associated with a subsea WI solution can be expected to be less than with topsides solution – principally due to the costs of installing a high pressure WI pipeline. The cost differential will increase in favour of subsea WI the longer the step out distance from the host platform becomes. This may enable satellites to be tied back at an earlier stage and at a significantly lower cost. In some cases SWIT will therefore be ‘game changer’ to materialize discoveries within limited design lifetime windows of existing infrastructure.

Figure 16 illustrates how SWIT can be applied in area developments, where discoveries and satellite fields can be tied back to existing infrastructure.

**Development and Qualifications**

The development of the SWIT technology started back in 2002 and has gone through several phases of testing. The most important tests so far are:

1. The 15 months full scale test carried out 2009 to 2010 of a SWIT pilot.
2. The 9 months full scale test carried out 2012 to 2013 with SWIT combined with membranes to produce sulphate free and low salinity water
Full scale SWIT pilot test, 2009 – 2010 (Pinchin, D. 2011)

Funding and technical guidance came from Joint Industry Project (JIP) members Shell, Total, ConocoPhillips, GDF SUEZ, Seabox and Norwegian Research Council.

The SWIT pilot was placed at a depth of 65 m in the Oslo fjord, next to a national water research centre, NIVA. Treated water from the SWIT unit at the seabed was piped into the research centre onshore, allowing continuous monitoring and sampling. The EC and HRG were monitored and controlled remotely via the net from Seabox’ office in Stavanger, some 500 km away.

The results have given some clear indications about the best equipment selection and method of operating that equipment that will enable a robust and reliable subsea membrane treatment system to be deployed on the seabed.

The significance of this testing was that operators commonly only include for WI coarse filtration with solids removal down to a ca. 80 micron level. This indicates that the ‘solids in water’ quality via subsea treatment is adequate for most injection duties.

The bio fouling and souring potential results show that the combination of on line electro chlorination (with sufficient residence time) and hydroxyl radical generation (HRG) proved very efficient in the killing of SRB’s and significantly better than that achievable with normal topsides disinfection – thus avoiding or significantly delaying the onset of biofilms.

As the SWIT treatment system does not remove dissolved oxygen, it is possible to achieve aerobic conditions all the way to the reservoir thus preventing one of the key conditions required for any surviving SRB to reproduce. The test results showed an ability to maintain a clean (free of biofilm) water injection system. This, plus the use of corrosion resistant materials, will significantly reduce the likelihood of microbial induced corrosion. Once aerated water enters the reservoir environment, rapid oxygen (and chlorine) reactions will take place and remove remaining oxygen from the water.

The SWIT uptime was 99.8% over the whole test period where the remaining 0.2% was related to software debugging at the beginning of the test and power cuts. This compares very favourably to typical availability of topsides WI treatment plants of 85% uptime.

The 15 months full scale test of SWIT gave very successful results, particularly on disinfection. SWIT was therefore considered be a suitable seawater treatment system for most WI applications. It also showed SWIT to be an attractive pre-treatment stage for feeding a membrane system, to remove sulphate and salt. This lead to the planning of a new JIP and a new pilot test. Funding and technical guidance came from JIP members Exxon, Statoil, Lundin, Wintershall, Pall Corporation (industrial partner), Seabox and Norwegian Research Council.

Test combining SWIT and membranes, 2012-2013

The SWIT pilot was returned to seabed in the Oslo fjord, at the same location as in previous test. The treated water was piped to NIVA where membrane skids and equipment were located. The JIP testing ran for 9 months in total and enabled investigation of several treatment train combinations of SWIT, pre-filtration and RO / Nano filtration membranes. The test results have given some clear indications about the best equipment selection and method of operating that equipment that will enable a robust and reliable subsea membrane treatment system to be deployed on the seabed.

The significance of this testing is related to water chemistry problems of, souring, scaling and oil / water wettability. Some reservoirs require sulphate to be removed or reduced from the injection water to avoid scaling and souring of the reservoir. In other cases a reduced salinity of the injection water give enhanced oil recovery (EOR) effects. In both cases the water has to be treated with membranes to remove sulphate (SO\text{4}^{2-}) or salt (Na\text{+} Cl\text{-}) ions.

Traditional topside membrane plants suffer from water which is not sufficiently clean and membrane plant has to be frequently shut down to be cleaned by acid washing to remove bio fouling and solids.

Both above Joint Industry Projects (JIP) were verified by the oil company participants and have provided the data required to enable the technology to be passed through their own technology qualification programs.

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2 NIVA: The Norwegian Institute for Water Research, Drøbak, Oslo
Figure 17 gives an overview of the different components and the type of water produced at each stage – superior water for normal water injection, water for matrix flooding, and low salinity (for EOR) and sulphate free water.

The findings of this JIP pave the way to advance existing subsea treatment techniques and provide ‘tailor made’ water quality for injection into reservoirs – thus enabling significant IOR / EOR improvements and economic development of offshore oil fields.

Subsea WI / SWIT applications

SWIT is a new ‘tool in the toolbox’ which opens for new ways of developing new fields and optimizing existing fields. SWIT can be used in many different ways, the list below illustrates a wide range of potential water treatment applications and configurations (including some hybrid solutions):

1. **New field developments** – Significant benefits could include: Flexibility in reservoir drainage strategy (e.g. phased introduction), reduced size and weight on structures, cost and utilities savings, and decoupled WI well drilling.
2. **Optimising existing fields in production** – Revitalising WI capacity and well locations could lead to pinpointing infill locations for improved sweep. Acting on ‘real time’ information like production, pressure and new seismic surveys tracking the water flood front and identifying unswept oil by new injection points. Subsea WI could therefore be a ‘game changer’ in putting the reservoir engineer in ‘the driving seat’ and optimizing recovery based on understanding of the reservoir, not limited by facility and infrastructure constraints.
3. **Tie-back of satellites** – SWIT allows in many cases a significant lower development cost making nearby potentials profitable – with minimal implications to the host platform.
4. **Unreliable / expired lifetime of existing WI facilities.** E.g. #1: reinstatement of WI in satellite fields if water injection pipeline has corroded. Easy installation with no pipeline crossing issues. At end of field life the unit can be moved to new location. E.g. #2: Install SWIT unit next to existing platform feeding water to dry wells on topside, saving weight and place.
5. **Re-pressurize** tail-end gas (and oil) fields where reservoir pressure is lower than hydrostatic head, allowing for ‘injection’ without pump (‘dump’ water into the reservoir)
6. **Gas Fields – Enhanced Gas Recovery.** Some fields experience limited aquifer support and long term planning includes pressure support. With depleted reservoir pressure water can be ‘dumped’ into the reservoir.

7. **Feed to topsides membrane plants.** If sulphate removal or Low Salinity injection is required for EOR. A SWIT unit placed next to the platform will provide superior quality water to feed topside membranes thus improving membrane lifetime and treatment plant uptime.

8. **Feed to subsea membrane plants.** A complete integrated subsea facility including membrane systems is currently being processed for final qualification and is expected to be available for operation in 2015.

9. **Testing of formation injectivity** for potential CO₂ storage purposes

10. **Cooling water:** prevention of fouling in cooling water systems for both topsides and subsea equipment.

**Produced Water**

The treatment and disposal of produced water (PW) is a common problem for topsides production facilities. The three most common ways of dealing with PW water are to:

1. Treat for overboard disposal (in accordance with strict environmental discharge regulations)
2. Treat for injection into loss / disposal zone well(s)
3. Treat for injection into WI well(s) for IOR purposes.

In order to improve environmental impacts whilst improving oil recovery levels, option 3) is seen by many operators as being the preferred option – if achievable. Problems associated with injection of PW for IOR are well documented (Khatib, Z. and Verbeek, P. 2002, His, C.S. et al.1994, Flatval, K. B. et al 2004, Guan, L. et al. 2005) and are mainly associated with:

- Water quality issues (very variable oil and solids content)
- Availability of sufficient quantities of PW at stable flow rates
- Souring and scaling potential when remixed with reservoir fluids

During recent years the cleaning capabilities of PW treatment plant has improved significantly. Mixing of PW with seawater can overcome the problems of stable flow but significantly adds to the problem of souring and scaling potential – due to the high sulphate content of seawater. It is therefore an intention that the SWIT + membrane technology may be used to provide sulphate free injection water which in turn could enable mixing with PW for IOR purposes.

**Discussion**

At the onset of a field development, information regarding required injection flow rate, required water quality, flood patterns and number of injection points / wells, is limited to that obtained from an exploration / appraisal well. Reservoir cores, well fluid sampling and other information gained from the appraisal well is then combined with other information to provide an estimation of production rates for the field. This combined with fluid compositions, pressures, temperatures etc. are used for production facilities design.

It is by no means uncommon for these estimations to be incorrect when it comes to the actual field conditions experienced under operating conditions and subsequently grow in variation as the field operational life progresses.

Design of a WI plant will normally fall into these initial (pre-production) design considerations for the platform facility and hence be ‘locked in’ for the duration of the field life – unless changes are economically justified. Traditional water injection from offshore facilities is therefore unlikely to be designed for optimal field drainage.

Subsea water injection can provide a good deal of flexibility in being able to adjust field drainage strategies to meet actual reservoir conditions and production trends. Being able to adjust WI to meet ongoing field situations can include:

**Timing:** WI can be implemented as / when required, into the areas of the reservoir most receptive to pressure maintenance / water drive.

**Flow rates:** WI quantities can be adjusted to meet requirements.

**Flood patterns:** the ability to introduce flood patterns that most suit the reservoir can be implemented. More areas of the reservoir (pockets of bypassed oil) can become recoverable.

**Drilling:** being able to decouple the drilling of water injection wells and production wells will mean that the
platform drilling facilities can be used solely for production optimisation. A remote drilling rig can be employed to drill the (shorter, less deviated) WI wells on a timescale to suit production.

**Water Quality**: the existing technology qualified SWIT system can provide seawater at as good/better quality than is required by the majority of reservoirs. SWIT + membranes enables the possibility to inject ‘tailor made’ water thus improving oil production potential (EOR) and also overcoming problems with souring and scaling.

This paper has described the technology of subsea water treatment available via the SWIT system and has explained the testing conducted and readiness for field deployment as seen by major operators. It can also be seen that the SWIT technology can be used in different ways for a variety of applications.

**Conclusion**

The SWIT technology offers new ways of managing reservoirs and assets, to reduce cost and emissions and for IOR and EOR. It allows to put the reservoir engineer into the ‘driving seat’, optimizing oil production and recovery based on reservoir insight and opportunities, and not limited by pre-set topside and slot constraints. SWIT is an enabler for marginal satellite developments, and for optimizing area developments. The capability to produce any quality water at seabed will enable cost efficient low salinity projects for EOR.

SWIT enables a step change in reservoir and asset management that can accelerate production and increase recovery.
Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>bpd</td>
<td>Barrels per day</td>
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<tr>
<td>CBR</td>
<td>Crude oil Brine Rock (system)</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>EC</td>
<td>Electrochlorinator</td>
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<td>GAB</td>
<td>General Aerobic Bacteria</td>
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<td>HF</td>
<td>Hollow Fibre</td>
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<td>HRG</td>
<td>Hydroxyl Radical Generator</td>
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References